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Nuclear Power in Countries with Limited Electrical Grid Capacities: The Case of Armenia

A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

IAEA
International Atomic Energy Agency

NUCLEAR POWER IN COUNTRIES WITH LIMITED ELETRICAL GRID CAPACITIES: THE CASE OF ARMENIA

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A REPORT OF THE INTERNATIONAL PROJECT ON INNOVATIVE NUCLEAR REACTORS AND FUEL CYCLES (INPRO)

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in November 2000 under the aegis of the IAEA. Since then, INPRO activities have been continuously endorsed by the IAEA General Conference and by the General Assembly of the United Nations.

The objectives of INPRO are to help ensure that nuclear energy is available to contribute, in a sustainable manner, to meeting energy needs in the 21st century, and to bring together technology holders and users so that they can jointly consider the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles. One of the initial tasks of the project was the elaboration, testing and validation of the INPRO methodology, which can serve as a basic tool for evaluating different nuclear energy systems within a uniform framework to assess their compliance with sustainability goals. This phase, referred to as Phase 1, continued from 2001 to 2006.

On the basis of a decision of the 9th INPRO Steering Committee in July 2006, INPRO entered its second phase, with three main areas of activity: methodology improvement, infrastructure/institutional aspects and collaborative projects. During this phase, a number of nuclear energy system assessments (NESAs) were performed, at the request of INPRO members, and a number of collaborative projects on different topics were launched.

This publication is a result of a collaborative project undertaken during Phase 2 of INPRO. It presents a study of the issues related to the implementation of a nuclear power programme in countries with small capacity grids.

Six INPRO members — Armenia, Chile, France, the Russian Federation, the United States of America and Viet Nam — initiated the collaborative project on this topic. During implementation of the project, it was decided that Armenia could be taken as a case study, since its previous NESA provided important information supplementing the data obtained during the current investigations.

The report was finalized and reviewed by the project participants and IAEA staff during consultants meetings in 2010 and 2011 and partially updated by IAEA staff in 2015. The IAEA greatly appreciates the contributions made by the study participants, in particular A. Gevorgyan and V. Sargsyan (Armenia), who provided the main analysis of the Armenian electrical grid.

The IAEA officers responsible for this publication were V. Lysakov and A. Grigoriev of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The activities within this collaborative project on Implementation Issues for the Use of Nuclear Power in Small Countries were aimed at contributing to the achievement of the overall goals of Phase 2 of INPRO and have been implemented in line with the procedures agreed upon under the INPRO Project and with the responsibilities of the participants in this project.

In countries that lack natural energy resources the issues of energy security and independence take high priority. In addition to providing security and independence, nuclear power can significantly help reduce emissions harmful to the environment. Nuclear power becomes economically attractive when its share in the total energy system is properly considered. Comparatively limited nuclear programme provides a substantial contribution to national power capacity. It is important to note that non-electrical applications of nuclear energy systems (NES) were not considered in this study but could be in the future.

In addition to issues that are common to any nuclear system's development, this study has considered some requirements that are specific to small countries. These include: (1) a study of NES safe operation in small grids and (2) an investigation of fresh nuclear fuel supply, spent nuclear fuel (SNF) options and radioactive waste management.

As a producer of nuclear power that relies on imported fresh nuclear fuel, country embarking on nuclear power or developing already existing NES is very interested in a final solution for dealing with SNF and waste management. Further development of the nuclear option is therefore dependent on the assurance of both fresh nuclear fuel supply and long term management of SNF and high level waste (HLW). Management of spent fuel is part of the sustained safe and effective operation of NESs. Ensuring the safety and security of SNF, which will remain hazardous for a longer time than recorded history, is technically and socially challenging and the current generation must assume this responsibility. Any NES that addresses long term development should satisfy requirements for safety, environmental protection, economics, proliferation resistance, and the effective management and use of SNF. This project aims to assist decision makers in small countries to develop a comprehensive approach to waste management and SNF management that is socially acceptable, technically sound, environmentally responsible, and economically feasible.

Operating experience with nuclear power plants (NPPs) in grids of limited capacity — especially in developing countries — has shown that the safe and efficient utilization of NPPs can be hindered by grid disturbances and by incompatibility between certain characteristics of the grid and those of the NPP.

Frequent disturbances originating in small grids induce temperature and pressure transients in various NPP processes, resulting in thermal and mechanical stress in plant components. The transient stress due to major disturbances such as full load rejection, islanding and unit tripping — together with cyclic stress caused by small but continuous disturbances — may lead to a reduction in component life.

Statistically, the frequency and duration of unsafe situations — such as loss of power events that may lead to loss of coolant accidents — for reactors in small grids are much greater than those in the environment of high performance grids. If the probability of a failure to shut down the reactor during an unsafe situation is to be maintained at the same low level (less than one in a million), the reliability of the protective system hardware of NPPs in small weak grids may require enhancement.

The off-site protective electric power supply system should have adequate capacity to provide the necessary support for safe startup, running and plant shutdown. Additionally, the off-site system must be capable of dispatching the load and remaining stable. It must also have a protection system that keeps disturbances at a low level and of short duration and which prevents disturbance propagation through the system.

Introduction or development of nuclear energy in the country's energy system requires consideration of a number of infrastructural issues and may be specific in countries with developing economies. Among those, the issues of importance are those of the grid compatibility and nuclear waste and SNF management.

This study was undertaken to consider certain challenges which a small country may experience introducing the nuclear option into the strategic plan of the energy mix development.

"Small," throughout this report, refers to a country's grid capacity size; "small" is not used as a geographic or economic description.

The purpose of this study is to assess the role of NES in providing sustainable energy supply and to identify crucial areas of Research and Development (R&D), in particular with regard to management and development of existing electrical grids and radioactive waste management.

Armenia was selected as a case study because it could provide the information which may serve as a basis for more detailed study. Such information was obtained during previous investigations made in Armenia with regard to further development of its energy system and expansion of nuclear sector in particular.

1.2. STRUCTURE OF THE PUBLICATION

The study contains an introductory part devoted to the analysis of the Armenian natural resources potential and describes the existing energy system including the current state of the electrical grid.

The description is also provided for a geopolitical situation of Armenia, some aspects of which affect the energy independence and are rather specific for Armenia at the moment, however, may occur to some other small countries. Therefore, it provides added value to the analysis of the approach to economic development and energy system strategic planning, which could be applicable to other countries in case of similar situations.

The methodological approach taken within the project uses the INPRO methodology framework and explores different calculation tools, i.e. Model for Analysis of Energy Demand (MAED), Dynamics of Energy System of Atomic Energy (DESAE), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), Nuclear Fuel Cycle Simulation System (NFCSS) and a software package for power flow and transient stability analyses developed by Bonneville Power Administration (BPA).

The applied software packages allow to analyse effects on energy demand of changes in socioeconomic and technical development, estimate long term nuclear fuel cycle material and service requirements and the material arising, formulate and evaluate alternative energy supply strategies consonant with user-defined constraints on new investment, market penetration rates for new technologies, fuel availability and trade, and environmental emissions, develop the prospective nuclear energy scenarios on regional and global scales and calculate the stability of the existing and expanding electric grids.

Section 3 describes the Armenian country profile and analyses existing energy resources. It concludes that natural resources in Armenia are rather scarce and should be kept as a strategic reserve. However, even in this case the expediency of the industrial use of these resources should be carefully evaluated from the economic and environmental points of view.

It describes a structure of Armenian energy system including a nuclear power plant (NPP) among other types of generating facilities. The section also contains electricity market description and study of potential power to be received from renewable sources of energy. It is stated in the conclusion that Armenia has no indigenous fossil fuel for industrial use. All types of such fuel are imported and the country may develop some economically feasible potential of domestic energy resources such as hydro, solar, and wind.

Section 4 is devoted to the results of analysis of key ways to increase living standards and form energy policy and strategy for power system development. It also presents the action plan for the energy sector development adopted by the protocol decision 14 “On Approval of the Concept for Ensuring Energy Security in the Republic of Armenia” of the Republic of Armenia Government session No. 50, on 22 December 2011 [1]. The measures for implementation of the main directions of Government activities are planned for realization till 2036.

These plans include strategic development of hydro, thermal, wind and nuclear power with the aim to achieve energy security and independence. However, as for the energy capacities, there are no quantitative estimates neither for the potential of geothermal, biogas, solar (thermal and photovoltaic) and other possible sources of renewable energy, nor for the activities towards bio-ethanol production and the possible consequences of the continuous exploration of oil and natural gas. The issue of the efficient utilization of the aforementioned potential remains within the focus of the policies conducted by the Ministry of Energy and Natural Resources of Armenia.

Section 5 provides some country specific requirements that are necessary for the development of Armenian NES. They should take into account energy security and independence, nuclear energy development requirements, regional integration, diversification of supplies, implementation of social policies, ensuring financial stability and economic efficiency and education system for nuclear sector.

Section 6 provides some results from the previous studies which gave some forecast for the substantiated growth of electricity generation with regard to the increasing energy demand for the period up to 2035. It was shown that, considering the forthcoming decommissioning of the Armenian NPP (ANPP), the most effective way was to develop nuclear power capacity in Armenia and this approach becomes even more feasible if gas price is increased. At the same time it was concluded that uranium price variations do not considerably influence the optimum set found for generation expansion planning in Armenia.

Section 7 summarizes main recommendations that are valid also for other small countries intending to introduce nuclear power based on the analyses provided in previous sections. The recommendations deal with activities on energy security, level of energy independence from imported energy sources, stability, availability, and diversification of fuel supply options, economics of energy expansion plans, regional, interregional, and international integration and cooperation, and regular demand forecasts updates.

Part B of the study and in particular Section 8 is devoted to the study of the Armenian grid stability. The analysis is performed on the basis of the given equivalent of Armenian grid stability, power system and data from Armenian high voltage network both of current and pre-assigned states.

Section concludes that existing high voltage electrical grid of Armenia is developed well enough, that implementation of planned new 400 kV voltage level till 2020 will significantly increase the network flow capacity and export/transit capability while assuring stable operation level of the system.

Section also states that a new 1000 MW nuclear unit needs to be commissioned in 2026 and additional study revealed that in the case of the high development scenario, the Armenian economy may require one more nuclear unit to be commissioned by 2036. The WWER-1000 reactor has been selected for the next steps of this study.

Section 9 presents calculations of the steady state and dynamic regimes of the Armenian power system that have been studied, including the new ANPP 1000 MW unit.

Calculations were made for four scenarios, each of which considered maximum and minimum network loads targeted at 2026 and 2036. In all scenarios, it is assumed that there are no power exchanges with the Georgian power system through existing (220 kV and 110 kV OHLs) or future (400 kV HVL) intersystem connections. It is shown that, in general, the grid is capable of accepting the introduction of a new NPP and of withstanding emergency regimes. It behaves in a stable and steady way but, in some cases, it would require either decreased NPP output or connection of a new high voltage line (HVL) for export/import operations or, sometimes, switching some network supporting systems.

Section 10 summarizes some general recommendations related to grid stability for countries with small grids.

Part C of the publication (Section 11 and 12) describes the strategy of the approach to the Armenian nuclear fuel cycle (NFC). The current strategy foresees a once-through NFC and, therefore, simulation of material flow for the NES comprising two pressurized water reactors with 1000 MW capacity and subsequent isotopic accumulations was performed.

Sections 13 and 14 present some options for radioactive waste management which were analyzed with regard to specific requirements for a small country, and general recommendations for the approach to the issue.

1.3. OBJECTIVES OF THE STUDY

The overall objectives of the study are to:

– Review the feasible technically and economically sound options for SNF and waste management that are available and to select three or four options applicable to a small country;
– Evaluate key indicators of uncertainty for nuclear power development in different SNF and waste management schemes;
– Analyse results and define key challenges for each SNF management option. Identify near, medium, and long term institutional measures and technical solutions for each management option;
– Assess the sustainability of NPP safe operation in the anticipated NESs within grids of limited capacity/stability in small countries. Apply the relevant INPRO methodology criteria for assessing the NESs' safe and reliable operation.

2. APPROACH, METHODOLOGY AND TOOLS

2.1. METHODOLOGICAL APPROACH

Nuclear power is one of the various technological options for producing electricity. The future role of innovative nuclear energy systems can be determined if analysis regarding future electricity generation considers long term capacity growth requirements and all possible supply options. The electricity sector is inescapably part of the overall energy system. The supply of all indigenous energy resources as well as the import possibilities of various fuels and nuclear fuel cycles must be considered. With this comprehensive approach, different strategies for NES expansion can be evaluated and possible roles for nuclear power in a country's future energy sector can be determined.

Small countries, like Armenia, which intend to join the nuclear community have underdeveloped nuclear infrastructure compared to mature countries.

Due to Armenia's small grid capacity, this analysis is framed around power system stability so that weak and bottleneck points of operation can be easily identified and appropriate measures can be recommended.

In geographically small countries, waste management introduces additional concerns because of the lack of a robust transportation system and storage area. This consideration has also defined the scope of the study. The methodological approach taken within the project uses the INPRO methodology framework.

The INPRO methodology [2] identifies a set of basic principles, user requirements and criteria in a hierarchical manner as the basis for the assessment of a NES (Figure 1).

It is intended that the fulfilment of a:

– Criterion for a NES is confirmed by the indicator(s) complying with the acceptance limit(s);
– User requirement(s) is confirmed by the fulfilment of the corresponding criterion (criteria) (bottom-up approach);
– Basic principle is achieved by meeting the related user requirement(s).

2.2. DESCRIPTION OF ENERGY PLANNING TOOLS

This section describes the energy planning tools used for forecasting and analysing future energy demand and for modelling and selecting the least cost energy supply strategy.

Model for Analysis of Energy Demand (MAED) evaluates future energy and electricity demand on the basis of assumptions of medium to long term socioeconomic, technological and demographic developments in a country or a region. The model systematically relates the specific energy needs for producing various goods and services to the social, economic, and technological factors that affect the demand for a particular fuel.

Energy demand is divided into a number of end use categories, each corresponding to a given service or the production of certain goods. The nature and level of demand for goods and services are determined by population growth, number of inhabitants per dwelling, number of electrical appliances used in households, people's mobility and preferences for transportation modes, national priorities for the development of certain industries or economic sectors, evolution of the efficiency of certain types of equipment and market penetration of new technologies or energy forms. The expected future trends for these determining factors, which constitute "scenarios", are introduced exogenously.

FIG. 1. Structure of INPRO methodology.

The energy demand for each economic sector can be evaluated when the determining factors mentioned above are understood. The total energy demand for each end use category is summarized as four main energy consumer sectors: industry (including agriculture, construction, mining, and manufacturing), transportation, service, and household.

The starting point for using MAED is constructing a base year energy demand pattern of a given country, followed by developing future scenarios of the social and economic evolution of the country and technological factors, such as efficiency and market penetration potential of alternative energy forms.

The model focuses exclusively on demand for specific energy services. When electricity, fossil fuel, and other forms of energy compete for a given end use category of energy demand, this demand is calculated in terms of useful energy and then converted into final energy. Non-substitutable energy uses, like motor fuel for cars or electricity for lighting, are calculated directly in terms of final energy. Energy demand is calculated not only annually (as for all other forms of energy), but hourly as well. Such calculations serve as input data for further analysis of the energy generating system.

MAED provides a systematic framework for evaluating the effect of a change in socioeconomic and technical development on energy demand.

Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is designed to formulate and evaluate alternative energy supply strategies consonant with user-defined constraints on new investment, market penetration rates for new technologies, fuel availability and trade, and environmental emissions. The underlying principle of the model is the optimization of an objective function (e.g. least cost, lowest environmental impact, maximum self-sufficiency) under a set of constraints. The backbone of

MESSAGE is the techno-economic description of the modelled energy system. This includes the definition of the categories of energy forms considered (e.g. primary energy, final energy, useful energy), the fuels (commodities) and associated technologies actually used (e.g. electricity, gasoline, ethanol, coal, district heat), and energy services (e.g. useful space heat provided by type of energy/technology).

Technologies are defined by their inputs and outputs (main and by-products), their efficiency, and their variability if more than one input or output exists (e.g. the possible production patterns of a refinery or a pass-out turbine). Economic characteristics include investment costs, fixed and variable operation and maintenance costs, imported and domestic fuel costs, and estimates of levelized costs and shadow prices.

Fuels and technologies are combined to construct energy chains, where the energy flows from supply to demand. The model takes existing installations into account, including their vintage and their retirement at the end of their useful lives.

The investment requirements can be distributed over the construction time of a plant and can be divided into different categories to reflect the requirements of industrial and commercial sectors more accurately. The requirements for basic material and for non-energy inputs during construction and operation of a plant can also be accounted for by tracing their flow from originating industries either in monetary terms or in physical units.

For some fuel, ensuring timely availability entails considerable cost and management efforts. Electricity has to be provided by the utility at exactly the same time it is demanded, and MESSAGE simulates this situation.

Environmental aspects can be analysed by keeping track of, or limiting, pollutants emitted by various technologies at each step of the energy chains. This helps to evaluate the impact of environmental regulations on energy system development.

MESSAGE uses the projections of useful or final energy demand from MAED to generate the energy supply system. The most powerful feature of MESSAGE is that it provides the opportunity to define constraints for all types of technology. The user can, among other options, limit one technology in relation to other technologies (e.g. a maximum share of wind energy that can be handled in an electricity network), give exogenous limits on technologies (e.g. a limit on cumulative SO_2 or greenhouse gas emissions), or define additional constraints between production and installed capacity (e.g. ensure take-or-pay clauses in international gas contracts, forcing customers to consume or pay for a minimum share of their contracted level during summer months). The model is extremely flexible and can be used to analyse energy and electricity markets and climate change issues.

2.3. DESCRIPTION OF FUEL CYCLE STUDY TOOLS

This section describes the nuclear fuel cycle study tools used for calculating quantities and isotopic composition of spent nuclear fuel and radioactive waste.

The Nuclear Fuel Cycle Simulation System (NFCSS) [3] is a scenario-based simulation system to estimate long term nuclear fuel cycle material and service requirements and the material arising. The code uses simplified approaches to make estimations.

The NFCSS is able to calculate — by year over a very long period — nuclear fuel cycle requirements for all types of reactors. Calculations can be performed for a single reactor, a reactor park in a country, or NPPs worldwide. Natural uranium, conversion, enrichment, and fuel fabrication quantities can also be estimated. Furthermore, the quantities and qualities (isotopic composition) of unloaded fuel can be evaluated to let the user apply a recycling strategy if desired.

Data inputs are reduced to a few basic items in order to let non-nuclear fuel specialists develop different energy scenarios. The calculation speed of the system is fast enough to enable comparison of different options in a considerably short time. The NFCSS is designed to be an optimum mixture of accuracy, simplicity, and speed.

NFCSS calculations can cover the period ranging from the beginning of nuclear energy production to 2050 or 2100. In order to support estimations for the future term, NFCSS stores historical data in its database.

Historical data come mainly from the existing IAEA database (PRIS). Other authoritative publications and consultant reports are also sources for historical data. Future projection data can be calculated by using publications from different institutions. The IAEA's Energy, Electricity and Nuclear Power Estimates up to 2050 (the 2013 edition is the latest) is one of the authoritative publications which was used to calculate future nuclear power projection data in the NFCSS.

Fresh fuel requirements and spent fuel isotopic composition are then automatically calculated from a set of internal parameters that have been selected by experts and introduced in the programme. The user may then choose to use spent fuel stockpiles to develop a recycling strategy. The estimation of accumulation of actinides, including minor actinides, is one of the capabilities of the simulation. Those accumulation estimations might be used to compare any future fuel cycle options for transmutation of minor actinides.

The model uses simplified approaches to calculate the fuel cycle requirements. These simplified approaches enable the code to estimate the long term fuel cycle service requirements for both open and closed fuel cycle strategies.

The main assumption in the model is that it is possible to simulate the nuclear fuel cycle by taking into account the evolution of using different types of reactors over the years, without the precision of using a reactor-by-reactor database. In order to do this, commercial existing NPPs are grouped into seven types: pressurized water reactor (PWR), boiling water reactor (BWR), pressurized heavy water reactor (PHWR), advanced gas-cooled reactor (AGR), gas-cooled reactor (GCR), graphite-moderated boiling water reactor (RBMK), and water-cooled water-moderated reactor (WWER). There are a few power plants, which are not included in this list due to their insignificant share in the total nuclear power capacity. The users could introduce the different reactor types to the system if desired.

The NFCSS can be described as a simulation tool that makes calculations using a set of input parameters to produce a set of output parameters. The input parameters used on annual basis in the model may be divided into three groups:

– **Strategy parameters**, such as nuclear capacity and reprocessing/recycling strategies, reactor-type mixture and load factors;
– **Fuel parameters**, such as average discharge burn-up, average initial enrichment and average tails assay;
– **Control parameters**, such as share of mixed oxide fuel in the core of reactors using this type of fuel, lead and lag times for different processes, process loss coefficients, use of depleted or enriched uranium, and the number of reprocessing cycles.

The results are divided into the following groups:

– **Nuclear fuel cycle front end** — natural uranium requirements, conversion requirements, enrichment service requirements, and fresh fuel requirements;
– **Nuclear fuel cycle back end** — spent fuel, total individual nuclides including uranium, plutonium and minor actinides, reprocessing requirements.

The Dynamics of Energy System of Atomic Energy (DESAE) 2.2 code [4] is a system research model designed for developing the prospective nuclear energy scenarios on regional and global scales. The model has been developed in the Kurchatov Institute, which is one of the premier research centres of the Russian Federation.

The mathematical model of DESAE 2.2 code, as currently developed, calculates the nuclear fuel cycle requirements, material balances, and economic parameters in the framework of nuclear energy scenario development with a given combination of nuclear reactors during a specified timeframe.

To analyse the prospective nuclear energy development scenarios, DESAE 2.2 provides options to:

– Study the scenarios both in regional and global scale;
– Vary the scale and structure of the NES by commissioning different types of reactors at different rates;
– Modify the reactor characteristics and to study their influence on variation of NES parameters;
– Expand the data library with addition of new reactor types;
– Study both open and closed fuel cycles;
– Alter the spent fuel recycling capacity and external fuel cycle duration;
– Run the code in interactive mode with typical estimated time of about one minute.

DESAE 2.2 has been developed in such a way as to provide for saving earlier calculated variants and to enable the results to be viewed both in graphic and in Excel mode.

2.4. DESCRIPTION OF GRID STABILITY STUDY TOOLS

Modelling of high voltage electric network was carried out for a stability study with the use of a software package [5] developed by Bonneville Power Administration (BPA). The software package includes Interactive Power Flow (IPF) and Transient Stability Program (TSP) software. It allows the use of steady-state regime output data calculated by the IPF as entry data for TSP in order to study various accident regimes. The calculation algorithm used in this package is rather stable against calculation data spreading and allows the study of regimes that are even unallowable from the point of view of system real operation, but possible in theory.

Prior to the development of the IPF program, BPA developed the Power Flow Program (PFP) itself, and the Power System Analysis Package (PSAP). The PFP is a collection of Fortran-coded computer programs permitting the analysis of the steady-state operation of an electric power network. The IPF program consists essentially of the PFP part of PSAP and a graphical user interface specially designed for power flow data input, output, and manipulation.

IPF helps electric power system planning and design engineers investigate a given electric power network’s various operating parameters, such as:

– Bus voltage distribution;
– Line real and reactive power flows;
– Line overloads;
– System reactive requirements;
– Area interchange control;
– Transformer tap settings;
– Remote-bus voltage controls;
– Effects of load shedding, generator dropping, line outages.

In order to make more efficient use of computer memory space and computation time, the program uses advanced techniques of large-system analysis including the Newton-Raphson method of solution of algebraic equations and sparse-matrix computation techniques.

The IPF program offers many features. These include:

- Free form structured program command languages;
- Extensive error messages for maximum aid to the user;
- Basic and extended power flow capabilities;
- User-selectable printed output reports;
- User-selectable microfiche reports on a fiche file;
- Easy-to-use graphical user interface;
- Easy-to-edit graphical display of coordinate file data.

The BPA Transient Stability Program (TSP) program was developed in accordance with Western Systems Coordinating Council (WSCC) specifications and provides an effective tool for performing the dynamic simulation of a power system when disturbed from its steady-state condition under various perturbations.

There are two methods of solution used in this program. All differential equations are linear and solved by the trapezoidal rule of integration. The network equations are solved iteratively using the triangularized admittance matrix.

The swing program is divided into solution and output portions. The solution portion creates a swing solution file, which saves all output data for all buses in the study. This structure allows the user to run the solution portion and save the swing solution file. Then, using the swing solution file, the power flow output file, and the swing output data file, the user can run any number of output jobs without resolving the solution.

The program is designed to run in conjunction with the BPA PFP, and requires a power flow output file as input. The program also has a save data feature, which allows the user to enter the majority of the swing, input data via a save data file and enter only the line switching and control cards in the swing input file. This is useful when a series of swing studies are run using the same basic data but with different system perturbations.

3. ARMENIAN COUNTRY PROFILE

3.1. COUNTRY OVERVIEW

The Republic of Armenia is a small, landlocked, mountainous country, located at the crossroads of Europe and Asia, sharing borders with Turkey to the West, Georgia to the North, Azerbaijan to the East (with Nakhichevan to the Southwest) and the Islamic Republic of Iran to the South. The capital city of Armenia is Yerevan.

According to the *Constitution* adopted through a national referendum on 27 November 2005, Armenia is an independent and democratic country with a presidential system of government. The President is elected by popular vote for a five-year term. The executive body is the Government of Republic of Armenia headed by the Prime Minister. The National Assembly is the legislative body of the country (131 seats; members serve four-year terms).

The population of the country was around 3 017 100 inhabitants in 2013 (Statistical Yearbook of Armenia, 2014).

With an average elevation of about 1700 meters above the sea level (ranging from 400-3000 meters), Armenia is the most mountainous country of the Caucasus region. The lowest elevation (380 m above sea level) is in the Debed River valley, and the highest (4090 m above sea level) is Mt. Aragats.

Armenia is a country with very limited natural resources: hydro energy is the only indigenous source of energy.

Lake Sevan is one of the largest highland fresh-water lakes in the world, located about 1900 m above sea level. Its total area is about 1400 km^2. The main rivers in Armenia are: Araks (1072 km total length, 158 km within the territory of Armenia), Arpa (126 km, 90 km in Armenia), Hrazdan (146 km), Debed (178 km, 152 km in Armenia), and Vorotan (179 km, 119 km in Armenia).

The Armenian climate is continental with hot summers and cold winters due to the highland character of the land. The temperature fluctuation has worsened because of deforestation. In winter, temperatures may reach -46°C, while in July and August temperatures may reach +42°C. The summer period is very long and dry, lasting for about four months. The average precipitation is around 300 mm per year.

The total land area of the country is 29 743 km^2. Only 17% of that is arable. Meadows and pastures make up about 30% of the territory, and forest and woodland about 12%. Administratively, Armenia is divided into 10 regions (Marzes), plus the capital city Yerevan.

The nature of the Armenian economy is in flux: shifting from an industrial to a service-oriented one. As a result, energy generation — which reached 15 billion kilowatt-hours (kW·h) in 1988 — has been reduced by about two times and has stabilized at around 7.7 billion kW·h annually from 2000.

The most recent economic development indicators are summarized in Table 1.

TABLE 1. MAIN ECONOMIC INDICATORS (2012/2013)

GDP (current US$ million)	9960 / 10 430
GDP per capita (current US$)	3293 / 3458

TABLE 1. MAIN ECONOMIC INDICATORS (2012/2013) (cont.)

GDP growth (%)	+6.9 / +3.6
Unemployment rate (%)	17.3 / 16.2

3.2. ENERGY RESOURCES

According to the development strategy of Armenia [6], all economically feasible domestic energy resources of the country must be utilized. However, there are not enough available indigenous resources to meet the country's demand. Therefore, in the future, Armenia will have to import (as it does now) the necessary quantity of energy resources envisaged for the energy sector.

Regardless of the political situation, social climate, or attitude towards nuclear power, a thorough investigation is needed of energy sector development. It is very important to research the future of nuclear power as a practically infinite resource for generation of electricity.

Unfortunately, there are no proven reserves of uranium or thorium in the country, which means that for the nuclear option, import of nuclear fuel will be necessary.

On the other hand, 70 assemblies are discharged from the unit 2 of ANPP each year, and therefore the existing ANPP will accumulate around 3233 SNF assemblies on-site after the permanent shutdown of the plant in 2026. These fuel assemblies will have to be removed from the plant prior to its decommissioning. A number of alternatives are identified and evaluated in this plan, including continued wet storage in the reactor building, interim dry storage at the ANPP site or some other site within Armenia and disposal of the SNF in another country for interim storage or final disposition. Interim dry storage at the ANPP site is seen as the most feasible option.

Armenia has country-specific requirements for NES considerations, such as energy security and independence, survivability of the energy system, economic stability within the South Caucasus region, guarantee of primary energy sources, environmental protection, and flexibility of NPP operational modes to satisfy different grid regimes and rate of employment.

3.2.1. Indigenous and renewable energy resources

Though it lacks most organic fuel resources, Armenia has a considerable capacity for domestic renewable energy resources.

The theoretical potential of hydro resources is 21.8 billion kW·h; the technically available potential is 7–8 billion kW·h; and the economically feasible hydro potential is about 3.6 billion kW·h. 1.75 billion kW·h has already been generated and the rest of the economically feasible capacity is expected to be realized over the next 15 years.

Two main hydro power plants generate the majority of this power: Sevan-Hrazdan and Vorotan cascades, which are both considered large hydropower plants (HPPs). The construction of new large HPPs — Meghri (with the capacity of 130 MW, providing 800 million kW·h annual generation), Loriberd (66 MW, 220 million kW·h annual generation), and Shnogh (70 MW, 280 million kW·h annual generation) — will add significantly to this mix. The economically feasible potential of small HPPs is around 1000–1100 million kW·h: 780–790 million kW·h of which is already generated by the existing small HPPs.

Armenia also has considerable wind energy resources. The theoretical wind potential is about 10.7 GW·h; the technically available potential (assuming a 10% power ratio) is about 1.1 GW·h. It is expected that Armenia will reach this potential during the next 20 years.

The potential for solar energy in Armenia is great, particularly for thermal power generation. The average annual inflow of solar energy per square unit of horizontal surface is 1720 $kW \cdot h/m^2$, and one fourth of Armenia's territory is exposed to 1850 $kW \cdot h/m^2$ intensity of solar energy annually. The solar intensity hours for the Sevan area is a record-breaking 2800 hours. The share of annual direct irradiation to the overall territory is about 65–70%, which is sufficient from the viewpoint of concentrating solar collector application. Due to available international tariff rates, solar energy utilization for electricity generation is also possible in Armenia.

Although biomass is not currently a widespread energy source in Armenia, a large biogas installation (generating 8000 m^3 methane per day) has already begun operation via foreign investment attraction. Over the next 15 years, it is possible that total methane production per day will reach 100 000 m^3, assuming more installations are put into operation.

Geothermal resources also appear promising. Ongoing evaluations show positive assessment of geothermal resources as a renewable energy resource for both private investors and international investment organizations.

Investigation of Armenian oil and gas availability, dating from 1947, has not revealed any abundance. The field is risky and expensive, so its development depends on foreign and private investment.

Geological investigations show that there is a certain quantity of fossil fuel in Armenia; however, it has little industrial importance due to low caloricity and volume. Combustible shale reserves amount to 17–18 million tons in Ijevan, Shamut and 6 million tons in the territory of Djermanis. Moreover, there are 128 million tons of prospective shale reserves in Dilijan and 100 million tons of prospective coal reserves in Ijevan. Before a final decision can be made regarding fossil fuel utilization, investigations and feasibility studies with regard to the environmental impact of mining — such as erosion, the de-aquation of soil, and resulting deforestation — must be undertaken. Fossil fuel should be considered as a strategic reserve until these studies are complete and mining of fossil fuel in comparison with natural gas becomes economically viable for heat and hot water supply.

Energy conservation has been referred to as its own energy source. According to an approximation, conservation measures could save 20% of energy consumed. According to the *Law on Energy Saving and Renewable Energy* and to the programmes of its development and implementation, energy saving is of great importance for Armenia.

3.2.2. Primary energy supply

Armenian total primary energy supply increased from 2.61 million tons of oil equivalent (Mtoe) in 2010 to 2.76 Mtoe in 2011, then increased to 3.02 Mtoe in 2012. The largest part of the country's primary energy supply came from imports (69.7% in 2010 and 79.8% in 2013). The main energy indicators are given in Table 2 below.

TABLE 2. MAIN ENERGY INDICATORS

Items	2010	2011	2012	Change	
				2010 vs 2011 (%)	2012 vs 2011 (%)
Production (Mtoe)	0.88	0.89	0.81	+1.1	-9.0
Energy net imports (Mtoe)	1.82	2.09	2.41	+14.8	+15.3
Energy net exports (Mtoe)	0.09	0.22	0.20	+144.4	-9.1
TPES (Mtoe)	**2.61**	**2.76**	**3.02**	**+7.1**	**+9.4**
TPES per capita (toe/cap.)	0.86	0.89	1.0	+3.5	+12.4

Oil-based trade is a function of demand in the free market. Only a few major players dominate imports. Gas transmission and distribution systems (including the Abovian Underground Gas Storage facility) are operated by Gasprom Armenia, CJSC, which controls the importation, transportation, storage, and supply of gas for all of Armenia.

The electricity market is split into three sectors: production, transportation, and distribution/supply. Some companies are State owned; others are private. In the internal market, the Distribution Company is the sole buyer of electricity from all generation companies and the single seller to consumers.

The action plan for the energy sector developing was adopted by the protocol decision 14 “On Approval of the Concept for Ensuring Energy Security in the Republic of Armenia” of the Republic of Armenia Government session No. 50, of 22 December 2011 [1].

3.3. ENERGY SECTOR OF ARMENIA

3.3.1. Description of energy system of Armenia

In January 2013, the Armenian energy sector had a total installed capacity of about 4146 MW, 2628 MW of which was available.

The summary of the installed capacity of power plants in the Armenian power system is presented in Table 3.

TABLE 3. INSTALLED CAPACITY OF POWER PLANTS IN ARMENIA

Power Plant	Installed Capacity (MW)
ANPP (WWER-440)	407.5
Hrazdan TPP	1110
Hrazdan-5 (gas and steam turbines unit), Hrazdan TPP	440
Yerevan TPP	550
Combined cycle co-generation power unit, Yerevan TPP	242
Vanadzor TPP	94
Sevan-Hrazdan cascade of HPPs	562
Vorotan cascade of HPPs	404

TABLE 3. INSTALLED CAPACITY OF POWER PLANTS IN ARMENIA (cont.)

Power Plant	Installed Capacity (MW)
Small HPPs (<30 MW)	~282
Wind power plant	2.6

Thermal power plants (TPP) capacity is about 2436 MW in January 2013. TPPs operate on gas/fuel oil (black oil). The Yerevan TPP (commissioned during 1963–1968) has an installed capacity of 550 MW, the Vanadzor TPP (commissioned during 1964–1970) has an installed capacity 94 MW and the Hrazdan TPP (commissioned during 1966–1973) has an installed capacity of 1110 MW. The new combined cycle co-generation power unit, with an installed capacity of 242 MW, began operation in April 2010 at the Yerevan TPP and gas and steam turbines units, with an installed capacity of 440 MW, began operation in April 2012 at the Hrazdan TPP.

The ANPP consists of two power units with WWER-440/270 reactors. Unit 1 was commissioned on 22 December 1976 and unit 2 was commissioned on 5 January 1980. Their combined power output was 815 MW(e). After the earthquake in 1988, the former Soviet Union Ministers’ Council made a decision to shut down the units of ANPP. Unit 1 and unit 2 were shut down on 25 February 1989 and 18 March 1989, respectively.

The collapse of the former Soviet Union resulted in a severe energy crisis in Armenia. On 7 April 1993 the Government of Republic of Armenia decided to restart unit 2. Before the decision was made on the unit 2 restart, the Government of Republic of Armenia had invited a group of international organizations and companies which were asked to advise Government officials. Following the recommendations from the IAEA, the World Association of Nuclear Operators (WANO), Framatome, Bechtel, Rosenergoatom, and others, a Concept for the ANPP unit 2 operation restart was developed. ANPP unit 2 restarted on 5 November 1995, 6.5 years after it was originally shut down. Restart of unit 2 ended the energy crisis and Armenia moved to a regular power supply schedule.

The total installed capacity of ANPP is now 407.5 MW(e). Due to the climate conditions, the design output of the WWER 440 reactors (440 MW(e)) cannot be reached.

On 19 April 2012 Republic of Armenia Government decision “On Extension of Service Life of unit 2 of Armenian NPP” was issued. According to this decision, the Minister of Energy and Natural Resources was assigned to organize activities on development of the programme on extension of service life of ANPP unit 2 and to estimate the amount of financial resources required for implementation of these activities, as well as to submit them to the Armenian Government for discussion in September, 2013. According to protocol decision 11, the Republic of Armenia Government session No. 12, of 27 March 2014 adopted the programme for the design lifetime extension of ANPP unit 2 operation.

The “Energy Security Ensuring Concept of the Republic of Armenia” was adopted by the President of Republic of Armenia on 23 October 2013, according to which, it is important to increase the safety level of unit 2, and based on the importance of national energy security and independence, the necessity of constructing a new unit was restated. This concept also discussed the possibility of continuing the operation of ANPP unit 2 after 2016.

The hydro power plants (HPP) total installed capacity was about 1188 MW in January 2013. The Sevan-Hrazdan HPP Cascade is responsible for 47% of that capacity and the Vorotan HPP Cascade – for 33%. Small HPPs make up the remaining 20%.

The transmission network consists of 1527 kilometres of 220 kV overhead lines (HVL) and 14 substations, as well as 3083 kilometres of 110 kV overhead lines and 119 substations. The entire 220 kV network and 580 kilometres and 18 substations of the 110 kV network are operated by the High Voltage Network CJSC. Electric Networks of Armenia CJSC operates the remaining portion of the 110 kV network. The transmission network has a circular structure and an extensive capacity, and is considered well developed. The Armenian networks of 110 kV and 220 kV can provide all the needed electricity to the domestic market and have the ability to transmit significant power within a regional market. Armenia has intersystem connections with all neighbouring countries.

A 400 kV (with 1000 MW transmitting capacity) double circuit overhead line (Hrazdan TPP-Tabriz) linking Armenia to the Islamic Republic of Iran and 400 kV one circuit overhead line (600 MW) between Armenia and Georgia (Hrazdan TPP-Ksani) are under construction.

The distribution network includes 101 substations of 110 kV, 110/35/10/6/0.4 kV overhead lines and cables, 278 of 35 kV substations, 10 625 of 10(6)/0.4 kV substations and 120 transformers with 1000 kVA and higher installed capacity.

Armenia was initially connected to the **gas network** of the former Soviet Union in 1959 and about 2000 kilometres of transmission pipelines have been built since then. During the former Soviet Union era, the gas transmission infrastructure of the Caucasus (Armenia, Georgia and Azerbaijan) was operated as an integrated network. Gas was supplied mainly from Central Asia by gas pipelines passing through the territory of Azerbaijan and Georgia.

This situation changed with the breakup of the former Soviet Union and the change in the geopolitical outlook of the Caucasus itself. Currently, the two gas pipelines connecting Azerbaijan to Armenia are shut down. The only open route for the import of gas into Armenia is from the Russian Federation via Georgia.

In March 2007 the Iranian-Armenian gas pipeline was constructed and from then on Armenia can import gas from the Islamic Republic of Iran.

In 2013, the natural gas demand was 2.361 billion m^3 (1.956 billion m^3 was imported from the Russian Federation and 0.405 billion m^3 was imported from the Islamic Republic of Iran).

The gas transmission and distribution systems (including the Abovian Underground Gas Storage facility) are operated by Gasprom Armenia, CJSC, owned 100% by Gazprom of Russian Federation. Gasprom Armenia controls the import, transportation, storage, and supply of gas in the whole territory of Armenia.

The Abovian underground gas storage facility is located near Yerevan and occupies a site of 140 hectares. Its construction began in 1962 and it has a design capacity of about 190 million m^3. It is used mainly for seasonal regulation of the gas supply. The gas is stored in caverns leached to underground salt layers. Eighteen wells have been drilled in total. The compressor station has a design injection pressure of 12.5 MPa.

Some of the gas sector’s main indicators as of December 2013 are given in Table 4 below.

TABLE 4. GAS SUPPLY SYSTEM MAIN INDICATORS

Armenia’s gasification level	~94%
Length of the main pipelines	13 153 km
Number of communities supplied with gas	552

TABLE 4. GAS SUPPLY SYSTEM MAIN INDICATORS (cont.)

Number of consumers	652 360
with potential consumers	*675 053*
Import	2361 million m^3
Abovian underground gas storage facility	118 million m^3

In 2013, 14% of natural gas was used for electricity generation. Other significant gas consumers are residents (30%) and transport (25%) (Figure 2).

As displayed in Figure 3, electricity generation reached 15 billion kW·h in 1988, which is about 2 times more than the annual 7.7–8.0 billion kW·h level in 2000–2013. This fluctuation was characterised by the drastic reduction of foreign and domestic power markets caused by the split of the former Soviet Union and severe earthquake in 1988.

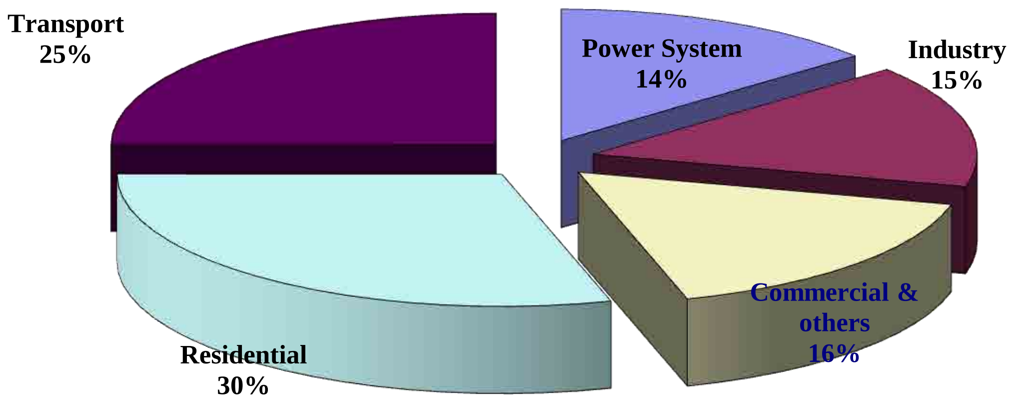

FIG. 2. Gas consumption per sector in 2013.

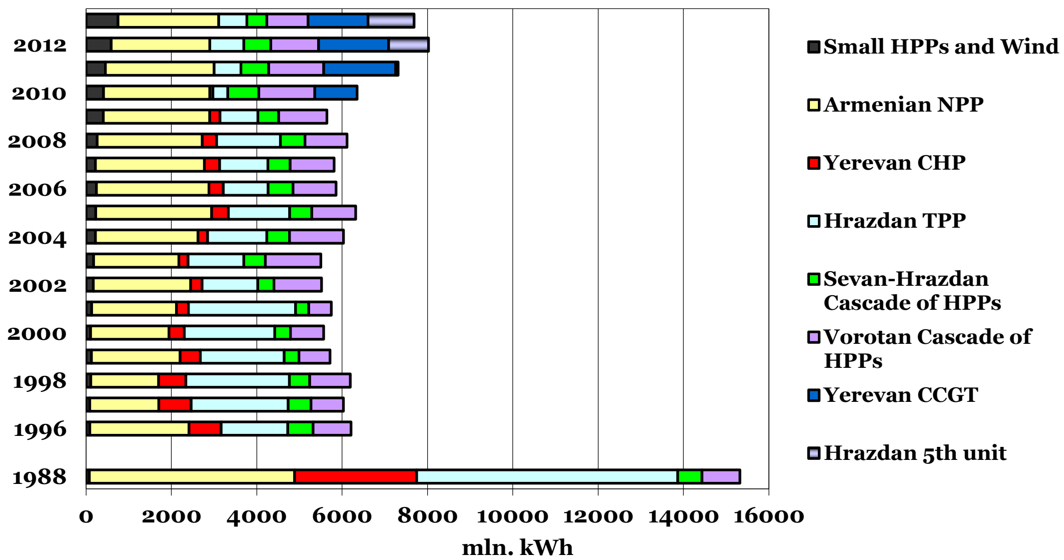

FIG. 3. Structure of electricity generation by power plants up to 2013.

3.3.2. Electricity market structure

The Government of Republic of Armenia has divided the power sector into three subsectors: generation, transmission, and distribution. Privatization was carried out first in the distribution subsector, transferring the activities of sale and retail trade in power into private hands, bringing a measure of order to establishing and securing acceptable conditions for the subsequent privatization of generating capacity. The generation and distribution sectors are slated for privatization first (Figure 4).

In Armenia, the electricity market regime is based mainly on the *Energy Law of the Republic of Armenia* and monitored by Public Services Regulatory Commission of Armenia. The Government of Republic of Armenia represented by Ministry of Energy and Natural Resources of Armenia is responsible for development and implementation of State policy on energy and natural resources. The regulatory framework of the energy sector is under the control of Public Services Regulatory Commission of Armenia.

The market is divided into three sectors: production, transportation, and distribution/supply. The main players in the electricity market in Armenia are:

- Generation companies:
  - Armenian Nuclear Power Plant — State owned;
  - Hrazdan TPP — private;
  - Vanadzor TPP — private;
  - Sevan-Hrasdan cascade of HPP's — private;
  - Vorotan cascade of HPP's — State owned;
  - Yerevan TPP — State owned;
  - Small HPPs — private;
- Transportation Company: the High Voltage Electrical Network — State owned, responsible for electricity transmission from power plants to the distribution network and for organizing electricity import/export with neighbouring countries;
- Distribution Company: Energy Network of Armenia — private.

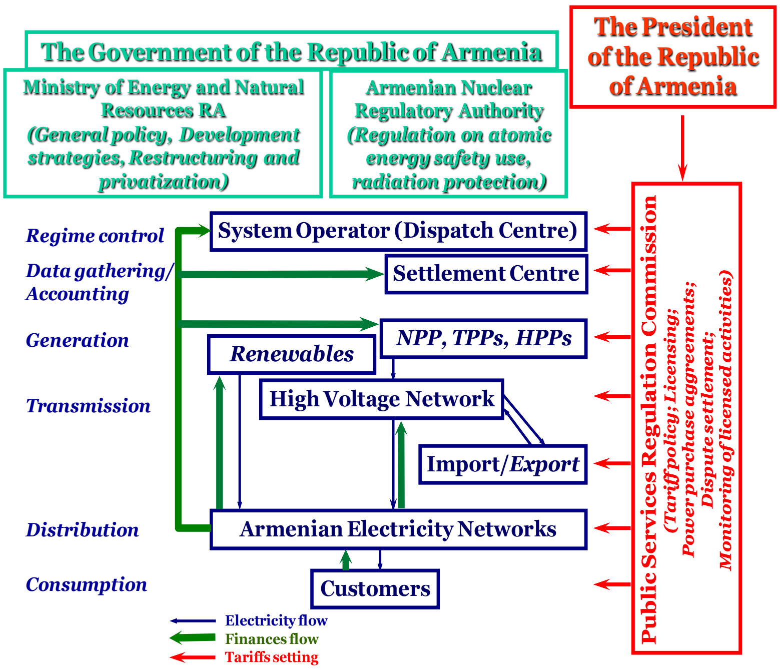

FIG. 4. Structure of Armenian power sector.

Besides these market players, the following State owned companies provide market services:

- The Power System Operator (National Dispatch Centre) is responsible for ensuring the technically feasible regimes of operation;
- The Settlement Centre is responsible for measuring, preparing, rendering information about commercial electrical energy flow and making it available to market players.

In the internal market, the Distribution Company is the only purchaser of electricity from all generation companies and seller to consumers. The distribution company pays for services under fixed tariffs to servicing companies.

3.4. CONCLUSIONS

On the basis of the above mentioned descriptions, the following can be concluded:

- Armenia has no indigenous fossil fuel for industrial use. All types of such fuel are imported;
- The country may develop some economically feasible potential of domestic energy resources in hydro, solar, and wind;
- The Armenian energy sector was designed to operate within the trans-Caucasus power system of the former Soviet Union and now, after its split-up, a lot of installed power plant capacity is disconnected from the grid and cannot be used in this system;
- The electricity market has a single buyer structure. The single buyer is the Distribution Company — Electricity Networks of Armenia;
- The Public Services Regulatory Commission is responsible for licensing the construction of new generation capacities and transmission and distribution networks. It also establishes tariffs for generation companies in the form of electricity retail tariffs for each voltage level.

PART A: ENERGY PLANNING

4. ENERGY SECTOR DEVELOPMENT STRATEGY OF ARMENIA

This section presents the results of analysis of key ways to increase living standards and form energy policy and strategy for power system development. It also presents main items of the Protocol decision 14 "On Approval of the Concept for Ensuring Energy Security in the Republic of Armenia" of the Republic of Armenia Government session No. 50, of 22 December 2011 [1]. Measures, presented in this section, describe the main directions of Government's activities planned for realization up to 2036.

4.1. GENERAL PROVISIONS

The *Action Plan of Energy Sector development of Armenia* closely matches the provisions of the *National Security Strategies of Armenia*. It is based on the "Armenia least cost energy development plan" developed in 2014.

The main objective of the Armenian energy sector development strategies is to formulate strategic targets and determine the fundamental directions towards their achievement. These targets are based on sustainable development principles adopted by the international community and are guided by provisions of the national security strategies of Armenia. The fundamental directions for the operation of the Ministry of Energy and Natural Resources of Armenia ensuing from the principles of the *National Security Strategies* are to:

– Provide reliable energy supply at low cost to satisfy the fundamental needs of all customers, and enhance energy conservation efforts in the meantime;
– Implement methods of energy import such that security and economy are not affected by uncontrollable political impacts on Armenia;
– Ensure maximum utilization of domestic energy resources and nuclear energy;
– Ensure the safe operation of the ANPP after 2016 until it is possible to replace it with relevant energy sources, and proceed with the decommissioning without any unacceptable economic, ecological, and energy security impacts;
– Ensure an ecologically safe energy supply based on the principles of sustainable development and in compliance with the international environmental commitments of Armenia;
– Construct a financially stable energy system, encourage the economically efficient operation of all energy suppliers which would bring forth interest from investors and private capital;
– Create an electric energy system that is export-oriented and generates high added value.

4.2. ENERGY SECURITY AND INDEPENDENCE

Energy security can be defined as a guarantee of stable and reliable supply of fuel and energy resources at affordable prices and minimum environmental impact for completely meeting the demand of a country both in normal development conditions and in emergencies.

Energy security would be ensured and the dependence from any supplier would be reduced if Armenia diversified its supply sources and plans for fuel storage and emergency preparedness. Such fuel supply diversification — especially important with the ANPP decommissioning — will also improve Armenia's ability to bargain for better prices and terms of delivery, and will reduce the likelihood of price shocks to Armenian customers.

Diversification of energy sources obviously requires diversification of supply routes. For Armenia today, the only real solution is the Iranian-Armenian gas pipeline and the restoration of the electric energy sector's parallel operation with other power systems within the region.

The current level of economic activity in Armenia could be maintained by less energy consumption and less dependence on imported fuel, while simultaneously enjoying a higher level of energy security. Thus, Armenian national security and economic competition could be enhanced by promoting energy efficiency.

Energy independence in Armenia will be characterized not only by the level of utilization of domestic renewable energy resources and a portion of nuclear generation, but also by the implementation of activities aimed at the utilization of the energy conservation potential.

Thus, the objective of ensuring an adequate level of national energy security and independence includes the following critical directions of the energy sector development strategies:

- Utilization of renewable energy resources and energy conservation;
- Nuclear energy;
- Diversification of supplies and regional integration;
- Ensuring environmental safety;
- Ensuring social policies, financial stability, and economic efficiency.

The structure of power generation in Armenia with consideration of the aforementioned principles of ensuring energy security is to:

- Give priority to and within the next 20 years completely utilize the domestic portion of renewable energy resources for power generation, which may amount to about 4.7 billion kW·h, including:
    - Hydro energy — 3.6 billion kW·h, around 1.75 billion kW·h of which have already been utilized;
    - Wind energy — 1.1 billion kW·h (these capacities are mainly seasonal; this assessment does not include the portion of possible power generation at the account of geothermal resources).
- Use the new ANPP unit and thermal power plants, including those operating combined generation, which could cover the rest of the required energy generation.

The aforementioned energy generation structure is the best option for Armenia due to the State's energy independence and security policy requirements.

4.3. NUCLEAR ENERGY

The Government of Republic of Armenia has made a commitment to its citizens and to the European Commission that the ANPP will be decommissioned. This will necessitate adequate replacement power. Until the time when the unit 2 is shut down, the Government will support an extensive programme of safety improvements for this unit. However, required extensive costs and the absence of diversified supply sources now make any near term shutdown date unrealistic. Indeed, the current least cost power supply plan makes it clear that shutdown of the unit 2 of the ANPP will lead to significant increases in the bills of the Armenian customers and further reliance on gas imports.

Further operation of the unit 2 of the ANPP after 2016 would require mitigating the risks associated with such a decision. The NPP has environmental commitments, though it is not considered an air pollution source. To date, more than US $100 million has been invested to enhance the level of safety at the ANPP. An additional safety upgrade expenditure of a few million dollars per year will be necessary after the completion of safety enhancement operations. Safety issues arising from the ageing of the plant will require particular attention and financing, as will the training of plant staff and instilling a safety culture.

When the unit 2 of the ANPP is decommissioned, Armenia will lose an important element of diversity in its current energy mix.

The forecasts of nuclear fuel and natural gas prices growth tendencies by 2050 also speak in favour of building a new nuclear unit. Under conditions of irreversible natural gas price increase — conditional upon the decrease of natural gas resources and reduction of the number of exporters — the price for nuclear fuel may be considered relatively stable and competitive.

Natural gas prices are influenced by world prices for crude oil, which have significantly increased since 2003. Natural gas prices at the western border of Russian Federation have also demonstrated a tendency to rise. The natural gas price is the main determining factor in forecasting the cost of power in Armenia. The 2014 Armenia least cost energy development plan, developed on the order of the Ministry of Energy and Natural Resources of Armenia and with technical assistance from US Agency for International Development (USAID), reviews the moderate (average annual price increase of around 3.2% at the border) and high (average annual price increase of around 5.1% at the border) scenarios for natural gas price increase for Armenia.

In the meantime, it is planned that during the next 20 years, the cost of nuclear fuel will have an annual 0% increase.

The results of the 2014 Armenia least cost energy development plan record that:

- There is no economically justified alternative to life extension of the existing ANPP up to 2026. The ANPP’s generating capacity could be replaced with new thermal generation capacity; however, this approach would result in higher overall costs, higher fuel price risk, and less energy diversity and security;
- Construction of new 1000 MW WWER nuclear unit in 2026 is cost-effective in all scenarios except when there is no swap after 2026 and if Russian gas prices are assumed to be set according to Russian-Armenian Intergovernmental Agreement, in this case the cost-effective option is smaller nuclear unit SMR-360 MW;
- None of the Armenian HPPs (existing or new) has the capacity to operate under baseload because of the limited reservoir capacity. The option of baseload capacity generation with least costs for the Armenian electric energy system can be realized only by nuclear or thermal generation;
- The planned Meghri HPP (with 130 MW of installed capacity) will not be able to serve the Armenian baseload during the considered time period (according to the financial scheme of the HPP construction, the entire generated power will be directed to the Islamic Republic of Iran);
- Development of new HPP (Shnokh, Loriberd, Meghri and small HPPs), as well as wind and geothermal energy sources, are cost-effective options in all scenarios considered, while solar is not competitive unless incentives are provided;
- To cover the near term requirements of the current swap arrangement there is a need for installation of 620 MW of additional thermal capacity starting 2018; however, this capacity will be underutilized in the later years once the nuclear plant is added (unless additional export opportunities are developed).

Based on the analysis of the price increase scenarios for gas and strategic and economic discussions, it is recommended that Armenia should:

- Decommission the ANPP immediately after the construction and commissioning of the new nuclear unit;
- Conduct a comprehensive safety and environmental assessment for the ANPP site to determine compliance with the requirements of decommissioning and new nuclear unit construction;
- Develop a comprehensive decommissioning plan to be ready five years prior to the commencement of the ANPP decommissioning;
- With its own resources and with the help from donor organizations, fund the safety improvement activities and provide the required investments for the safe operation of the ANPP after 2016;
- Develop an action plan to provide for the funding scheme of the new nuclear units with up to 1000 MW and resolution of construction related issues, including the dimensions of the unit and its decommissioning in future.

4.4. DIVERSIFICATION OF SUPPLY AND REGIONAL INTEGRATION

Analysis and assessment of the opportunities for diversification of supply, regional integration and electricity export are critical elements of the operation of Armenia's Ministry of Energy and Natural Resources.

The analysis of material from the Islamic Republic of Iran, Turkey and the South Caucasus countries demonstrates that these countries have chosen to be self-sufficient in their power sector development. This will inevitably cause undesirable changes in the available energy balance. Moreover, the energy resources of the Caspian Sea basin will be exported through the East-West fuel transportation highways, bypassing the territory of Armenia, which will diminish the role of Armenia from the perspective of electricity export.

Strong competition for servicing the energy markets of the region will appear in the future. It is clear that the country with the most rapid implementation of its development programmes — especially in areas oriented towards export and creating high added value — will obtain political and economic privileges. In other words, the policy of these countries should be based on the development of a political and economic atmosphere that will attract foreign investors. This becomes particularly important for the development of such capital-intensive industries as the energy sector.

The Iranian-Armenian gas pipeline main is a stable alternative for the sole gas pipeline from the Russian Federation to Armenia across the territory of Georgia. Construction of this gas main is justified and has a prospective strategic importance. The Armenian Government made great efforts and successfully completed the construction of the alternative gas main.

Given the fact that part of the generated electricity necessary for satisfying the winter peak load in Armenia comes from fossil fuel, and that full-scale use of natural gas both by the residential sector and by the industrial sector is highly preferable, Armenia must have enough storage capacity to overcome unexpected interruptions of import. Storage and equipment for fuel transportation in and out of storage should be reliable.

With the new NPP, Armenia will have the opportunity to generate inexpensive electricity and reduce the size of obligatory environmental payments associated with the emission of hazardous material from TPPs. The electricity generated by the NPP could compete with the electricity in the regional power market.

In November 2004, the Conference of Energy Ministers in Baku convened at the EC initiative, which was founded to foster energy cooperation between the European Union (EU) States, the countries of the Caspian Sea basin, and their neighbouring States. The primary goal was to establish easy transportation of fuel and energy resources (typically oil and natural gas) to the EU from the aforementioned territories, which would benefit all States involved. Armenia is considered an energy exporting country in this framework. Moreover, the country's location and existing and expandable underground gas storage infrastructure are advantageous for transporting energy resources. The Cooperation Agreement arranged by the EC — if capable of ensuring legislative, political, and institutional compliance by all participating bodies — would maximize the Armenian energy system potential and create opportunities for attracting EC investment.

In order to establish political and economic stability in the region, Armenia must accelerate its development programmes, especially those concerning electricity for export. Such an opportunity points to the need to create baseload power generation capacities in Armenia. They would ensure Armenian involvement not only in the Caspian region, but also in the Black Sea energy systems.

4.5. ENSURING SOCIAL POLICIES, FINANCIAL STABILITY AND ECONOMIC EFFICIENCY

Armenian energy system is no longer operating as an instrument for affecting social policy; it is now rather a system that private companies exploit to make profit and attract investments for development.

In order to mitigate the social consequences associated with the consumption tariff increase due to the installation of new capacities and implementation of major projects of strategic importance for Armenia, the Government must strive to attract 'soft' loans and as many grants as possible. In Armenia, the construction of new capacities and the implementation of major projects merely through the attraction of private capital cannot be implemented.

The expansion of the gas distribution network in a stable and economically acceptable manner, carried out by Gasprom Armenia, CJSC, would help to provide gas to all consumers and would undoubtedly contribute to heat supply recovery. It would also promote the construction of heat and cogeneration units and autonomous and distributed (decentralized) generators.

Primary measures taken to ensure financial stability and economic efficiency should include:

- Continuous development of the energy market;
- Completion of the privatization process by involving foreign firms, encouraging competition among private companies, and prohibiting the concentration of all energy capacities in one owner;
- Creation of a favourable legal and economic environment for investment and compliance with EU legislation;
- Conduct of balanced tariff policies for investors and consumers;
- Gradual transition from a regulated market towards a competitive one.

The Government should render all possible financial assistance to the latest global developments in energy research that are applicable to Armenia, in:

- Energy conservation;
- Energy market development;
- Development of alternative small energy generating capacities;
- Development of oil, gas, and other fossil fuel exploration, and industry development;
- Development of new technologies for nuclear reactor decommissioning.

4.6. CONCLUSIONS

These activities should be accomplished by 2035 in order to maintain the existing level of energy independence and security in Armenia.

As for the energy capacities, there are no quantitative estimates either for the potential of geothermal, biogas, solar (thermal and photovoltaic) and other possible sources of renewable energy, or for the activities towards the receiving of bio-ethanol and possible consequences of the continuous exploration for oil and natural gas. However, the issue of the efficient utilization of the aforementioned potential is within the focus of the policies conducted by the Ministry of Energy and Natural Resources of Armenia.

5. SOME ARMENIAN NES SPECIFIC ASPECTS AND REQUIREMENTS

In Section 4, the country specific requirements for NES considerations were formulated as:

- Energy security and independence;
- Nuclear energy development;
- Regional integration;
- Diversification of supplies;
- Ensuring social policies, financial stability and economic efficiency;
- Education system for nuclear sector.

Some of the above mentioned requirements were already described in detail. Some additional information is presented here. Data provided below is connected with the timeframe of the Government’s development strategy.

5.1. ENERGY SECURITY AND INDEPENDENCE

One of Armenia’s main strategic issues of development is energy security and independence.

As internationally accepted, nuclear energy is considered an internal energy reserve despite fuel and considerable expertise coming from abroad. The assessment of the independence and reliability level of the Armenian energy system is given below.

The independence of the energy system should be assessed in terms of the percentage of electricity generation using internal energy resources, including the NES, as shown in Figure 5.

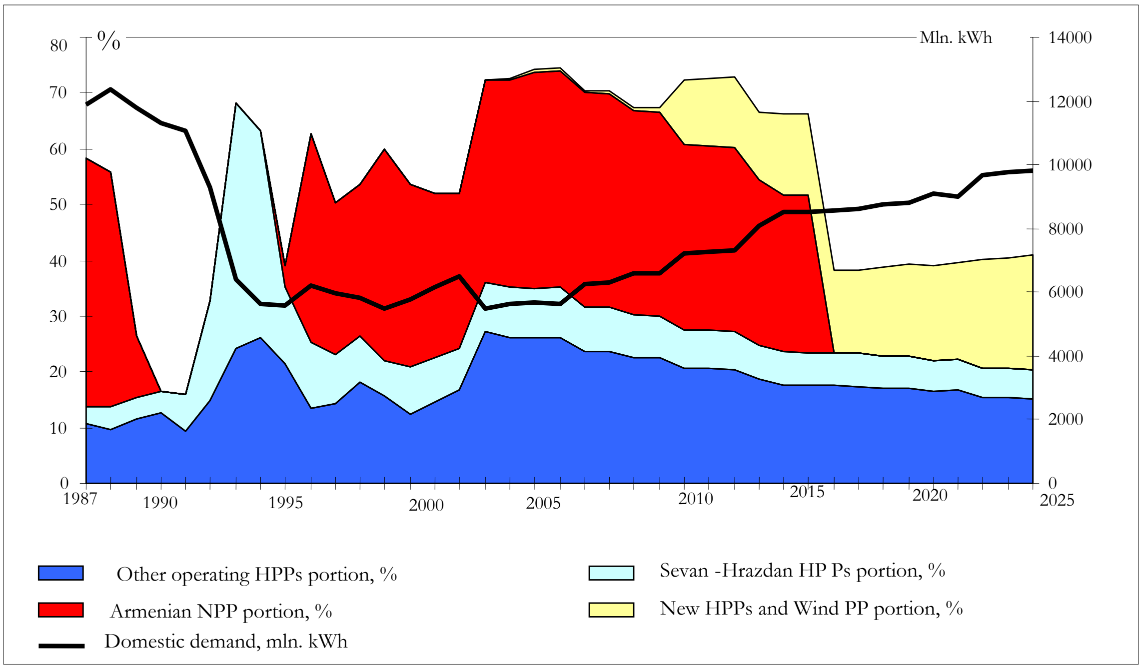

FIG. 5. Level of the electric energy independence from imported energy sources.

Between 1992 and 1995, Armenia was highly independent of fuel imports. However, the energy crisis, regimes of mandatory rolling outages, deteriorated quality of electricity, decrease of the Lake Sevan water level and other circumstances appeared as a result of such independence.

The situation improved after re-commissioning of the ANPP and a considerable increase in the Vorotan HPP's generation output due to abundant rain in recent years. Presently, rapid increases in domestic demand are projected to bring a slow but continuous decrease in the level of independence. In 2016, the level of independence from fossil fuel imports will rapidly decrease due to decommissioning of the ANPP. The independence level will reach 40% and slowly go up because of the construction of the new large Loriberd and Shnogh HPPs and large wind power plants.

ANPP decommissioning will reduce independence regardless of the year of decommissioning. However, if it is accomplished in 2016, dependence will exceed 60%. Although decommissioning in 2016–2026 will not cause significant change in the level of independence, but it will be associated with certain risks. In particular, any possible delay of construction of new power plants may cause a power shortage. Moreover, liabilities incurred by the Armenian energy system towards the foreign markets may cause serious dangers.

Energy system reliability should be measured by the ability to cover the threshold level of reserve capacity. The two scenarios are:

– Isolated operation of the energy system, requiring a 30% reserve;
– Parallel operation with neighbouring energy systems, requiring a 10% reserve.

These required reserve levels are consistent with international practice.

The results of the analysis performed for the first scenario are shown in Figure 6.

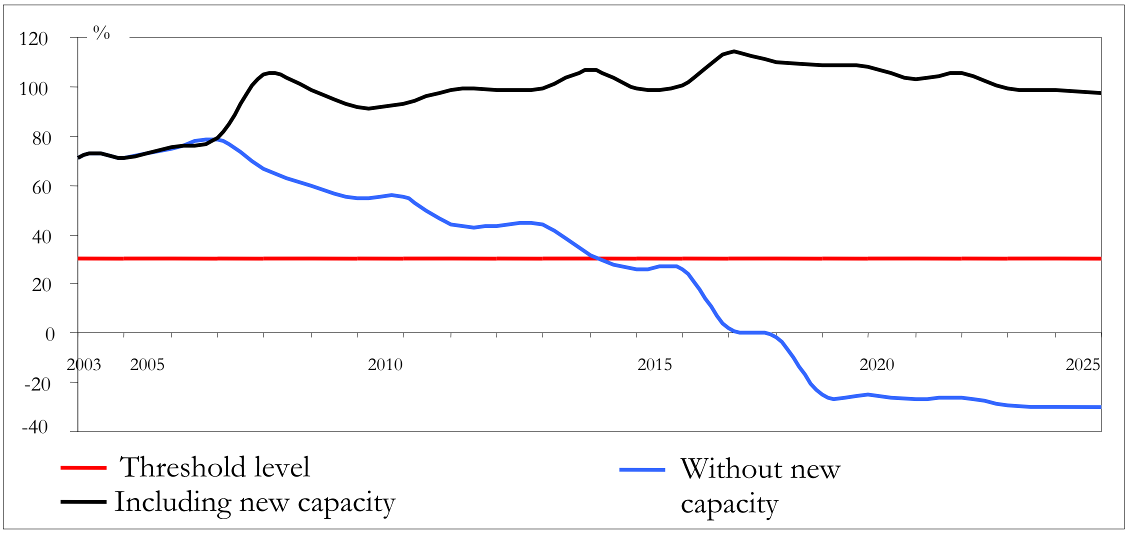

FIG. 6. Level of reserve capacity available to cover domestic demand.

Operation of existing generation facilities will increase their depreciation. As a result, reliability will decrease. Thus, without new capacity, the reserve level will gradually decrease, becoming less than the threshold level by 2014 and causing a deficit after 2017.

With new capacity, the level of reserves will cover domestic demand. After 2017, it will reach approximately 100% and will not decline within the review period (Figure 6).

The analysis for the second scenario is provided in Figure 7 below. The level of reserves with development of new capacity was below the threshold level in 2007 and a reserve deficit occurred after 2009.

With new capacity, the level of reserves required for the domestic market will be completely ensured up till 2019; although the reserves will fall below the required level after that year, no threatening reserve deficit will occur for the remaining period.

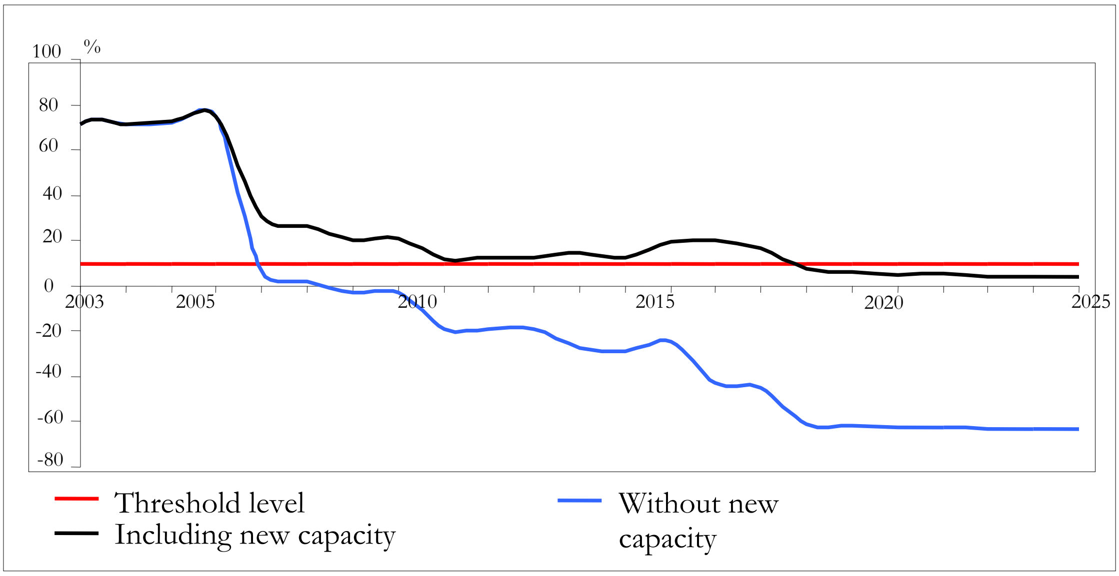

FIG. 7. Level of reserve capacity available to cover the total demand.

Considering the traditional role of the Armenian energy sector as an exporter and the current trend towards integration into regional energy markets, as well as agreements with the Islamic Republic of Iran, a continuous and considerable growth of electricity exports is expected. Generation required to cover the domestic market demand will not reach the 1980 level until 2025. However, export volumes growing rapidly, they will reach the 1980 level in 2020 and will gradually increase in parallel with the economic and energy development of regional markets.

5.2. ECONOMIC STABILITY WITHIN THE SOUTH CAUCASUS REGION (REGIONAL INTEGRATION)

Strong competition to serve regional energy markets will appear in the future. The country with the most rapid implementation of its development programmes, especially in areas oriented to export and to creating high added value, will achieve political and economic advantages. In other words, Armenian policy should be based on developing a political and economic atmosphere that will attract foreign investors. This becomes particularly important for the development of a capital-intensive industry like the energy sector.

As for future regional cooperation, it is also possible that nuclear power will provide a competitive advantage to countries whose electric systems will not need to incur substantial additional costs to mitigate greenhouse gas emissions from thermal power plants.

The private energy companies will encourage positive regional cooperation.

5.3. GUARANTEE TO GET PRIMARY ENERGY SOURCES (DIVERSIFICATION OF SUPPLY)

Analysis and assessment of opportunities to diversify supplies, achieve regional integration, and increase electricity export are critical elements of Armenia's energy sector development strategies.

The Islamic Republic of Iran, Turkey, and the South Caucasus countries have chosen self-sufficient power sector development [7]. This will inevitably bring undesirable changes in the energy balance. Moreover, the energy resources of the Caspian Sea basin will be exported through East-West fuel transportation routes, bypassing Armenia, which will decrease the potential of Armenia to export electricity.

The funding of first phase of construction of the Iranian-Armenian gas pipeline is a good example of supply diversification and regional integration. The Iranian construction costs and the gas cost will be offset by the export of agreed amount of electric energy to the Islamic Republic of Iran. This arrangement ensures demand sufficient to support full and efficient operation of Armenian power plants, including replacement and modernization. It also supports development of an export orientation for the Armenian energy system and expansion of the transmission network.

It will be necessary to promote a substantial quantity of renewable energy projects as well as projects enhancing the country's energy independence. Of course, the least costly and most sustainable way to enhance energy supply is to stop wasting it. Armenia could attain its present level of economic activity at much lower energy cost if its ratio of energy to the GDP was closer to international averages. When the real costs of energy are taken into account, many energy efficiency measures become economically desirable and should be encouraged. It is necessary to continue activities to determine the economic efficiency of exploration and extraction of domestic fossil fuels (oil, gas and solid fuels).

5.4. ENVIRONMENT PROTECTION

Environmental issues regarding the future protection of Lake Sevan are important. Figure 8 presents the history of water balance of the Lake Sevan.

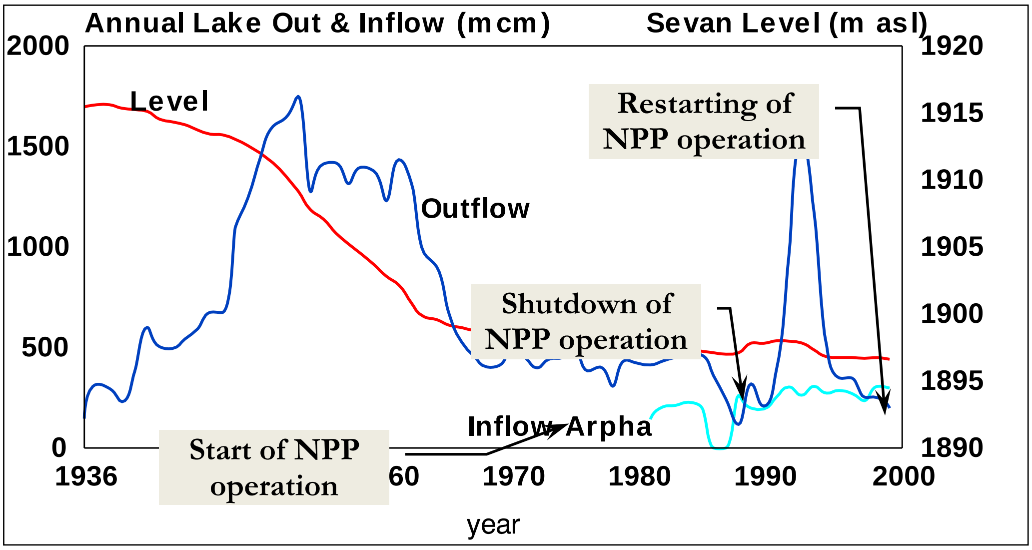

FIG. 8. Water balance of Lake Sevan.

This chart clearly shows how nuclear energy influences natural resource protection.

Starting from 1936, the outflow of water from Lake Sevan was artificially increased for energy use (electricity production). That period can be characterized by the intensive construction of Sevan-Hrazdan HPP cascade. As a result, the level of the lake rapidly decreased. In the mid-1960s, TPPs in Yerevan and Hrazdan were constructed and water was drawn from Lake Sevan for irrigation needs only.

During the 1992–1995 energy crisis caused by a blockade, the hydro potential of Sevan Lake was overexploited by drawing excessive water from it for hydro generation (Fig. 8). Only re-commissioning of unit 2 of ANPP in 1995 reduced outflow from the lake up to a level which could cover the irrigation needs of Armenia.

If the ANPP were replaced by thermal generation, serious environmental problems would arise due to drastic growth of greenhouse gas emissions compared with a nuclear development scenario.

5.5. RATE OF EMPLOYMENT

Countries like Armenia, which lack energy resources, should plan their energy development on the basis of energy independence and energy safety parameters and should develop their own energy sources, including nuclear energy. Armenia has developed a nuclear energy infrastructure, such as nuclear energy institutes, calibration and construction companies, and educational institutions, where future nuclear system specialists are educated and prepared.

Technical staff is trained not only in Armenia. As a rule, key specialists pass the probation period in leading nuclear training centres of the Commonwealth of Independent States (CIS) and other countries. Many specialists have work experience in similar NPPs of CIS countries (Russian Federation, Ukraine) and countries of the former Eastern Bloc (Bulgaria, Hungary, Eastern Germany, Czechoslovakia).

Abandoning nuclear energy would create social problems. More than 2200 highly qualified specialists would lose their jobs, whereas building a new nuclear unit would create more than 10 000 new positions in the construction field. Moreover, the availability of scientific potential that can be directly engaged in nuclear technologies is of particular importance.

Thus, decommissioning of the ANPP means not only deactivating a certain power source, but also the shutdown of a whole science-intensive and high technology community. On the other hand, the “safe store” technology of NPP decommissioning will require the high-qualified personnel.

Thus, the existence of nuclear technologies in Armenia now and in the future has great positive influence on the employment rate in the energy sector.

5.6. ENHANCEMENT OF INTEGRATED EDUCATION SYSTEM FOR NUCLEAR SECTOR IN ARMENIA

In view of energy security and energy independence, Armenia is paying special attention to nuclear energy development.

Activities have been in progress towards construction of a new nuclear unit in Armenia since 2008. The Law on construction of a new NPP in the Republic of Armenia, adopted on 27 October 2009 by the Government of Republic of Armenia, would serve as a legal basis for the construction of a new NPP in Armenia.

The need for qualified specialists is becoming an ultimate necessity for Armenia regarding the construction of new nuclear units as well as operation, continuous safety improvement, and decommissioning of the ANPP.

Armenia is the only country in the entire Caucasus region that has been operating an NPP for over 30 years. Qualified specialists are required for the already existing ANPP, Armenian Nuclear Regulatory Authority (ANRA), Nuclear and Radiation Safety Centre, Armenian Scientific Research Institute of Operation of NPP (ARMATOM), Scientific Research Institute of Energy and other research institutes to address issues and challenges in view of new developments of nuclear energy in Armenia.

Armenia has two main institutions preparing nuclear experts: the State Engineering University of Armenia (SEUA-Polytechnic) and Yerevan State University (YSU). Armenian specialists from ANRA, the NPP, and support organizations participate in scientific visits and training in Europe, the USA and other countries. This is conducted under IAEA technical cooperation projects and international aid programmes.

To educate and train nuclear specialists, two departments of the Yerevan State University and the State Engineering University of Armenia currently offer specialities in the field of nuclear energy. However, an improved and integrated education system for the nuclear energy sector in Armenia is still essential. Therefore, a concept of human resource management was approved by the Government of Republic of Armenia. Implementation of knowledge management for all phases, including design, construction and commissioning, operation, and decommissioning — both for the existing and for future NPP units — are the main parts of the concept.

An evaluation of human resource needs in conjunction with new NPP construction in Armenia was carried out under the IAEA technical cooperation project ARM-005. The report of that feasibility study of nuclear energy development in Armenia, titled Evaluation of Human Resource Needs for a New Nuclear Power Plant: Armenian Case Study, was completed in 2008 and was published as an IAEA TECDOC-1656 [8] in 2011. The analysis, which covers all stages of construction of the new nuclear power unit, relates both to the sponsoring organization and to the regulatory agency dealing with nuclear power in Armenia.

Armenia is currently engaged in the following activities:

- Item 11 of the Government Protocol of Session No. 26 dated 8 July 2010 approved a programme of subsidies intended to encourage attendance and academic achievements by students in the nuclear field;
- Under IAEA technical cooperation project ARM-006, the IAEA is providing laboratory equipment and training to strengthen educational programmes at the SEUA and the YSU;
- Under USAID project Aid to the Energy Sector to Strengthen Energy Security and Regional Integration, a task has been initiated to support curriculum development at SEUA and YSU to restructure and improve the curricula in nuclear engineering and nuclear physics and increase the knowledge level of university graduates entering the nuclear workforce.

Significant expansion of staffing at the Ministry of Energy and Natural Resources, ANRA and MetsamorEnergoAtom CJSC is expected to support new unit design and procurement after selection of strategic partners and investors is completed. Armenia’s contract with Worley Parsons (as the management organization for the new NPP) requires developing specific training plans for personnel working at the preconstruction phase and construction phase of the project and for personnel responsible for project safety. Worley Parsons is also responsible for developing a plant-specific training programme for the plant operating staff.

Enhancement of the Armenian nuclear educational system and comprehensive development and upgrade of the training system for personnel for the nuclear power sector will include the provision/support of:

- Management of training system development and operation;
- Organizational structure and staffing of the training system;
- A training centre;
- Training programmes and materials using a systematic approach to training for various categories of personnel;
- Simulators (full-scope, compact);
- Multifunctional multimedia computer-based training systems for various jobs and activities;
- Training and development of instructors;
- Training and development of nuclear power sector managers.

5.7. CONCLUSIONS

The following conclusions can be drawn from this Section:

- Decommissioning of the ANPP will decrease Armenian energy independence;
- Use of domestic renewable energy resources would mitigate the possibility of decrease of independence level from the ANPP decommissioning. However, use of domestic renewable energy resources will not substantially change the long term level of energy independence. Renewable energy reserves are limited and Armenian socioeconomic development will increase energy demand;
- Although importing new generating capacity on schedule will ensure reserve capacity adequate to cover domestic demand, the critical situation associated with coverage of total demand, including exports, will not change;
- Decommissioning prior to attracting equivalent capacity will decrease energy system reliability in particular due to reduction of the reserve level;
- Premature decommissioning will also reduce the integration of the Armenian power system (APS) into regional markets and will necessitate attracting new thermal plants earlier than scheduled if obligations are to be met;
- The need for qualified specialists is becoming an ultimate necessity for Armenia with regard to constructing new nuclear units as well as for operation, continuous safety improvement and decommissioning of the ANPP;
- Enhancement of Armenian nuclear educational system and comprehensive development and upgrade of the training system for personnel in the nuclear power sector is being implemented.

6. ENERGY DEMAND ANALYSIS AND PROJECTION IN ARMENIA

6.1. OVERVIEW OF PREVIOUS STUDIES CONCERNING ARMENIA'S ELECTRICITY AND ENERGY OUTLOOK

6.1.1. Gas security of supply to Armenia in the framework of the shutdown of the Metsamor NPP

This research reviews Armenian energy demand considering various economic changes and heating needs scenarios in the country, and was done in framework of TACIS project in 2003. In short, the primary factors which control energy demand elasticity (particularly in residential and commercial sectors) are tariff modification and the coordination of local energy prices with those of the world market.

It is likely that in response to increasing industrial energy demand the shortages in district-heating systems will have to be met with the direct use of natural gas.

Considering the growth of the Armenian service sector, the energy demand from the transport sector is likely to increase. This increase will primarily come from condensed natural gas use. The demand forecast for this product is sensitive to international prices of liquified petroleum gas, gasoline, and gasoil. Government policies (such as taxation on fuel consumption) should affect the demand for these fuels.

In the industrial sector, energy demand forecasting should carefully consider energy intensive industries such as cement, rubber, non-ferrous metals, and large food industries. It should also account for fierce international competition, the difficulties associated with penetrating world markets, and transportation cost increases.

This forecasting assumes high efficiencies and low losses in the gas and electricity industries in order to achieve maximum effectiveness in the economic sector. Additionally, it assumes that natural gas storage is feasible and realistic. The forecast does not predict any significant change in the regional gas demand pattern.

Commissioning a new hydroelectric power plant would make the Metsamor shutdown easier. However, this study focused only on developing TPPs and subsequent consideration of their gas needs. In this case, Metsamor could be shut down between 2010 and 2015. Another way to consider replacement of Metsamor is the construction of a new NPP.

In short, if Metsamor power plant is shut down, then hydro and thermal power plants must be developed. In this case, if the gas supply in the existing pipeline is interrupted, then only major economic sectors would have to be given priority in the electricity supply. In order to reduce this risk, a new gas pipeline from the Islamic Republic of Iran was constructed.

6.1.2. Energy and nuclear power planning study for Armenia

This study was published in 2004 under the name "Energy and Nuclear Power Planning Study for Armenia", IAEA-TECDOC-1404 [7] and its major conclusions are as follows:

– Energy and electricity demand: it was assumed that the rate of growth of electricity demand for various scenarios varied from 4.4% per year up to 5.6% per year and that the growth rate of demand for energy will be between 7.7% and 8.7% per year. In various scenarios, the rate of growth of peak load is also forecasted at 8% for the reference scenario and 4% for the low scenario;
– Overall energy demand-supply balance: the results of optimum development of power plants together with the other energy carriers show that if an NPP is built, the index of energy independency (percentage of the energy demand coverage by national energy

resources) will increase to 38.2%. If the NPP is replaced instead by combined cycle units, then the independency index will fall to 2.5%;
– Least cost plan for expanding the electricity generation system: a total of 3094 MW of power generation capacity has to be added in the period from 1999 to 2020 in order to meet the electricity demands as projected in the reference scenario. The contribution of nuclear power in terms of capacity is 1280 MW, which remains unchanged under the wide variation of influential parameters such as capital cost, discount rate, and prices of alternative fuel;
– Environmental assessment: The results obtained with the help of SIMPACTS code (Simplified Approach for Estimating Environmental Impacts of Electricity Generation) indicate that the power plant development plan with NPPs contributing to the electricity generation system is much more suitable than all other scenarios from an environmental perspective.

The most important recommendations resulting from this study are to:

– Repair and rehabilitate hydroelectric and thermal power plants as soon as possible;
– Implement demand side management as soon as possible;
– Commission Meghri, Loriberd, Shnokh HPPs, and 75 MW small hydroelectric plants between 2012 and 2017. Implement a 15 MW wind energy power plant and other renewable energy conversion projects and a 668 MW TPP;
– Reconstruct and develop electrical links with neighbouring countries. Reconstruct and expand underground gas storage facilities, store crude oil and petroleum products at a reasonable level, develop an NPP based on modern technologies in parallel with the process of retiring and dismantling the old NPP.

6.1.3. Armenia power sector 2006 least cost generation plan

This study was done in the framework of USAID assistance in 2006. Considering its results and taking into account strategic and economic issues, the following recommendations were made, pointing out a necessity to:

– Shut down the existing unit of ANPP in 2016;
– Implement a comprehensive study about site safety and environmental viability for dismantling the old NPP and constructing a new NPP on the same site;
– Prepare a comprehensive programme for the ANPP decommissioning at least five years before decommissioning initiation;
– Anticipate financial resources for the ANPP decommission, provide a reliable reserve of capital for this purpose, assign a financial manager to manage the expenditures under the supervision of international organizations;
– Provide sufficient capital to meet the costs for improving the safety conditions of the ANPP and ensuring its safe performance until 2015;
– Prepare a plan for evaluating Armenia’s ability to raise capital for constructing a new NPP;
– Prepare a plan for evaluating Armenia’s ability to raise capital for replacing thermal units in Yeravan and Hrazdan with new units;
– Develop local renewable energy resources to provide diversity and independency in energy resources;
– Prepare and implement a plan to encourage productivity in the energy sector so that consumer investment in new and efficient equipment is economically justifiable;
– Prepare and implement a plan for minimizing the effect of the ANPP decommissioning, and regulate new electricity tariffs accordingly;

– Determine capital needs, and prepare and implement a project for evaluating low-income consumer needs in order to provide them with government subsidies.

Some modelled cases and results given in Part B of this report are closely linked with the outcomes of this USAID project.

6.1.4. National assessment study in Armenia using the INPRO methodology for an innovative nuclear energy system in a country with small grids

The main goal of the study was to assess NES role in providing sustainable energy supply in the 21st century and to identify R&D directions for further development of nuclear technology (final report was published in 2008).

The main conclusions from this study are as follows:

– The population growth rate in Armenia by the end of 21st century is assumed to be around zero (as in many European countries today) and the level of urbanization will reach 78%;
– The main economic indicator — the GDP — is expected to reach around US $65 billion in 2100 with an average annual growth rate of around 3.28%;
– The total final energy demand by the end of the long term planning period is expected to be 7.5 times higher than in the base year;
– One of the most important types of supplied energy in Armenia will still be electricity. Total consumption is expected to amount to 42 TW·h in 2100;
– The analyses of the MAED calculations show that Armenia will need to increase its installed capacities to meet the electricity demand.

6.1.5. Development of the Armenian electrical grid scheme

Investigations into developing a new 400 kV network in Armenia (this would introduce a new voltage level) and subsequently expanding it to neighbouring power systems have been made by the Energy Network Design Institute of Armenia in the project “Development of the Armenian electrical grid scheme (2010, 2015, 2020)” (project was done in 2007).

Some main conclusions of this study are as follows:

– To ensure the admissible voltage level and to reduce active power losses in the electrical grid, it is desirable to construct a new 400/220 kV substation ‘Noravan’ with input/output of the double circuit Iranian-Armenian HVL of 400 kV;
– It is necessary to install a reactance in the Hrazdan TPP 400 kV substation to ensure the allowable voltage levels and to adjust reactive power flow;
– Short circuit current calculations show that there is no need to replace any equipment in the existing network. Additional equipment for the new 400 kV network might be required;
– Connecting new 400 kV overhead line (OHL) and increasing electricity exportation to neighbouring power systems will significantly reduce the risk of unstable operation of ANPP and the power system as a whole.

Many scenarios have been studied within the above mentioned projects. These scenarios consider different aspects of country development, such as GDP and population growth, industry, services, and transportation sector evolution, and growth of household living standards. The results of all these studies and other analyses carried out through different national and international projects illustrate the necessity of operating a nuclear unit in order to meet the electricity demand in the near and long term future.

On the basis of the results of the studies, an integrated and generalized long term energy demand scenario for Armenia has been defined and formulated as described below.

6.1.6. Armenia least cost energy development plan

The "Armenia least cost energy development plan" project was carried out in 2014 within the scope of the USAID projects "Low Emissions Strategies and Clean Energy Development in Europe and Eurasia" led by Tetra Tech and USAID grant "Support to National and Regional Energy Planning and Capacity Building at the Scientific Research Institute of Energy".

The main objective of the project is to elaborate the energy development strategy of the country taking into consideration economic developments of the past years, available potential of technologies and resources and laws and strategic plans of Government. Apart from considering a business-as-usual development pathway for Armenia, several alternative scenarios were analysed to assess impacts of various key energy system technical and economic options, and their implications for energy security and independence of the country.

The Armenian energy planning model MARKAL was applied to examine the plausible evolution of the Armenian energy system under various circumstances to assist the Government decision making process. The model is the culmination of a four-year research effort carried out by the Scientific Research Institute for Energy team assisted by DecisionWare Group under the auspices of USAID.

This report describes the current power sector in Armenia, highlights the key assumptions underlying the model depiction of the Armenia energy system, provides an overview of the new technology options available to the model, presents the business-as-usual reference scenario, explains the results of the least cost generation planning analysis undertaken, and provides conclusions and recommendation with respect to the "Armenia least cost energy development plan".

The main findings from the "Armenia least cost energy development plan" analysis are presented below:

- There is no economically justified alternative to life extension of the existing Armenian Nuclear Power Plant (ANPP) up to 2026. The ANPP's generating capacity could be replaced with new thermal generation capacity; however, this approach would result in higher overall costs, higher fuel price risk, and less energy diversity and security;
- New hydroelectric power plants (Shnokh, Loriberd, Meghri and Small HPPs) as well as wind and geothermal energy sources are cost-effective options in all scenarios considered, while solar is not competitive unless incentives are provided;
- Development of new 1000 MW WWER nuclear unit in 2026 is cost-effective in all scenarios except when there is no swap after 2026 and if Russian Federation gas prices are assumed to be set according to Russian-Armenian Intergovernmental Agreement, in this case the cost-effective option is smaller nuclear unit SMR-360 MW;
- To cover the near term requirements of the current swap arrangement, there is a need for installation of 620 MW of additional thermal capacity starting in 2018, however this capacity will be underutilized in the later years once the nuclear plant is added (unless additional export opportunities are developed);
- (Re)negotiating some flexibility in the swap levels for the 2018-2026 period (to 335/2901/4238 GW·h rather than 6000/6905/6905 GW·h) and arranging for continuation of the swap past 2026 reduces the total system cost by 329€ million compared to the Reference scenario;
- Lower Russian gas price results in more natural gas going to the demand sectors and in electricity generation eliminating the need to extend the lifetime of the existing NPP;

- Energy efficiency promotion demonstrates fuel and economic savings with a drop in electricity consumption resulting in 180 MW less new thermal capacity being needed;
- To implement the least cost generation strategy Armenia will have to invest €6,489 billion over the next 20 years.

Therefore, to implement the "Armenia least cost energy development plan" Armenia will have to make important decisions and implement in a timely manner the identified steps, most notably:

- ANPP life time extension;
- Meeting the requirements of the existing Iranian-Armenian Agreement and extending it after 2026;
- Construction of the 400 kV Armenian-Iranian transmission line;
- Providing reliable power flows with Georgia through construction of a 400 kV line and a Back-to-back converter;
- Construction of new combined cycle co-generation power units in the near term (unless the swap is renegotiated);
- Promotion of medium-size HPPs;
- Development of alternative energy within a reasonable scope;
- Moving forward with the new NPP development process.

6.2. ELECTRICITY DEMAND FORECAST

The total electricity demand has two components — domestic and external exchanges (export/import).

There is no direct and positive correlation between the level of economic production in the country and the domestic electric power consumption over the last decade. Non-availability of reliable economic and energy statistics in Armenia, a tendency to overweigh positive trends in electricity consumption, uncertainty in the emigration of Armenian citizens to other countries, and the replacement of electrical heaters with gas and other heaters make the domestic electricity demand forecast for Armenia a very challenging and complex task.

The next section of this study considers domestic demand in three scenarios (with 3%, 4%, and 5% growth).

In near future, there are two neighbouring countries with export/import potential for Armenia: the Islamic Republic of Iran and Georgia.

Due to growing electricity demand in Georgia and continued natural gas price increases, Georgia could provide a market for electricity export from Armenia. However, the fact that Georgia's peak demand occurs during the same period as Armenia's could negatively affect this prospect.

The Islamic Republic of Iran trades power with neighbouring countries. While it exports power to Iraq, Turkey, Pakistan, Azerbaijan and Afghanistan, it imports power from Armenia and Turkmenistan. Armenia already has a number of electricity contractual commitments to the Islamic Republic of Iran.

Unlike Armenia, peaks of electricity demand of the Islamic Republic of Iran occur in the summer months. This peak load is approximately 50% higher than the winter peak; some regions of the Islamic Republic of Iran experience shortages of electricity during this time. The difference in peak demand periods creates an excellent opportunity for Armenia to export power to the Islamic Republic of Iran during periods of relatively low domestic consumption.

Table 5 provides the information on power exchange possibility with neighbouring countries through existing power transmission lines for the period up to 2030.

TABLE 5. POWER EXCHANGE POSSIBILITY WITH NEIGHBOURING COUNTRIES THROUGH EXISTING POWER TRANSMISSION LINES

Interconnection type	Total, P_{nom} (MW)
Islamic Republic of Iran – HVL-220kV “Ahar–1,2”	400
Georgia,	300
Including:	
HVL 220kV “Alaverdi”	200
2 TLs 110kV “Lalvar”, “Djavakhq”)	100
Total power export to neighbouring countries	**700**

Table 6 provides information on the power exchange with neighbouring countries through pre-assigned (in future) power transmission lines.

TABLE 6. ANTICIPATED POWER EXPORT TO NEIGHBOURING COUNTRIES THROUGH PRE-ASSIGNED POWER TRANSMISSION LINES

Interconnection type	P_{nom} (MW)	Periods	
		2025	2035
Islamic Republic of Iran including:	1130	1130	1130
– HVL-220kV from Meghri HPP – HVL-400kV from Hrazdan TPP	130 1000	130 1000	130 1000
Georgia – HVL-400kV, winter/summer	350/-350	350/-350	350/-350
Total power export in winter/summer	**1480/780**	**1480/780**	**1480/780**

It is technically feasible to export significant amounts of electricity to neighbouring countries, particularly with the pre-assigned 400 kV lines from Armenia to the Islamic Republic of Iran and Georgia.

Table 7 illustrates the expected domestic and export electricity demands for the years 2015, 2025, and 2035.

Domestic demand does not make substantial changes in the 3%, 4%, and 5% growth scenarios; therefore 5% growth has been used for the next steps of the study. As in further studies power exchanges with the Georgian power system are not considered, Table 7 shows forecast of electricity demand without export to Georgia.

TABLE 7. EXPECTED DOMESTIC & EXPORT ELECTRICITY DEMAND 2015-2035

Electricity Demand (GW·h)	Years		
	2015	2025	2035
Domestic	6581	8344	9884

TABLE 7. EXPECTED DOMESTIC & EXPORT ELECTRICITY DEMAND 2015-2035 (cont.)

Electricity Demand (GW·h)	**Years**		
	2015	**2025**	**2035**
Export to Islamic Republic of Iran	**1201**	**6905**	**6905**
Total	7782	15648	16789

6.3. MODELLING OF ARMENIA'S ENERGY NETWORK IN MESSAGE SOFTWARE

MESSAGE software modelling is performed in two stages. In the first stage, different energy levels, from exploiting primary energy resources to the final energy consumption, have to be introduced for the software.

Afterwards, energy carriers at each level and the corresponding input parameters are defined for the software. Energy conversion technologies, energy storage technologies and energy transmission technologies define the relationship between various energy levels to clear the entire path of energy flows from initial levels to the final ones in MESSAGE software.

The MESSAGE software depicts the Armenian energy network in Figure 9 below. Since Armenia does not have any domestic fossil fuels, the energy carriers at the primary level are imported from neighbouring countries.

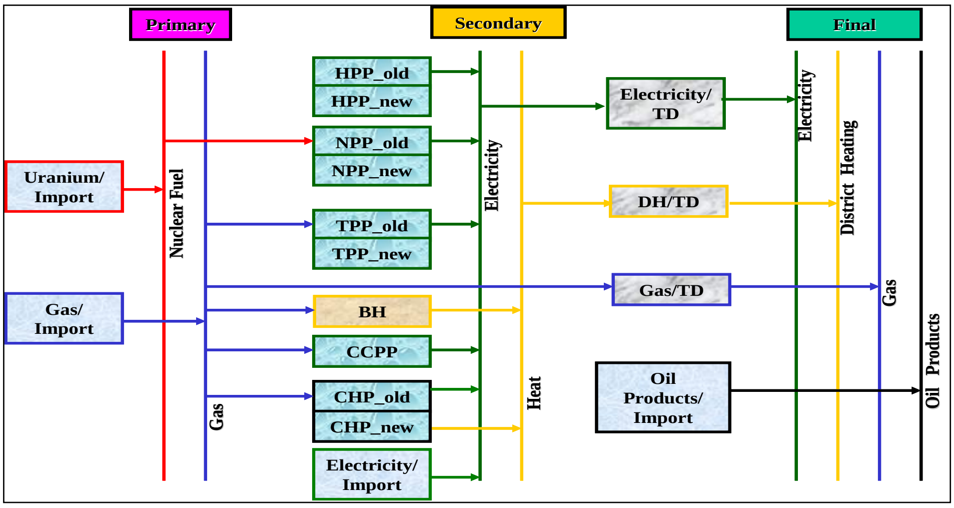

FIG. 9. Armenian energy network simplified in MESSAGE tools.

6.4. SIMULATION RESULTS

Table 8 describes the planning of new generation capacities — obtained from the simulation results — of the Armenian power system for the period 2025–2035. It is assumed that a new WWER-1000 type of nuclear unit with 1000 MW of installed capacity will be commissioned in 2026.

TABLE 8. NEW GENERATION CAPACITIES IN ARMENIAN POWER SYSTEM

Power plant type	**Values of new capacities (MW) by a certain date**	
	2025	**2035**
TPPs, including:	**620**	**0**
– New combined cycle co-generation power units	620	0
Power plant type	**Values of new capacities (MW) by a certain date**	
	2025	**2035**
HPPs, including:	**136**	**130**
– Meghri	0	130
– Loriberd	66	0
– Shnokh	70	0
Small HPPs	**148**	**0**
NPP, including:	**385**	**1060**
– Life extension of existing plant	385	0
– New NPP	0	1060
Wind farms	**3**	**150**
Power plant type	**Values of new capacities (MW) by a certain date**	
	2025	**2035**
Geothermal power plant	**30**	**0**
Solar PV	**40**	**0**
Total	***1362***	***1340***

Table 9 summarizes power balances for the available and planned capacities of the Armenian Power system from 2025–2035.

TABLE 9. TOTAL POWER BALANCES FOR ARMENIAN POWER SYSTEM

Power plant type	**P_{nom} (MW)**		
	2015	**2025**	**2035**
ANPP	**385**	**385**	**1060**
Hrazdan TPP, including:	**810**	**440**	**440**
– Hrazdan TPP	370	0	0
– Hrazdan-5 (gas and steam turbines unit)	440	440	440
Yerevan TPP, including:	**242**	**242**	**242**
– Yerevan TPP	0	0	0
– Combined cycle co-generation power unit	242	242	242
New combined cycle co-generation power units	**0**	**620**	**620**
Sevan-Hrazdan HPPs cascade	**562**	**562**	**562**
Vorotan HPPs cascade	**404**	**404**	**404**
New HPPs, including:	**0**	**136**	**266**
– Meghri	0	0	130
– Loriberd	0	66	66
– Shnokh	0	70	70

TABLE 9. TOTAL POWER BALANCES FOR ARMENIAN POWER SYSTEM (cont.)

Power plant type	P_{nom} (MW)		
	2015	**2025**	**2035**
Small HPPs	**282**	**370**	**370**
Wind power plants	**3**	**3**	**150**
Geothermal power plant	**0**	**30**	**30**
Solar PV	**0**	**40**	**40**
Total	**2628**	**3232**	**4184**

Reserve capacity is the ability of the under-loaded generation facility to provide reserve power when needed. Control capacities are required to cover random fluctuations of electricity consumption.

Based on the analysis of the load flow, reserve and control capacities, Table 10 introduces complete balances of power for 5% load growth for 2015, 2025, and 2035.

TABLE 10. POWER BALANCES WITH CAPACITY RESERVE IN 2015, 2025, 2035 (MW)

No.	Description	Years		
		2015	**2025**	**2035**
	I. Power Demand			
1.	Armenian power system load	1335	1729	2207
2.	Transmission to other power systems:	750	1880	1880
	– Islamic Republic of Iran	400	1 530	1 530
	– Georgia	350	350	350
3.	Losses	73	145	165
4.	Capacity Reserve	400	450	500
	Total demand	**2558**	**4204**	**4752**
No.	**Description**	**Years**		
		2015	**2025**	**2035**
	II. Power Supply			
1.	Installed capacities of power plants, including:	**2688**	**3232**	**4184**
	Thermal power plants	1052	1302	1302
	Nuclear power plant	385	385	1060
	Hydropower plants*	966	1102	1232
	Small HPPs	282	370	370
	Wind power plants	3	3	150
	Geothermal power plant	**0**	**30**	**30**
	Solar PV	0	40	40
Total supply excess (+), deficit (-)		***+130***	***-972***	***-568***

* Generation by Sevan-Hrazdan cascade of HPPs assumed for all prospective years 137.4 MW in winter maximum mode.

It is preferable to keep a capacity reserve of at least 10% of demand. Thus, the reserve capacity deficit will not be in an alarming situation.

Table 10 above shows that there will be a power deficiency (supply is less than demand) in 2025 and in 2035 even with the addition of a new 1000 MW NPP operable in 2026. There are two options to ensure power flow during the winter (peak demand time) of 2035. One is to add another power plant. The other — the preferred option — is to adjust distribution of power supply from the Islamic Republic of Iran between Armenia and Georgia depending on the available export amounts of power from the Iranian generation capacities.

6.5. CONCLUSIONS

Reviewing the results above the conclusions can be drawn as follows:

– Total installed power plant capacities will increase from 2850 MW in 2015 to 4484 MW in 2035;
– The minimum electric power reserve capacity is assumed to be 500 MW for 2035;
– Electricity generation will grow from 7.8 billion kW·h in 2015 to over 16.8 billion kW·h in 2035;
– Policies of electricity generation expansion are significantly influenced by gas price fluctuations. Development of nuclear power capacity in Armenia becomes more feasible when gas price is increased;
– Uranium price variations do not considerably influence the optimum set found for generation expansion planning in Armenia.

7. GENERAL RECOMMENDATIONS FOR PART A

On the basis of the analyses made in previous sections related to Armenia, the following recommendations can be generalized for other small countries:

– Energy security plays a crucial role for the stable and secure development of the economic sector itself and a country as a whole;
– Level of energy independence from imported energy sources in a country's development scenarios holds significant sway over the decision making process;
– Stability, availability, and diversification of fuel supply options should be carefully considered in energy sector expansion strategies;
– The economics of energy expansion plans plays one of the major roles in the elaboration of strategy development programmes. Yet ensuring the highest possible levels of energy security and energy independence may have more central roles;
– Regional, interregional, and international integration and cooperation may reduce problems related to safe and secure energy system operation as a whole, and to each of its separate different parts;
– Demand forecasts updates should be carried out regularly as changes in economic situations in small countries have a quick and direct impact on energy demand level.

PART B: GRID STABILITY ANALYSIS

8. DEFINITION OF DESIGN PARAMETERS

8.1. EXISTING HIGH VOLTAGE NETWORK

The Armenian power system (APS) comprises 220–110 kV power transmission OHLs and spans Armenia's entire territory. The only 330 kV HVL line from Hrazdan TPP to Aghstafa (Azerbaijan) is currently inoperable. The APS has a ring structure and a high capacity, which ensures reliable operation and allows the implementation of electricity inside systems and intersystem power exchanges. Hrazdan TPP, the ANPP, Shamb HPP and Spandaryan HPP directly generate power for the 220 kV network. The remaining major power stations are connected to 110 kV network. The system has fourteen 220 kV substations.

The equivalent scheme of the APS has been used in the study. A graphic illustration of the scheme, numeration and titles of nodes, and HVL parameters are given in Figure 10 and Table 11 below.

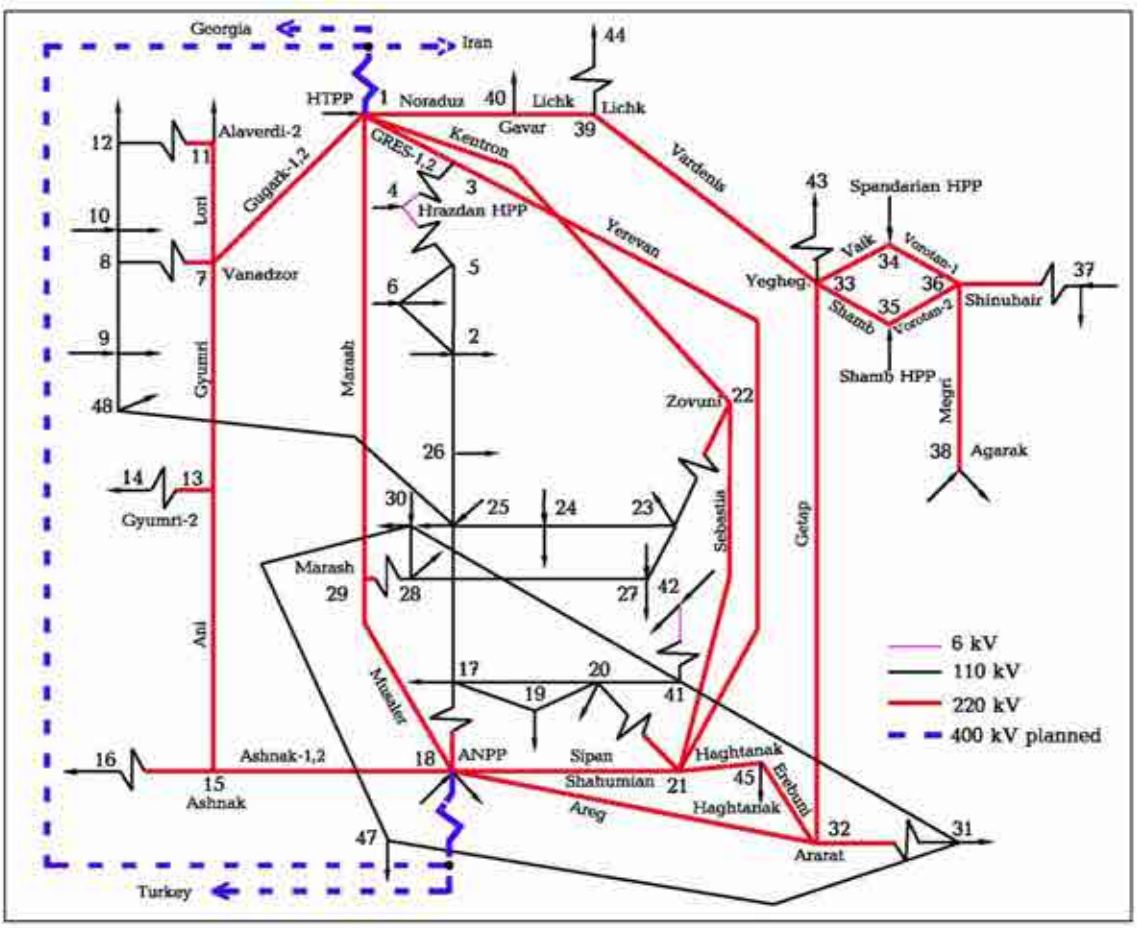

FIG. 10. Equivalent scheme of Armenian power system.

The scheme above includes all existing TPPs, the ANPP, all stations of Sevan-Hrazdan and Vorotan cascades of HPPs, and also all 220 kV OHLs, all 220 kV substations and the majority of 110 kV OHLs. This scheme is consistent with the appropriate scheme used by the system operator.

The permissible OHL boundary values are given in Table 12. It is clear that Sipan HVL (approximately 570 MW) and Yerevan HVL (490 MW) have reached maximum transmission capacity. Another four 220 kV OHLs (Erebouni, TPP-1,2, Gougark-1,2 and Haghtanak) have approximately 300 MW capacity. The rest have less than 300 MW.

TABLE 11. NODE NAMES OF EQUIVALENT SCHEME OF ARMENIAN POWER SYSTEM

1. Hrazdan TPP (unit part)	17. ANPP-110	33. SS Yeghegnadzor
2. Hrazdan TPP (CHP part)	18. ANPP-220	34. Spandaryan HPP
3. SS Hrazdan HPP-220	19. SS Echmiadzin	35. Shamb HPP
4. SS Hrazdan HPP	20. SS Shahumyan-110	36. SS Shinuhayr
5. SS Hrazdan HPP-110	21. SS Shahumyan-220	37. Tatev HPP
6. Sevan HPP	22. SS Zovuni-220	38. SS Agarak
7. SS Vanadzor-220	23. SS Zovuni-110	39. SS Lichk
8. SS Vanadzor-110	24. Arzni HPP	40. SS Kamo
9. SS Vanadzor TPP	25. Argel HPP	41. Yerevan HPP-110
10. Dzora HPP	26. SS Charencavan	42. Yerevan HPP-6
11. SS Alaverdi-220	27. Kanaker HPP	43. SS Yeghegnadzor-110
12. SS Alaverdi-110	28. SS Marash-110	44. SS Lick-110
13. SS Gyumri-220	29. SS Marash-220	45. SS Haghtanak-220
14. SS Gyumri-110	30. Yerevan TPP (CHP part)	46. Tbilisi TPP
15. SS Ashnak-220	31. SS Ararat-110	47. SS Mkhchyan-110
16. SS Ashnak-110	32. SS Ararat-220	48. SS Spitak-110

TABLE 12. HVL-220 KV CAPACITIES OF ARMENIAN POWER SYSTEM ($\cos\varphi = 0.9$)

No	Name	Capacity (MW)	No	Name	Capacity (MW)	No	Name	Capacity (MW)
1.	Ani	283	9.	Kentron	285	17.	Shamb	285
2.	Areg	285	10.	Lichk	295	18.	Sipan	569
3.	Ashnak-1,2	566	11.	Lori	243	19.	TPP-1,2	658
4.	Erebuni	329	12.	Marash	285	20.	Vaik	233
5.	Getap	285	13.	Megri	283	21.	Vardenis	233

TABLE 12. HVL-220 KV CAPACITIES OF ARMENIAN POWER SYSTEM (cosφ = 0.9) (cont.)

No	Name	Capacity (MW)	No	Name	Capacity (MW)	No	Name	Capacity (MW)
6.	Gugark-1,2	658	14.	Musaler	285	22.	Vorotan-1	243
7.	Gyumri	285	15.	Noraduz	295	23.	Vorotan-2	285
8.	Haghtanak	329	16.	Sebastia	285	24.	Yerevan	487

Currently installed capacities of 220/110 kV autotransformers are given in Table 13. At least two (auto)transformers are installed in all 220 kV substations that mainly ensure (n-1)[*)] criteria. The ANPP and Ashnak's substations are exceptions, with only one (auto)transformer each. However, in both cases (n-1) criteria are ensured by fairly well developed 110 kV networks.

TABLE 13. CAPACITY OF (AUTO) TRANSFORMERS 220/110 KV

NN	SS name	No. of units × capacity (MV·A)	Total capacity (MV·A)
1.	Hrazdan HPP	2×120	240
2.	SS Vanadzor	2×125	250
3.	SS Alaverdi	2×63	126
4.	SS Gyumri	2×125	250
5.	SS Ashnak	1×63	63
6.	SS ANPP	1×200	200
7.	SS Shahumian	2×125	250
8.	SS Zovuni	2×125	250
9.	SS Marash	1×250, 1×125	375
10.	SS Ararat	2×63	126
11.	SS Shinuhair	3×63	189
12.	SS Yeghegnadzor	2×63	126
13.	SS Lichk	2×63	126

[*)] *For multiple transmission lines delivering power to the same point, if one of the lines goes out of service, the remaining lines must be able to carry both the load they were carrying before the event, plus the load carried by the line that is out of service.*

8.2. PRE-ASSIGNED (FUTURE) ARMENIAN HIGH VOLTAGE NETWORK

Combining the capacities of the 220 kV and 110 kV lines from ANPP unit 2 results in total capacity of between 855 MW and 2040 MW, with a reliable capacity of approximately 1380 MW. This existing capacity would be insufficient for the concurrent operation of unit 2 and the new NPP. Additions of a 1000 MW NPP and pre-assigned (future) 400 kV transmission lines from ANPP are shown in Table 14.

Table 15 shows pre-assigned power system interconnections between Armenia and neighbouring countries.

In addition to the above pre-assigned power system interconnection lines, another 220 kV line (installed in 2015) between Meghri HPP and Agarak will be required for power export to the Islamic Republic of Iran.

TABLE 14. PRE-ASSIGNED HIGH VOLTAGE POWER TRANSMISSION LINES FROM THE ANPP

Name of line	**Voltage (kV)**	**Length (km)**	**Aluminum conductor cross Section (mm^2) × conductors/phase**	**Maximum capacity (MW)**
Hrazdan	400	80	500 × 2	1250
Horasan	400	170	500 × 2	1000

TABLE 15. PRE-ASSIGNED POWER SYSTEM INTERCONNECTIONS BETWEEN ARMENIA AND NEIGHBOURING COUNTRIES

No	**OHL name**	**OHL voltage (kV)**	**From**	**To**	**OHL length (km)**		**Conductor grade**	**Maximum capacity (MW)**
			Armenia	**neighbouring country**	**Total**	**In Armenia**		
1	Tabriz (2 circuit)	400	Hrazdan TPP	Tabriz (Islamic Republic of Iran)	432.0	332.0	2×AC-2×500	2000
2	Georgia	400	Hrazdan TPP	Ksani (Georgia)	170.0	90.0	AC-2×300	785

8.3. CONCLUSIONS

The following conclusions can be made from this Section:

- The existing high voltage electrical grid of Armenia is well enough developed to ensure the flow of expected power within both the country and export/transit through the system only for a few coming projection years;
- Implementation of new 400 kV voltage level in the Armenian grid till 2020 will significantly increase the network's flow capacity and, as a result, will provide considerable export/transit capability and will increase stable operation level of the system;
- A new 1000 MW nuclear unit needs to be commissioned in 2026;
- An additional study shows that in the case of the high development scenario, the Armenian economy may require one more nuclear unit to be commissioned by 2036;
- The WWER-1000 reactor has been selected for the next steps of this study (overview of the reactor's operation systems is presented in Appendix I).

9. ASSESSMENT OF SAFETY AND STABILITY OF GRID OPERATION

9.1. MAIN ASSUMPTIONS AND SCENARIOS

Steady state and dynamic regimes of the Armenian power system have been studied taking into account the new ANPP 1000 MW unit. Measures have been suggested to maintain system indicators in steady state and dynamic regimes within allowed limits.

This section summarizes the results of the detailed study, which used the IPF and TSP computer tools described in the Section 2.3.

To perform the steady state and dynamic studies some power flow regimes had to be calculated. 2013 was selected as a base year for the calculations. Substation capacity distribution in winter (maximum on 31 December 2013, 21:00) and summer (minimum on 18 June 2013, 05:00) served as a basis for the establishment of respective regimes for the forecast years (2026 and 2035). 2013 data were provided by the settlement centre and system operator. The APS maximum possible internal consumption amounted to 1283 MW; the minimum was 391 MW.

On the basis of the base year figures and forecasted consumption data, system substation load volumes were calculated for 2026 and 2035 by multiplying the 2013 load values with the following conversion factors:

$$\mathbf{k_{2026,max} = \frac{P_{2026,max}}{P_{2013,max}} = \frac{1910}{1283} \approx 1.4887}, \quad \mathbf{k_{2026,min} = \frac{P_{2026,min}}{P_{2013,min}} = \frac{550}{391} \approx 1.4066},$$

$$\mathbf{k_{2035,max} = \frac{P_{2035,max}}{P_{2013,max}} = \frac{2370}{1283} \approx 1.8482}, \quad \mathbf{k_{2035,min} = \frac{P_{2035,min}}{P_{2013,min}} = \frac{780}{391} \approx 1.9949}.$$

The year 2026 was chosen as the commissioning year of the new reactor and 2035 was chosen for analysing system power flows and their influences on NPP safety operation and grid regimes.

Minimum voltage considerations were required for analysing (over)voltage regimes that may arise due to HVL under-loading. Future operation conditions involving the 1000 MW NPP unit also had to be considered. Maximum regime considerations were required for the network load study.

The winter minimum and summer maximum regimes of the Armenian power system are nearly identical, and fall in the middle of the aforementioned maximum and minimum ranges.

One of the peculiarities of the APS is that the total generation capacity of the whole system in a number of cases is comparable with the ANPP generation capacity itself. This factor has an impact on system operation, especially in the minimum regimes.

For the forecast years it was assumed that HPPs produce as much capacity as in 2013 in the respective summer and winter regimes.

The steady-state regime scenarios described in Table 16 have been taken into consideration in this study.

In all scenarios it is assumed that there are no power exchanges with the Georgian power system through existing (220 kV and 110 kV OHLs) or future (400 kV HVL) intersystem connections.

TABLE 16. MODELLED STEADY-STATE REGIMES SCENARIOS

Scenario No.	Year	Regime title	Internal demand (MW)	Export to Islamic Republic of Iran (MW)
1.	2026	Winter maximum regime	1910	450
2.		Summer minimum regime	550	750
3.	2035	Winter maximum regime	2370	600
4.		Summer minimum regime	780	1000

IPF calculation results are given in diagrams where the active power flow direction is marked by an arrow and the number next to the arrow shows its value. Reactive power values and directions are given in brackets (if reactive power flow is opposite to active power direction, it is given as a negative number). Node per unit voltage value is written under the node (the software allows the user to present voltage in nominal units). If it deviates by ±5%, the node is grey and if the voltage deviates by ±10%, the node is black. IPF also allows the user to control links (lines and transformers) overloading. In case of lines overloading, the design and admissible current are given in amperes under the link. If the overloaded link is a transformer, then the designed and nominal power values are written in MV·A under the link. Since different bus-bar voltage levels and substation transformers have been modelled independently, then more than one node in the modelled scheme is compatible with the same substation.

The TSP calculation results are also presented in diagrams. In this report only generator angle (in our case compared with Hrazdan TPP) in degrees, generator active power in MW, generator reactive power in MV·A, generator bus voltage per unit, and bus frequency deviation in hertz are shown. The time measurement unit is one cycle, which is equivalent to 0.02 seconds.

9.2. STEADY-STATE STUDY RESULTS

9.2.1. Modelling power scenarios

In scenario 1, the results of system power flow calculations are illustrated in Figure 11. The results show some problems in the APS. They are:

- Overloading of the ANPP’s autotransformer. In conditions of a maximum permissible capacity of 200 MV·A, the autotransformer’s capacity increases to 217 MV·A;
- Overloading of 220 kV Sipan HVL. Instead of the permissible current level of 900 A, the line transmits approximately 970 A;

– Voltage fluctuations in the distribution network of Zangezour region is larger than ±5%, but is within the allowable ±10% limit. Voltage level adjustments in these nodes can be made by changing autotransformer pivot positions and by regulating generator voltages in that region. For this reason, special measures for voltage level regulation are not considered in this study.

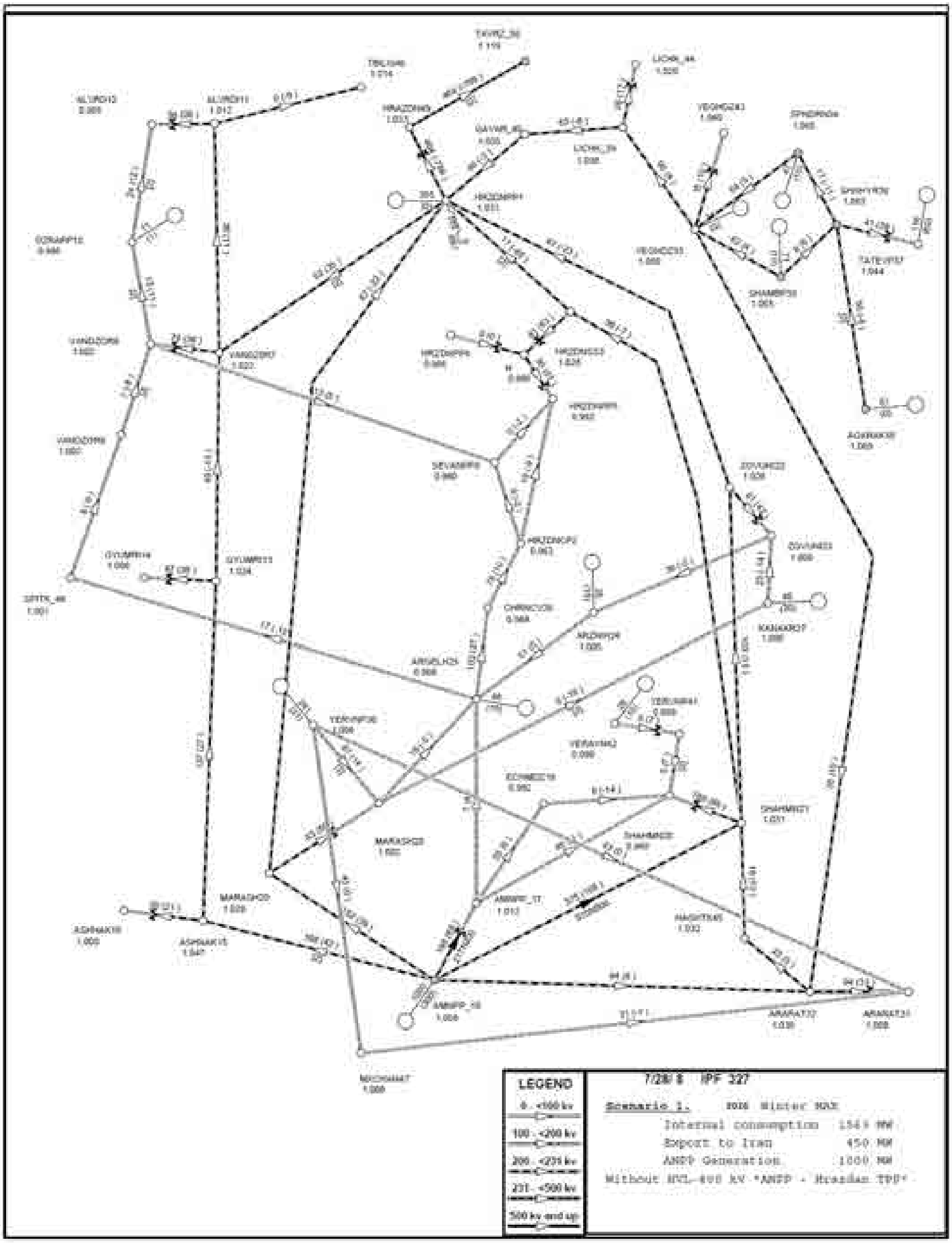

FIG. 11. Scenario 1. 2026 winter max regime without HVL-400 kV ANPP-Hrazdan TPP.

Two options are suggested for solving these problems:

– Installation of a second autotransformer in the ANPP substation and upgrade of the Sipan HVL by changing the wire cross-section, or by switching it to a double-circuit HVL, or by building a second HVL;
– Construction of a new HVL for ANPP-Hrazdan TPP 400 kV. Additional calculation of Scenario 1 have been carried out for such an addition and the ANPP's operation at full capacity (1000 MW). Results from this calculation are illustrated in Figure 12.

Figure 12 displays all problems resolved in Scenario 1, but it should be noted that the loading of the existing autotransformer of the ANPP's 220 kV substation is near the maximum permissible limit (192 MV•A; the maximum allowable limit is 200 MV•A). In this case, the proposed installation of the second autotransformer remains desirable.

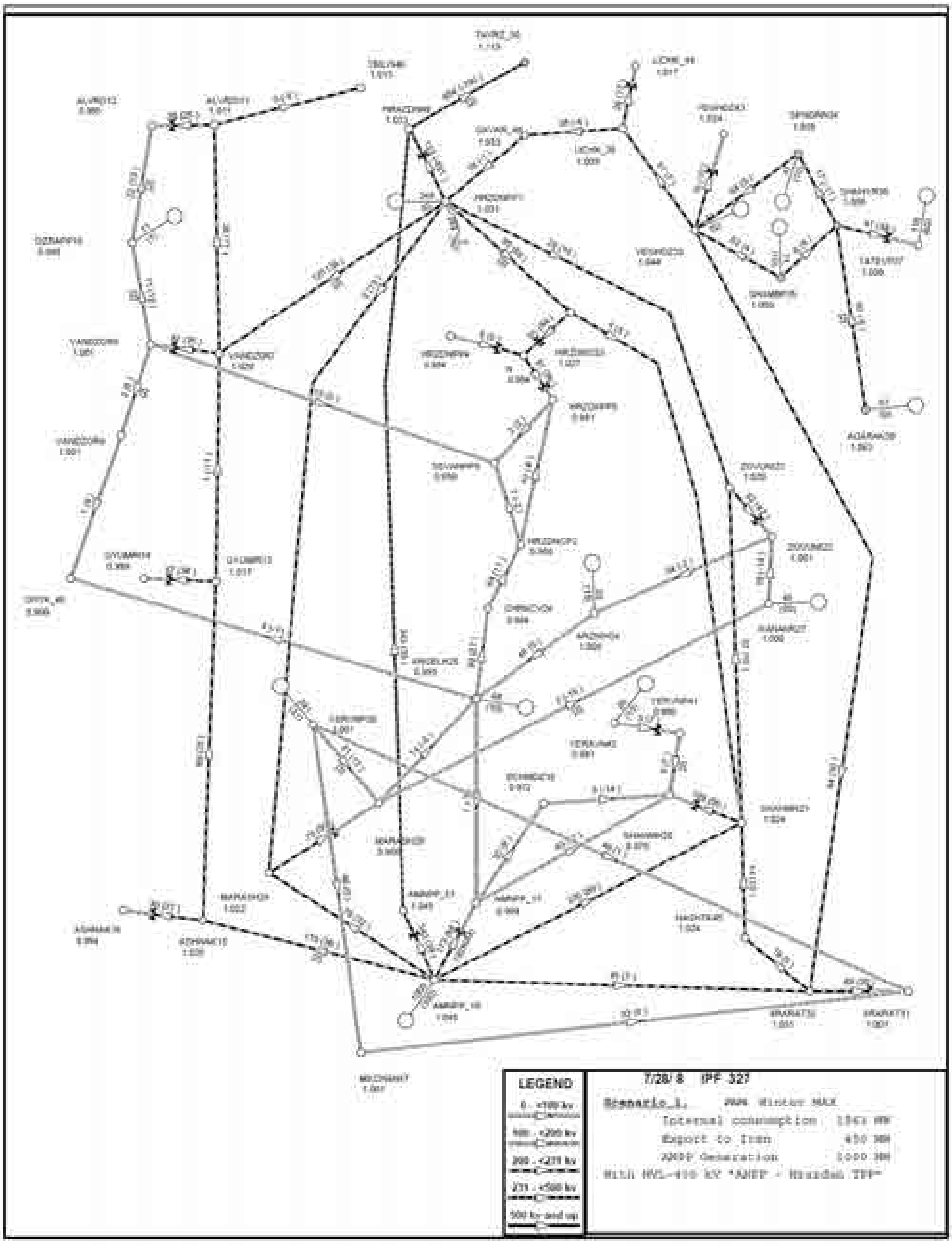

FIG. 12. Scenario 1. 2026 winter max regime with HVL-400 kV ANPP-Hrazdan TPP.

The system power flow for scenario 2 is given in Figure 13.

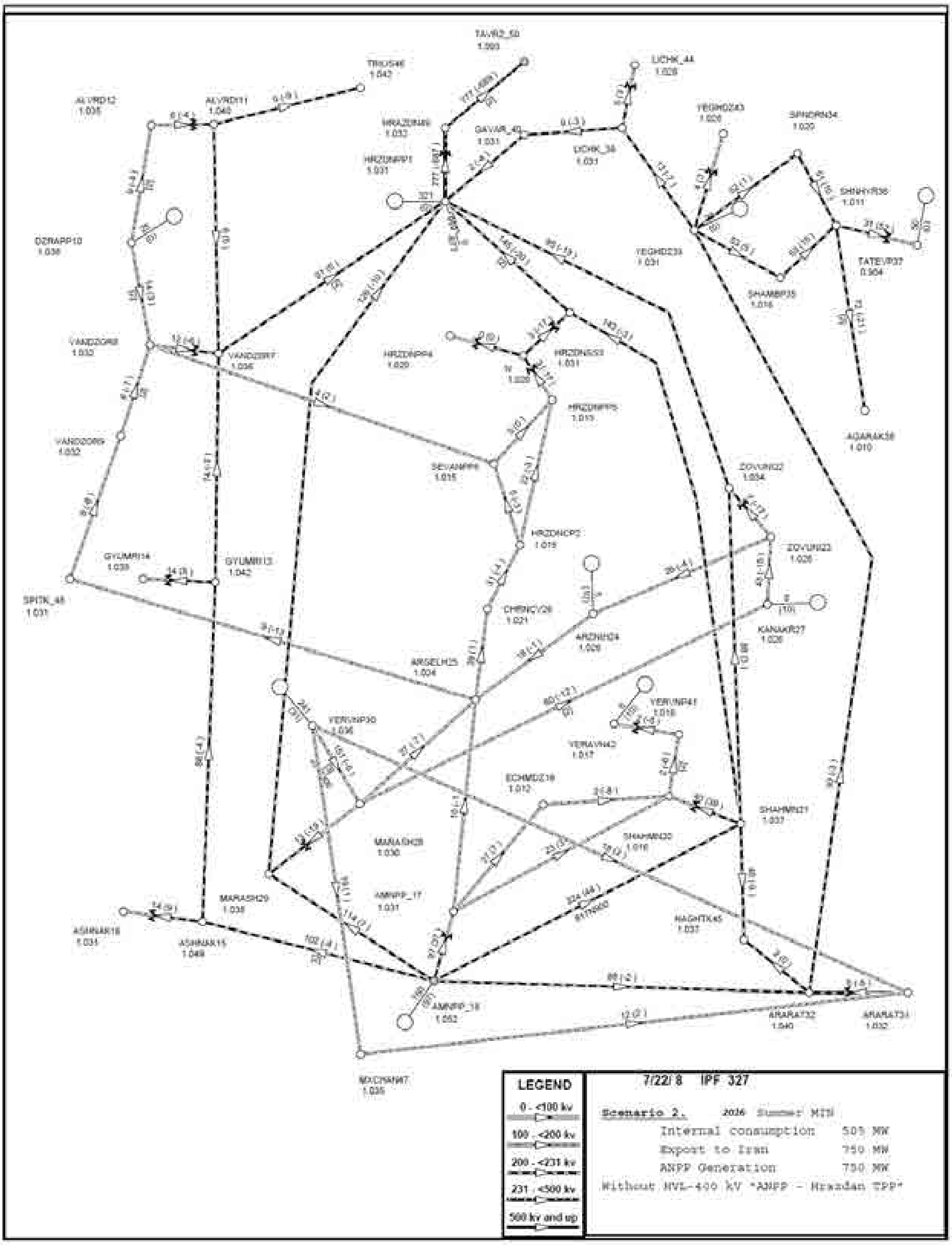

FIG. 13. Scenario 2. 2026 summer min. regime without HVL-400 kV ANPP-Hrazdan TPP.

For 2026, it is impossible to ensure system stability in the case of a new nuclear unit full loading (1000 MW). Stability is ensured for 75% loading. Without the ANPP-Hrazdan TPP 400 kV new HVL, no significant problems appear in the system. However, the 220 kV Sipan HVL's loading is near the maximum allowable limit (817 A instead of 900 A).

Additional calculations of Scenario 2 have been carried out for the case of existence of the ANPP-Hrazdan TPP 400 kV new HVL and ANPP's operation at 75% capacity (750 MW). The results are illustrated in Figure 14. In this case, all problems in the system disappear.

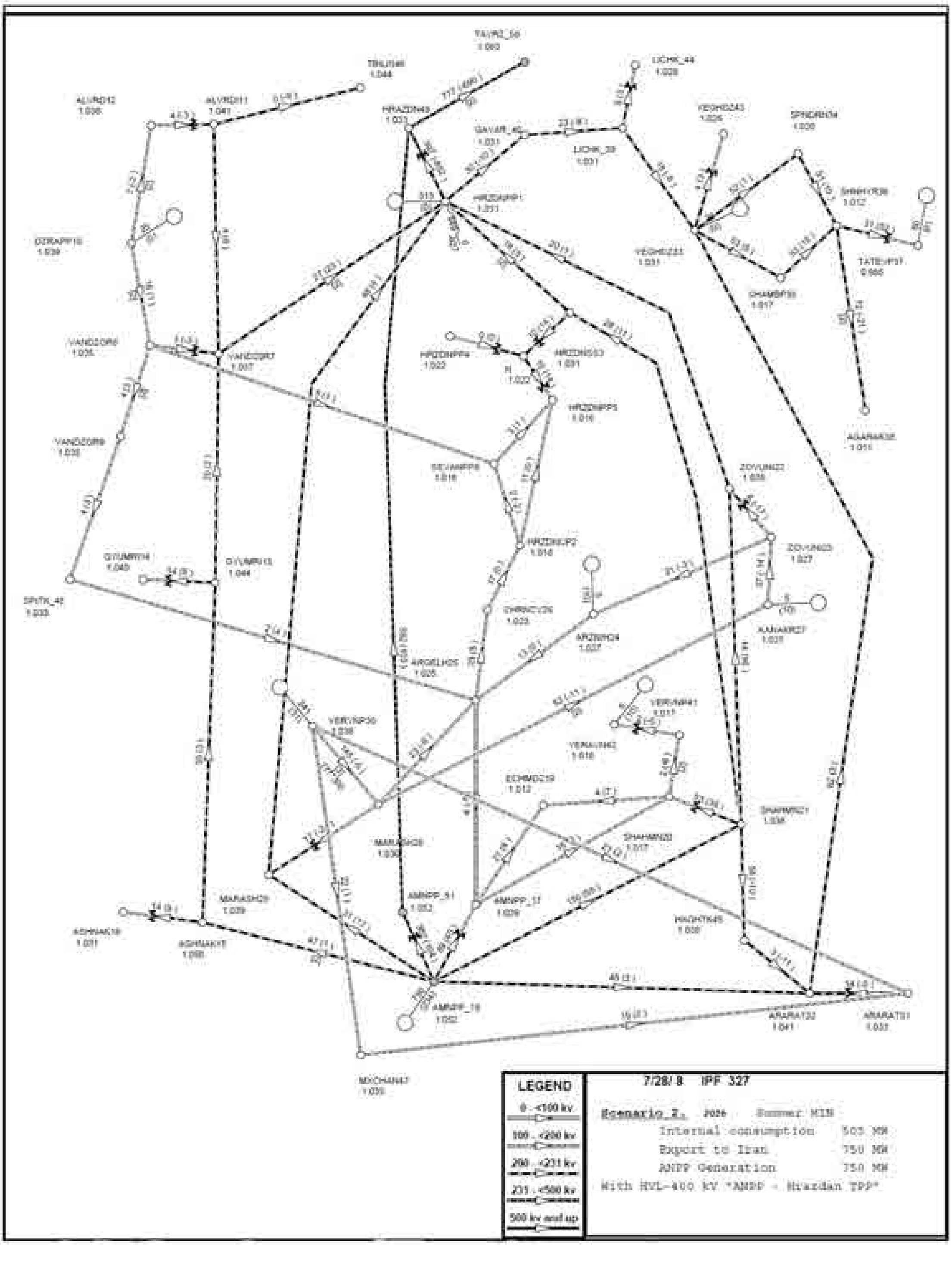

FIG. 14. Scenario 2. 2026 summer min. regime with HVL-400 kV ANPP-Hrazdan TPP.

System flow distribution calculation results (upon non-existence of ANPP-Hrazdan TPP 400 kV new HVL) for Scenario 3 are illustrated in Figure 15.

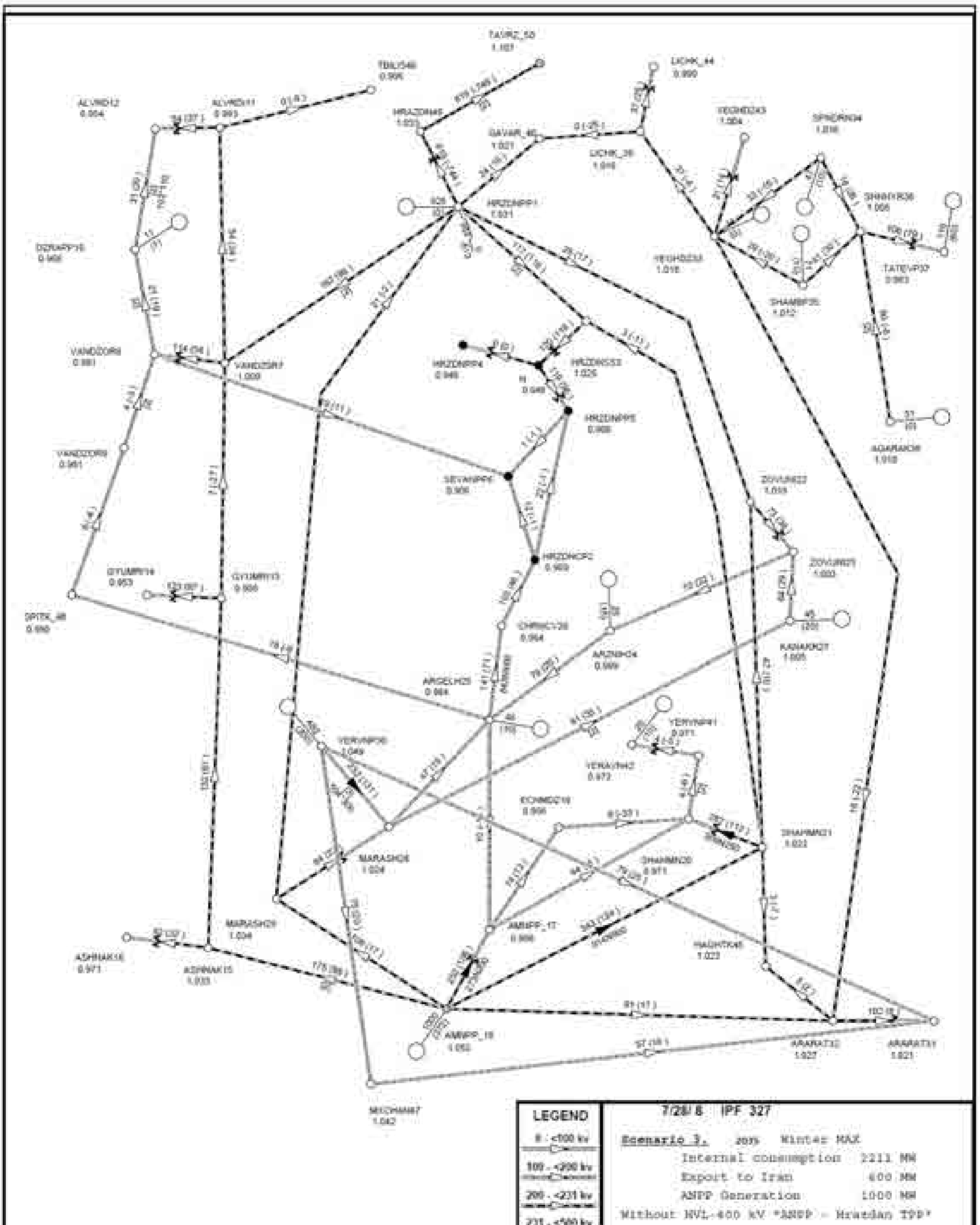

FIG. 15. Scenario 3. 2035 winter max. regime without HVL-400 kV ANPP-Hrazdan TPP.

There are problems in this scenario as well. The Sipan HVL current reaches 914 A, while its allowed limit is 900 A. The new unit's and Shahumyan-2 substations' autotransformers are overloaded, and load becomes 273 MV·A (200 MV·A) and 309 MV·A (250 MV·A) respectively. Similar problems appear with Yerevan TPP's, Vinil, Kauchouk, Southern-1, 2 and Nairit-1, 2 110 kV OHLs' overloading.

Overloading of the Sipan HVL disappears in the presence of the ANPP-Hrazdan TPP 400 kV new HVL (Figure 16), but the above mentioned autotransformers and 110 kV OHLs remain overloaded.

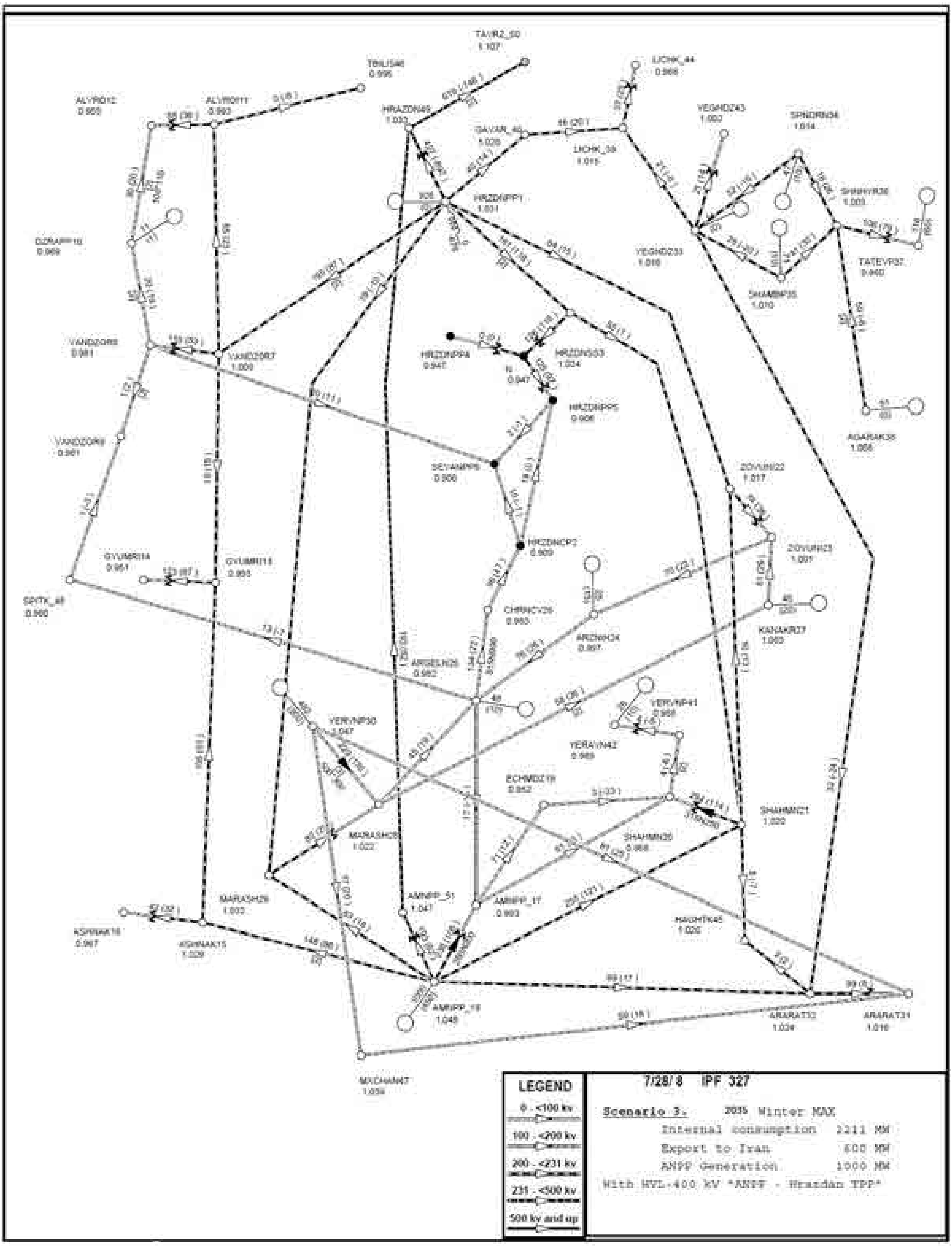

FIG. 16. Scenario 3. 2035 winter max. regime with HVL-400 kV ANPP-Hrazdan TPP.

Figure 17 depicts the system flow distribution calculation results for Scenario 4 (without the ANPP–Hrazdan TPP 400 kV new HVL).

In this scenario, Sipan 220 kV HVL is overloaded (1083 A instead of the allowable 900 A) as well as the Vinil, Kauchouk, Southern-1, 2 and Nairit-1, 2 110 kV OHLs of Yerevan TPP.

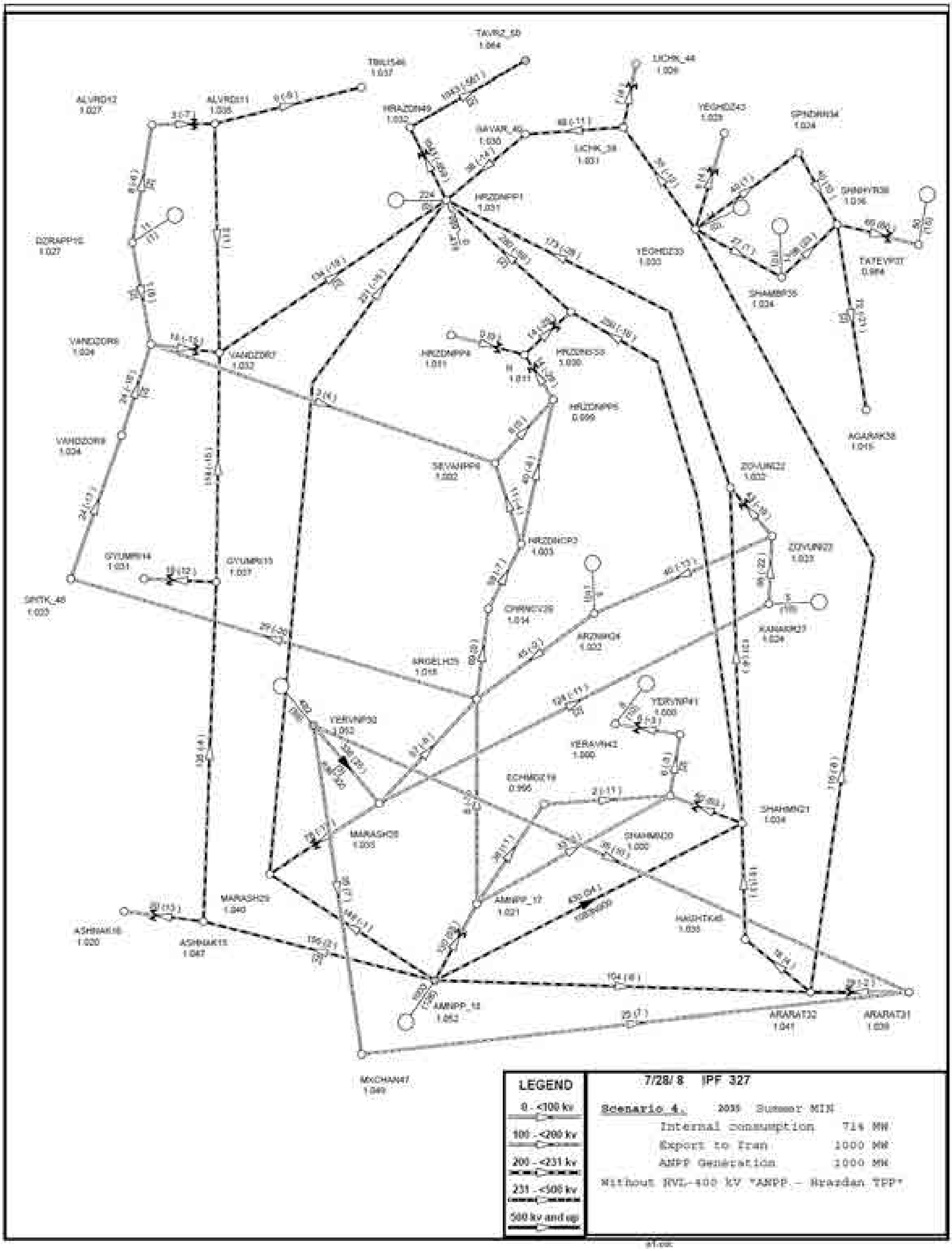

FIG. 17. Scenario 4. 2035 summer min. regime without HVL-400 kV ANPP-Hrazdan TPP.

Again, the Sipan HVL overload disappears in the presence of the ANPP-Hrazdan 400 kV new HVL (Figure 18), but the above mentioned 110 kV OHLs remain overloaded.

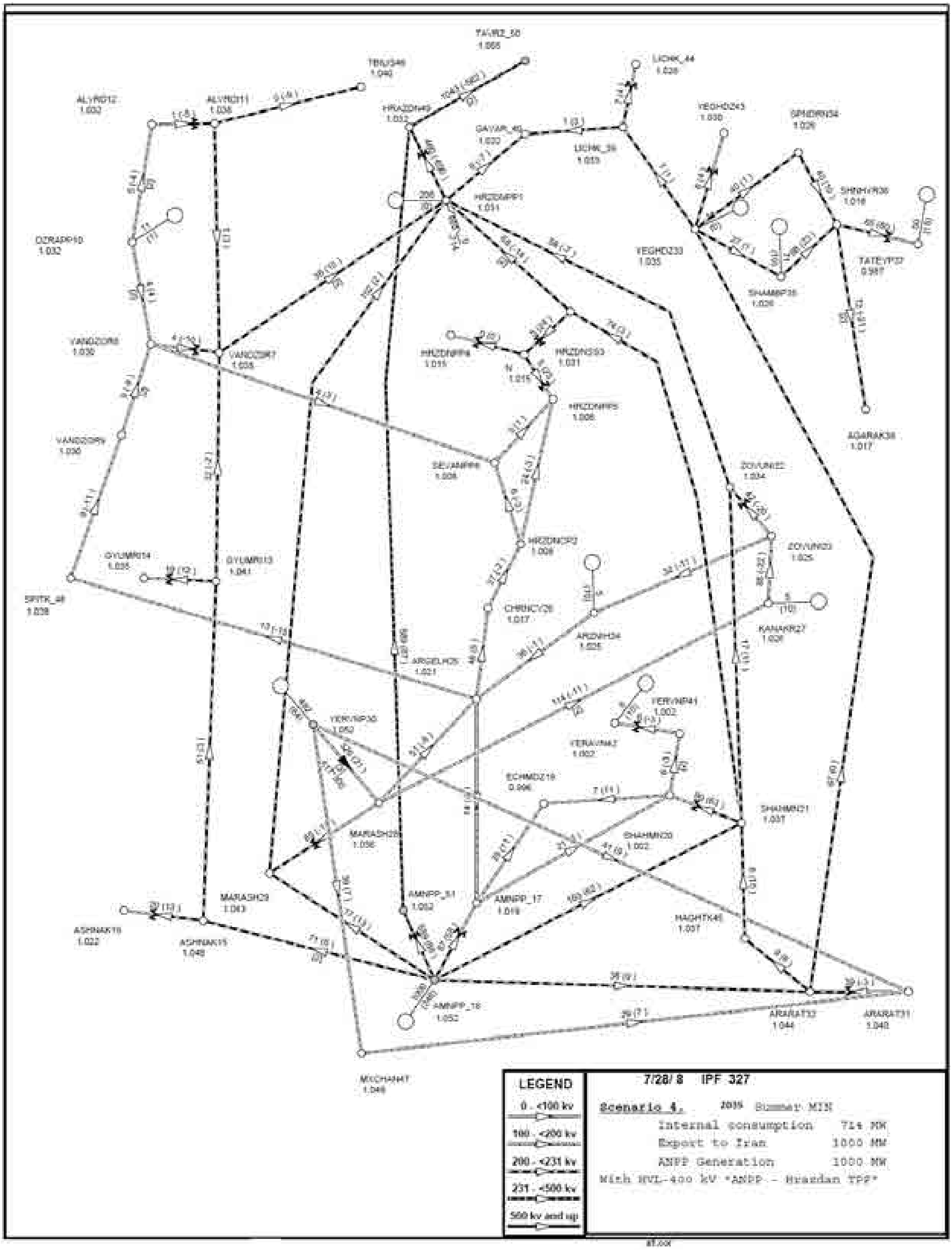

FIG. 18. Scenario 4. 2035 summer min. regime with HVL-400 kV ANPP-Hrazdan TPP.

9.2.2. Conclusions and recommendations of the steady-state assessment study

Thus, taking into consideration the following assumptions:

- Using designed values of forecast load transmission as compared with year 2013, there are no capacity exchanges with the Georgian power system;
- The output levels of major HPPs for forecast years are stable and basically equivalent to the 2013output level;
- Equipment resources for all existing old units of TPPs and the ANPP will be depleted in 2018 and 2026 respectively and removed from the APS.

The calculations suggest that it would be advisable to:

- Build ANPP–Hrazdan TPP 400 kV new HVL. This will allow undesirable overloading to be avoided in all considered scenarios. Only in 2035 — during winter maximum regime — is overloading observed at Yerevan TPP's OHLs, for which elimination may be achieved by the increase of Vinil, Kauchouk, Southern-1, 2 and Nairit-1, 2 OHL capacities (addition of wire cuts or construction of additional lines);
- Install an additional autotransformer at the ANPP's 220 kV substation if the ANPP–Hrazdan TPP 400 kV new HVL is not built. In this case, an increase in Sipan 220 kV HVL's capacity is also required, using one of the following options: adding wire cuts (in case additional load is ensured by the bearings), adding double-chain HVL transformation, or constructing a second parallel power transmission line. Capacity increase of Vinil, Kauchouk, Southern-1, 2 and Nairit-1, 2 OHLs also remains in force (addition of wire cuts or construction of additional lines).

9.3. STABILITY STUDY RESULTS

The main purpose of the APS stability study is to anticipate potential emergencies during which dynamic regime parameters would not meet the stability requirements.

This study has been carried out for all four previously described scenarios assuming the presence of the ANPP–Hrazdan TPP 400 kV new HVL. The study includes only modelling of the following two cases of multipart types of emergency faults:

- Three-phase short circuit on the ANPP 220 kV bus-bars, after 0.11 seconds the ANPP disconnects and short circuit disconnects, and after another 0.12 seconds Tabriz 400 kV HVL disconnects;
- Three-phase short circuit on Hrazdan TPP 400 kV bus-bars, after 0.11 seconds Tabriz 400 kV HVL and short circuit disconnects, and after another 0.12 seconds ANPP disconnects.

Modelling the above mentioned emergencies is sufficient for studying conditions to ensure the APS stations' synchronous operation and for producing allowable frequency indicators (according to volume and duration) in dynamic regimes stipulated by the new ANPP 1000 MW unit capacity.

Operation of the power stations generator speed governors and under-frequency load shedding (ULS-I) equipment has also been modelled for the calculations.

The following operations are carried out by the ULS-I in the APS:

- It starts to operate 0.15 seconds after the moment when the system frequency goes down to 48.6 Hz and lower values;
- Each step of the ULS-I switches in the system with the increment of 0.1 Hz frequency reduction;
- The entire system load is connected to the ULS-I except for power station self-consumption and VIP customers in order to prevent frequency decrease starting from 46.6

Hz in complicated emergencies. This means that the entire system load will be disconnected by the 21st step of the ULS-I operation.

The ULS-II is operated in the system as an automatic reserve for the ULS-I that ensures that:

- It starts operation 4.0 seconds after the moment when the system frequency goes down to 48.6 Hz and remains in operation as long as it remains lower than the mentioned value;
- Each step of the ULS-II starts operation every 4.0 seconds;
- The entire system load is connected to the ULS-II except for power station self-consumption and VIP customers in order to ensure frequency increase of up to 48.6 Hz in 48 seconds.

Due to some restrictions in modelling, this study addresses operation of only ULS-I, which has been modelled in five successions each with a 20% disconnection possibility of the entire system load. This approach is sufficient for having a general picture of dynamic regimes. ULS-II has not been modelled in order to avoid additional complications.

The detailed calculation results (each scenario includes two of the above mentioned cases, marked ***a*** and ***b***) shown in Figures 41-80 are given in the Appendix I and summarized below.

It should be noted that in the scenarios 1a, 1b, 2b, 3a, 3b relative angles of all station generators operating in the system fluctuate collectively and do not create a risk of an asynchronous regime. The electric power deviation amplitude has a tendency to decline, which eliminates the danger of a turbine's unallowable acceleration. Stations reactive capacity levels are within allowable limits; only Hrazdan TPP, as a balancing node, tries to consume the designed extra reactive capacity. Voltage levels are within short term allowable limits and have a tendency to reach the normal level. Frequency decreases in all cases to not more than 48.0 Hz, but upon operation of ULS-I, it increases without any complications. Thus, the dynamic regimes described in these scenarios run normally and prevent the occurrence of post-emergency steady-state regime unallowable conditions.

For scenario 2a the calculation results show that certain complications appear in the system in this regime. Relative angles of all station generators operating in the system vibrate collectively except for Dzora HPP and Yerevan HPP, which are approximately 140 cycles (2.8 seconds) offset from synchronous operation regime with the system. It is, however, not a dangerous situation since their output comprises only 2.5% of the entire system generation and, after running out of synchronous operation, their disconnection would not lead to unwanted consequences. Software calculations are stable and allow assessment of certain indicators of the future regime. Stations reactive capacity levels are similar to Scenarios 1a and 1b. Voltage levels are within short term allowable limits (except for Dzora HPP's bus-bars which inadmissibly increase after approximately 420 cycles (8.4 seconds), but before that the HPP must be disconnected) and have a tendency to reach the normal level. Frequency decreases to 46.6 Hz (Figure 55, Appendix I) and upon operation of ULS-I it increases without any complications. Thus, the dynamic regime described in this scenario will run normally upon disconnection of Dzora HPP and Yerevan HPP and will prevent the occurrence of post-emergency steady-state regime unallowable conditions.

The results show that certain complications can also appear in the system in the regimes in Scenarios 4a and 4b. Relative angles of all station generators operating in the system vibrate collectively except for Dzora HPP and Yerevan HPP, which are approximately 160 cycles (3.2 seconds) for Scenario 4a and 170 cycles (3.4 seconds) for Scenario 4b offset from synchronous operation regime with the system. It is not dangerous, since their output makes 1.0% of the entire system generation and after running out of synchronous operation their disconnection would not lead to unwanted consequences. Software calculations are stable and allow assessment of certain indicators of the future regime. The maximum electric power surge falls on Hrazdan TPP, but its deviation amplitude has a tendency to decline that eliminates the danger of a turbine's unallowable acceleration. Stations reactive capacity levels are within allowable limits; only Hrazdan TPP, as a balancing node, tries to consume the designed extra reactive capacity. Voltage levels, after certain major deviations, are within short term allowable limits and have a tendency to reach the normal level. Frequency decreases to 47.0 Hz for both scenarios (Figures 75 and 80) and, upon operation of ULS-I increases without any complications. As a result, the dynamic regimes described in both scenarios will run normally upon disconnection of Dzora HPP and Yerevan HPP and prevent the occurrence of post-emergency steady-state regime unallowable conditions.

Summarizing the calculation results of dynamic regimes for 2026 and 2035, the following should be noted:

- The Armenian power system has a rather good potential to withstand emergency regimes;
- Voltage levels in all considered dynamic regimes are within short term allowable limits and have a tendency to reach the post-emergency allowable level;
- The level of reactive capacities of stations is within allowable limits;
- Frequency, in the worst case, drops to the allowable 46.6 Hz and, upon operation of ULS-I, increases without any complication.

9.4. FINAL CONCLUSIONS AND RECOMMENDATIONS

Therefore, the main conclusions from the performed calculations are that:

- It will not be possible to use the new nuclear unit at full 1000 MW capacity only in the 2026 summer minimum regime unless additional export to neighbour countries is arranged;
- The Armenian power system has a rather good potential to withstand emergency regimes;
- Voltage levels in dynamic regimes are within short term allowable limits and have a tendency to reach the post-emergency allowable level;
- Station reactive capacity levels are within allowable limits;
- Frequency, in the worst case, decreases to the allowable 46.6 Hz limit and, upon operation of ULS-I, increases without any complication.

The main outcome recommendations from the conclusions are:

- Building a new ANPP-Hrazdan TPP 400 kV HVL would allow to avoid overloading the OHLs and autotransformers. Overloading at Yerevan TPP's OHLs might occur only during the 2035 maximum winter regime. To withstand this situation, the capacities of the OHLs connected to the Yerevan TPP's bus bars should be increased;
- Disconnection of Dzora HPP and Yerevan HPP in 2.8 seconds during their asynchronous operation must be possible;
- Without the ANPP-Hrazdan TPP 400 kV new HVL, installation of an additional autotransformer at the ANPP 220 kV substation is required;
- Integration into the regional electricity market will increase APS stability, including its main generation units.

10. GENERAL RECOMMENDATIONS FOR PART B

Some general recommendations for countries with small grids related to grid stability are as follows:

- Investigation of a system is necessary where the total generation capacity is commensurable with the generation capacity of the NPP itself;
- OHLs connected to the NPP should have sufficient capacity to transmit the generated power from the NPP side to the grid's consumption nodes;
- Special attention should be paid to ensuring the stable/low variation voltage level in the substations connected to the NPP;
- During transient regimes, the electrical network must ensure fast recovery of regime parameters (especially the voltage and frequency) to their admissible level during the permissible timeframe. This is to prevent the potentially negative influence of the parameters on the safe operation of technological parts of the NPP;
- The reliability and safety of NPP operation should be increased, which can be achieved not only via safety system upgrades, but also by introduction of automatic anti-accident measures in transmission and distribution systems;
- A NES should be operated within a small grid system in conjunction with the power systems of neighbouring countries.

PART C: BACK END OF NUCLEAR FUEL CYCLE

11. EVALUATION OF BACK END OF NUCLEAR FUEL CYCLE OPTIONS FOR SMALL COUNTRIES

11.1. MODELLING SCENARIO DEFINITION FOR ARMENIAN NUCLEAR ENERGY SYSTEM

The first WWER type reactor, with a capacity of 1000 MW(e), is planned to be commissioned in 2026 and after 60 years of operation to be decommissioned in 2086. The second WWER type reactor, also with a capacity of 1000 MW(e), is planned be commissioned in 2036 and after 60 years of operation to be decommissioned in 2096. Reactor specific data and short description of its major systems are given in Appendix III.

Installed capacities are given in Table 17 and in Figure 19.

TABLE 17. TOTAL INSTALLED CAPACITY

	2026	2036	2086	2096
Installed capacity (GW(e))	1	2	1	0

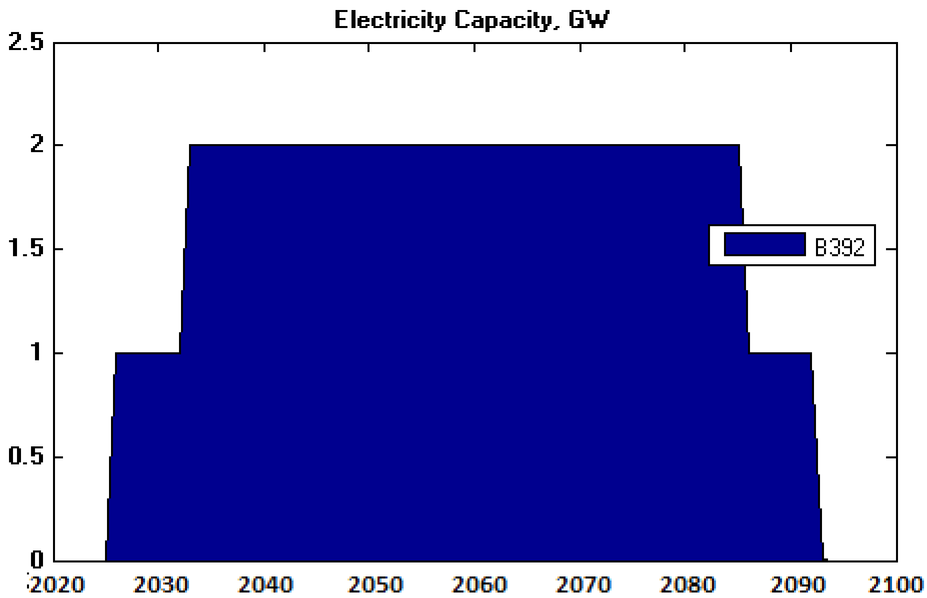

FIG. 19. Total installed capacities, GW(e).

The reactor data for the uranium fuel cycle type are necessary for calculating key indicators for NES consideration. Major specifications of V392 nuclear unit are presented in Table 18.

TABLE 18. MAJOR SPECIFICATIONS OF V392 NUCLEAR UNIT

Major specifications		
Reactor net electric output	MW	999.5
Reactor thermal output	MW	3000

TABLE 18. MAJOR SPECIFICATIONS OF V392 NUCLEAR UNIT (cont.)

Thermal efficiency	%	33.3	
Load factor	%	80	
Life time	Yr	60	
Cooling time	Yr	9	
Core data			
		Initial loading	Annual reloading
Operation cycle length	EFPD	295	300/297 *
No. of fuel assemblies		163	49/48 *
Fresh fuel enrichment U235	%	2.48	3.92
No. of refuelling batches		-	3.3
Fuel residence time	EFPD	-	12 000
Specific power density	MW/tHM	42.5	
Average discharged burnup	MWd/t	11 700	42 400
Fresh fuel load	tHM	70.6	21.2/20.8 *
Fuel assembly		163	49

* even/odd annual reload.

The WWER V392 has an averaged burnup of 42.4GWd/t, specific power density of 42.5 MW/t, and load factor of 80%. Fuel cycle conditions are given in Table 19.

TABLE 19. ADDITIONAL CHARACTERISTICS

Additional characteristics	Thermal reactor
Tail assay enrichment	0.0015
Life time (yr)	60
Cooling time (yr)	9

Note: Cooling time of 9 years is defined for the maximum capacity of pool and quantity of fuel assemblies in annual reloading.

The DESAE code does not perform burnup or core management calculations but bases the calculations on tables of fresh and spent fuel compositions provided by the user. The WWER V392 has an enrichment of 3.92% during annual reloading and 2.48% in first loading. The fresh fuel composition data are shown in Table 20.

TABLE 20. FRESH FUEL CONTENT

Isotope	Annual reloading	First loading
U-235	0.0392	0.0248
U-238	0.9608	0.9752
Isotope	Annual reloading	First loading
Pu-239	-	-
Pu-240	-	-
Pu-241	-	-

The spent fuel composition data are shown in Table 21. It is assumed that the same isotopic composition remains in the annual reloading and final unloading. The DESAE code calculates changing isotopic composition in spent fuel.

TABLE 21. SPENT FUEL CONTENT

Isotope	Unloading
U-235	0.0098
U-236	0.005
U-238	0.9280
Pu-238	0.0002
Pu-239	0.0071
Pu-240	0.0027
Pu-241	0.0018
Pu-242	0.0007
Np-237	0.00069
Am-241	0.000085
Cm-244	0.000053
Fission products (FP) ~ 1 – ΣHMi =	0.0439

Note: The content of isotopes is a result of nuclear reactions in fresh fuel; the data presented do not take into consideration the change of isotope structure of spent fuel.

All data were presented in DESAE format and introduced in the DESAE reactor database.

11.2. SPENT FUEL CALCULATION FOR ARMENIAN CASE

A package based on MESSAGE, DESAE, and NFCSS codes is available at the IAEA as one of the potential packages to perform dynamic simulations. These codes were benchmarked by the IAEA. The code analysis has shown that all codes are applicable for modelling and analysing once-through nuclear fuel cycles. Nevertheless, only the DESAE code correctly takes into account isotopic decay in the reactor (^{241}Pu decay in particular) and gives detailed information about the isotopic composition of spent fuel. DESAE is a rather universal code and provides key indicators of the NES. It was chosen for the present study modelling purposes.

The code performs material flow analysis on the basis of a user-defined deployment scenario of reactors and fuel cycle facilities. The tabled fuel characteristics include data for annual and initial core compositions for the various reactors. The fuel composition is followed for 17 isotopes, i.e. ^{232}Th, ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{237}Np, ^{242}Am, ^{244}Cm, ^{129}I, ^{99}Tc, with one additional group for the other fission products.

DESAE enables the modelling of seven reactor types in parallel in one simulation with all of them having any sort of fuel exchange between the reactors. These fuel exchange paths need to be defined by the user (Figure 20). However, the fuel cycle representation in DESAE is made with only four fuel cycle facilities but without tracing losses in these facilities. The activity and radiotoxicity of spent fuel is calculated but repository needs are currently only defined by the volume of material to be stored. Proliferation risk is assumed to be dependent on the volume of relevant material, i.e. Pu.

The mathematical model of the DESAE 2.2 code calculates the nuclear fuel cycle requirements, material balances, and economic parameters in the framework of nuclear energy scenario development with a given combination of nuclear reactors during a specified time period. DESAE 2.2 has additional features which allow calculation of the following parameters (for all reactor types): the amount of fresh fuel loaded into the reactor; the amount of consumed Pu; the amount of Pu in spent fuel; the amount of consumed ^{233}U; the annual spent fuel generation; the annual quantity of Pu available from spent fuel; any time horizon, and others. In DESAE 2.2 there are two options to commission new nuclear capacities: step-wise (one year) and quasi-linear (time step 0.1 year), which will allow to avoid complexities when comparing results with other codes.

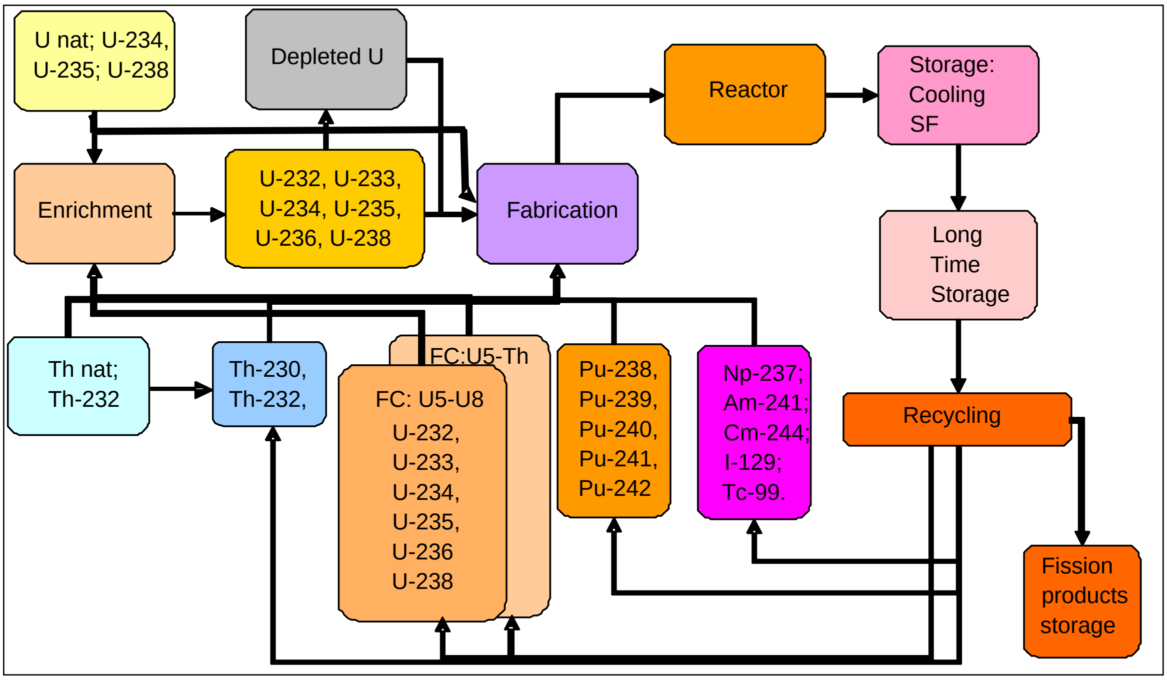

FIG. 20. Isotope flow scheme for DESAE code.

The once through fuel cycle in a WWER reactor includes (Figure 21):

- Natural uranium mining and milling;
- Enrichment;
- UOX fresh fuel fabrication;
- Depleted uranium stock;
- UOX SF cooling pool at NPP;
- UOX SF dry storage.

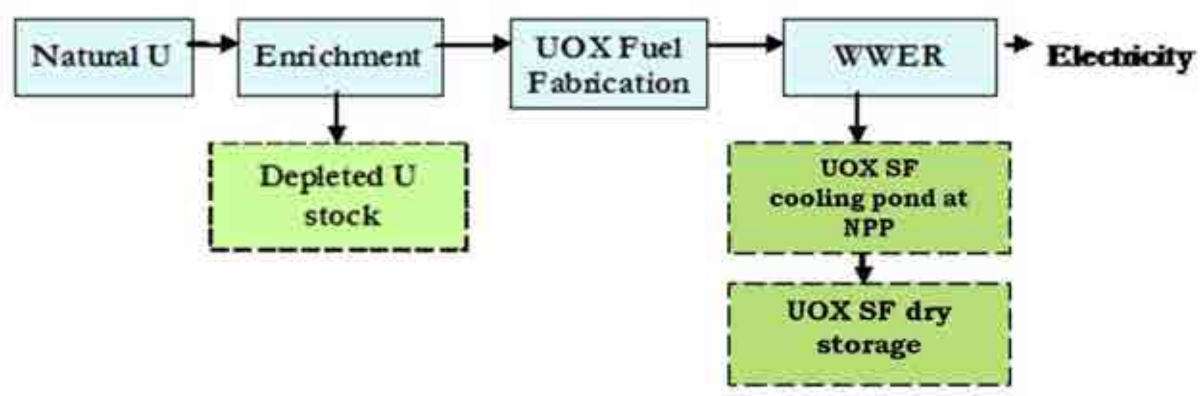

FIG. 21. Once through fuel cycle with WWER-thermal reactor.

Natural uranium is used in fuel fabrication. The needed amount of separative work units (SWU) is calculated. The content of ^{235}U in natural uranium is considered to be 0.711%. This value may be defined by the user. The depleted uranium goes to storage after enrichment. The content of ^{235}U in depleted uranium is specified in reactor characteristics. It can be the same or different for different reactor types. Capacities of fuel fabrication plants are not taken into account in DESAE 2.2. These capacities are always considered to be sufficient to produce the necessary fuel volume required for each type of reactor. After reactor irradiation, fuel goes to the cooling pool, where it cools for a specified time. After cooling, spent fuel is sent to dry storage. From dry storage, spent fuel can be sent for reprocessing with the purpose of further use or may be left in storage as long as determined. Dry storage is considered in the model as storage of raw material (spent fuel) for recycling plants. All heavy isotopes are sorted into groups of elements and their dynamics in the fuel cycle are considered as a whole. The following groups are taken into account:

1. Uranium in uranium cycle:

   ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U (in this combination, uranium isotopes are saved in a group for the uranium fuel cycle);

2. Neptunium:

   ^{237}Np;

3. Plutonium:

   ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu;

4. Americium:

   ^{241}Am;

5. Curium:

   ^{244}Cm.

The isotopic composition of the chosen groups changes due to radioactive decay and enrichment when the reprocessed uranium is used.

Isotopes undergoing radioactive decay are:

^{238}Pu, ^{241}Pu→^{241}Am, ^{244}Cm.

Radiotoxicity is calculated for spent fuel and for the fission products. In the latter case, biological hazards caused by heavy isotopes are not taken into account. The calculation is carried out for two components: inhalation and injection.

11.3. OUTPUT DATA FOR DESAE CALCULATION FOR ARMENIA NE SCENARIO

Results extracted from modelling were:

- Total installed capacities and electricity production;
- Natural uranium and SWU consumption;
- Fresh fuel requirement;
- Spent fuel discharged;
- Pu accumulation in spent fuel;
- Spent fuel in storage;
- Accumulation of fission products, minor actinides in spent fuel;
- Fission products decay heat;
- Radiotoxicity.

Total installed capacity and electricity production for WWER are shown in Figures 22 and 23.

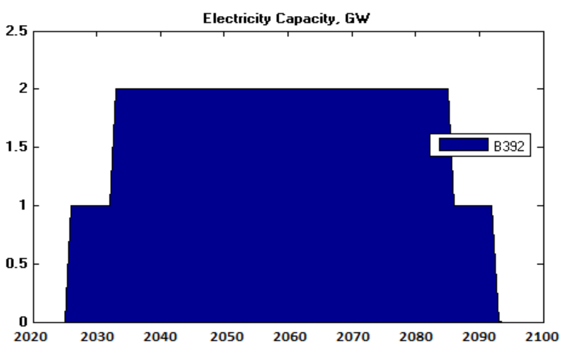

FIG. 22. Total installed capacity.

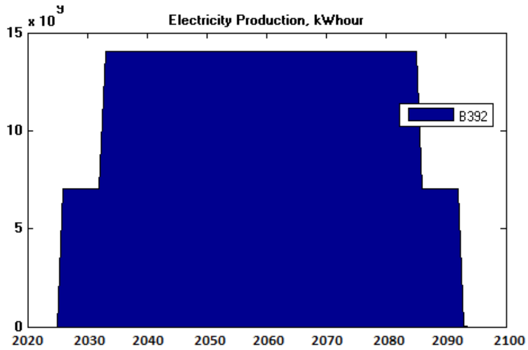

FIG. 23. Electricity production.

The first unit is introduced in 2026 and the second in 2036. The whole life cycle for two units starts in 2026 and ends in 2096. Two GW(e) of installed capacity produces 1.4 10^{10} kW·h of electricity annually. The cumulative consumption of natural uranium for the system is given in Figure 24. The total mass of consumed natural uranium would reach approximately 17.5 kt for the entire life cycle. Figure 25 shows the annual natural uranium and SWU requirements for uranium enrichment. The peaks correspond to the first load requirements. One WWER 1000 unit needs about 154 SWU/yr annual separation work and 141 t/yr of annual natural uranium. For two units these values double.

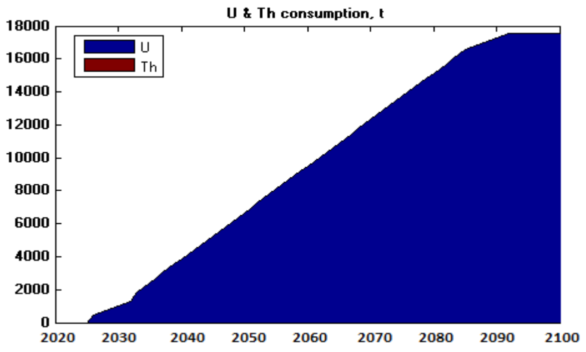

FIG. 24. *Long term cumulative consumption of natural uranium.*

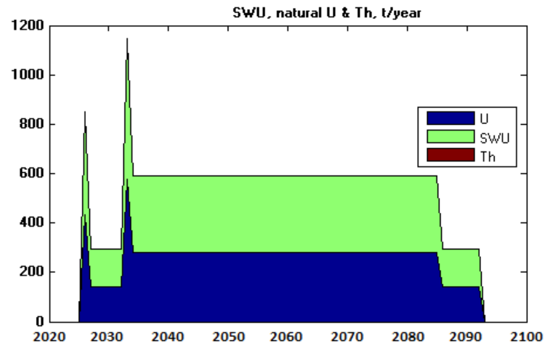

FIG. 25. *Long term annual natural uranium and separation work unit requirements.*

Annual fuel fabrication requirements and spent fuel discharge for the option under consideration are given in Figures 26 and 27. The peaks in the figures illustrate first loading and final unloading.

The annual requirements for fresh fuel for two units are about 42.1 tHM/yr, and discharged spent fuel is about 40.3 tHM/yr. The difference is due to the fission products in the spent fuel.

The total accumulation of spent fuel in the cooling pool at NPP and dry storage facilities are given in Figures 28 and 29.

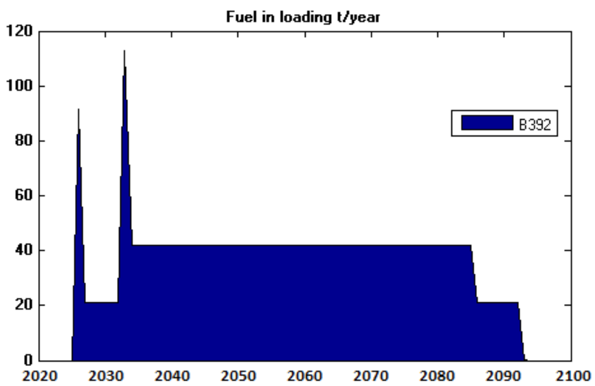

FIG. 26. Long term fresh fuel requirement.

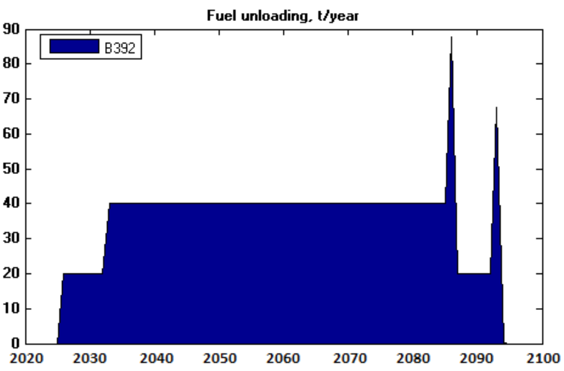

FIG. 27. Long term spent fuel discharged.

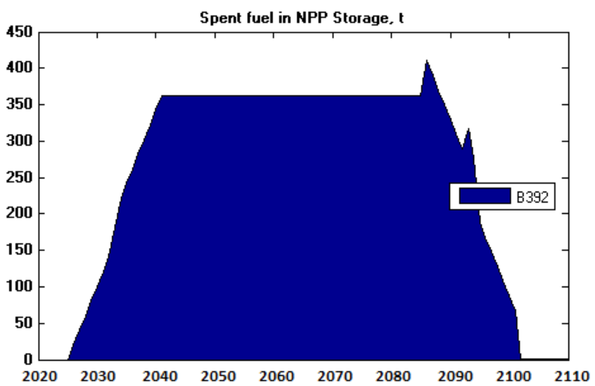

FIG. 28. Total accumulation of spent fuel in the cooling pool at NPP.

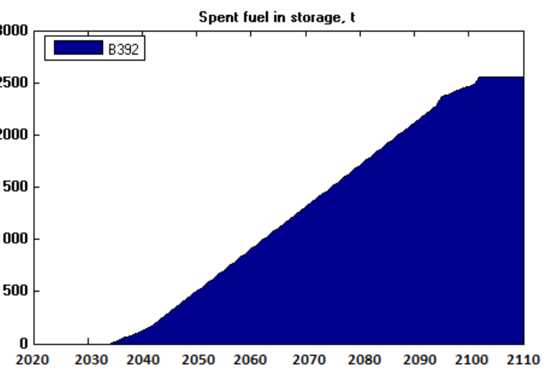

FIG. 29. Total accumulation of spent fuel in dry storage .

Annually, 362.7 tHM of spent fuel is stored in the cooling pool at NPP. The calculation is performed for nine years of cooling. Spent fuel comes to dry storage from the cooling pool. 2553.6 tHM accumulate by the end of the life cycle. Annually, 0.53 tHM of total plutonium is discharged out of the two reactor units (Figure 30).

A plutonium balance (cumulative production–cumulative consumption) is presented in Figure 31. There is no consumption of plutonium in the scenario so the figure gives the total plutonium accumulation, which reaches 20 tHM for the entire life cycle.

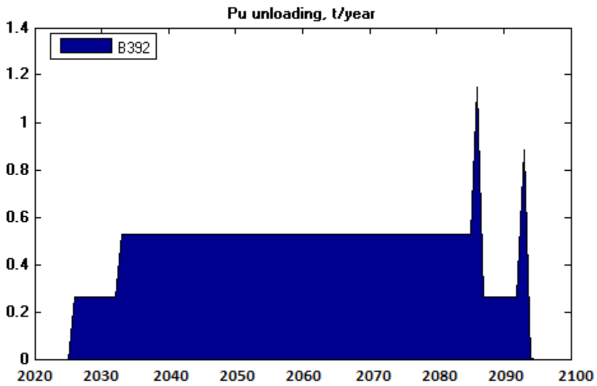

FIG. 30. Annual Pu discharged out of two reactor units.

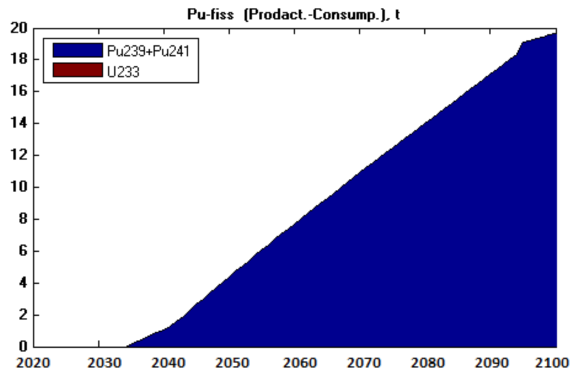

FIG. 31. Long term Pu balance (production–consumption).

The accumulation of plutonium isotopes (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu) and ^{237}Np in the spent fuel in dry storage is given in Figure 32.

The accumulation of minor actinides (Am&Cm and Np) in the spent fuel is shown in Figures 33 and 34. These values are about 3.5 tHM and 1.8 tHM, respectively, for the life cycle.

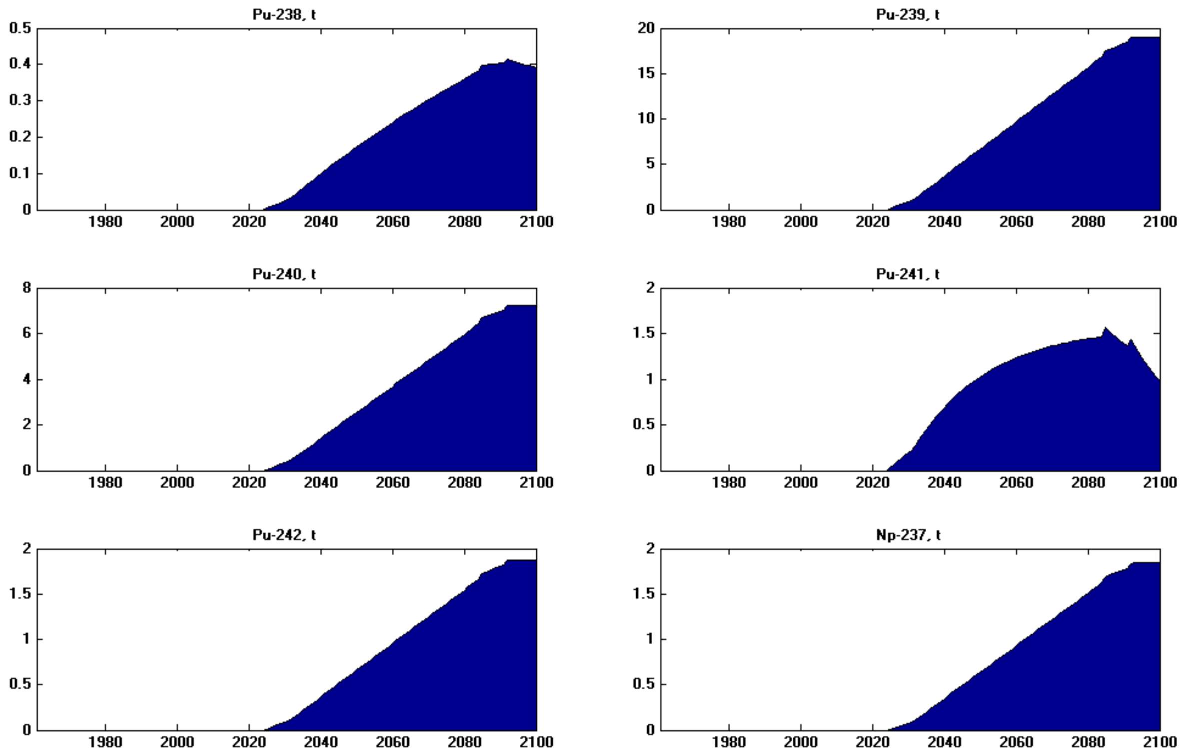

FIG. 32 Long term accumulation of plutonium isotopes in dry storage.

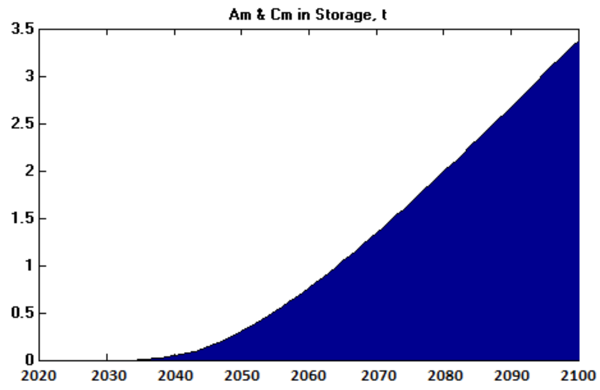

FIG. 33. Long term accumulation of MA (Am&Cm) in dry storage.

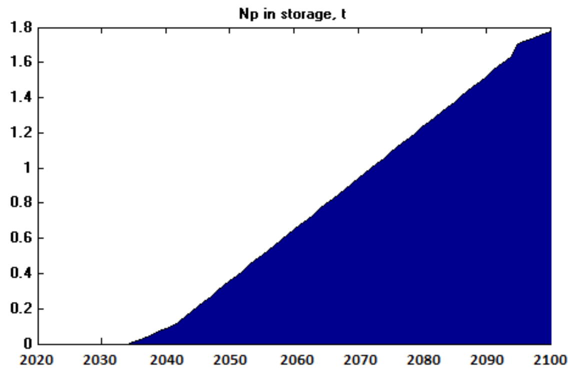

FIG. 34. Long term accumulation of MA (Np) in dry storage.

Uranium isotopes accumulation in spent fuel is given in Figures 35, 36 and 37.

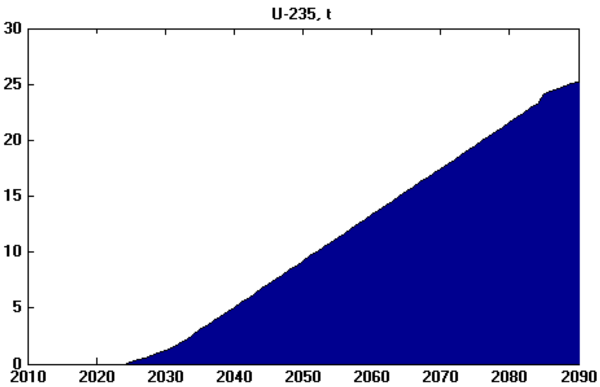

FIG. 35. Long term accumulation of ^{235}U in dry storage.

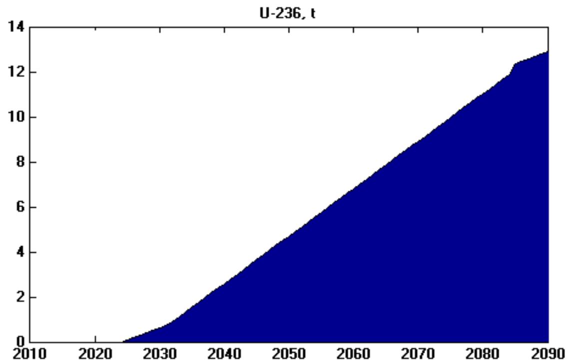

FIG. 36. Long term accumulation of ^{236}U in dry storage.

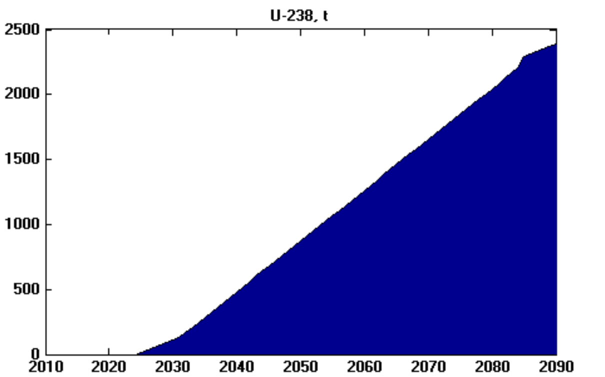

FIG. 37. Long term accumulation of 238U in dry storage.

The fission products in the spent fuel and fission product decay heat are presented in Figures 38 and 39. Radiotoxicity, calculated for inhalation and injection, is given in Figure 40.

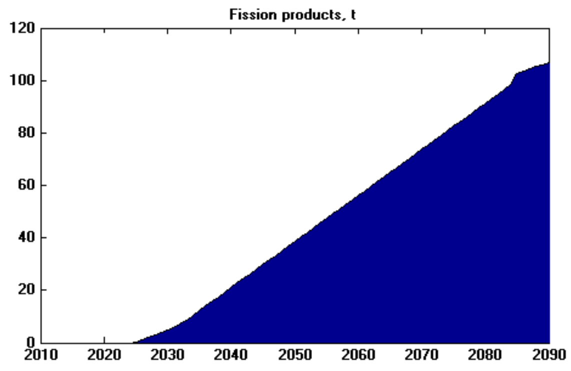

FIG. 38. Long term accumulation of fission products in spent fuel.

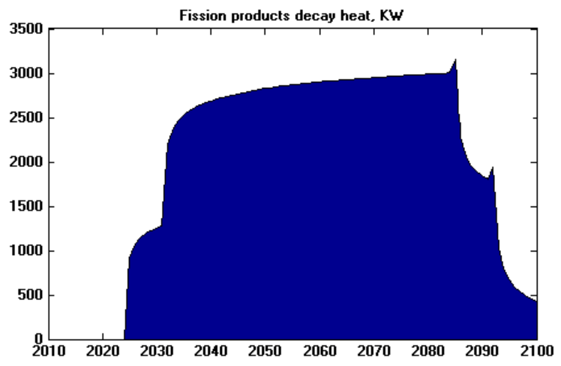

FIG. 39. Fission product decay heat.

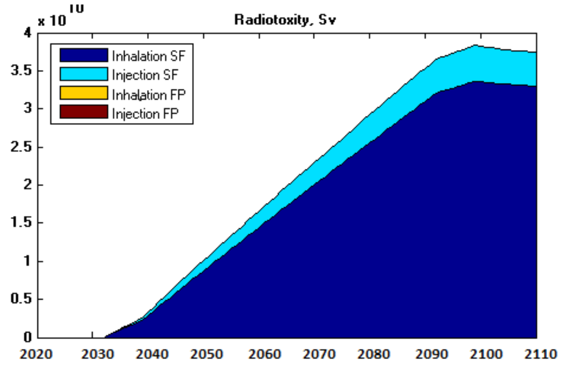

FIG. 40. Long term radiotoxicity.

A summary of the results presented above is shown in Table 22.

TABLE 22. MATERIALS BALANCE, RADIOTOXICITY AND DECAY HEAT BY END OF LIFE CYCLE FOR BOTH UNITS

Year of shutdown of the units		**2086**	**2096**
Natural U consumption (t)		16 554	17 543
SWU per year		308 000	154 000
SNF in cooling pool at NPP (t)		363	289
SNF in dry storage after cooling (t)		1914	2196
Pu isotopes in SNF (dry storage) (t)	^{238}Pu	0.33	0.37
	^{239}Pu	14.16	16.25
	^{240}Pu	5.38	6.18
	^{241}Pu	1.41	1.45
	^{242}Pu	1.4	1.6
	Total	22.68	25.85
	Fiss Pu	15.57	17.7

TABLE 22. MATERIAL BALANCE, RADIOTOXICITY AND DECAY HEAT BY END OF LIFE CYCLE FOR BOTH UNITS (cont.)

U isotopes in SNF (dry storage) (t)	^{235}U ^{236}U ^{238}U Total	19.5 9.97 1850 1880	22.4 11.44 2124 2158
MA in SNF (dry storage) (t)		3.69	4.38
Year of shutdown of the units		**2086**	**2096**
Am 241 in SNF (dry storage) (t)		2.28	2.76
Cu 244, in SNF (dry storage) (t)		0.048	0.051
Np 237, in SNF (dry storage) (t)		1.36	1.57
FP in SNF (dry storage) (t)		82	95
SNF radiotoxicity (dry storage) (Sv)	Inhalation Injection	2.83×10^{10} 4.02×10^{9}	3.21×10^{10} 4.52×10^{9}
SNF decay heat (kW)		2970	2993

The output data permits evaluation of NPP and dry storage. The dry storage of spent fuel provides a suitable buffer in the spent fuel management system and provides time for considering what should be the next step — disposal or recycling.

Decay heat is a very critical issue for storage volume. Fission products are major contributors to decay heat during the time horizon under consideration. It steadily increased in the range 2500–3000 kW as spent fuel accumulated. The maximum value (3160 kW) is reached in 2085 due to the discharge of the first full reactor core in 2076.

12. EVALUATION OF RADIOACTIVE WASTE AND SNF MANAGEMENT OPTIONS IN ARMENIA

For States that intend to develop nuclear energy, it is necessary and important to understand general problems related to radioactive waste and SNF safe management.

The section below summarizes current situation and possible options for SNF in Armenia.

12.1. SPENT NUCLEAR FUEL MANAGEMENT

The options for spent fuel management have to be viewed from two perspectives, namely:

– Currently available spent fuel management options;
– Future fuel cycle options.

The analysis of those two perspectives, due to the overlap, should be combined into a single spent fuel strategy.

This strategy should have flexibility in order to keep future options open. The spent fuel management strategy should allow either disposal or recycling of nuclear fuel after a storage period. Fuel may be recycled either after reprocessing with current mature technologies or within future innovative fuel cycles. It is not expected that a small country would develop its own reprocessing capability unless it is within a larger multilateral (regional) project.

Every endeavour should be made to minimize generation of spent fuel and costs related to spent fuel management. The volume of spent fuel could be decreased by increasing fuel burnup in the core. Burnup credit applications could lower the cost of several phases of post reactor spent fuel management.

Currently, there are two types of spent nuclear fuel storage used at the ANPP: wet storage cooling pools and a dry storage facility. The latter facility started receiving SNF in August 2000. Its capacity is 612 fuel assemblies. In 2005, an agreement was signed with French company TN International for construction of the additional three stages of the dry storage facility. The financing was allocated from the State budget of Republic of Armenia. The second stage was completed and put into operation in spring 2008. The first part of the spent nuclear fuel has been transferred into dry storage. The third stage of spent fuel dry storage construction is planned to be started in 2016.

In the option of expansion of on-site dry storage, the existing dry storage facility would be expanded to enable dry storage of all SNF on the ANPP site. While this option would require a significant investment, it has the advantage of using all nuclear safety systems within the ANPP and generating minimum annual operation and maintenance costs. Data provided in [9] and explained below can be used as an example for generalized financial analyses.

Under the option of new off-site dry storage facility, the storage facility would be constructed in Armenia but not on the ANPP site. Compared to the previous options, this option has a number of disadvantages. The cost of this option is summarized in Table 23.

Under the option of interim storage in another country, the SNF would be shipped to a foreign country for long term interim storage. The advantage of this option is that the regulatory aspects and the physical infrastructure required for the interim storage of SNF would not be provided by Armenia but by another country that, ideally, has the required infrastructure already in place.

The cost includes transportation of the SNF to the other country and interim storage of the fuel for an indefinite period. A cost estimate for this option is given in Table 23.

Permanent disposition in foreign country is similar to the previous one except that the foreign country would provide both interim storage and final disposition of the SNF. The cost includes transportation of the SNF to the other country and its permanent disposition. The cost estimate for this option is summarised in Table 23 based on data provided in the [9].

TABLE 23. SUMMARY OF ANPP SPENT FUEL MANAGEMENT COSTS

Option	**Projected shutdown date**	**Capital cost ($ million)**	**Operating cost ($ million)**	
			Annual	**50 years total**
Combination of wet and dry	N/A	5.9	4.2	209
Expansion of existing on-site dry storage facility	2004	25.5	0.22	11.0
	2009	33.7	0.22	11.0
New off-site dry storage facility	2004	39.9	0.22	11.0
	2009	49.1	0.22	11.0
Interim storage by another country	2004	90-180		
	2009	115-225		
Permanent disposition by another country	2004	350-580		
	2009	450-750		

13. CURRENT STATE OF THE ARMENIAN BACK END OF NUCLEAR FUEL CYCLE AND SOME SUGGESTIONS FOR ITS FURTHER DEVELOPMENT.

13.1. SPENT NUCLEAR FUEL AND RADIOACTIVE WASTE MANAGEMENT

13.1.1. Introduction

In Armenia, use of radioactive material started in the 1950s. Radioactive material has been in use in almost all fields, such as health, science, education, agriculture, geology, and energy.

The ANPP became the major source of radioactive waste and the only source of spent nuclear fuel after the first unit was put into operation in 1976. In the future, ore mining and extensive use of radioactive sources may generate a new stream of radioactive waste.

The ANPP will turn into an extensive source of radioactive waste during its decommissioning.

A radioactive waste repository was built in the 1950s, by a Yerevan municipal council decision, in a section of Sovetashen municipal waste facility. It was designated for the disposal of radioactive waste generated from radioactive material used for public health, science, and industrial purposes. Afterwards, it was discovered that the repository could collapse because of a probability of a landslide in that location. Therefore, it was decided to build a new repository in the operational area of the already functioning ANPP (at a distance of 1.5 km west from the ANPP main building). The new disposal facility was built as near-surface repository and it was put in operation in 1980. The repository is currently functioning but the considerable distortions of the envisaged plan make the entombment (immobilization) of radioactive waste from nuclear applications impossible. In 2009, the "Decontamination of Radioactive Waste CJSC" of the Ministry of Energy and Natural Resources of Armenia obtained a licence allowing the usage of the repository for the disposal of nuclear waste from nuclear applications but for only low and medium activity.

The initial operating plan of the ANPP did not assume continuous processing and immobilization for disposal of the radioactive waste generated as a result of its operation. In the ANPP there is storage for low, medium, and high activity raw radioactive waste (as generated) that was planned for the disposal of radioactive waste only after the operating period of the ANPP (30 years). Currently the ANPP storage facilities for low and high activity solid waste are only partially full and their capacity is sufficient to store the waste that will be generated until the termination of the ANPP operation. Regarding the storage of medium activity solidified liquid waste (evaporator bottom concentrate dried to salt cake condition), it is apparent that its volume is insufficient to store the containers of that radioactive waste that will have been generated by the time the ANPP operation is terminated.

The ANPP initial operating plan assumed that the plant's spent nuclear fuel will be kept for some time in spent fuel pools and then transported via special railway carriages to a nuclear fuel processing enterprise on the territory of the former Soviet Union. The last transfer of spent fuel was arranged in 1990. After the collapse of the Soviet Union, the transportation of the ANPP spent nuclear fuel became technically impossible. As the storage of waste in the pools impeded the start of the operation of the ANPP second unit, a dry storage facility for spent nuclear fuel was built on the territory of the ANPP. It was designed by a French company Framatome. The first block of the dry storage facility started operation in 2002 and the second – in 2008. Currently, the first block is full; it contains 616 spent fuel elements. The second block is intended for a capacity of 672 fuel elements.

In Armenia, radioactive waste and spent nuclear fuel safe management issues are:

– Incompleteness of the radioactive waste management system, since the generated radioactive waste is accumulated but not disposed of which is a burden for future generation;
– Absence of a long term plan for spent nuclear fuel (for more than 50 years ahead) and radioactive waste (up to 100 years ahead), which would ensure a development of adequate solution related to the safety issues of the radioactive waste and spent nuclear fuel management;
– Absence of a specialized State Organization for radioactive waste and spent nuclear fuel management, which hampers coordination of the activities of the entities involved in radioactive waste and spent nuclear fuel management;
– An insufficient level of internal expertise on radioactive waste and spent nuclear fuel management.

13.1.2. Radioactive waste and spent nuclear fuel safe management fundamentals

Through the IAEA, the international community has developed common principles of radioactive waste and SNF safe management, which are applicable to all countries and refer to all types of radioactive waste and SNF.

As an IAEA Member State, Armenia has undertaken obligations to provide for safe and peaceful use of nuclear energy by preventing and minimizing the risk of irradiation to the public and environment (including neighbouring countries).

Armenia's policy on radioactive waste and SNF safe management must ensure its compliance with the following fundamentals defined by the IAEA safety standards:

– Radioactive waste and SNF management implementation must not cause harm to health;
– Radioactive waste management and SNF implementation must not exert a harmful influence on the environment, including natural resources;
– Radioactive waste management must be implemented taking into account the results of the possible negative impact of radioactive waste on the population of neighbouring countries and the environment;
– Radioactive waste management implementation must ensure that the predictable impact of radioactive waste on the next generation at least does not exceed the acceptable levels of impact on the current generation;
– Radioactive waste management and SNF must not leave an additional unjustified burden on future generations;
– The legal system regulating radioactive waste management must ensure a distinct separation of competencies and obligations in radioactive waste management and provide for independent regulatory action;
– The generation of radioactive waste according to activity and volume must be kept on a practically possible minimum level;
– The interdependences of all the stages of radioactive waste generation and management must be taken into account;
– A high level of safety of radioactive waste disposal must be ensured during all stages of its life cycle.

Consistent with these objectives of radioactive waste and SNF safe management, the Government of the Republic of Armenia must ensure the implementation of the following conditions:

- Radioactive waste and SNF safe management implementation shall be funded by those legal and physical entities whose actions result in waste generation (polluter pays principle);
- The population must be aware of all the approaches of radioactive waste and SNF management as far as they do not contain any State, official, or commercial secret;
- The decisions on radioactive waste and SNF safety management should be based on the requirements of the IAEA safety standards and on research results of national and international scientific institutions;
- In case of vagueness in decision making on radioactive waste and safe SNF management, the preference will be given to a more conservative decision;
- A highly coordinated implementation of a radioactive waste and SNF management must be ensured to exclude duplications;
- International cooperation on radioactive waste and SNF management issues should be enhanced, which will highly promote the establishment of the concept requirements;
- Specialization and training for personnel involved in radioactive waste and SNF management should be organized.

13.1.3. Radioactive waste and spent nuclear fuel management strategic directions

Concerning radioactive waste and SNF management, the Republic of Armenia has ratified the international Conventions on the:

- Nuclear Safety;
- Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management;
- Civil Liability for Nuclear Damage (Vienna Convention);
- Physical Protection of Nuclear Material and Amendment to the Convention on the Physical Protection of Nuclear Material;
- Assistance in the Case of a Nuclear Accident or Radiological Emergency;
- Early Notification of a Nuclear Accident.

The legal acts of the Republic of Armenia regulating radioactive waste and SNF safe management are the:

- Law on *Atomic energy usage with peaceful purposes;*
- Law on *Licensing;*
- Government 375-N decree on *The establishment of radioactive waste import/export licensing order and license types*, 24 March 2005;
- Government 1219-N decree on *The establishment of radiation safety norms*, 18 August 2006;
- Government 1489-N decree on *The establishment of radiation safety rules*, 18 August 2006;
- Government 1367-N decree on *The amendment of Radiation Safety Norms and Radiation Safety Rules*, 27 November 2014. According to this amendment Radiation Safety Norms and Radiation Safety Rules now fully comply with IAEA Recommendations;
- Government 631-N decree on *The establishment of radioactive waste management norms*, 4 June 2009;
- Government 1291-N decree on *The amendment of establishment of radioactive waste management norms,* 19 November 2014;
- By Protocol Decision 19 of the Government of Republic of Armenia, Session No. 43 of 4 November 2010, “The Concept for Safe Management of Radioactive Waste and Spent Nuclear Fuel in the Republic of Armenia” was adopted. According to the Concept, the significant activities anticipated in that area are regulated and distributed between the departments of the Republic of Armenia.

In addition, 24 other Government decrees on the licensing of specific activities in radioactive waste and SNF safe management have been adopted and are currently in force. Although the adopted acts regulate the legal relations in radioactive waste and SNF management, the following activities also need further regulation:

– Radioactive waste State registry and record;
– Selection, planning, construction, operation and shutdown of radioactive waste and spent nuclear fuel storage and repositories;
– Implementation of long term institutional control in the closed repositories.

There is a need for relevant legal amendments in this respect, development of new legal acts or elaboration of the existing ones based on the IAEA safety standards and international experience.

In this context, the formulation of a foundation of radioactive waste management is of particular importance, and it will require certain amendments in the legislation. Respective international experience should be taken into account in the establishment of the radioactive waste management foundation.

The Ministry of Energy and Natural Resources of Armenia is the State administrative organization carrying responsibilities for radioactive waste and SNF safe management. However, the Ministry does not have a specialized organizational unit to coordinate and regulate radioactive waste and SNF management issues.

Hence, it is appropriate to establish adequate organizational structure based on the IAEA standards and international experience within the Ministry of Energy and Natural Resources, which is responsible for the coordinated implementation of radioactive waste and SNF management and for the safe operation of radioactive waste storage and repositories.

Radioactive waste and SNF safe management State regulation is implemented by the State Committee of Nuclear Safety, reporting to the Armenian Government. The recruitment of radioactive waste management specialists will become essential in parallel with the intensification of the activities in radioactive waste management.

Radioactive waste and SNF are considered State property, as established by the Armenian legislation. Therefore, it is important to have a dedicated State fund for radioactive waste and SNF management, which will provide for the coordinated and targeted funding of radioactive waste management activities. These activities should include collection and transportation of radioactive waste, establishment of radioactive waste treatment facilities, selection, planning, construction, operation and shutdown of radioactive waste and SNF storage facilities and repositories and the implementation of a long term institutional control in the closed repositories.

The legal and civil entities whose actions generate radioactive waste should be responsible for providing means and resources to the State fund. Other sources, not restricted by law, may also be involved in its replenishment. Such action will result in decreased budget allocations related to radioactive waste and SNF management activities.

Currently, there are no available radioactive waste processing facilities in Armenia, and it is not possible to convert radioactive waste into a condition suitable for transport, storage, or disposal. In addition, there are no available radioactive waste storage facilities and repositories conformant with contemporary requirements. The need for such facilities will become more evident for future disposal of radioactive waste generated after the termination of ANPP operation.

For the intended types and capacities of the new storage facilities and repositories, existing and expected (at least for the upcoming 50 years) radioactive waste (according to the classification) and SNF volume must be taken into account.

It is very important to implement targeted eco-geological research on Armenia's territory for the construction of new storage facilities and repositories. The research will serve to verify the acceptability of future sites.

It is very important, in terms of radioactive waste and SNF management, to constantly study international experience and development trends, to analyse and justify their application, since the implementation of broad and complex scientific research and technological elaborations may not be economically justifiable in Armenia.

As effective action aimed at improving radioactive waste and SNF management, national five-year development programmes must be developed and implemented in accordance with the established procedure of the Armenian legislation. Following the priorities, these programmes will define the required activities, timeframes, and responsible parties for implementation.

On 20 August 2013, Joint Convention on Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management entered into force. The first National report under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management was presented during the 5th review meeting in May 2015.

13.2. INFORMATION POLICY DEVELOPMENT

Public awareness of nuclear safety is vital. Comprehensive and accurate information on all approaches to radioactive waste and SNF safe management enhancement must be communicated to the population, public organizations and media, with the exception of information containing State, civil or commercial secrets. These actions will eventually result in a better understanding of relevant radioactive waste and SNF management issues.

Public awareness issues in nuclear safety are of great importance. Efforts must be made to:

(1) Increase the level of public awareness by communicating comprehensive information on nuclear technologies, radioactive waste and SNF management, highlighting the measures to confine and isolate sources of irradiation;

(2) Constantly study public opinion on radiation safety to combat emerging issues in a timely manner;

(3) Regularly communicate the existing nuclear safety standards and requirements to the population;

(4) Achieve public trust in the management of nuclear technologies in line with safety standards via adequate guarantees;

(5) Simplify the decision making process on nuclear issues, communicating real and balanced information to the public.

14. GENERAL RECOMMENDATIONS FOR PART C

14.1. PREREQUISITES FOR POLICY DEVELOPMENT

In order for the Governments to develop radioactive waste management policies, it is necessary to adhere to the Principles of Radioactive Waste Management [10]. Governments should base their policies on the:

- Current national legal framework;
- Current institutional structure;
- Applicable international conventions;
- Current national policies and strategies;
- Radioactive waste and SNF inventory;
- Availability of resources (human, financial, technical);
- Situation in other countries;
- Involvement of interested parties.

14.2. NATIONAL POLICY

(1) Allocation of responsibilities

Governments should establish a legislative and regulatory framework, including the designation of an independent regulatory body to enforce, among other things, the regulations for the safe management of SNF and radioactive waste (Articles 19 and 20 of the Joint Convention).

The national policy should identify the:

- Governmental organization(s) responsible for establishing the legislative and regulatory framework;
- Relevant regulatory body;
- Organization(s) responsible for ensuring that radioactive waste is safely managed (normally the licensee);
- Organization(s) responsible for the long term management of SNF and radioactive waste, and for radioactive waste for which no other organization has responsibility.

(2) Provision of resources

The national policy should set out arrangements for:

- Establishing the mechanisms for providing the resources or funds for the safe, long term management of SNF and radioactive waste;
- Ensuring that there are adequate human resources available to provide for the safe management of SNF and radioactive waste, including, as necessary, resources for training and R&D;
- Providing institutional controls and monitoring arrangements to ensure the safety of SNF and radioactive waste storage facilities and waste repositories during operation and after shutdown.

(3) Safety and security objectives

Article 1 (ii) of the *Joint Convention.*

(4) Waste minimization

Article 4(ii) of the *Joint Convention.*

(5) Export and import of radioactive waste

The national policy may specify:

- Conditions on the import and/or export of radioactive waste;
- An intention to store/dispose of radioactive waste on national territory;
- An intention to seek international/regional solutions.

(6) Management of spent fuel

The national policy on the management of SNF should be made clear (Preamble of the Joint Convention). The policy may, for example:

– Consider SNF a resource and seek to utilize the resource through reprocessing (nationally or internationally);
– Regard SNF as waste and specify that it be disposed of directly;
– State that SNF will be returned to the supplier.

(7) Management of radioactive waste

The national policy should identify the main sources of radioactive waste in the country — including the decommissioning of facilities, if appropriate — and should:

– Identify the intended national arrangements for the management of the main types of radioactive waste;
– Identify the end points of the management process;
– Recognize that some radioactive waste may be potentially hazardous for long into the future and, therefore, require implementation of long term safety measures.

(8) Naturally occurring radioactive material (NORM)

It is important that national policy should indicate the regulatory regime under which NORM is managed (Article 3.2 of the *Joint Convention*).

(9) Public information and participation

The national policy may indicate the State's intention to inform the public about proposed plans for radioactive waste management and to consult concerned parties and members of the public to aid in making related decisions (Paragraph (iv) of the Preamble of the *Joint Convention*).

14.3. STRATEGY DEVELOPMENT

(1) Identify end points

Strategies should address the long term pathway of each waste category, for example, by identifying the period for which safe storage can be ensured (minimum expected lifetime of waste packages) and plans for managing the waste beyond that time. The result of this step should be a generic management pathway for each radioactive waste category.

(2) Identify technical options

All of the appropriate alternative technical management options for a radioactive waste category to reach the identified end points should be identified. The potential technical options can be narrowed down through the elimination of those that, for various reasons, are unsuitable.

(3) Determine optimum strategy

The optimum strategy should be determined by comparing the relative advantages and disadvantages of each strategic option. This optimization process should result in a general strategy, which then needs to be further elaborated into an implementation plan.

(4) Assign responsibilities

Responsibilities for implementing particular parts of the strategy should be allocated, i.e. for particular stages of the waste management process but also for linkage between the stages. The result will be an infrastructure for strategy implementation with defined responsibilities.

(5) Supervision of implementation

Control mechanisms, such as accountability criteria and periodic reviews, should be established for ensuring the timely strategy implementation. In order to ensure that the strategy is periodically reviewed and updated, appropriate mechanisms should be established (milestones for strategy reviews). This would result in the establishment of tools for the supervision of strategy implementation.

(6) Long term planning

A long term strategic plan covering the expected lifetime of the programme and intermediate plans for the periods between significant milestones should be established. The plans should address:

- Assessment of data on radioactive waste generation: predicted waste inventories over time;
- Assessment of requirements for relevant technological equipment and facilities based on predictions of future radioactive waste generation;
- Specification of financial resources needed for technological and supporting equipment and facilities;
- Development of an executive plan for the next budgeting period.

The result will be a strategy for the long term management of radioactive waste in the country (or for a specific waste stream) which includes the details of how it is to be implemented.

14.4. REGIONAL COOPERATION

14.4.1. Shared facility

Countries may consider sharing dedicated radioactive waste management facilities. This approach has the benefit of decreasing the cost of waste management for all countries involved. Such approach is, for example, applied for melting and incinerating LLW.

Shared facilities could include multilateral facilities for storage and disposal. Such proposals have been made in the framework of the *Joint Convention* related to the multilateral storage of SNF (see report of the Second Review Meeting) and discussions have taken place between interested countries [11].

Another type of international sharing has occurred in relation to the reprocessing of SNF. Some countries with developed fuel cycle capacities have provided commercial reprocessing services to other (usually smaller) countries in which such activities would not be economical.

14.4.2. Country specific considerations

The selection of a waste management strategy in a country is often influenced by the nature and location of the country itself taking into account the following:

- Proximity to other countries: a country’s proximity to countries with well-developed nuclear facilities may influence the waste management strategy. In these circumstances, there is potential for sharing of technology and expertise. On the other hand, in countries that are geographically isolated from countries with nuclear expertise, independent solutions may be preferred;

– Country size: a country’s size may influence the choice of waste management strategy. For example, in very large countries, the possibility of centralizing national waste management facilities may be limited;
– Population density: in countries with high population densities, waste management facility siting may be constrained and the number of potential sites limited by their proximity to residential areas;
– Climate: climate conditions may affect the selection of processing options. Technologies appropriate to local climate conditions are preferred. In hot climates, for example, temperature sensitive options, like bituminization, should be avoided while solar evaporation (heating) should be considered.

15. GENERAL CONCLUSIONS AND RECOMMENDATIONS

(1) Study NES parameters that influence operational power system characteristics in transient and post-transient conditions for NES consideration for a country with a small grid;

(2) Continue improvement to the **UR2 Industrial and economic infrastructure**: "*The industrial and economic infrastructure of a country planning to install an innovative nuclear power system (INS) should be adequate to support the project throughout the complete lifetime of the nuclear power programme, including planning, construction, operation, decommissioning and related waste management activities*" of the INPRO area of Infrastructure with the **Criterion 2.6: Grid compatibility** (Appendix II) by organizing a joint project together with other INPRO Member States;

(3) Develop simplified calculation models of NES which would support the tasks mentioned in point 1;

(4) Continue NESA Support Package preparation;

(5) Coordinate INPRO methodology and NESA Support Package training cycles;

(6) Research fuel transportation problems and incorporate results into the INPRO methodology;

(7) Include assessments relative to energy security, energy independence, and power system operation safety.

APPENDIX I:

TRANSIENT STABILITY STUDY RESULTS

Scenario-1a: **2026 Winter MAX short circuit on ANPP's bus-bar with tripping ANPP disconnection of HVL-400 kV Tabriz.**

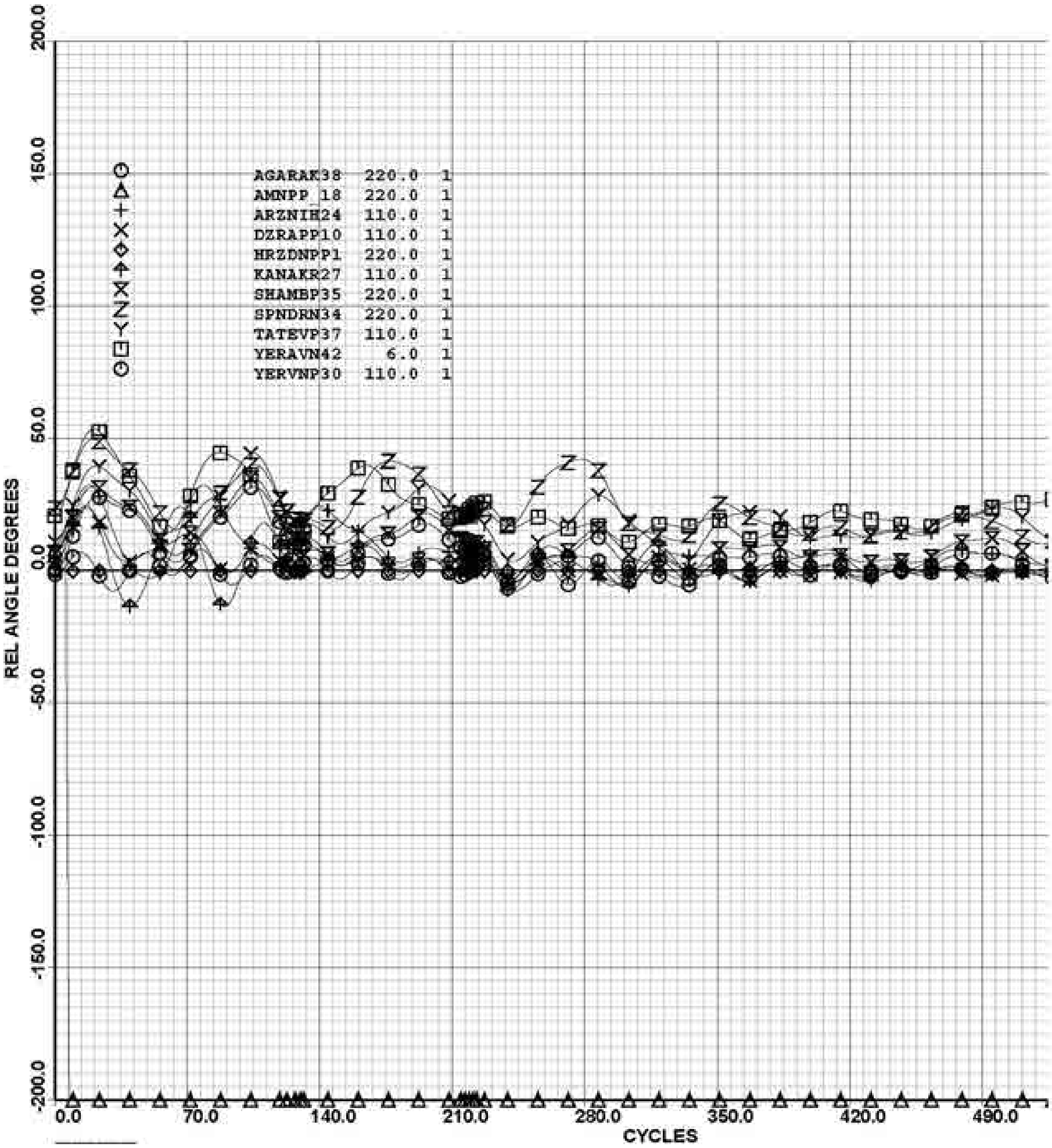

FIG. 41. Scenario-1a: real angle degrees of main generators of Armenian power system.

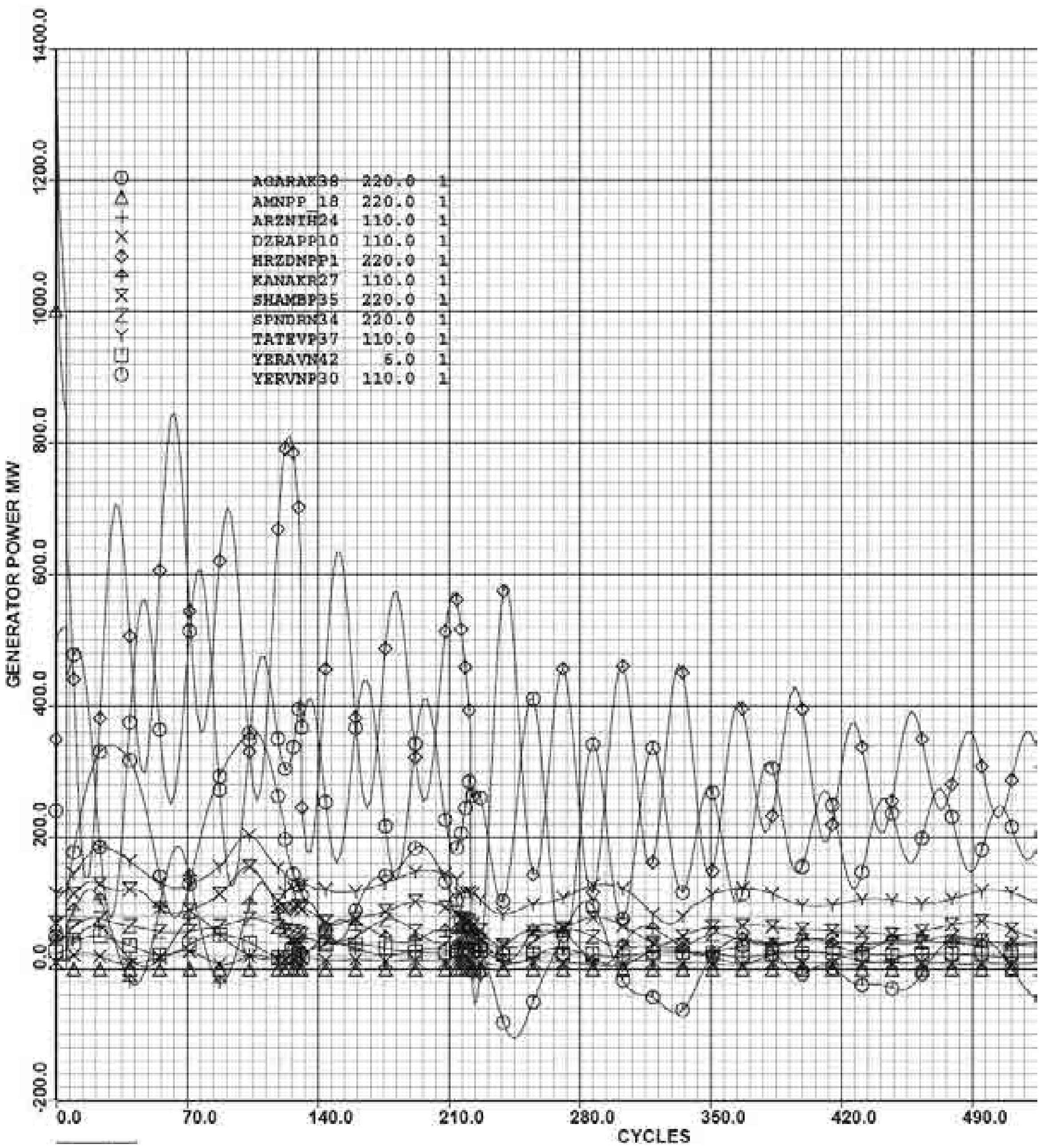

FIG. 42. Scenario-1a: active power of main generators of Armenian power system.

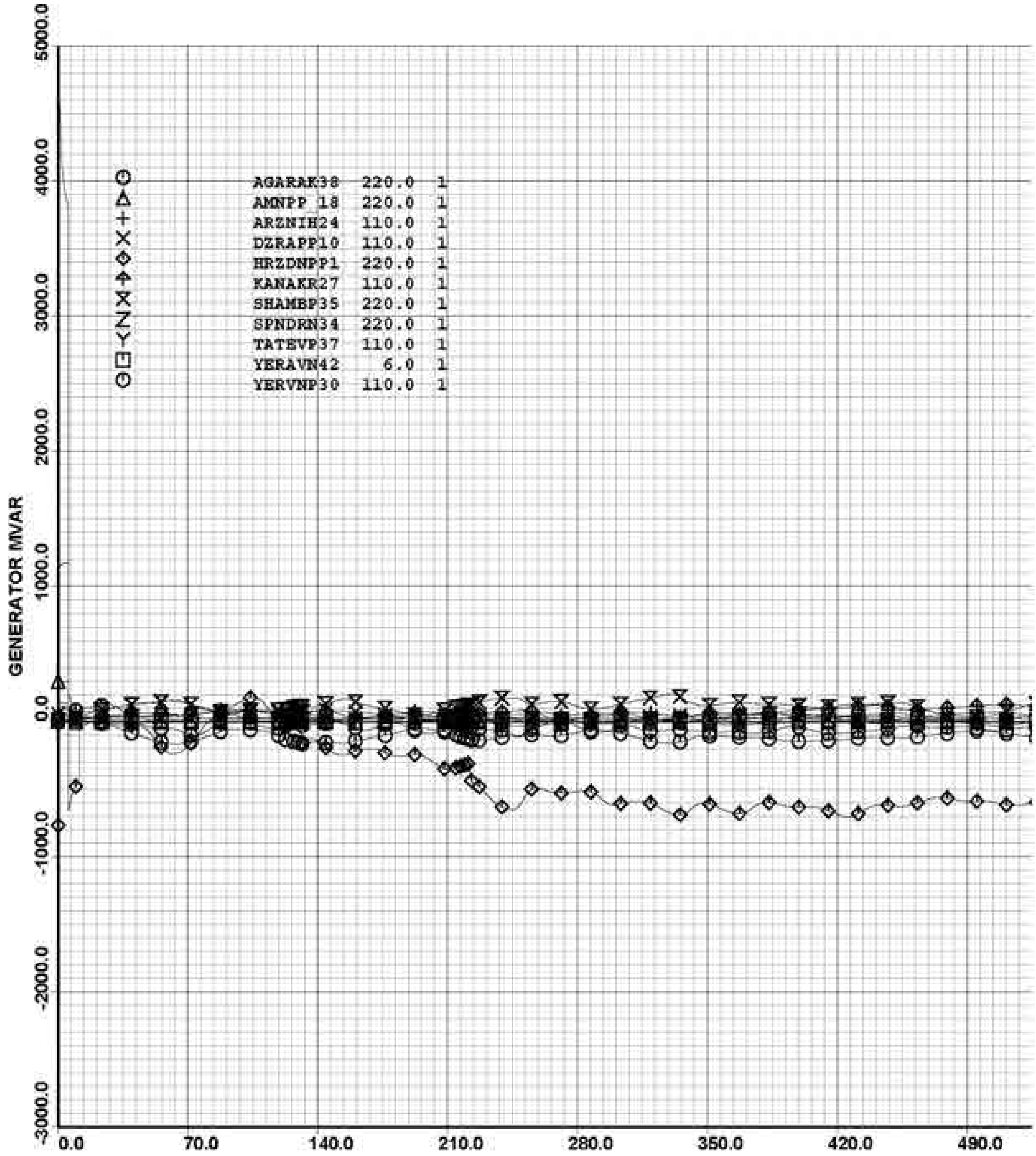

FIG. 43. Scenario 1a: reactive power of main generators of Armenian power system.

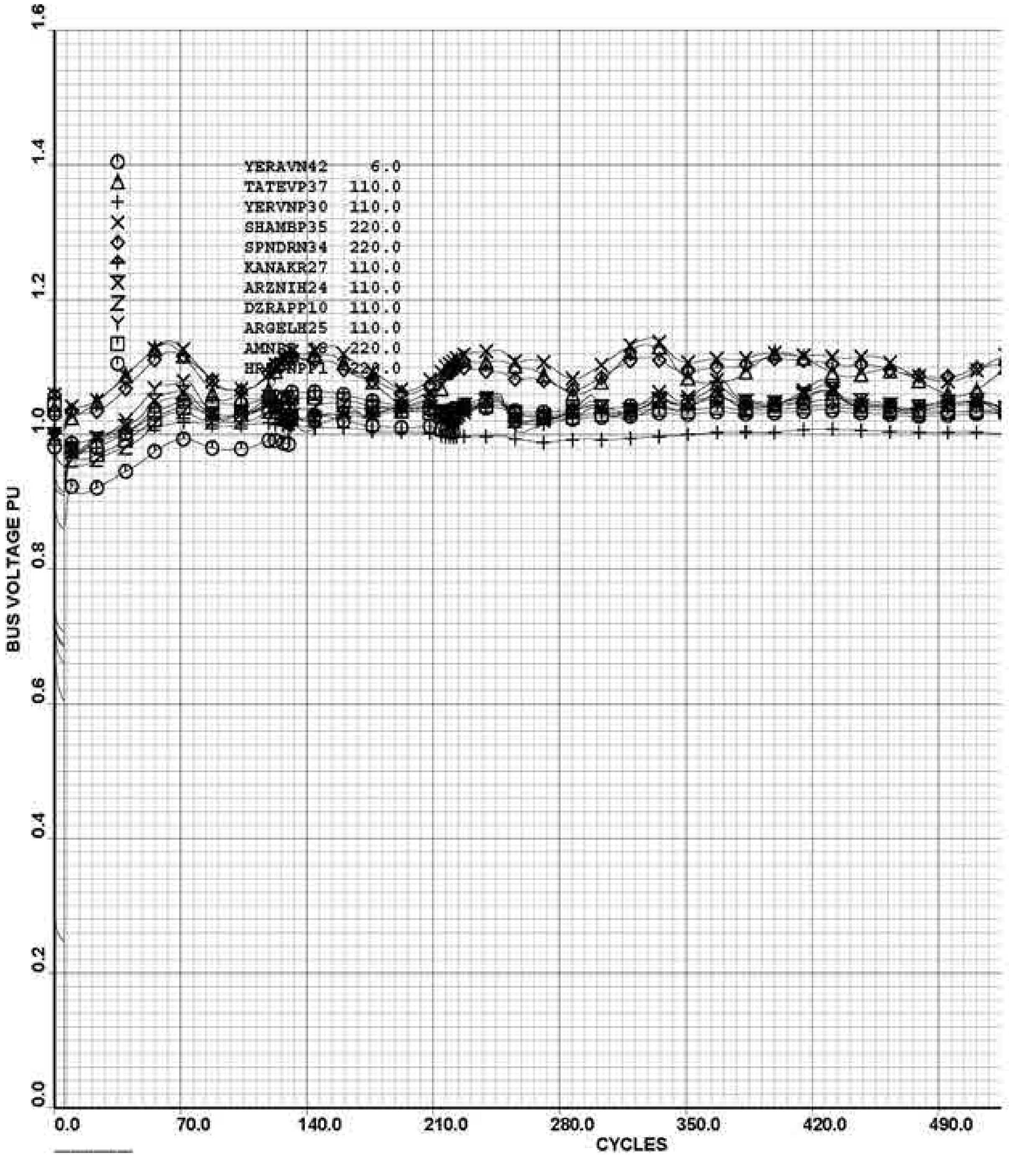

FIG. 44. Scenario 1a: voltages of the main generator buses of Armenian power system.

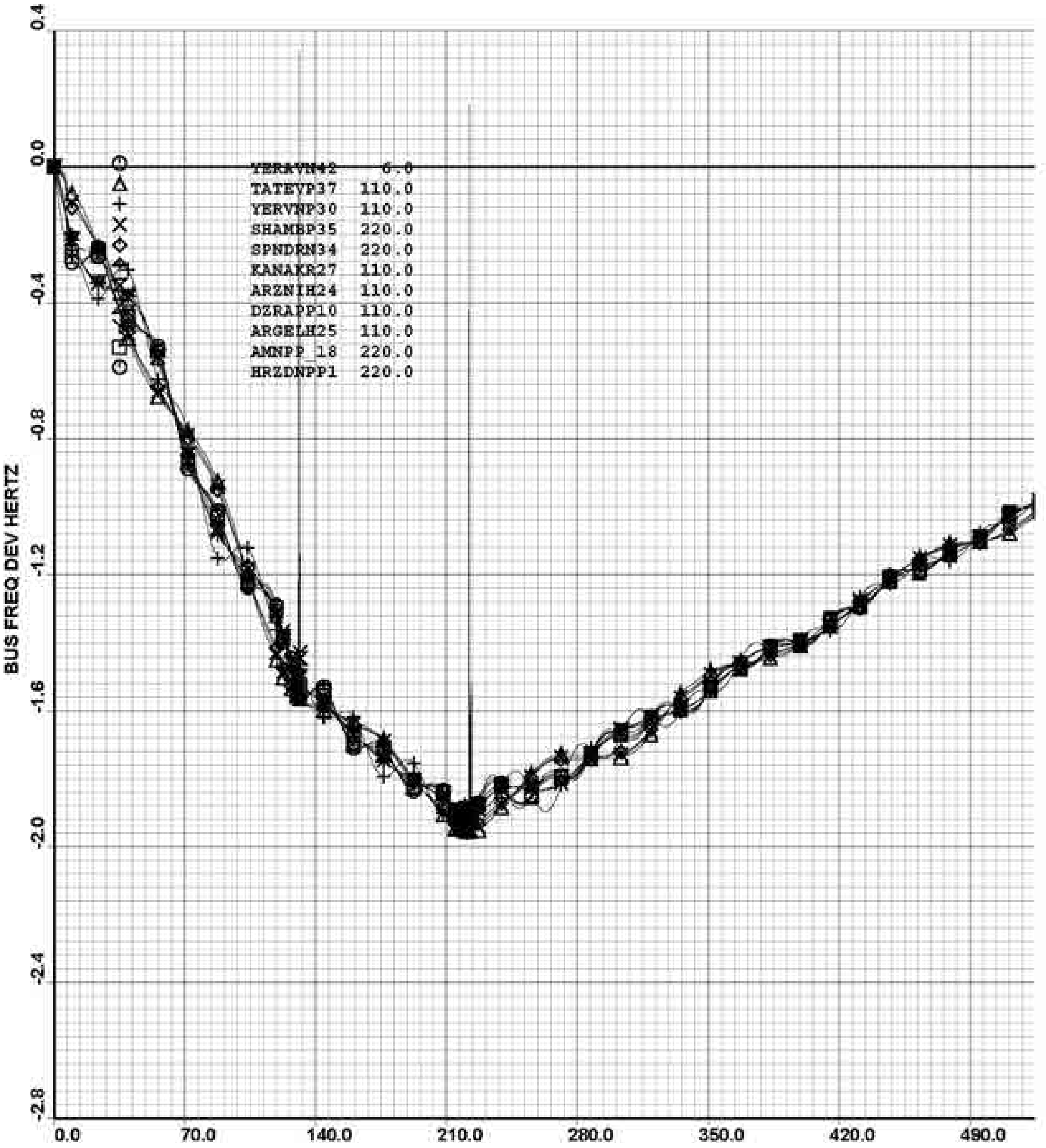

FIG. 45. Scenario 1a: frequencies of the main generator nodes of Armenian power system.

Scenario-1b: **2026 Winter MAX Short circuit on bus-bar of HVL-400 kV Tavriz with tripping HVL disconnection of ANPP.**

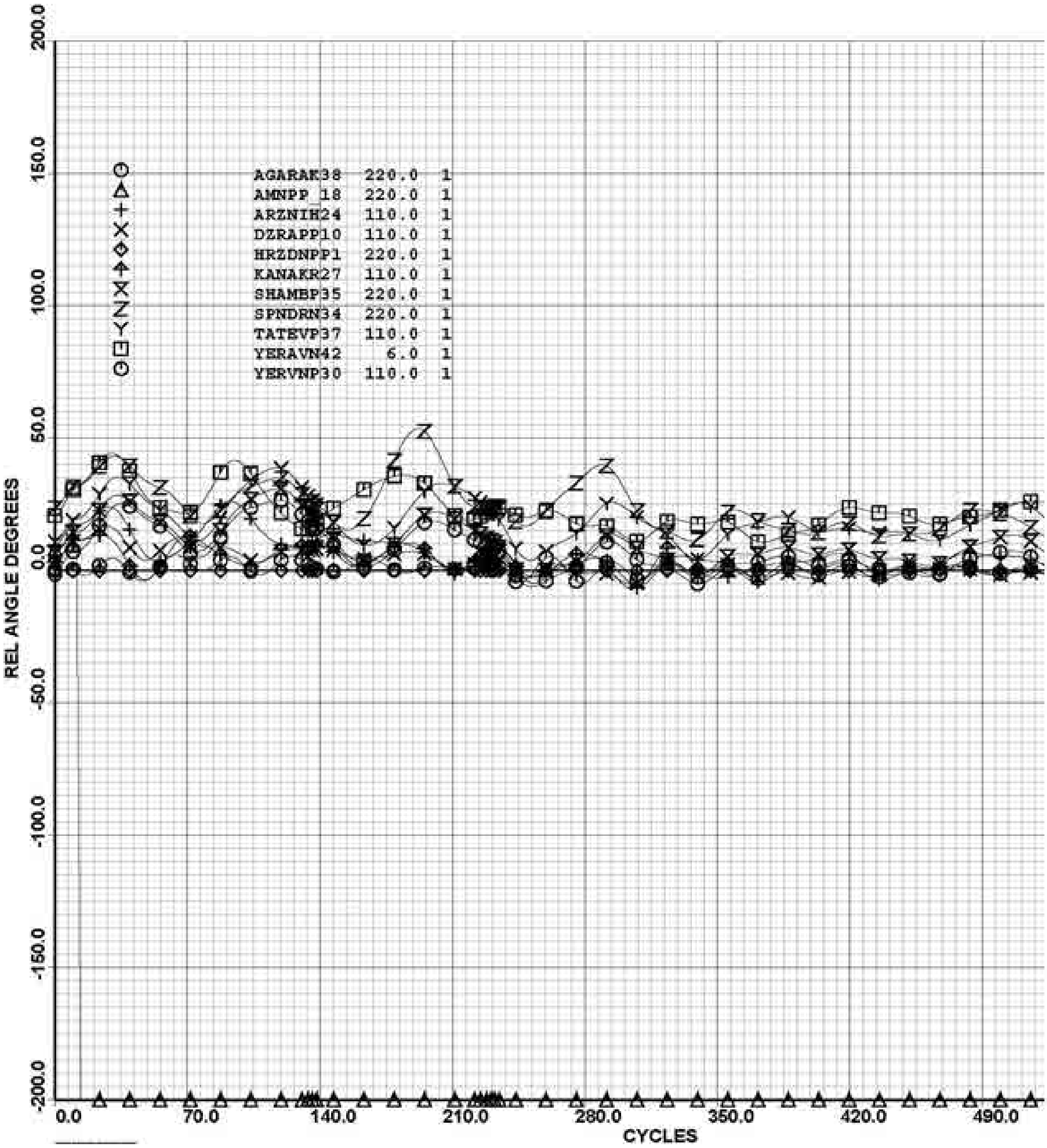

FIG. 46. Scenario-1b: real angle degrees of main generators of Armenian power system.

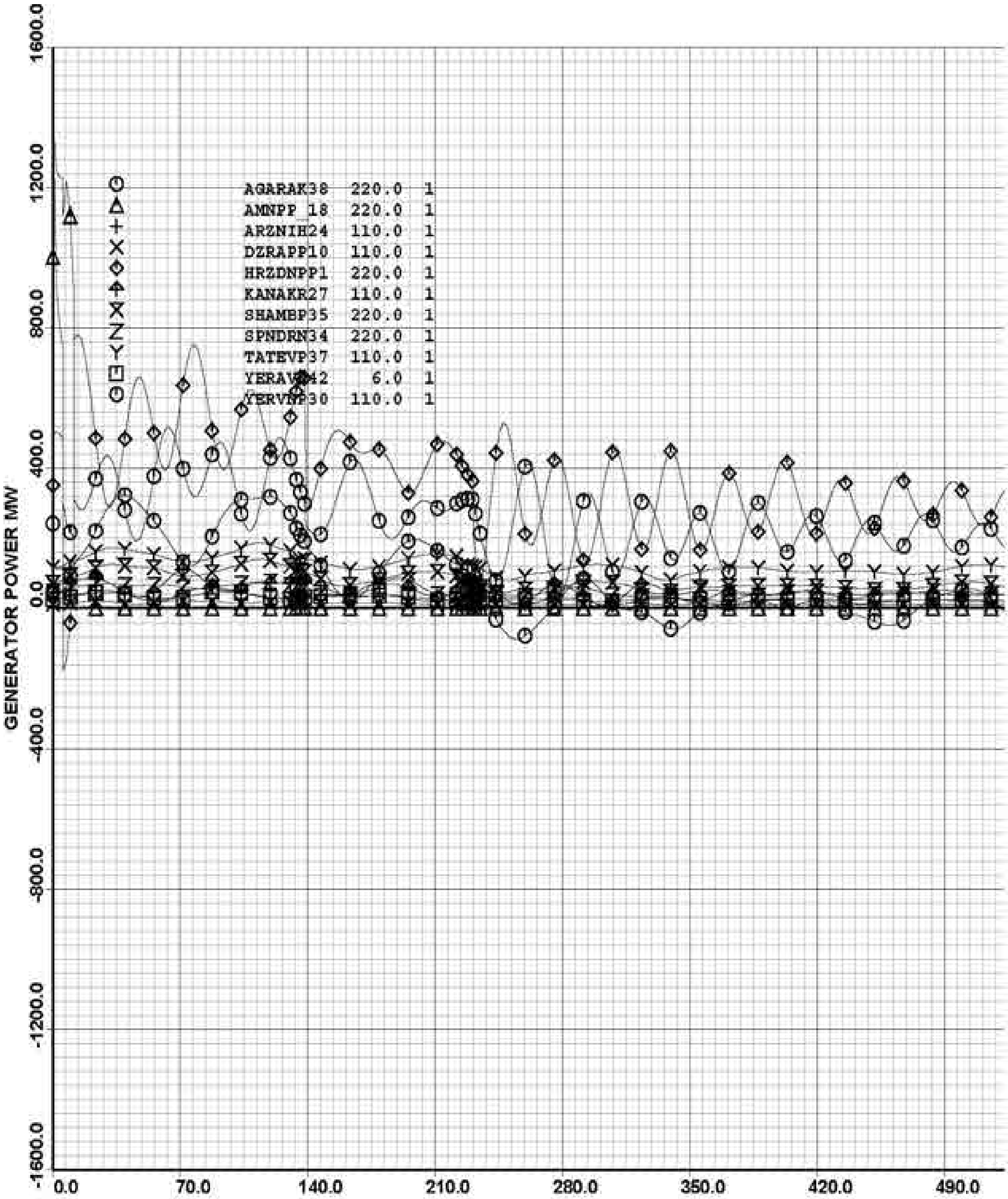

FIG. 47. Scenario-1b: active power of main generators of Armenian power system.

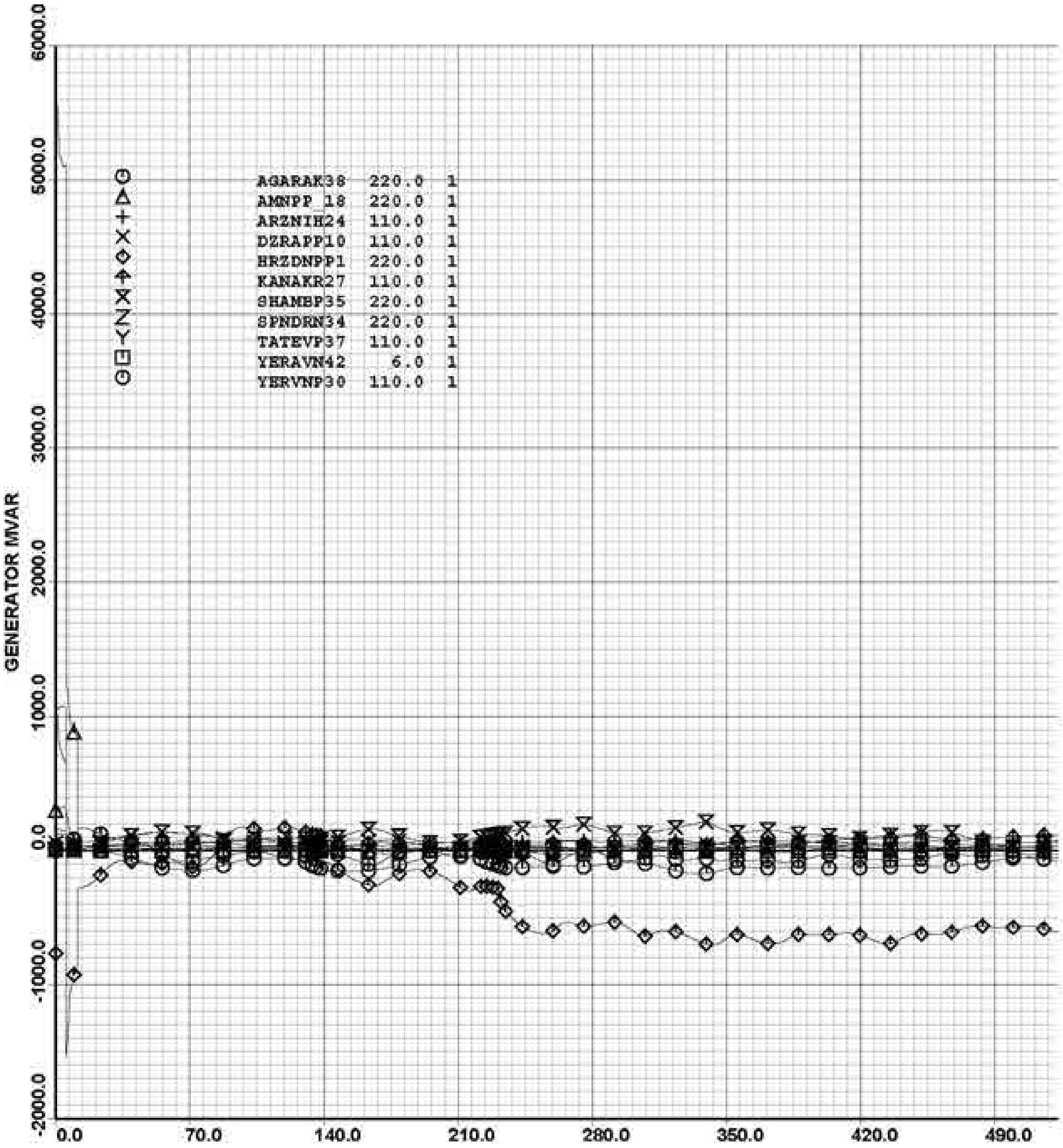

FIG. 48. Scenario-1b: reactive power of main generators of Armenian power system.

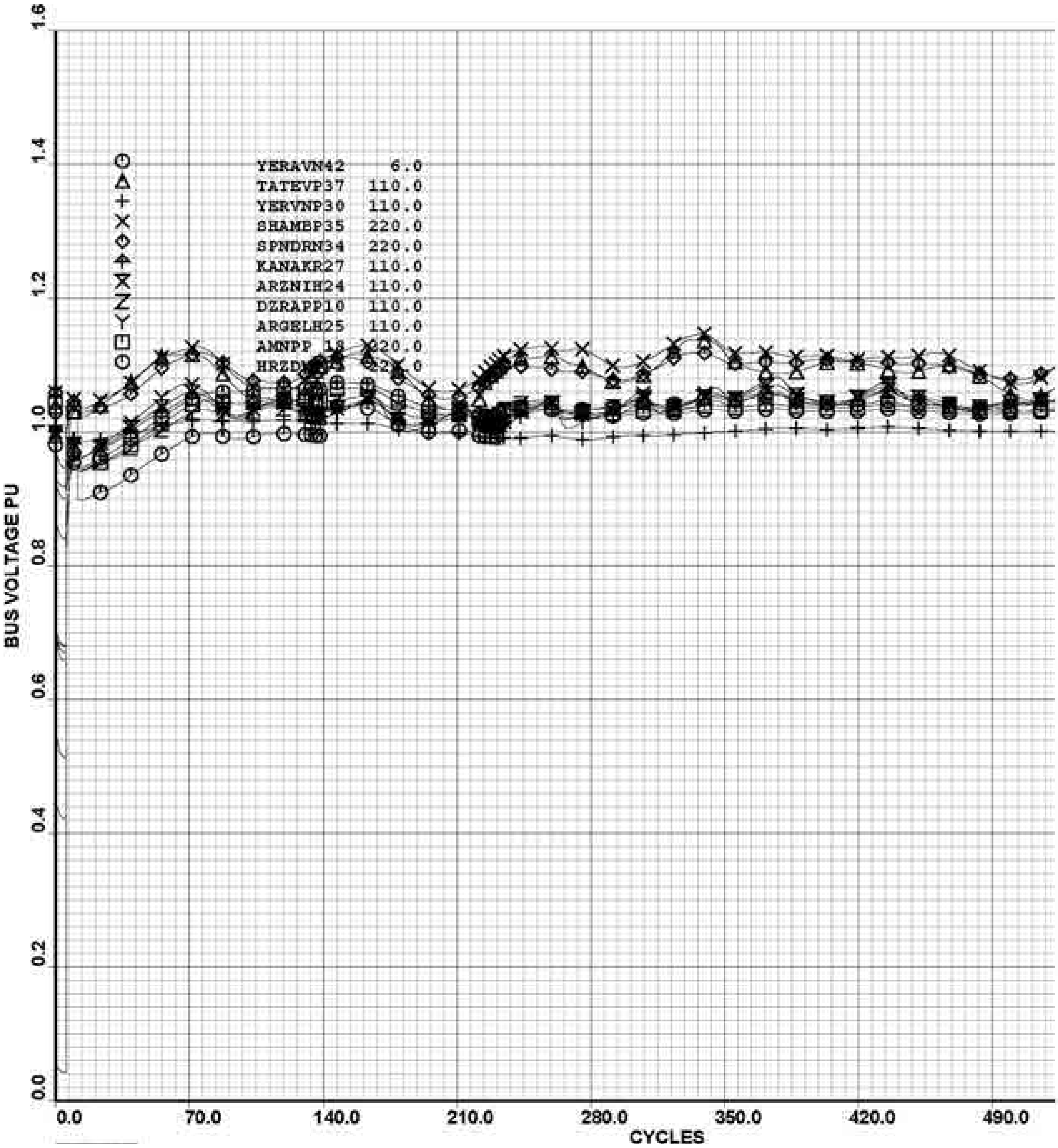

FIG. 49. Scenario-1b: voltages of the main generator buses of Armenian power system.

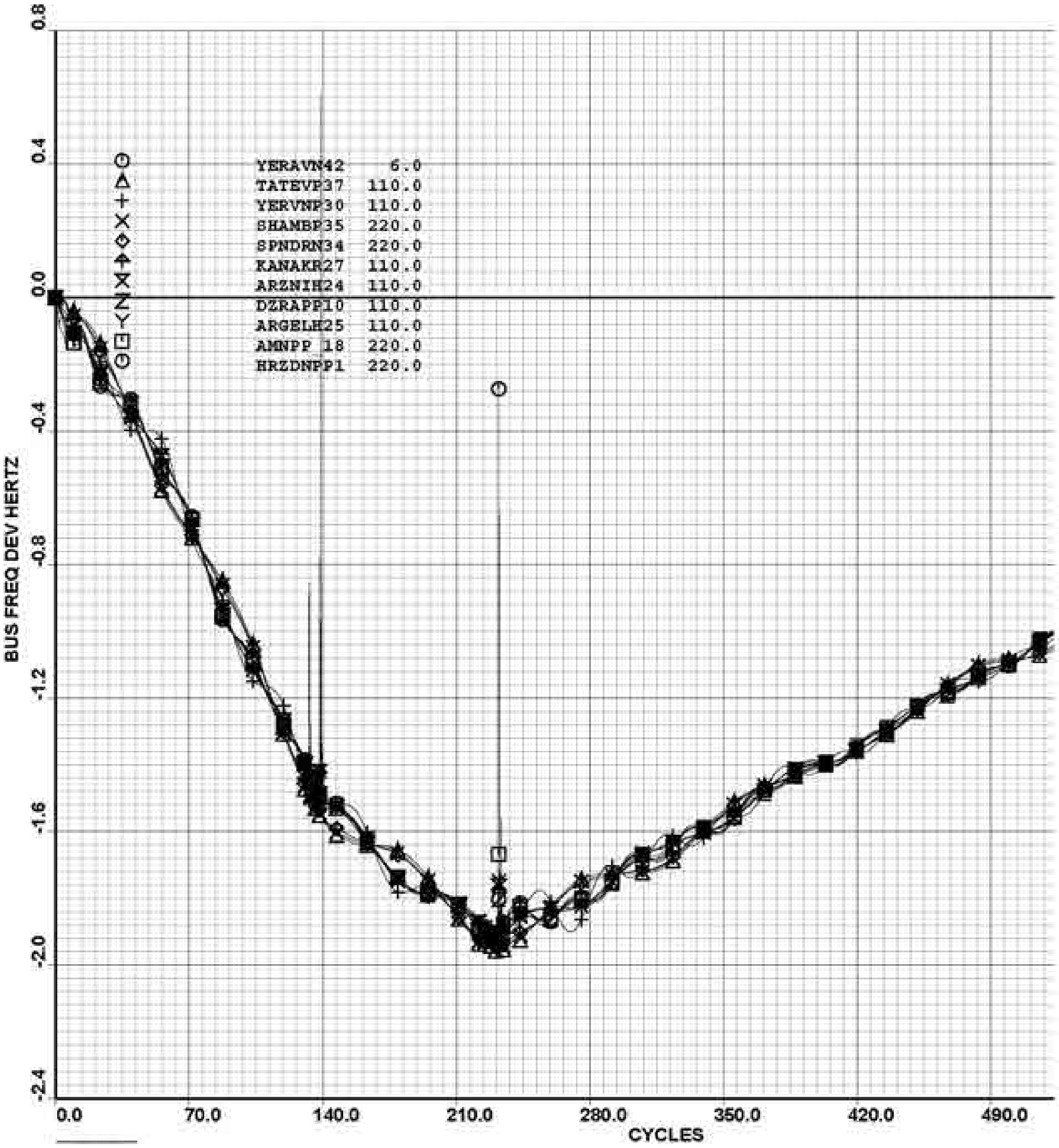

FIG. 50. Scenario-1b: frequencies of the main generator nodes of Armenian power system.

Scenario-2a: 2026 Summer MIN short circuit on ANPP's bus-bar with tripping ANPP disconnection of HVL-400 kV Tabriz.

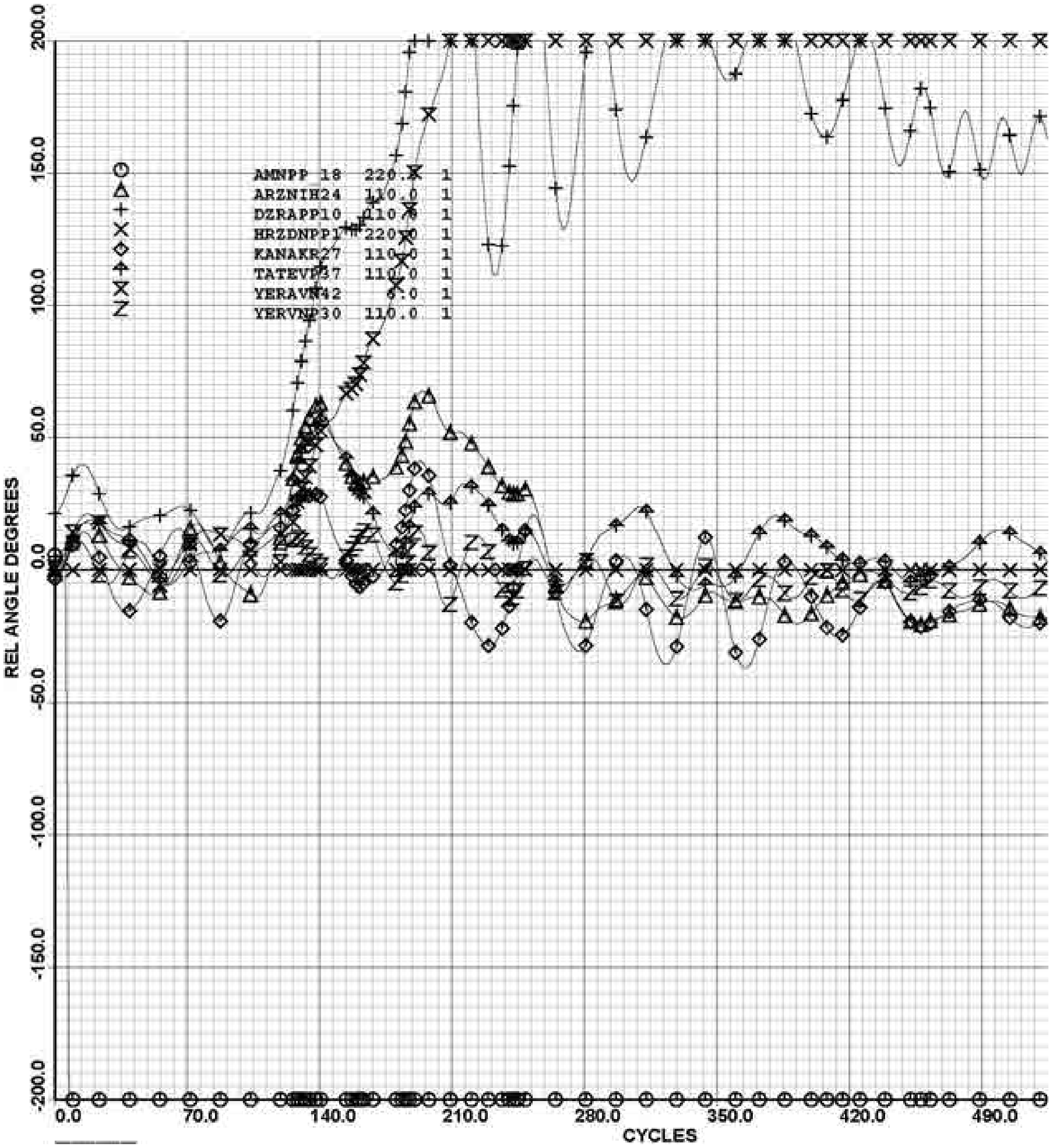

FIG. 51. Scenario-2a: real angle degrees of main generators of Armenian power system.

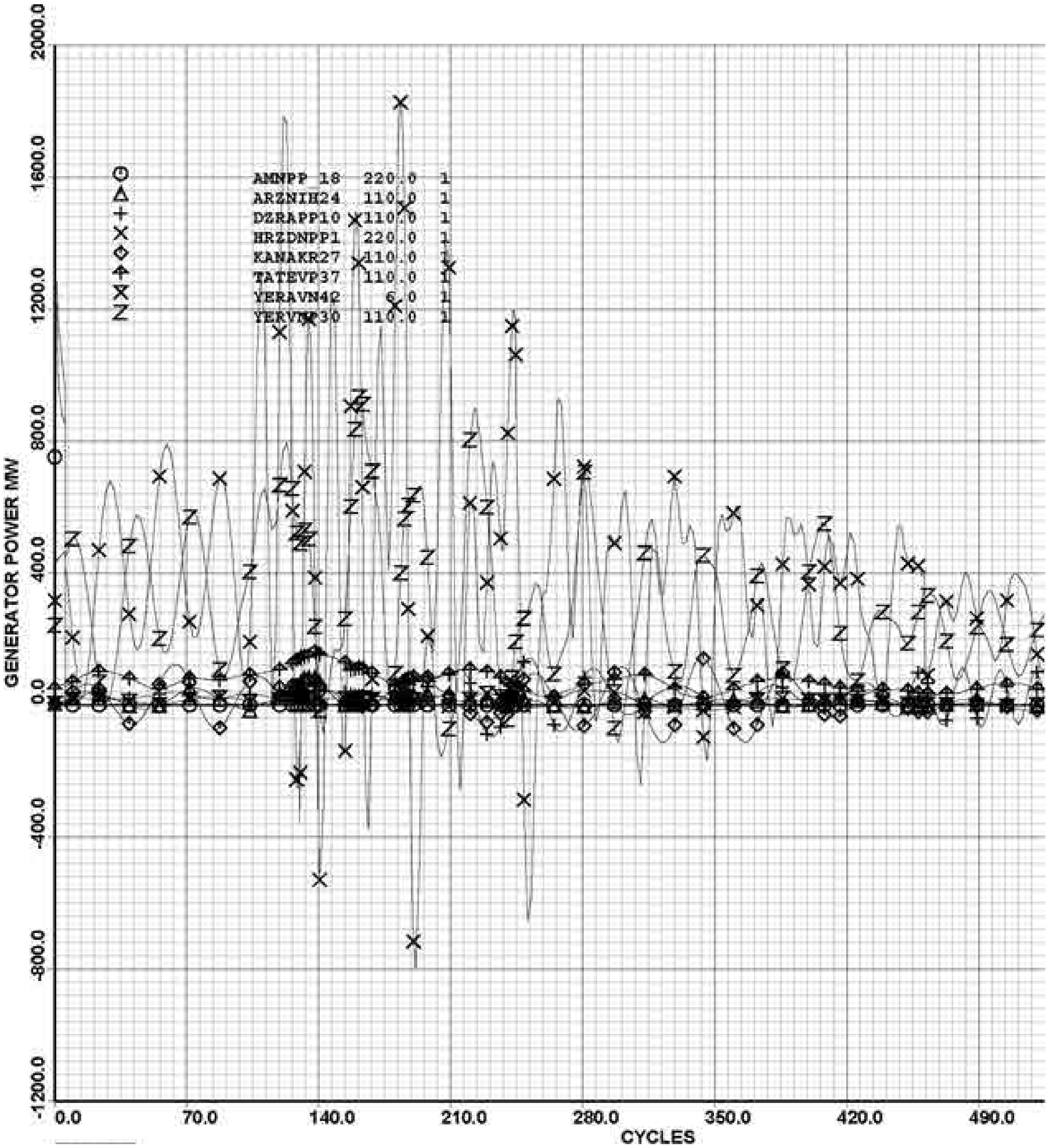

FIG. 52. Scenario-2a: active power of main generators of Armenian power system.

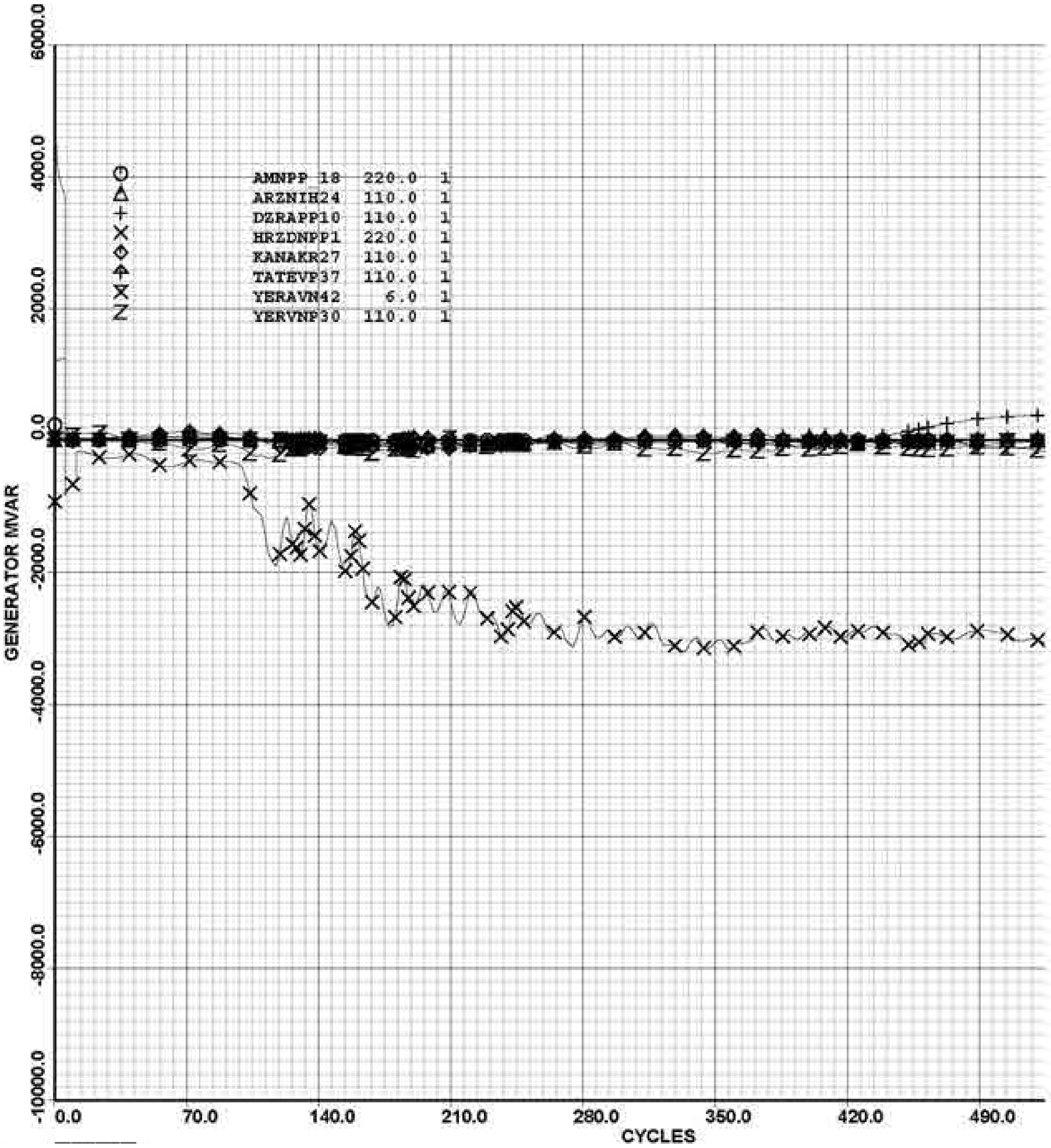

FIG. 53. Scenario-2a: reactive power of main generators of Armenian power system.

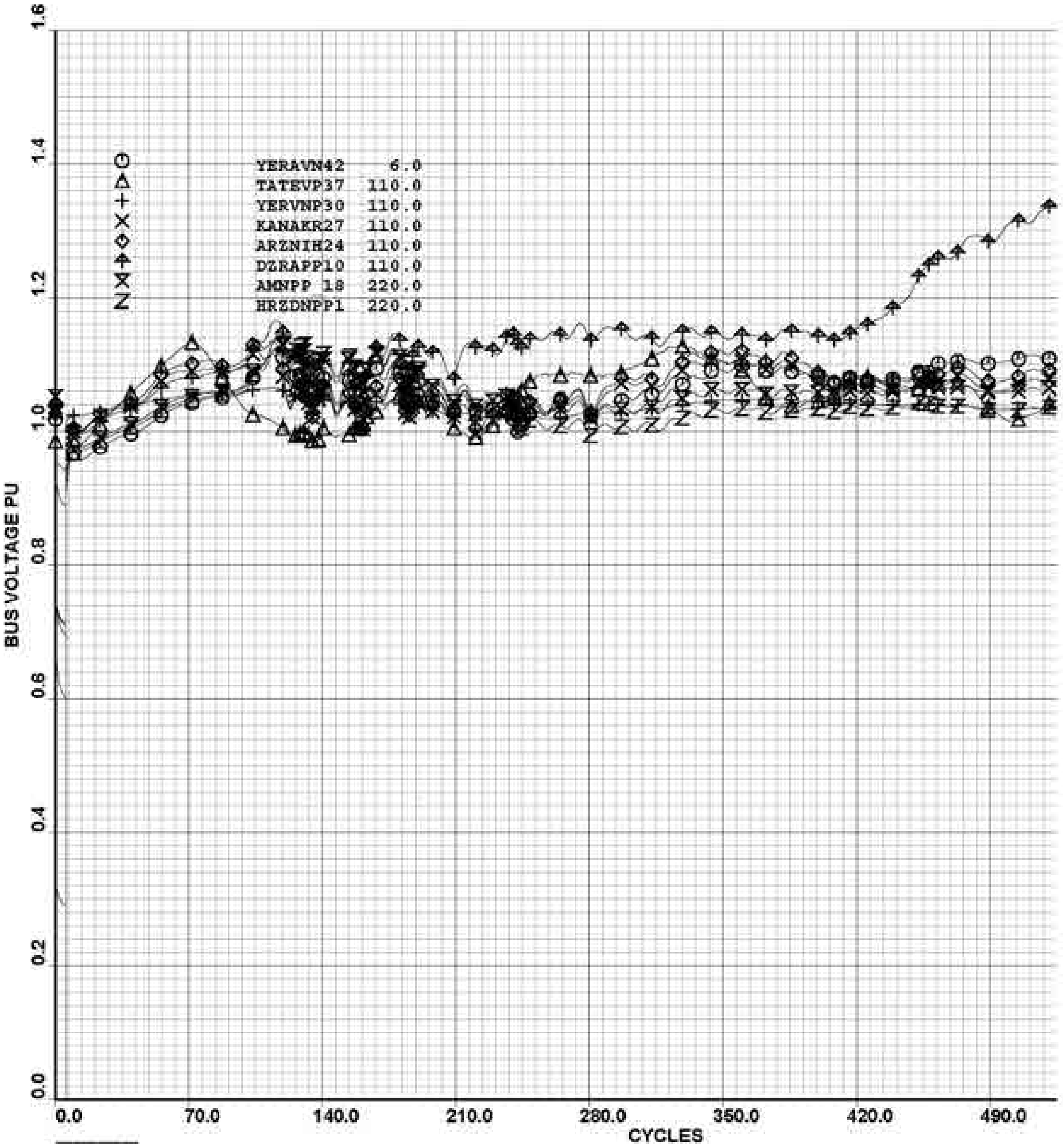

FIG. 54. Scenario-2a: voltages of the main generator buses of Armenian power system.

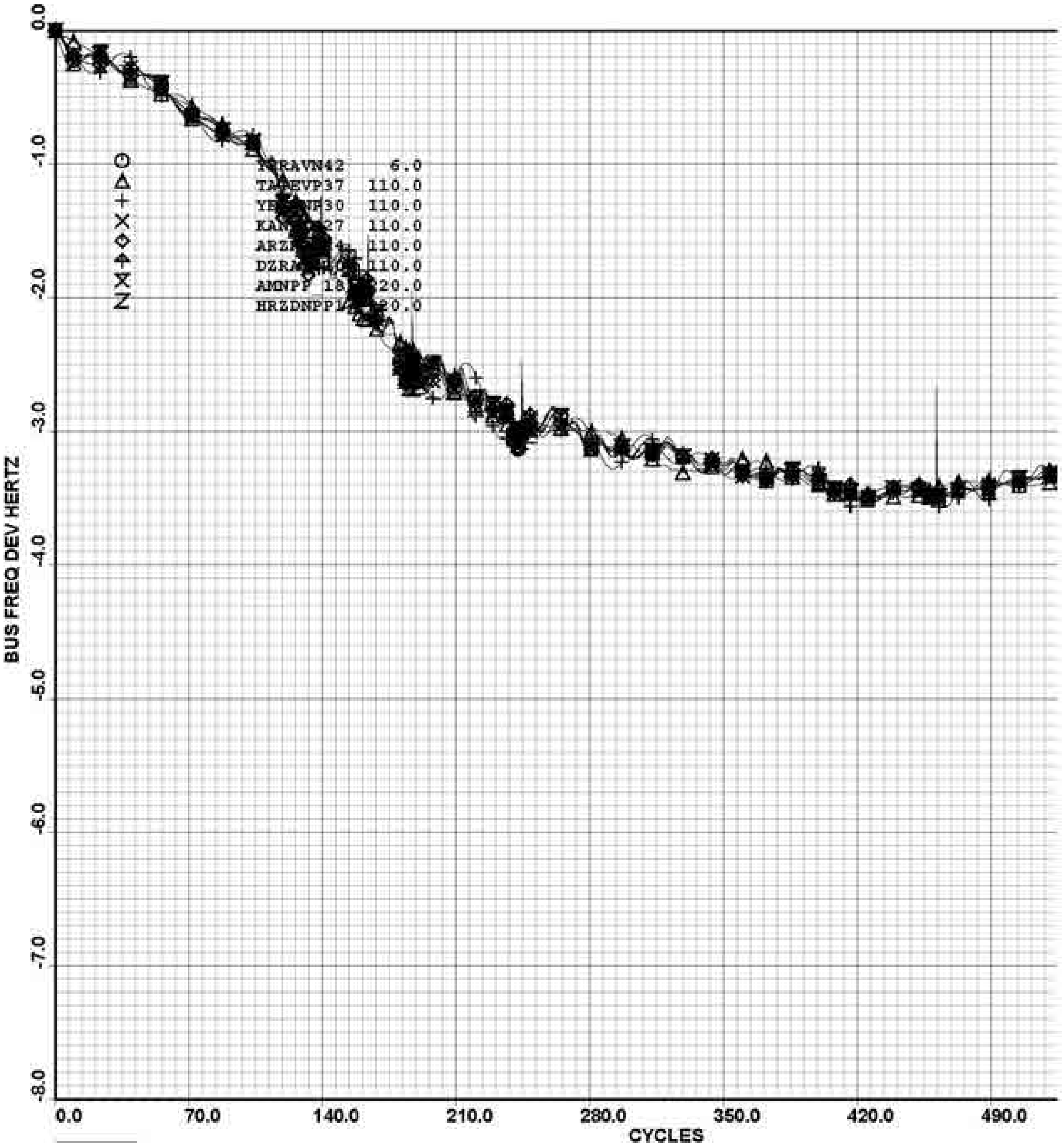

FIG. 55. Scenario-2a: frequencies of the main generator nodes of Armenian power system.

Scenario-2b: **2026 Summer MIN short circuit on bus-bar of HVL-400 kV Tabriz with tripping HVL disconnection of ANPP.**

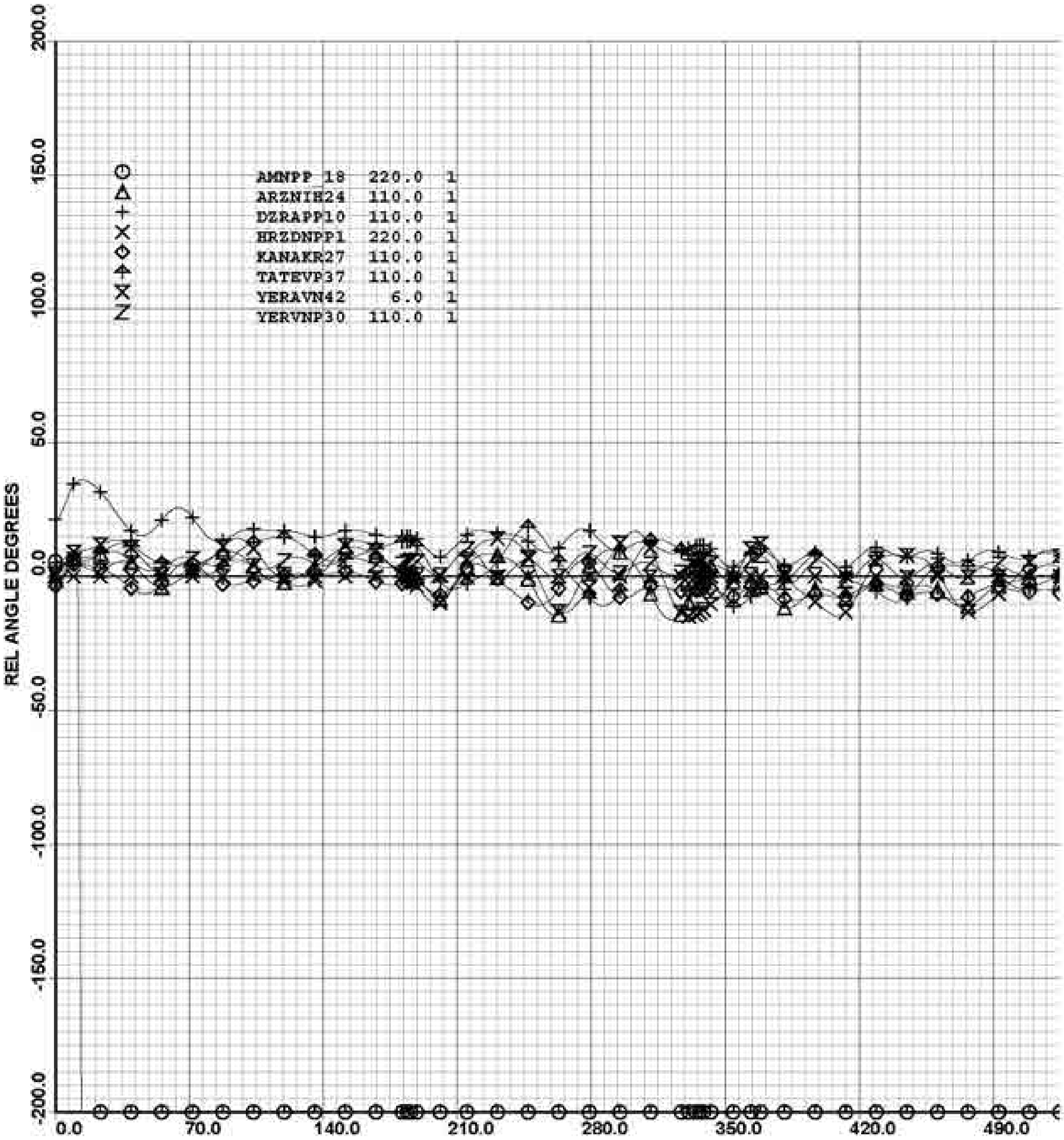

FIG. 56. Scenario-2b: real angle degrees of main generators of Armenian power system.

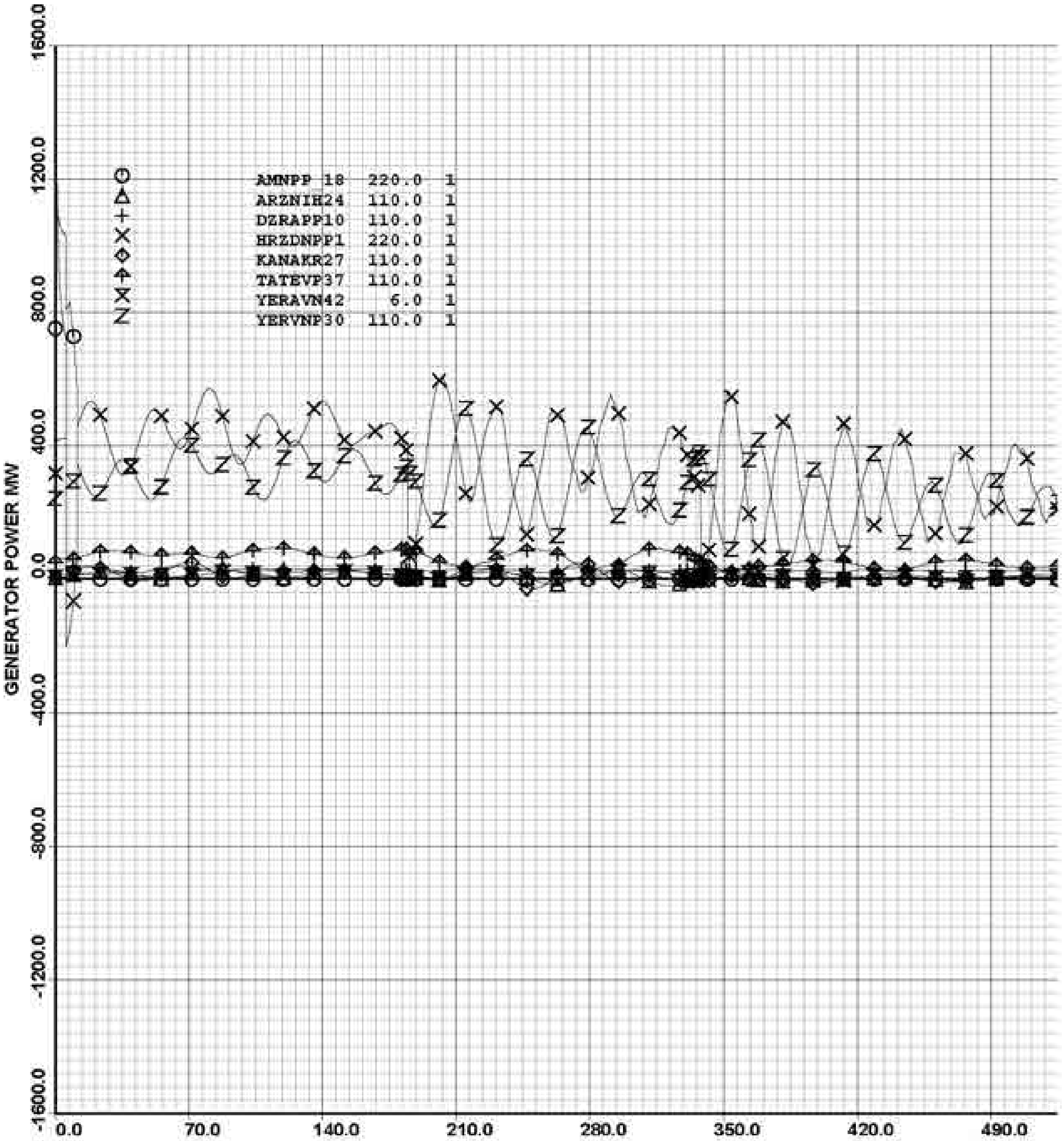

FIG. 57. Scenario-2b: active power of main generators of Armenian power system.

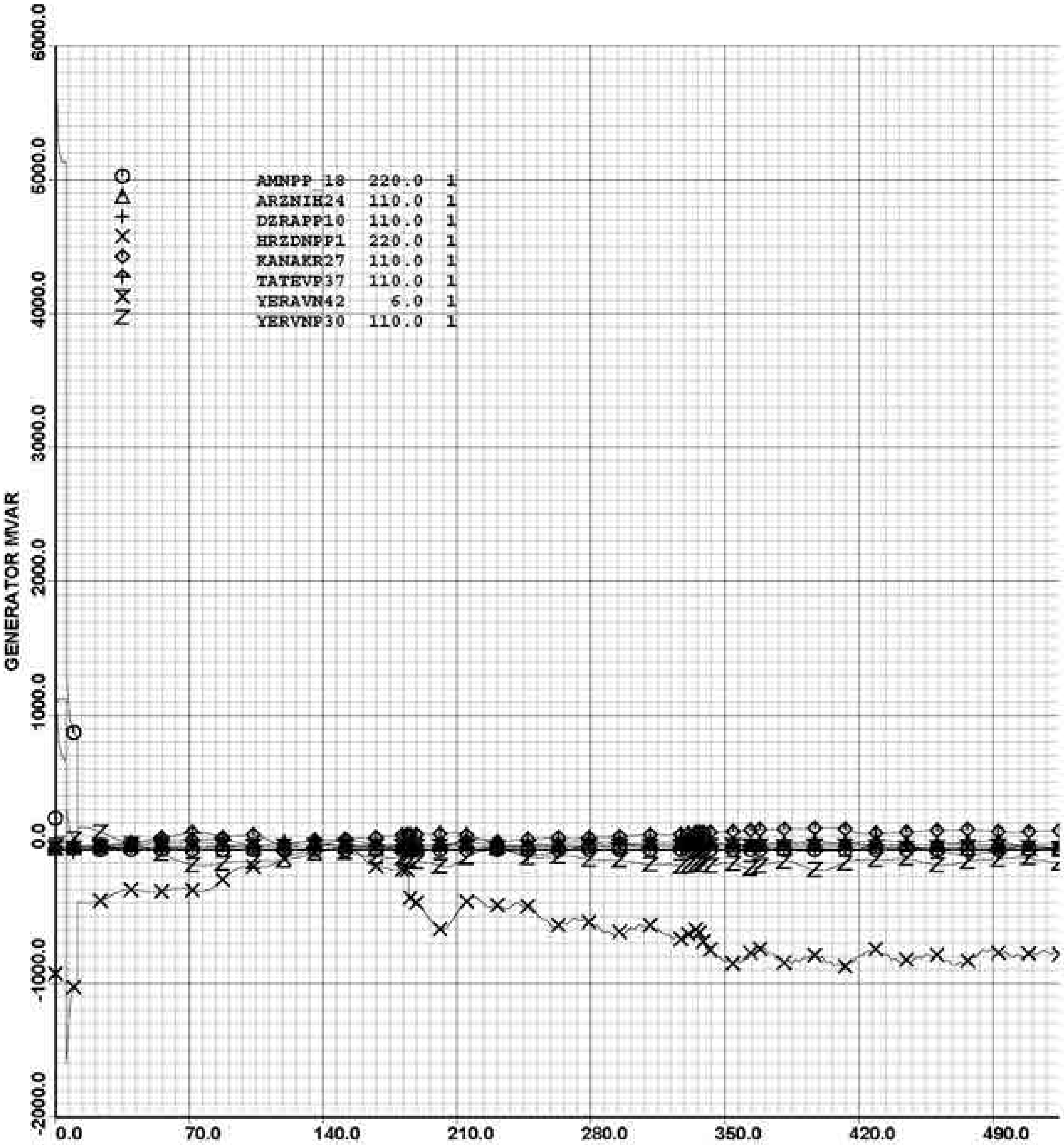

FIG. 58. Scenario-2b: reactive power of main generators of Armenian power system.

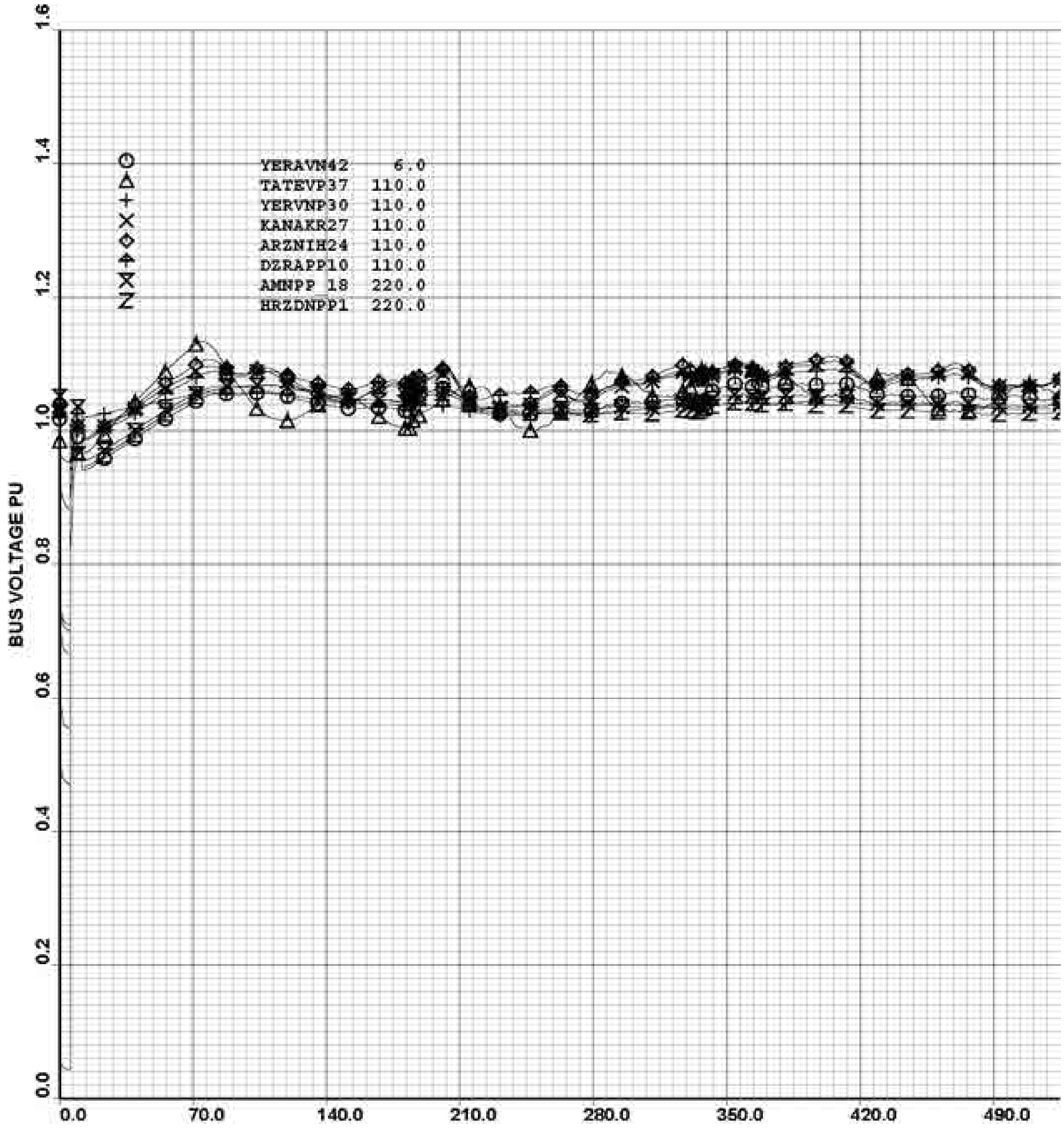

FIG. 59. Scenario-2b: voltages of the main generator buses of Armenian power system.

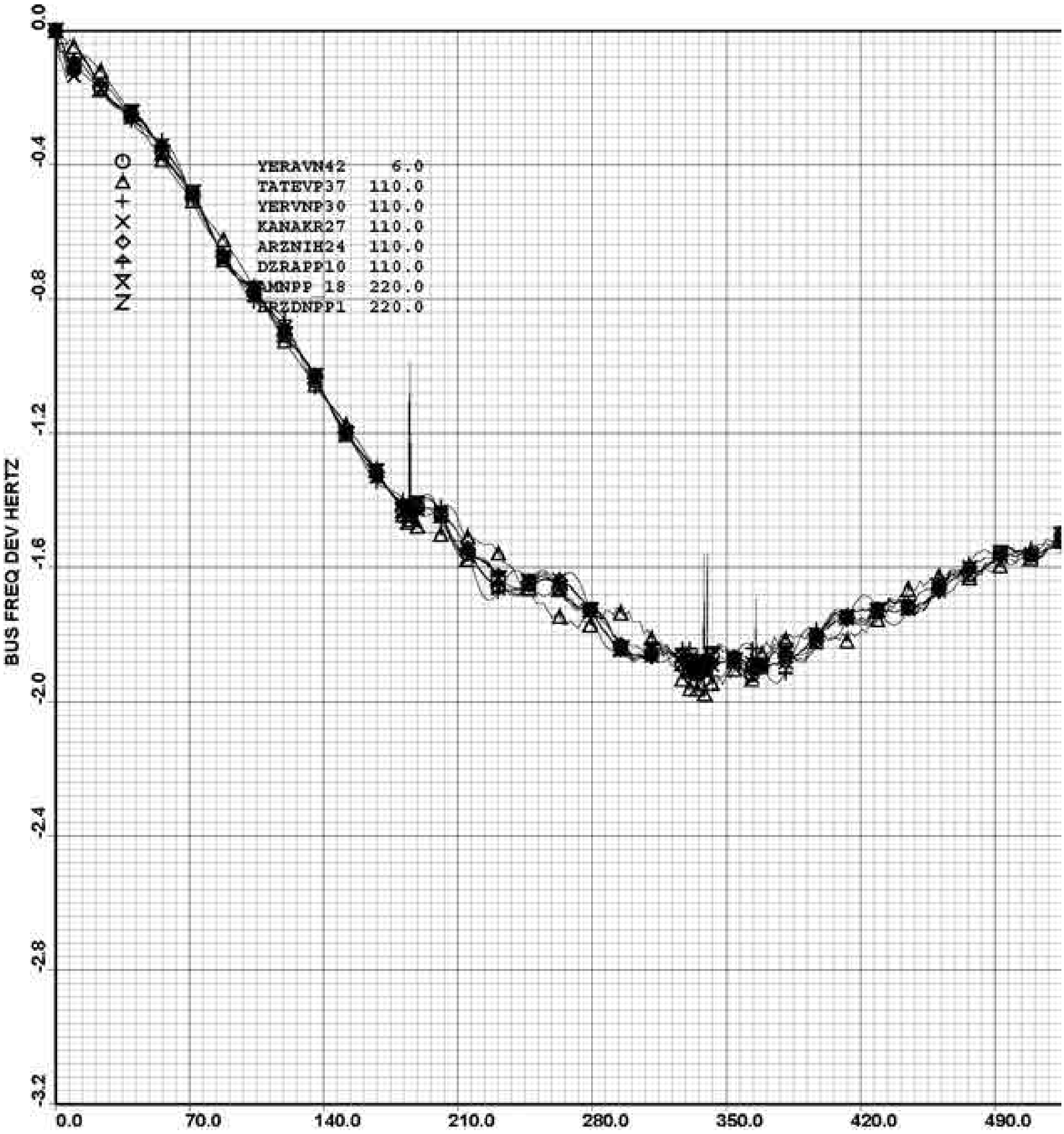

FIG. 60. Scenario-2b: frequencies of the main generator nodes of Armenian power system.

Scenario-3a: **2035 Winter MAX short circuit on ANPP's bus-bar with tripping ANPP disconnection of HVL-400 kV Tabriz.**

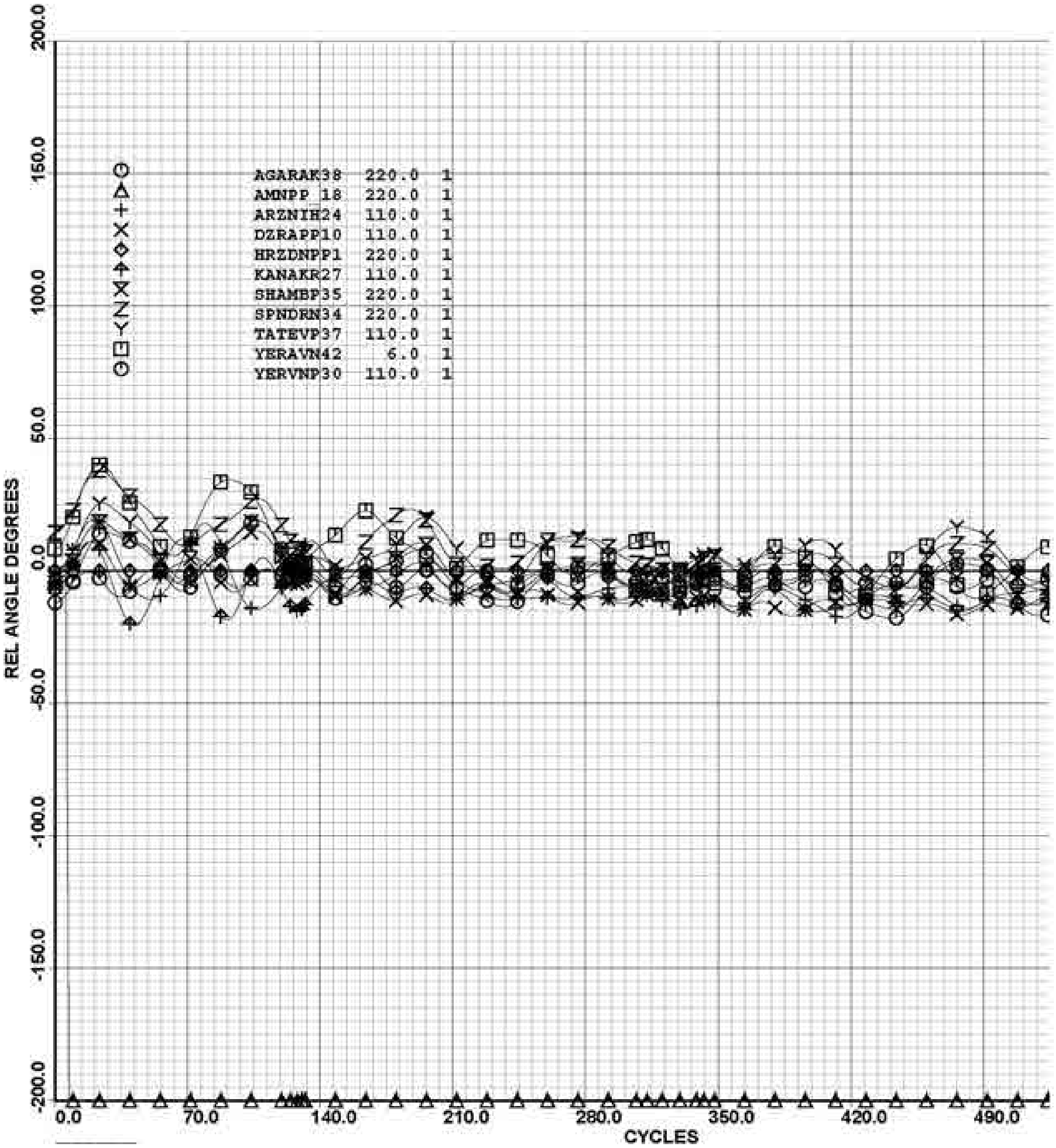

FIG. 61. Scenario-3a: real angle degrees of main generators of Armenian power system.

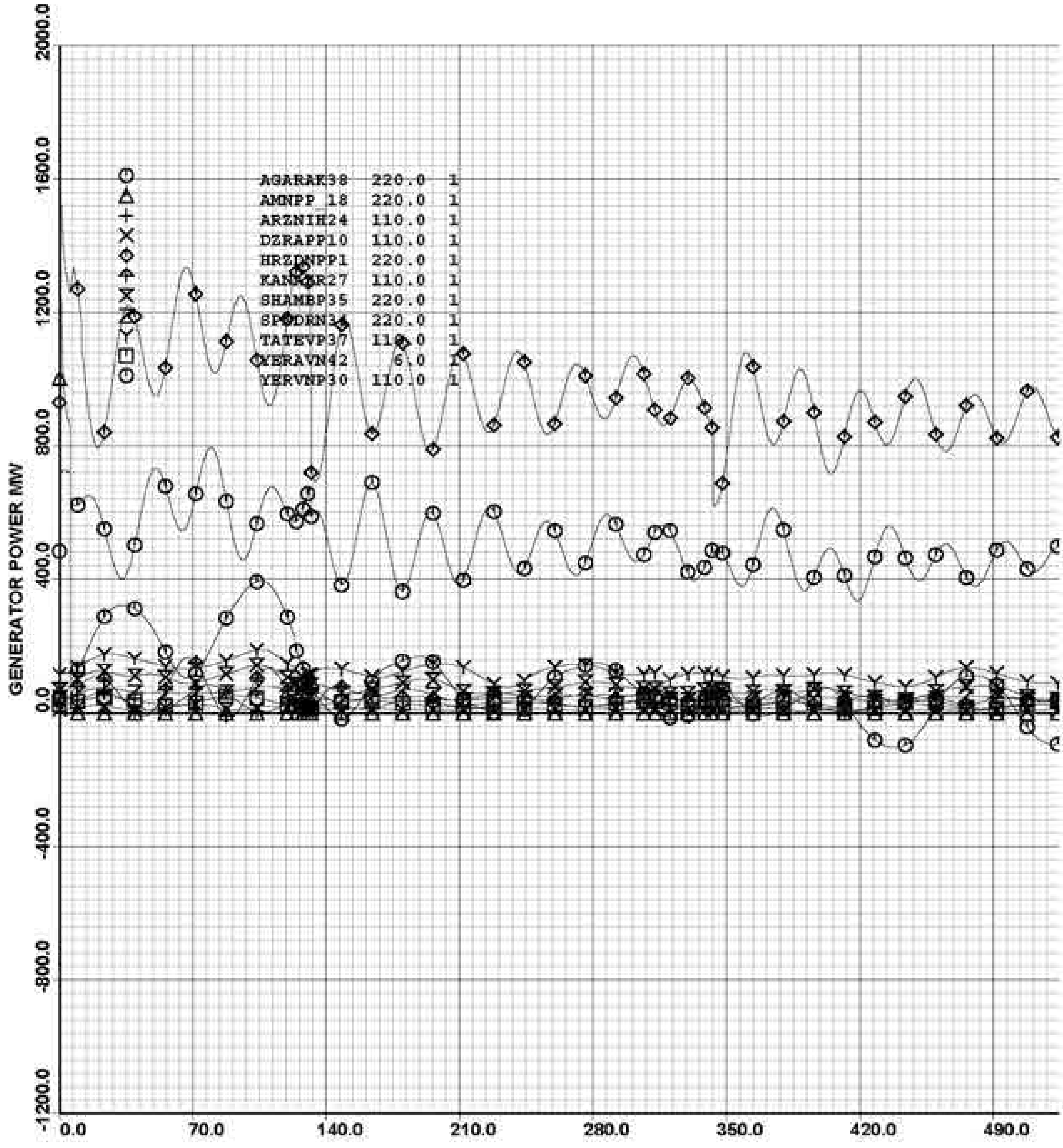

FIG. 62. Scenario-3a: active power of main generators of Armenian power system.

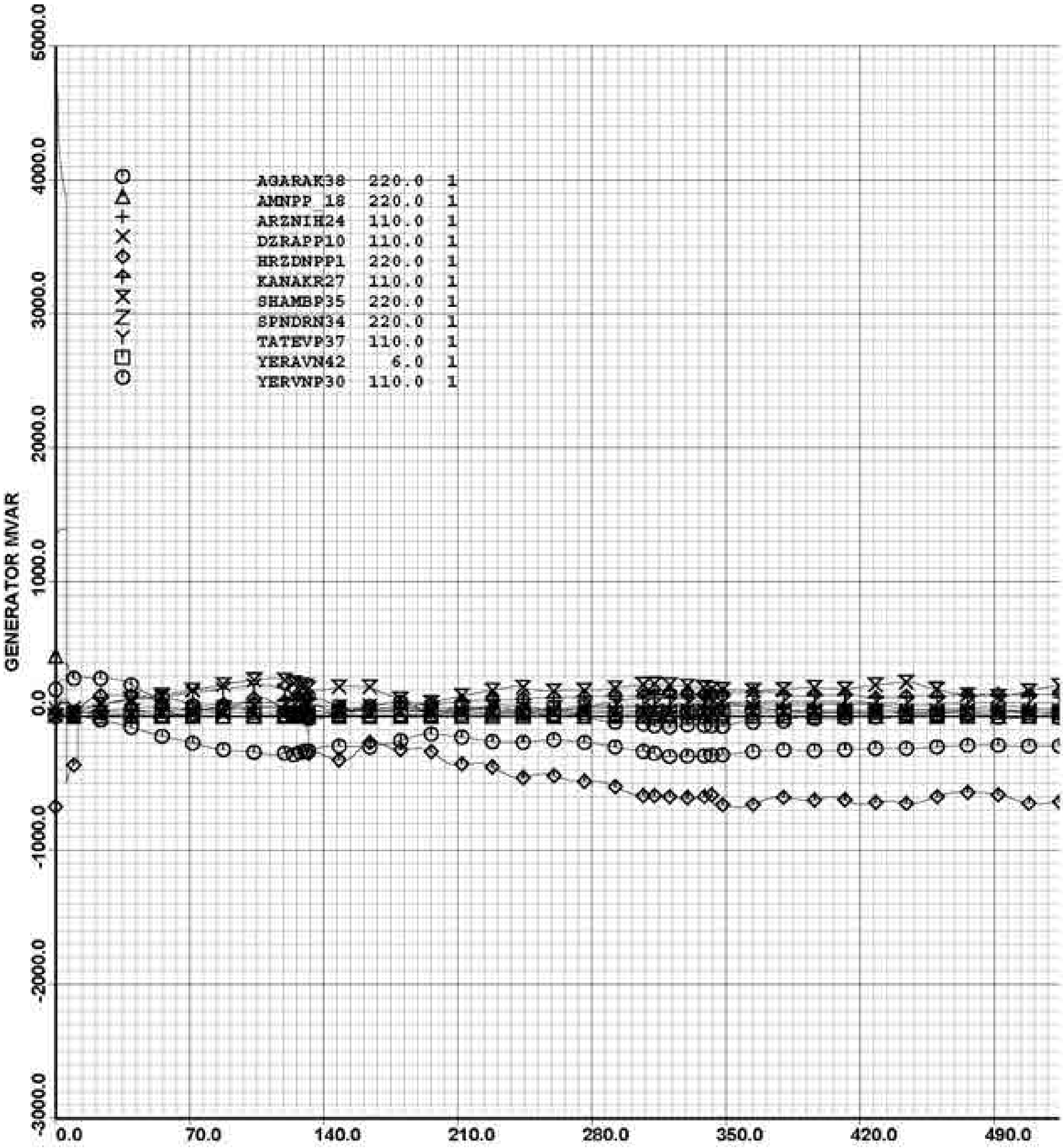

FIG. 63. Scenario-3a: reactive power of main generators of Armenian power system.

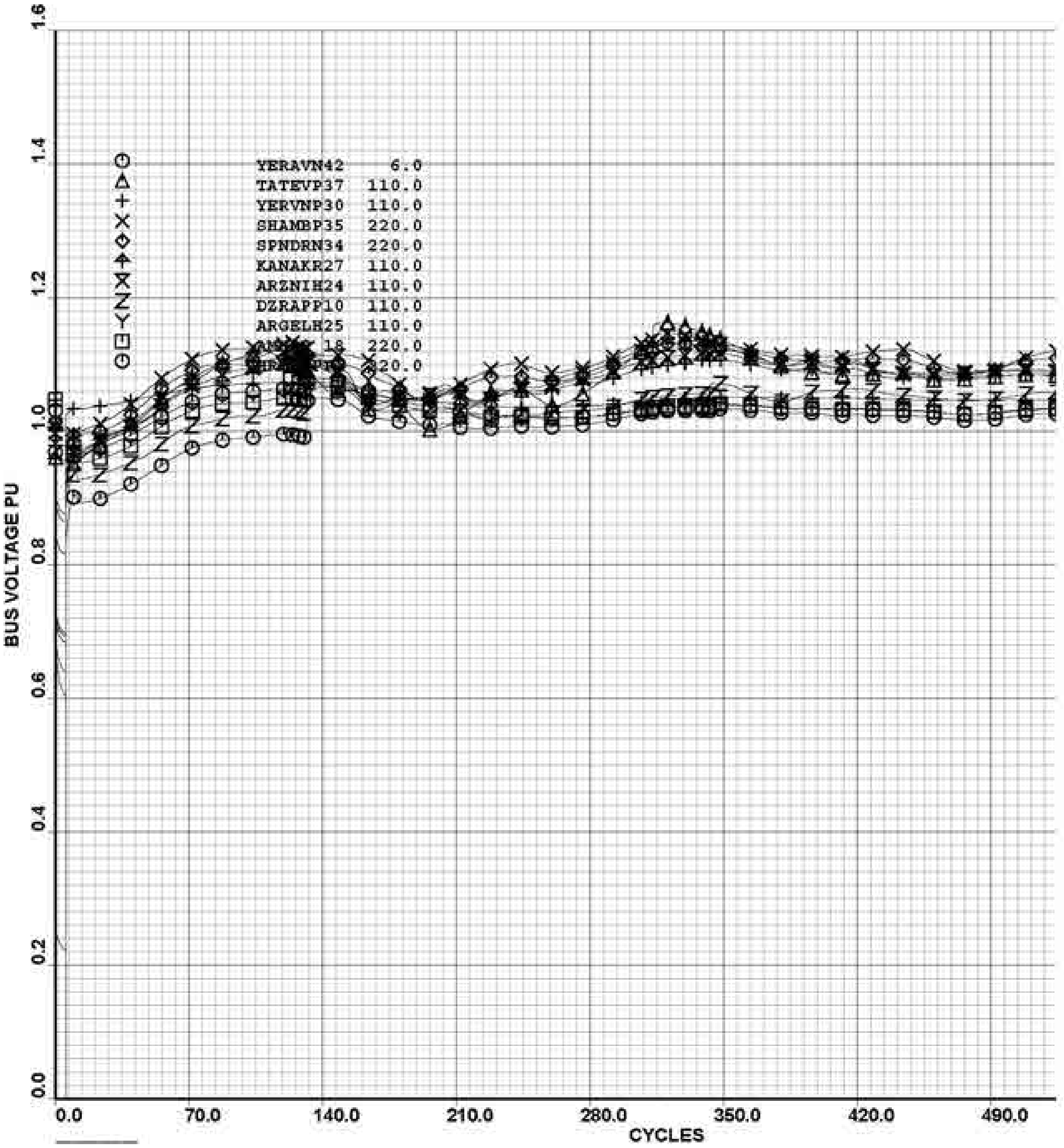

FIG. 64. Scenario-3a: voltages of the main generator buses of Armenian power system.

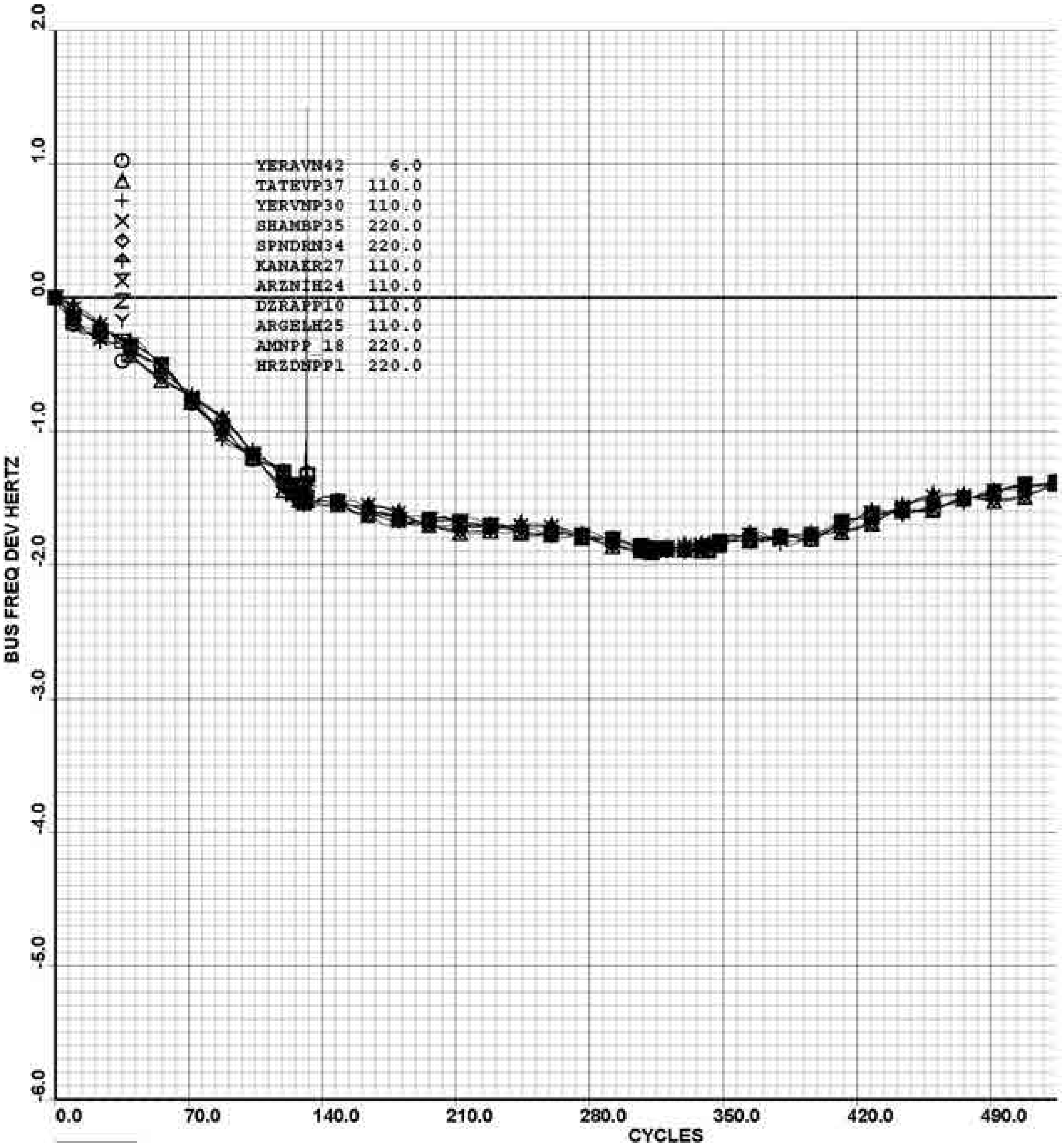

FIG. 65. Scenario-3a: frequencies of main generator nodes of Armenian power system.

Scenario-3b: 2035 Winter MAX short circuit on bus-bar of HVL-400 kV Tabriz with tripping HVL.

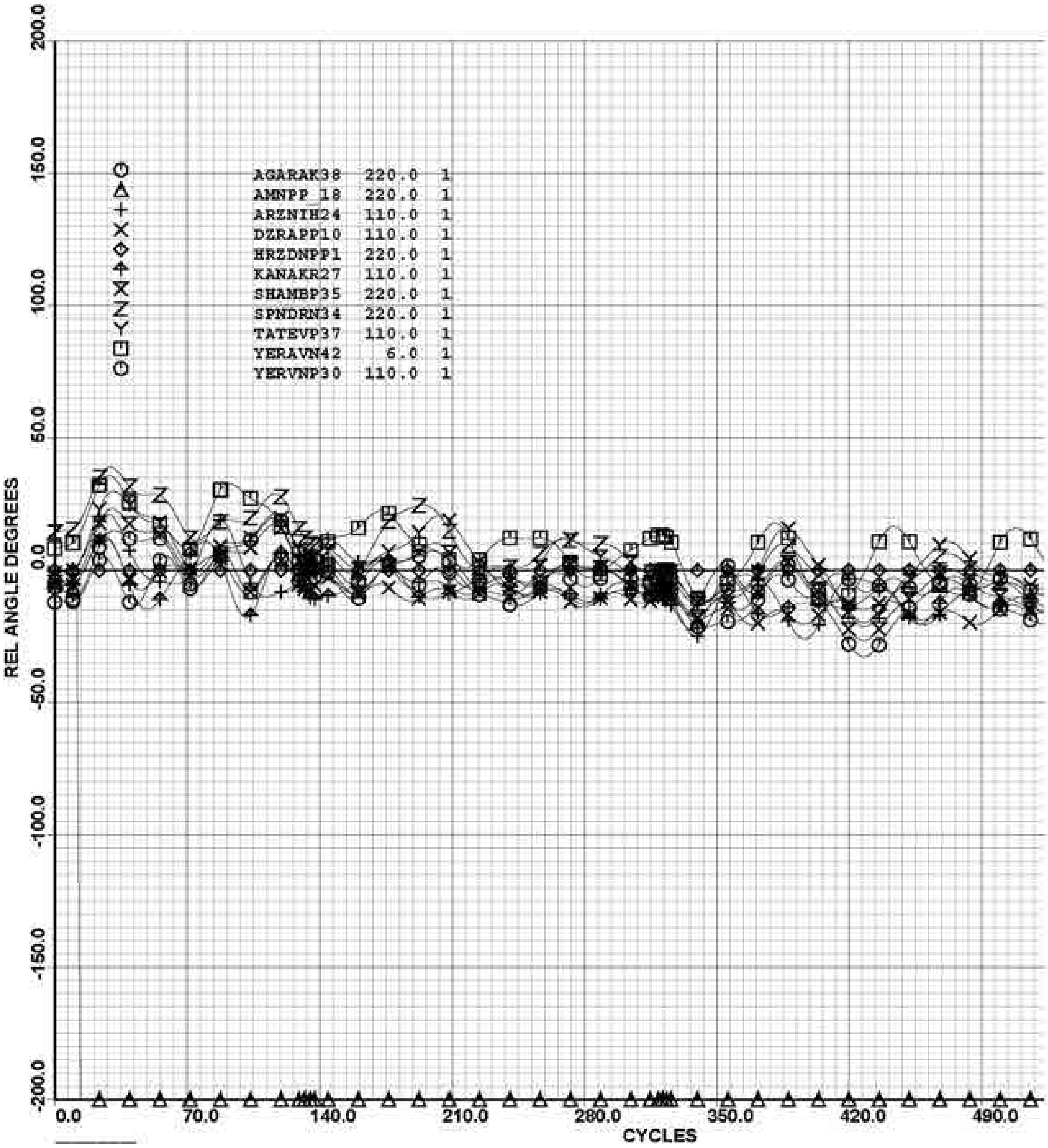

FIG. 66. Scenario-3b: real angle degrees of main generators of Armenian power system.

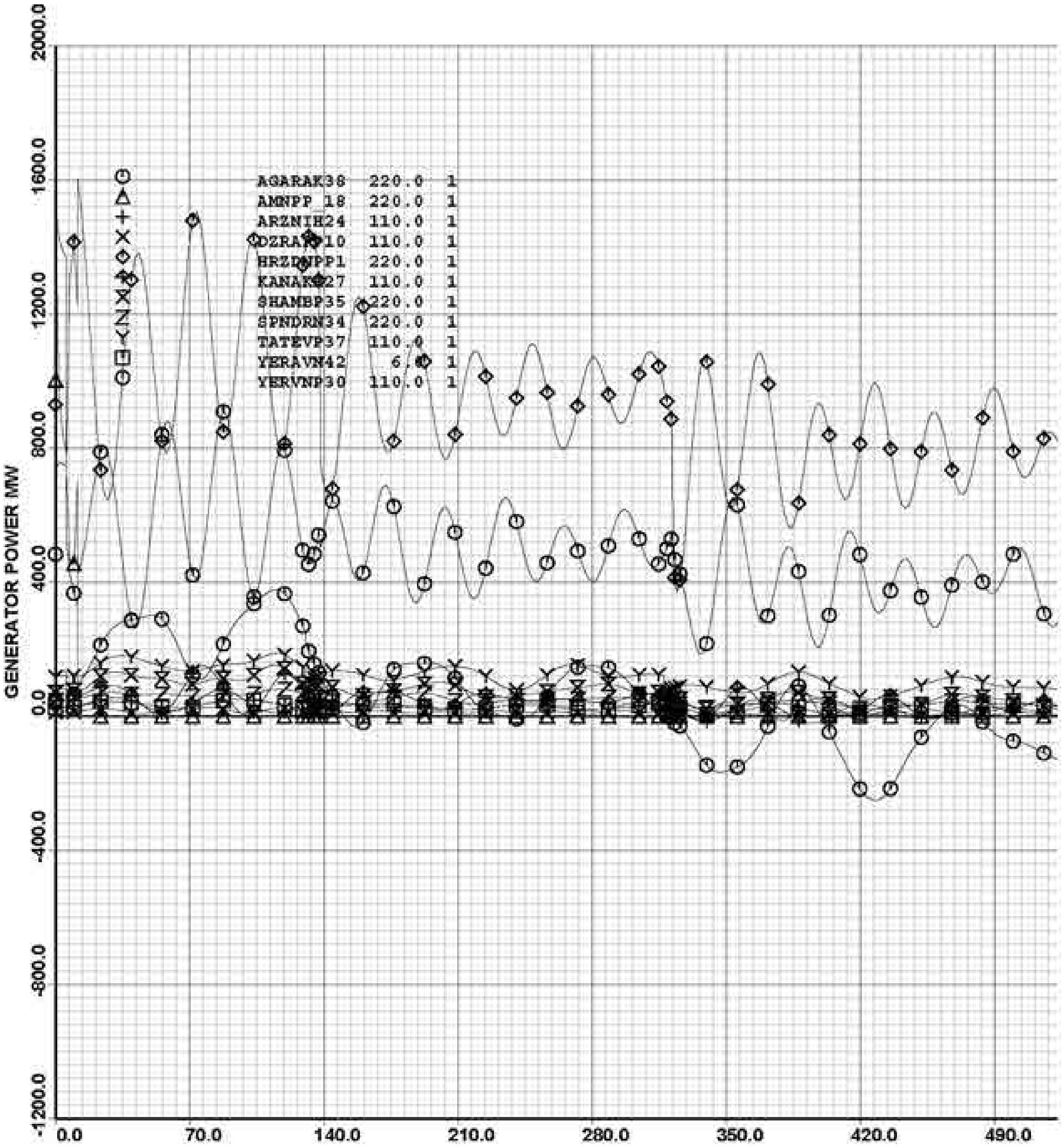

FIG. 67. Scenario-3b: active power of main generators of Armenian power system.

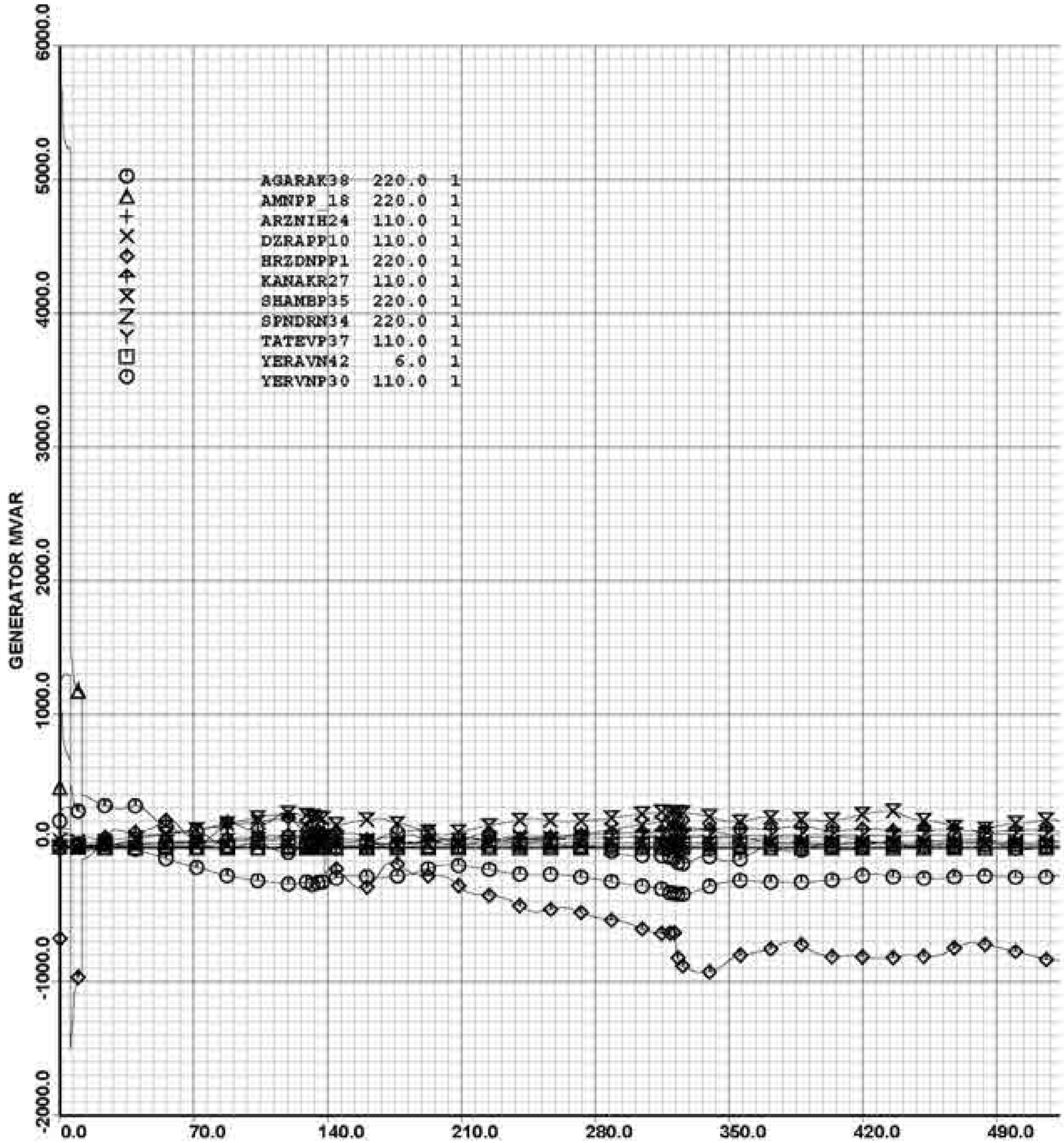

FIG. 68. Scenario-3b: reactive power of main generators of Armenian power system.

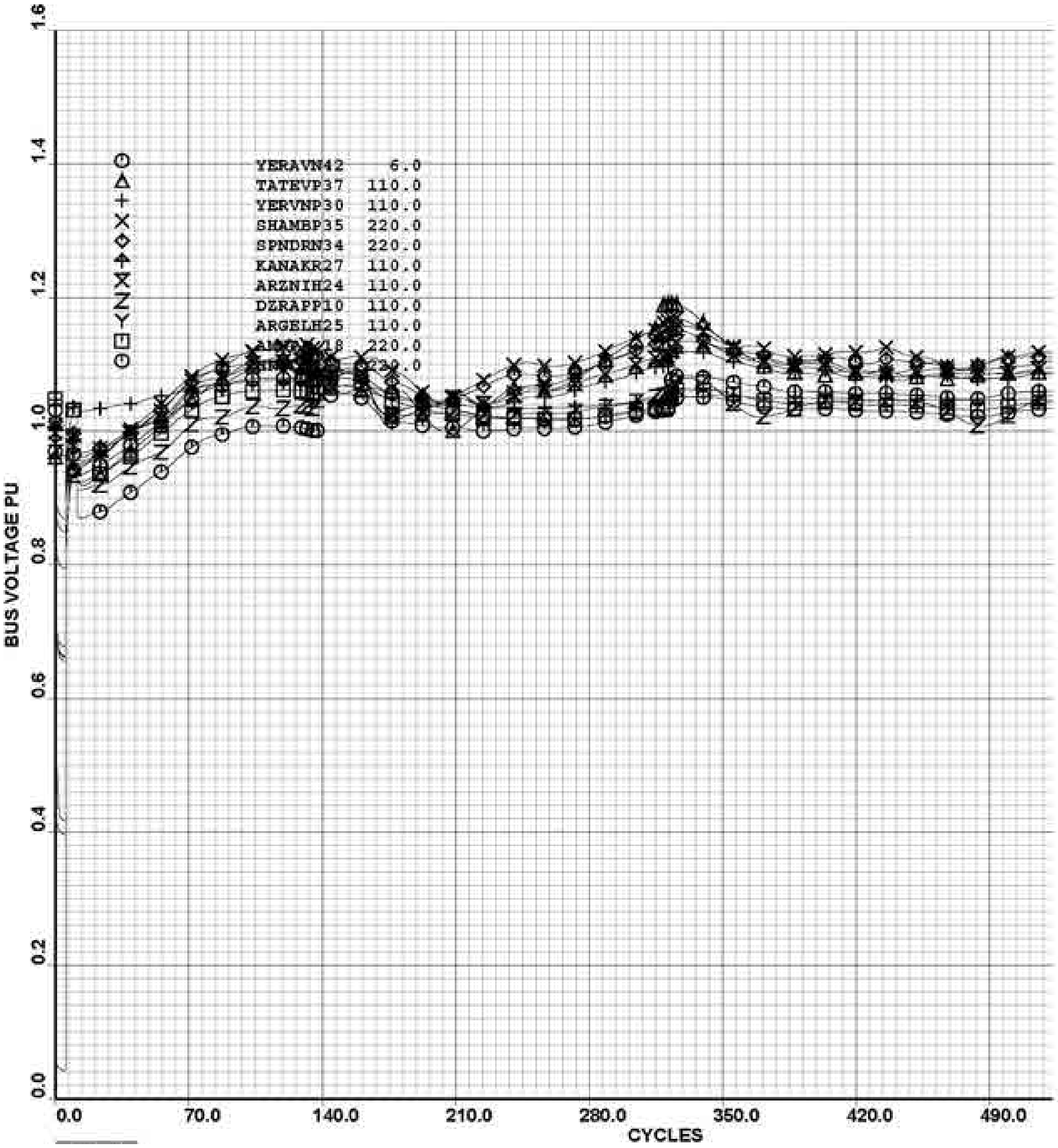

FIG. 69. Scenario-3b: voltages of main generator buses of Armenian power system.

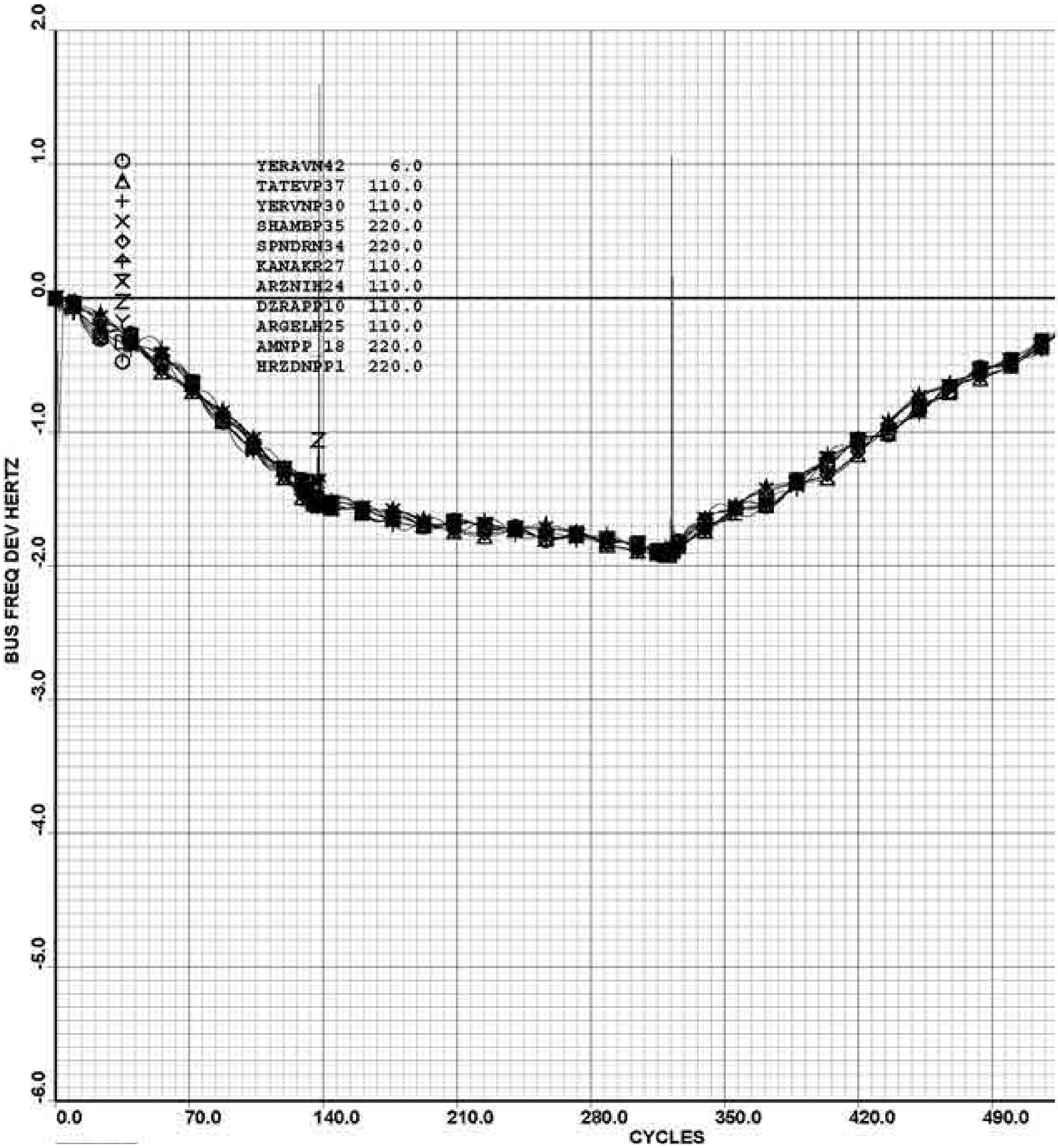

FIG. 70. Scenario-3b: frequencies of main generator nodes of Armenian power system.

Scenario-4a: 2035 Summer MIN short circuit on ANPP's bus-bar with tripping ANPP disconnection of HVL-400 kV Tabriz.

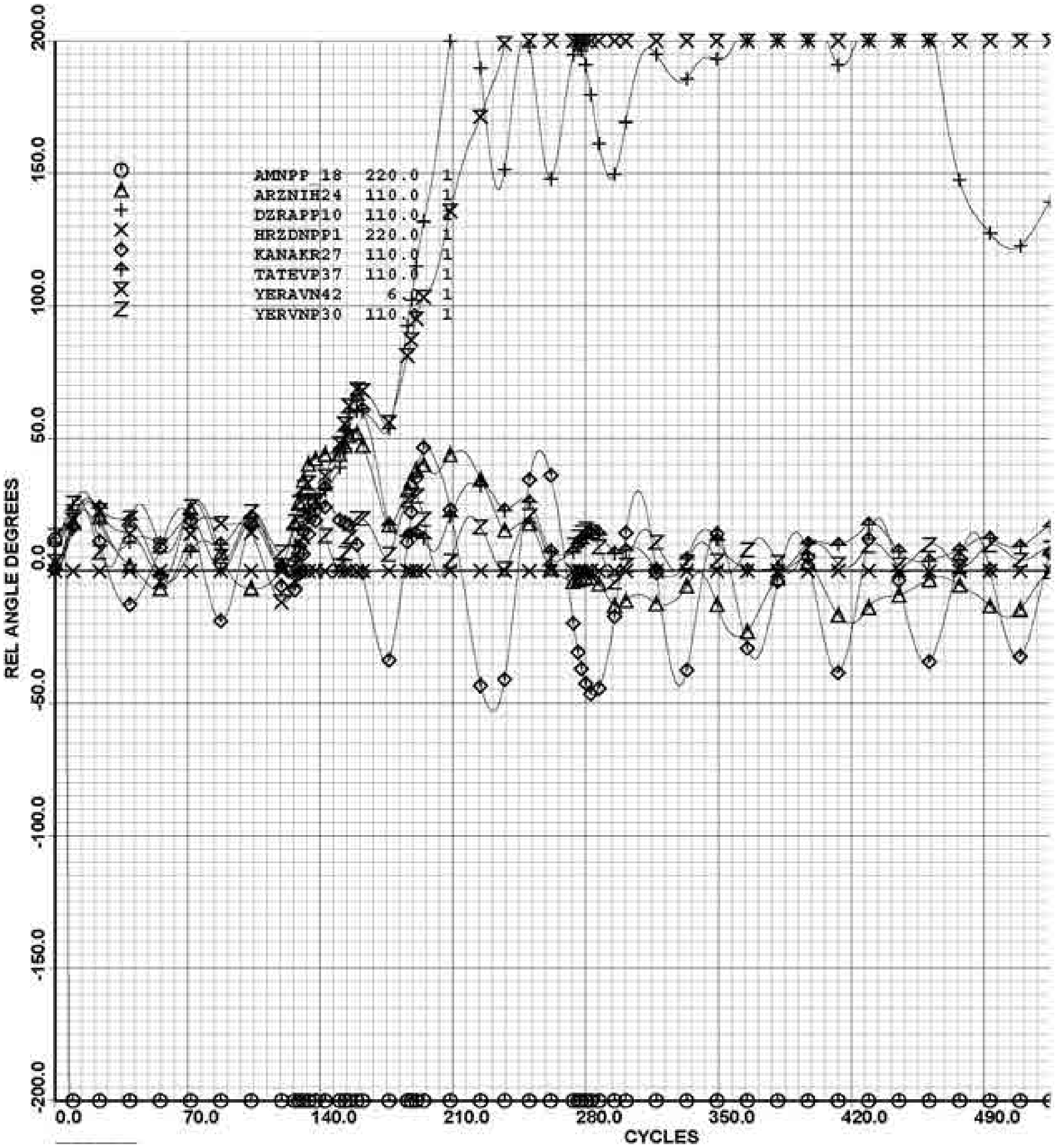

FIG. 71. Scenario-4a: real angle degrees of main generators of Armenian power system.

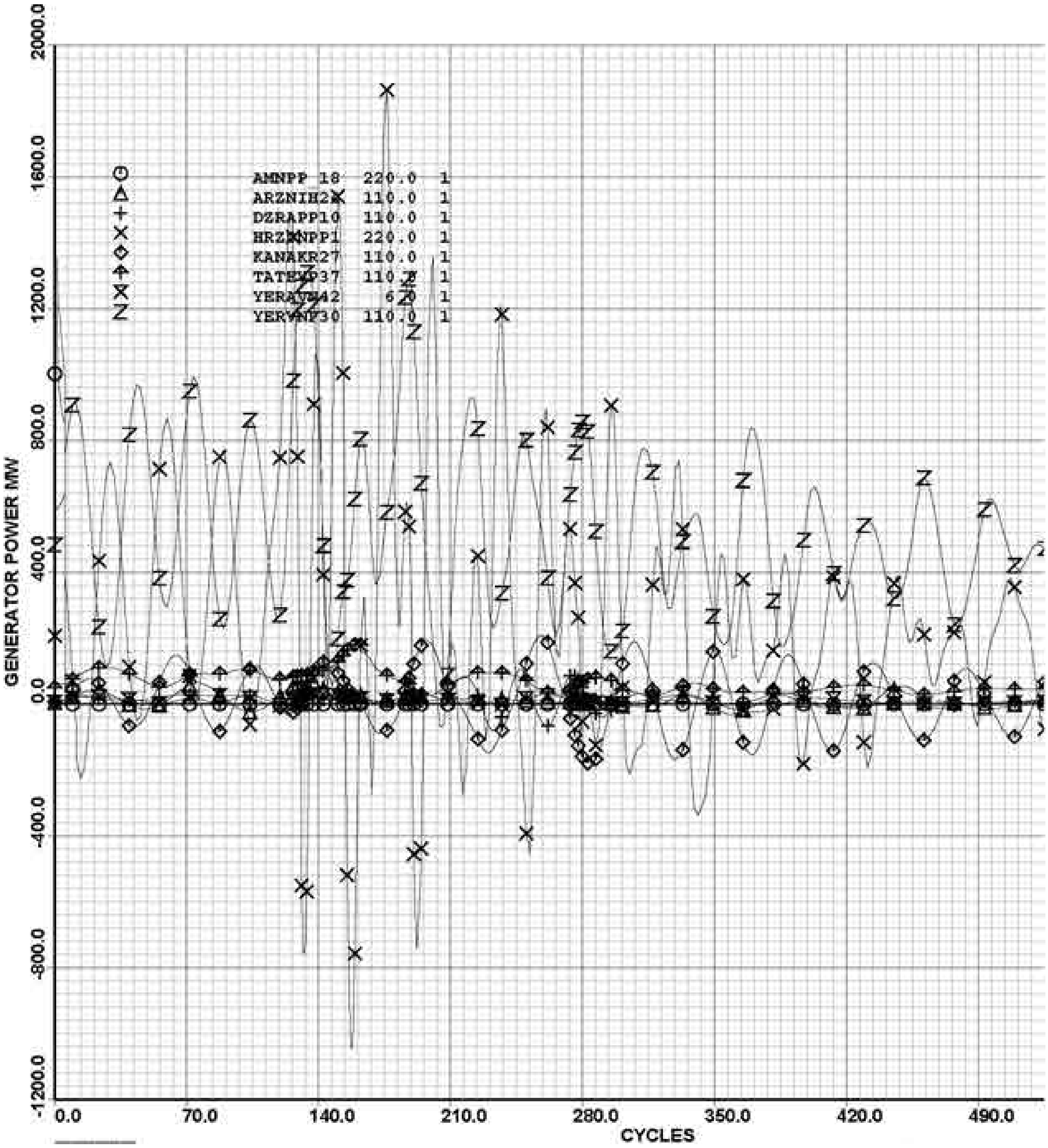

FIG. 72. Scenario-4a: active power of main generators of Armenian power system.

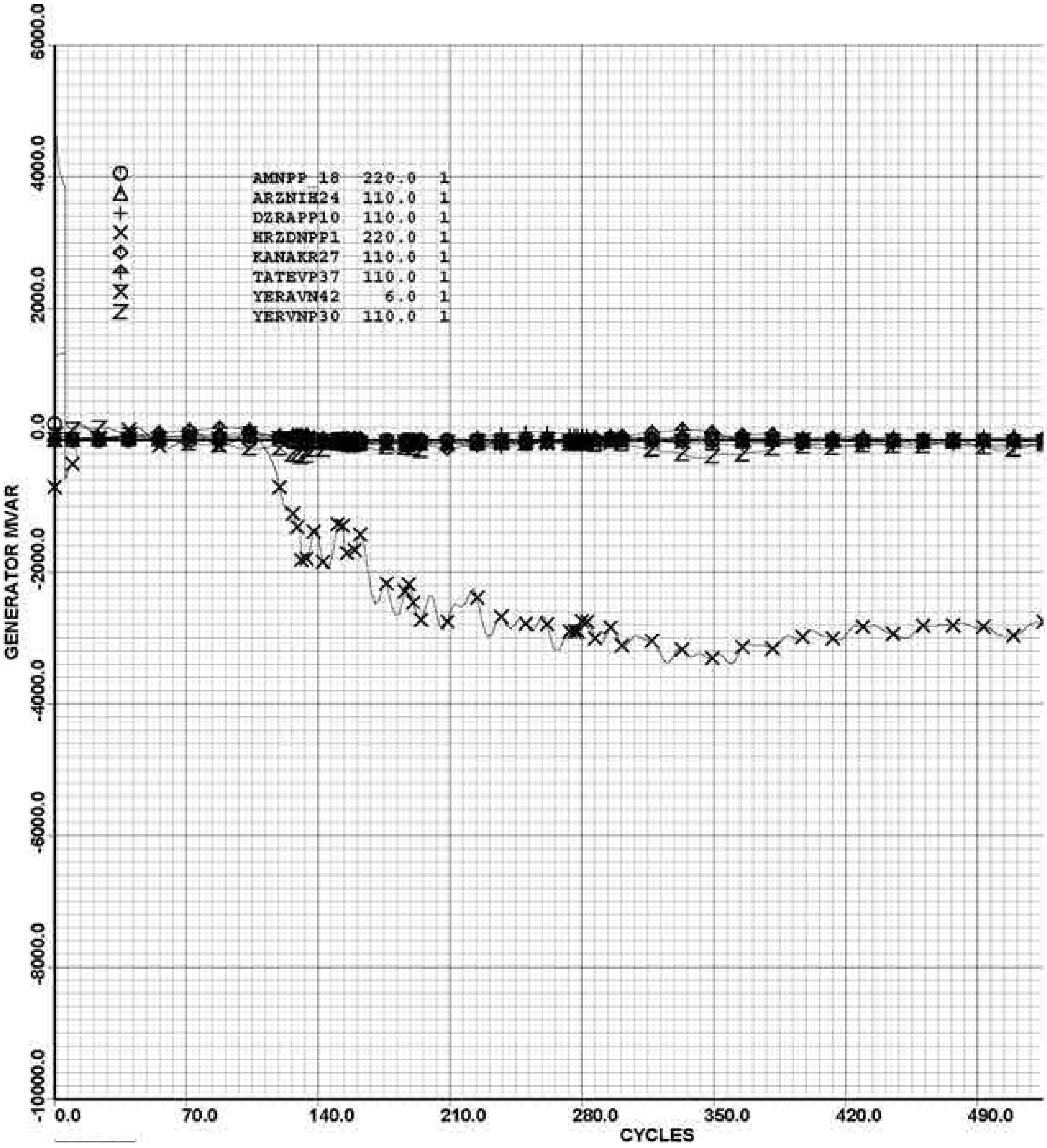

FIG. 73. Scenario-4a: reactive power of main generators of Armenian power system.

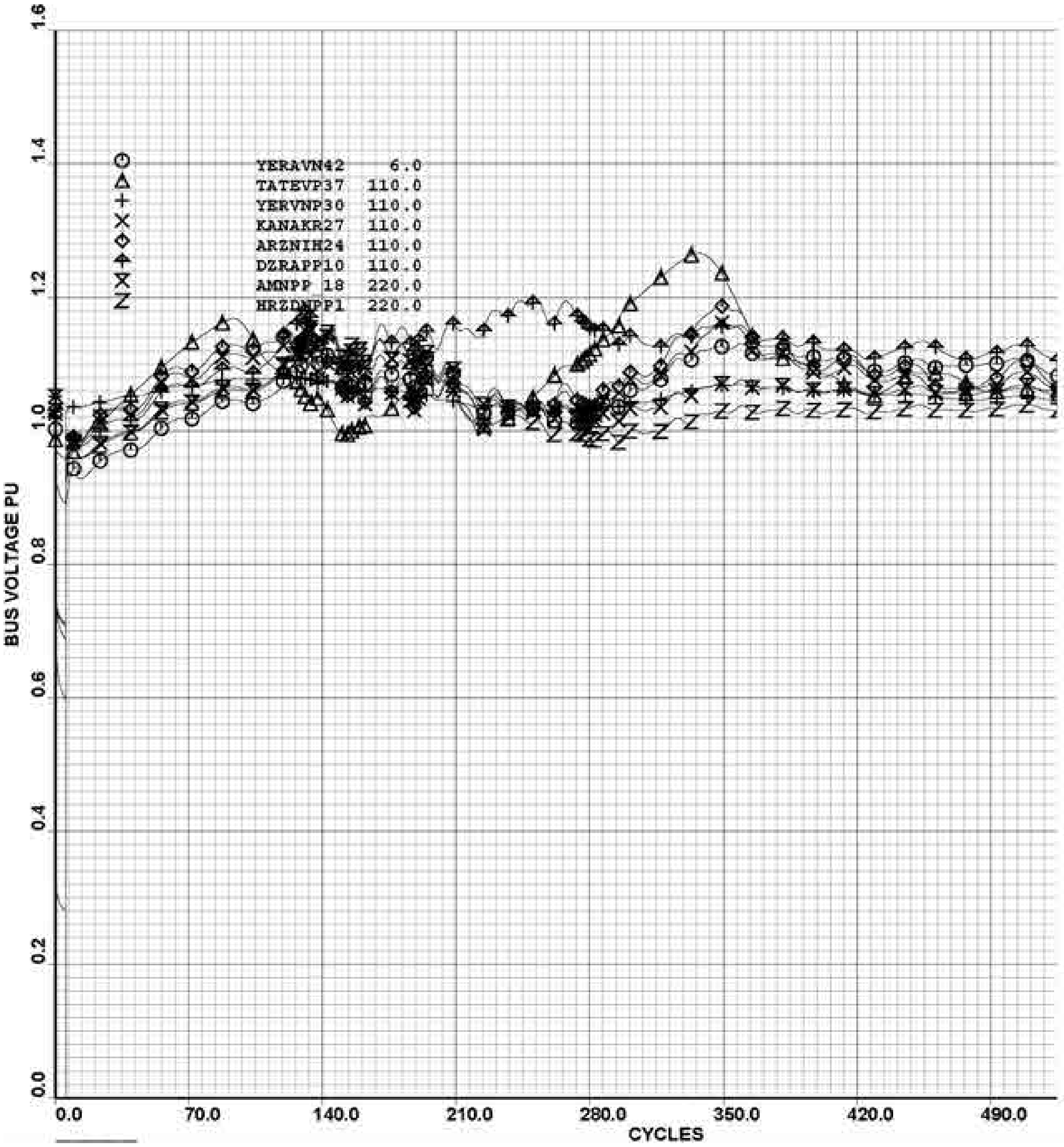

FIG. 74. Scenario-4a: voltages of main generator buses of Armenian power system.

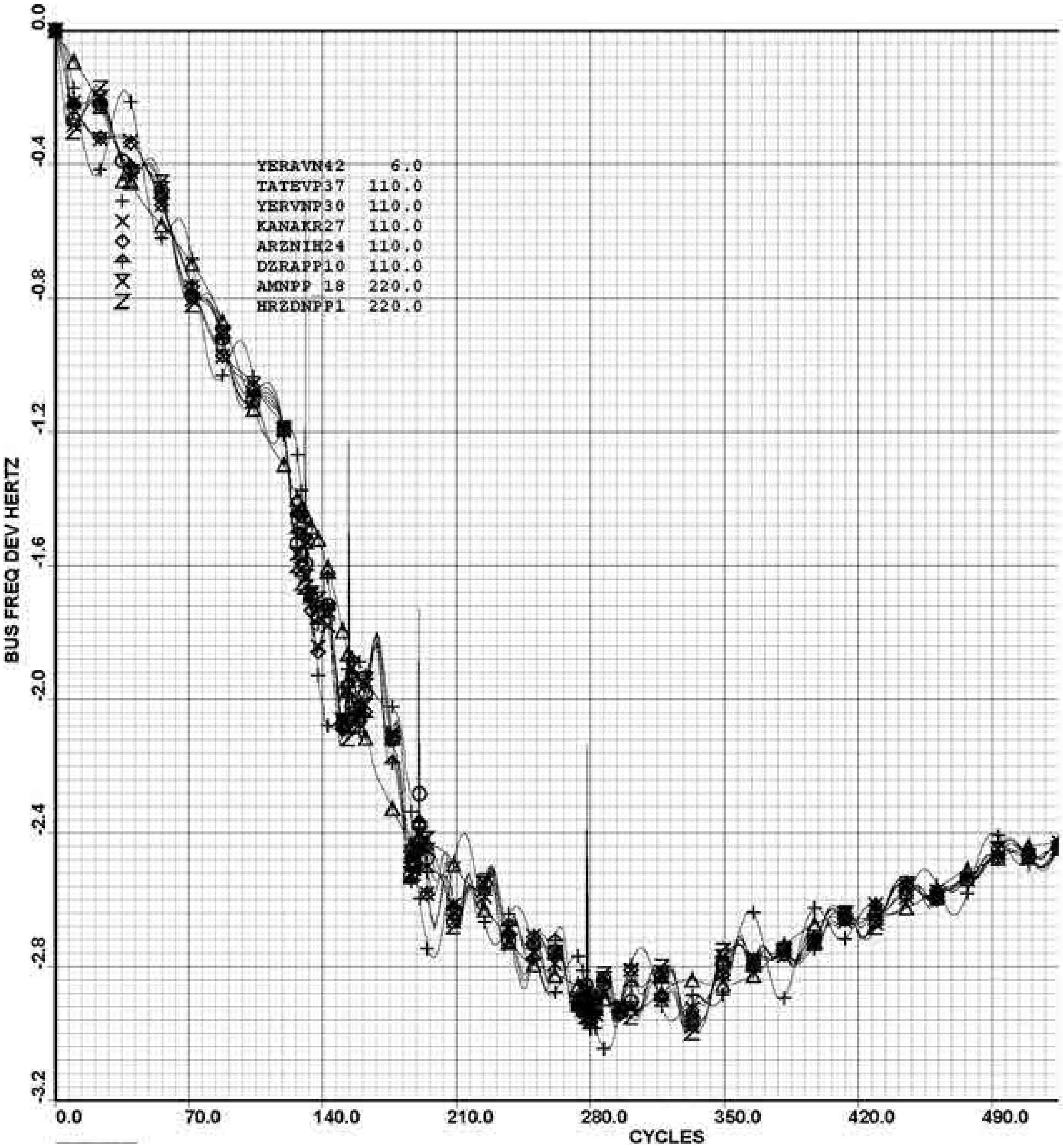

FIG. 75. Scenario-4a: frequencies of main generator nodes of Armenian power system.

Scenario-4b: **2035 Summer MIN short circuit on bus-bar of HVL-400 kV Tabriz with tripping HVL disconnection of ANPP.**

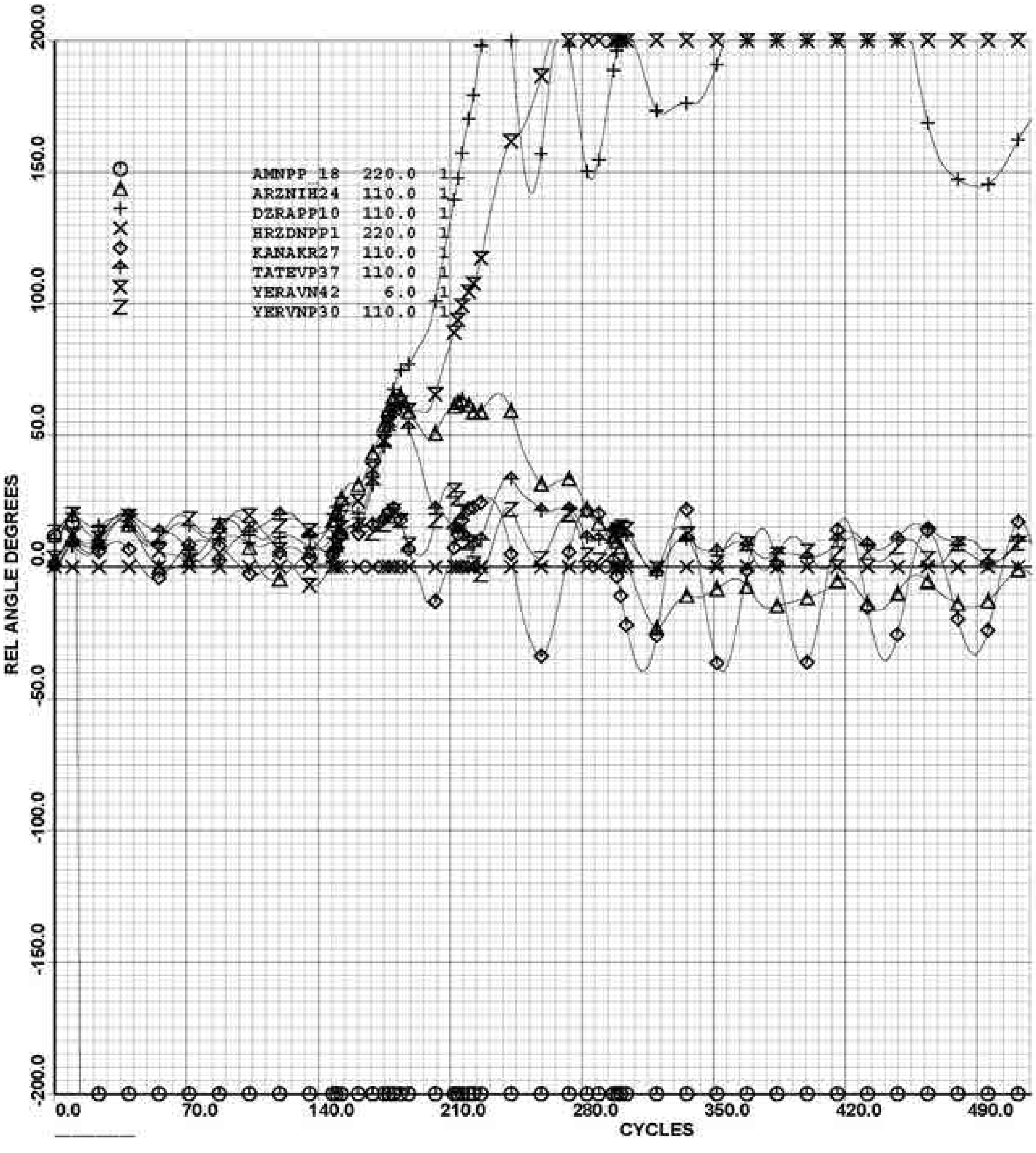

FIG. 76. Scenario-4b: real angle degrees of main generators of Armenian power system.

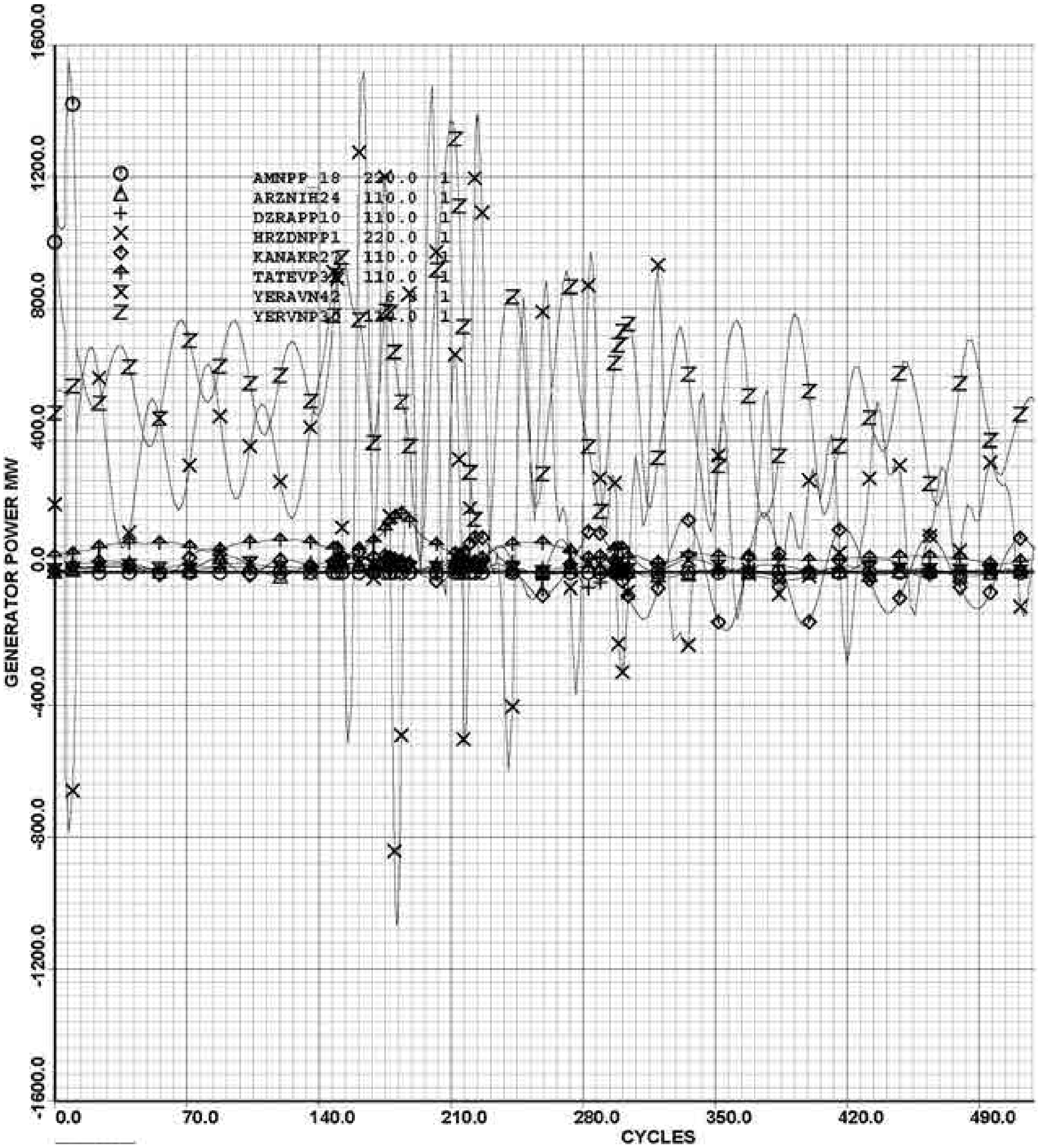

FIG. 77. Scenario-4b: active power of main generators of Armenian power system.

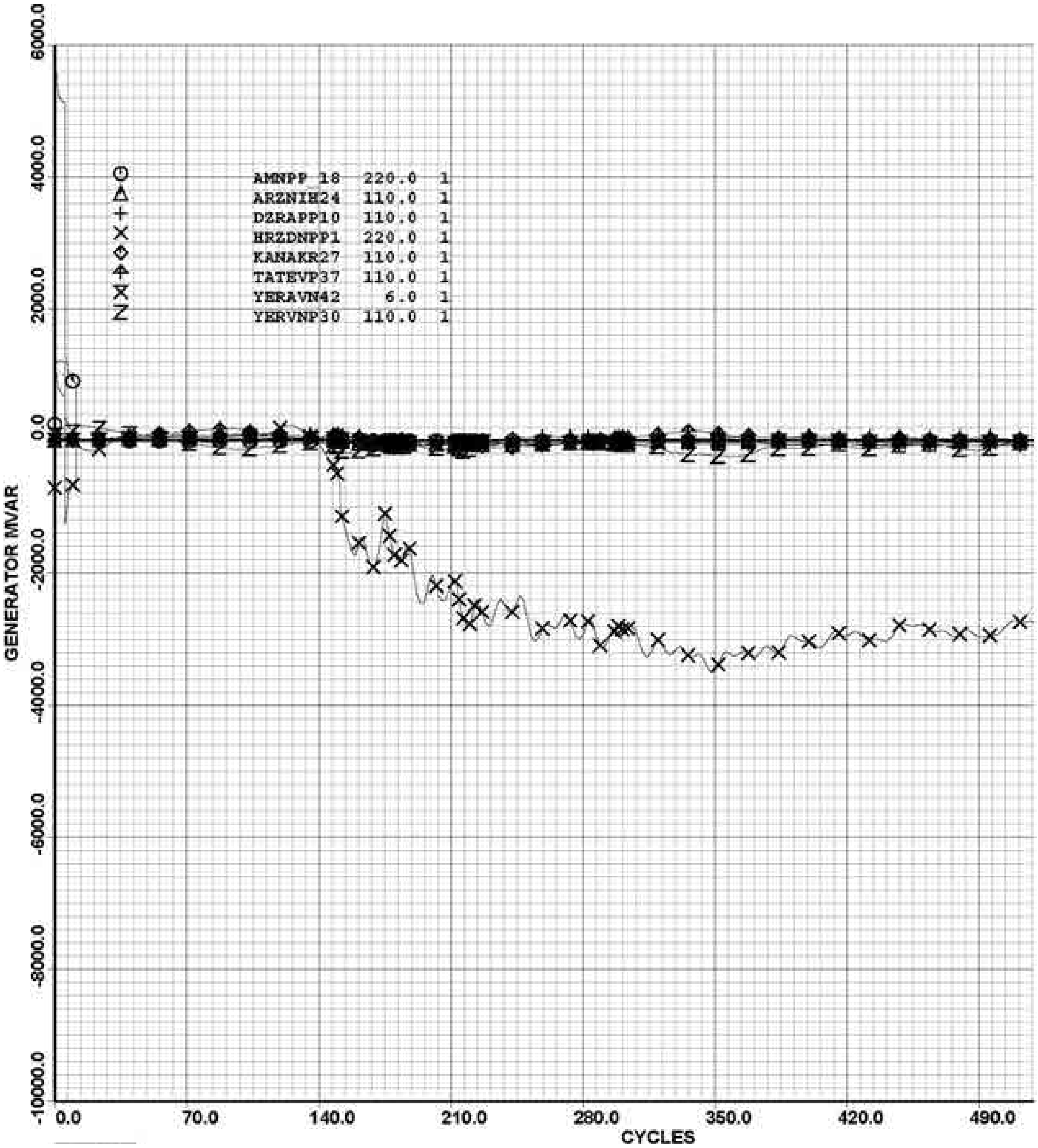

FIG. 78. Scenario 4b: reactive power of main generators of Armenian power system.

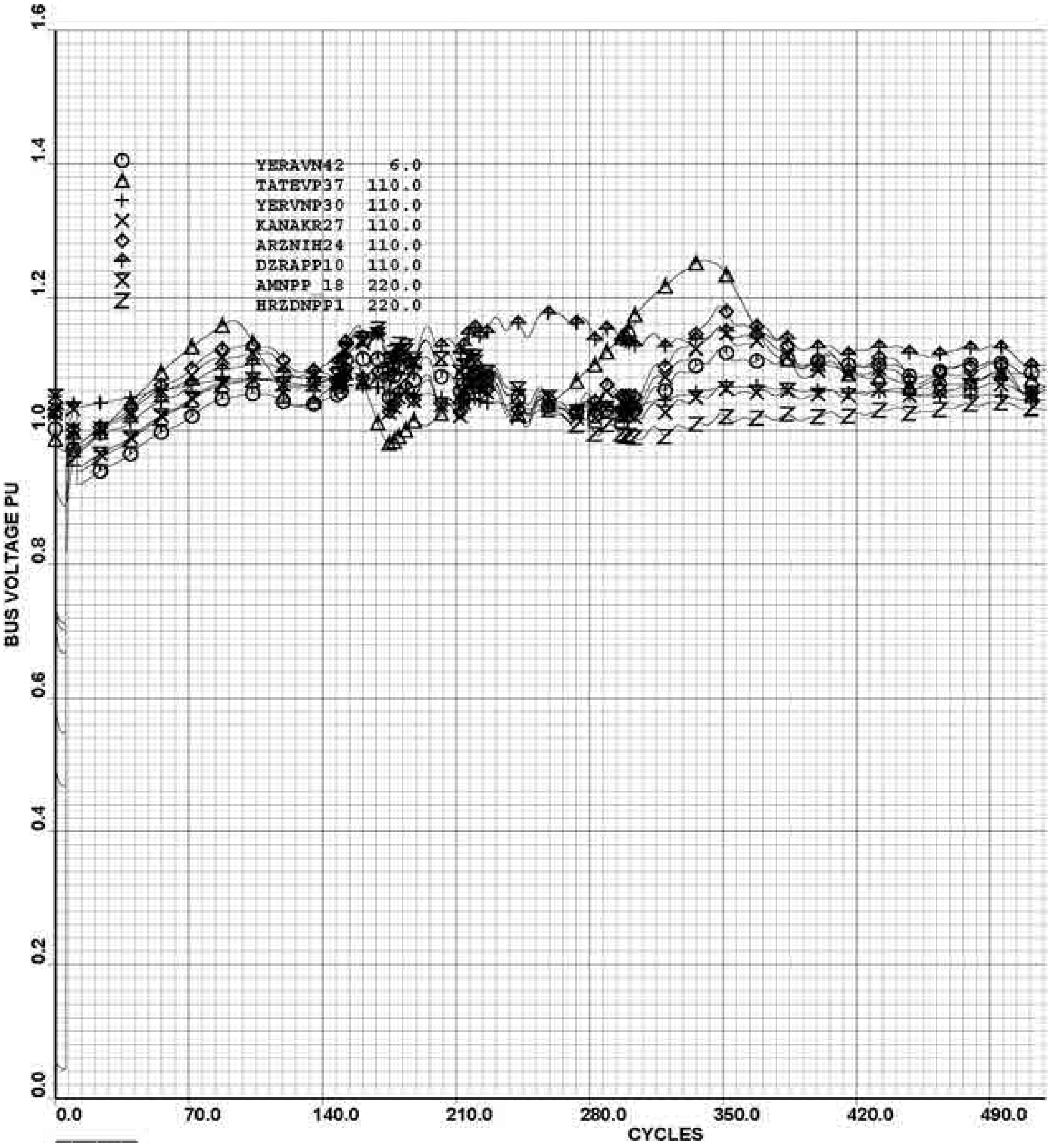

FIG. 79. Scenario-4b: voltages of main generator buses of Armenian power system.

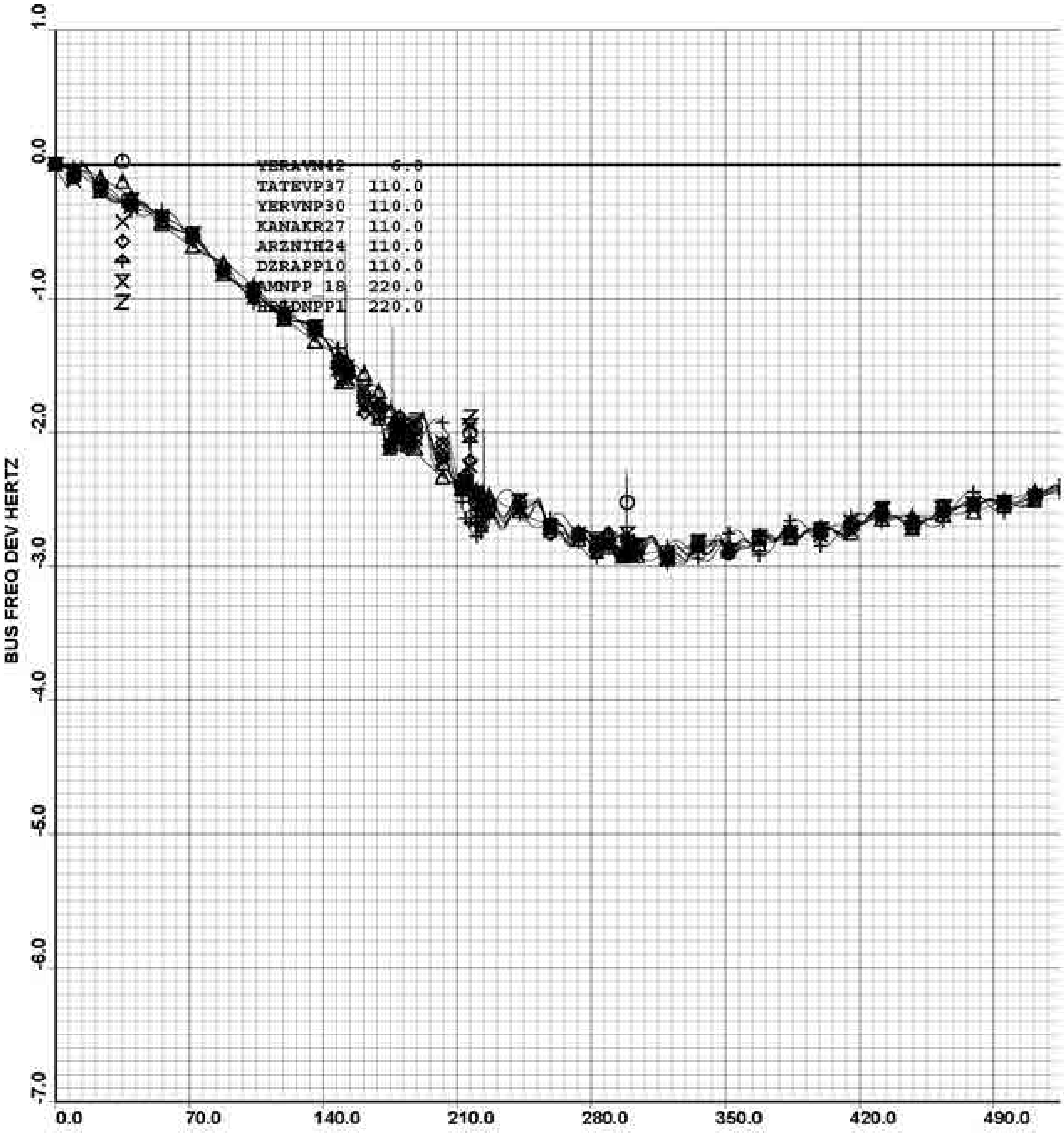

FIG. 80. Power plant frequency deviations in Scenario-4b.

APPENDIX II: SUGGESTIONS FOR INPRO METHODOLOGY IMPROVEMENT

II.1. INTRODUCTION

The use of reactors of commensurable power in a small electrical grid can be economically and ecologically expedient. However, the commensurability of nuclear units to the operating capacity of whole power systems necessitates special research on grid compatibility of the NES related to the reciprocal influence of emergency perturbations in the power system on parameters of operation of technological systems of the NES, and vice versa.

The safe and reliable operation of the power system means exclusion of large-scale system accident expansion. Such emergencies are accompanied by cutting off the significant part of consumers and power plants or by dividing the power system into synchronously working separate regions with the complete blackout of the areas linking them.

One of the most important criteria of reliable operation is the stability of the power system under dynamic disturbances. The indicator of system instability is unlimited increase in some part of the relative angles of generators which are oriented towards the chosen synchronously rotating axes.

In the power systems with large generation of electricity by NPPs, it is necessary to consider some features of NPP operation.

An NPP is considered safe if during its long operation under all conditions, including emergency, serious damage to the fuel rods in the reactor core is excluded; and localization of radioactive emissions and appropriate protection of NPP personnel, the neighbouring population and the environment from radiation effects is ensured.

Emergency perturbations in the power system can directly result in emergency regimes of NPP operation, such as:

– Accompanying reduction of coolant water flow, and of feed- and make-up water;
– Cut-off of the NPP auxiliaries;
– Operation under unexpected dumping and increasing of an electrical load;
– Also during other emergency situations at the power unit which depend on the work conditions of power system.

In this case, the safe operation criterion for such a power system should be not only the stability of accident- and after-accident regimes, but also keeping the basic technological parameters of the NPP within admissible limits.

Reducing system frequency and voltage on bus bars of an NPP means a diminution of drive turnover of NPP auxiliaries and, as a result, reduction of the main circulating pump and water feeding pump capability.

When the frequency and voltage in a system are reduced, two factors should be paid attention to, which can cause the scram of the unit or the reduction of its powerby the I&C systems. These factors will further aggravate the emergency situation in the power system:

– Lowering of the coolant flow-rate and, as a result, its temperature increase down to the emergency level on the output of the reactor can cause emergency protection actuation and reactor capacity reduction;
– Decreasing the water level in a steam generator when both the frequency and voltage fall low and long enough can cause steam generator emergency protection actuation and reactor scram.

Thereby the important controlled parameters of the NPP are the coolant flow, feed water flow-rate, steam generator steam pressure, and temperature differences in the reactor core.

Therefore, the outcome of the special study should be taken into consideration and reflected in the NES assessment studies using the INPRO methodology [12].

On the basis of the aforesaid and of the calculation results given in Section 8, and also of the experience gained for more than 30 years of ANPP operation in the Armenian electrical grid, it is suggested to improve the UR2 Industrial and economic infrastructure: "*The industrial and economic infrastructure of a country planning to install an INS installation should be adequate to support the project throughout the complete lifetime of the nuclear power programme, including planning, construction, operation, decommissioning and related waste management activities*" of the INPRO methodology in the area of Infrastructure by including the additional Criterion 2.6: grid compatibility.

The proposed criterion with its indicator, acceptance limit and evaluation parameters could read as follows:

II.2 CRITERION CR2.6: GRID COMPATIBILITY

Indicator IN2.6: *INS adequate response to steady state and transient regimes of power grid.*

Acceptance limit AL2.61: *matches local grid operational characteristics requirements.*

Assumed to have been defined in the NPP grid connection study.

Acceptance limit AL2.6.2: *matches INS operational characteristics requirements.*

Assumed to have been defined in the NPP grid connection study.

II.2.1. Evaluation parameter EP2.6.1: power grid requirements

The requirement parameters proposed for the grid are:

– Dynamic stability (relative angles of generators, which are oriented towards the chosen synchronously rotating axes);
– Power system frequency changing level.

II.2.2. Evaluation parameter EP2.6.2: INS requirements

The requirement parameters proposed for the NES (in case of WWER type reactors) are:

– Neutron power of the reactor facility;
– Electrical capacity of the main circulation pumps;
– Steam pressure in the steam generator;
– Input and output temperature differences in the reactor core.

II.3. CONCLUSION

These criteria allow the problems of influence of power system emergencies on the reactor operation parameters to be analysed. Such research allows judgement of the perspectives of operation of NES within a small power grid from the viewpoint of ensuring reliable and safe operation of such NES in power system emergency disturbances.

APPENDIX III:
OVERVIEW OF WWER-1000 SYSTEMS AND OPERATION

III.1. PLANT OVERVIEW

A WWER is similar to a PWR type reactor. The number following the reactor type usually indicates the rated power of the unit. Thus, WWER-1000 designates a unit with 1000 MW electrical power.

Heat that is generated in the reactor core from the fission of nuclei in the fuel is removed by the coolant (for an NPP with a WWER, the coolant is water or a water-steam mixture). After leaving the reactor core, the coolant is transported along the part of the primary circulation circuit called ‘hot leg’ to the steam generator.

The steam generator is a heat exchanger in which the heat from the primary circuit coolant transfers to the feed water of the secondary circuit to form steam.

After the steam generator, the coolant is transported along the part of primary circulation circuit called the ‘cold leg’ back to the reactor vessel.

There are four circulation loops in the primary circuit of an NPP with a WWER-1000 reactor. The coolant is pumped by four main circulation pumps, one installed in each loop.

In the secondary circuit, steam formed in the steam generators is transported to the ‘balance of plant systems.’ Most of the steam formed in the steam generators is sent to the turbine, with a much smaller part to the feed water heating.

After the turbine, steam is dumped to the condenser and condensed. From the condenser the water is transported through the low pressure heaters to the de-aerator for removal of non-condensable gases. From the de-aerator, feed water is transported through high pressure heaters to the steam generator.

III.2 NUCLEAR STEAM SUPPLY SYSTEM

The main systems of the NPP with a WWER-1000 reactor are the:

– Reactor;
– Primary circuit: main circulation pipelines, main circulation pumps (MCPs), steam generators;
– Pressurizer and primary circuit pressure compensating system;
– Primary circuit feed and bleed system, including boron regulation;
– Secondary circuit steam lines and feed water pipelines;
– Control and protection system (CPS);
– Safety systems.

III.2.1. Reactor

The WWER-1000 reactor is a vessel-type light water reactor where chemically purified water with boric acid serves as coolant and moderator. The reactor is intended for generation of heat within the NPP nuclear steam supply system. Regulation of reactor power and suppression of the fission chain reaction is carried out by two systems adjusting reactivity, which are based on different principles:

– Introducing solid absorbers — control rod system;
– Injection of liquid absorber — boron regulating system.

Control rods are used for changing reactivity in manoeuvring regimes and for reactor shutdown in normal and emergency operation conditions. Boron regulation is used for slow changes in reactivity. The boron concentration is changed during the life cycle.

The coolant is heated while it flows in fuel assemblies due to the energy of nuclear fission in the fuel. The coolant enters the reactor through inlet nozzles, passes a ring gap between the reactor vessel and the core well and, through a perforated bottom plate, enters the fuel assemblies installed in the reactor core. The coolant then passes through the perforated plate, enters the inter-tube space of the protection tubes block, then goes to the ring gap between the core well and the vessel and, through outlet nozzles, exits the reactor vessel to the hot leg.

The reactor includes the:

– Core;
– Reactor vessel;
– Core internals and upper block;
– Step-type electromagnetic control rod drive machines;
– Neutron flux measuring instrumentation.

III.2.2. Reactor core

The WWER-1000 core is composed of hexagonal fuel assemblies and is located on a hexagonal grid with constant pitch of about 236 mm. The number of fuel assemblies in the core depends on their size and the reactor rated power. The maximum size of a fuel assembly is limited by nuclear safety requirements in order to eliminate the possibility of critical mass occurrence, and the minimum size of the fuel assembly is limited by cost efficiency.

The WWER-1000 reactor core major characteristics are as follows:

– Total number of fuel assemblies in the core	163;
– Number of fuel assemblies with control rods	61;
– Height of heating part (in cold state)	3.53 m;
– Pitch between fuel assemblies	0.236 m;
– Pass section of the core in the heating part	4.17 m^2;
– Coolant flow rate through the core	17 650 kg/s;
– Reactor thermal power	3000 MW.

The fuel assembly for the WWER-1000 consists of a regular grid of fuel rods. In certain positions, fuel rods are replaced with non-fuel elements, e.g. absorbing elements of control rods (total of 18) or rods with burnable absorbers.

The WWER-1000 fuel assembly major characteristics are as follows:

– Number of fuel rods	312;
– Pitch between fuel rods	12.75 mm;
– Number of tubes for absorber elements	18;
– Length of fuel assembly active part	3530 mm;
– Number of distant grids (support plates)	14.

WWER-1000 fuel pin major characteristics are as follows:

– Fuel pin diameter	9.1 mm;
– Cladding thickness	0.69 mm;
– Cladding material	alloy — Zr110;
– Fuel part diameter	7.53 mm;

– Fuel material UO_2;
– Diameter of central aperture in fuel pellet 2.3 mm;
– Fuel density 10.4 g/cm^3;
– Enrichment of feeding fuel 3.3, 4.4, 3.0 and 4.0 %.

III.2.3. Main circulation pumps

The four MCPs are vertical centrifugal pumps with mechanical shaft seals. Each pump is driven by a vertical air-water cooled electric motor.

The MCP rotating part has significant rotation inertia and in case of loss of motor power, the rate of coolant flow decrease matches the reactor power rundown caused by a reactor trip. After the MCP has stopped completely, natural circulation maintains core cooling.

III.2.4. Steam generators

The steam generator is intended for heat removal from primary circuit coolant and forming saturated steam in the secondary circuit. Steam generators at NPP with WWER-1000 reactors are of the horizontal type. Primary side coolant goes via horizontal tube bundles, above the steam generator there is a steam collector. Through this collector, steam formed in the steam generator goes to the main steam header and then to the turbine.

While operated under normal conditions at rated power the following parameters are maintained in the steam generators:

– Pressure in steam generator (6.27+0.19) MPa;
– Temperature of feed water (220+5) °C;
– Water level (320+50) mm;
– Steam humidity at steam generators outlet not more than 0.2%.

III.2.5. Pressure compensation system

The principal objective of pressure compensation in WWER reactors is to keep the primary circuit coolant in a liquid state.

The pressure compensation system is intended for:

– Primary circuit pressure control during steady state and transients;
– Prevention of primary circuit equipment from exceeding the design base pressure;
– Increasing primary circuit pressure during startup of the nuclear steam supply system;
– Decreasing primary circuit pressure during cool down of the nuclear steam supply system.

The equipment included in the pressure compensation system is:

– Pressurizer;
– Bubbler-condenser;
– Steam dumping pipeline with impulse safety valves and relief valves;
– Pipeline for dumping steam-gas mixture from pressurizer with valves and constrictor;
– Injection pipeline;
– Pipeline connecting pressurizer with the hot leg of main circulation pipeline (connecting pipeline).

The pressurizer is a vertical tank connected to the hot leg of the primary circuit loop. To maintain constant pressure in the primary circuit, the pressurizer is equipped with a spray system and electrical heaters. The spray system is located at the top of the pressurizer and is used for injecting water into the steam volume to provide steam condensation and consequent pressure drop. Electric heaters, located in the lower part of the pressurizer, are used for water heating and consequent pressure increase in the primary circuit. They are also used for coolant heating during reactor startup.

The pressurizer size and volume of water are chosen to eliminate the regimes where steam from the pressurizer could appear in the main circulation pipelines.

The main parameters of the pressurizer are:

– Pressure 15.7 MPa;
– Temperature 346°C;
– Volume (total) 79 m^3;
– Water volume in rated state 55 m^3;
– Steam volume in rated state 24 m^3;
– Electric heaters power 2520 ± 190 kW.

The bubbler-condenser is designed for accepting steam from the pressurizer. It is a horizontal tank filled with water for two-thirds of its total volume. Inside the bubbler-condenser there are three distributing steam collectors located near the bottom, and heat exchanger tubes for cooling the water in the bubbler-condenser. There is a safety membrane that breaks when the pressure exceeds the emergency set point, thus dumping steam to the reactor containment.

Pressure change compensation is performed as follows.

Water in the pressurizer is heated by electric heaters located in the bottom part of the pressurizer. The water boils and steam forms a steam cushion in the upper part of the pressurizer. In steady state conditions, steam and water are in a saturated state. In transient regimes of the nuclear steam supply system, when the mean temperature of the coolant changes and density also changes respectively, coolant can flow through the connecting pipeline from/to the pressurizer. In such situations, the steam cushion dampens pressure changes due to evaporation of water and/or condensation of steam. Changes of coolant volume in the pressurizer also play an important role in the pressure compensation process.

In case of decreasing water volume and respective increasing steam volume, the pressure starts decreasing, but for lower pressure, the water boiling margin decreases too. As a result, water becomes oversaturated for the current pressure and water evaporation increases, leading to pressure increase.

When water volume increases and, respectively, steam volume shrinks, pressure starts increasing but, for increased pressure, the water saturation temperature is higher. As a result, steam becomes subcooled for the current pressure and steam condensation increases, leading to pressure decreasing. In the case of significant pressure rise, coolant is injected through the spray system located in the upper part of the pressurizer. This injection of relatively cold water results in condensation of steam in the steam volume and a consequent decrease of pressure.

The level in the pressurizer is maintained by an automatic controller that considers inputs from the current level and the primary circuit mean temperature. Regulation is carried out with valves in the feed and bleeds system.

The pressure in the pressurizer is maintained by an automatic controller that considers pressure input from the reactor vessel pressure. Regulation is carried out with electric heaters and with valves at injection pipelines.

In the steady state regime under normal operation conditions, one group of electric heaters is switched on. This group compensates for heat losses.

During reactor startup when the primary circuit is cold, instead of a steam cushion in the pressurizer, a nitrogen cushion is used. When the primary circuit and pressurizer are heated to operation temperature, nitrogen is replaced by steam.

In the process of reactor cool down, the automatic controller maintains the temperature difference between the primary circuit and the pressurizer by injection of cold water from the cold leg of the primary circuit loop or from the feed and bleed system.

III.2.6. Primary circuit feed and bleed system

The primary circuit feed and bleed system is designed for:

– Controlling the inventory of the primary circuit coolant;
– Changing boron concentration in the primary circuit coolant;
– Bleeding leakages from primary circuit equipment;
– Primary circuit coolant purification and return;
– Feeding water to MCP sealing;
– Feeding boron concentrate to the primary circuit in case of electric power loss.

Primary circuit inventory control is performed via feed and bleed valves. A pressurizer level below the set point indicates that there is insufficient coolant mass in the primary circuit and an additional amount of coolant is then fed into the primary circuit from the primary coolant storage tank until the level in the pressurizer reaches the set point. On the contrary, a pressurizer level above the set point indicates that there is excess coolant mass in the primary circuit, and the bleed flow increases while the feed flow decreases thus reducing coolant mass in the primary circuit.

Bleed coolant from the primary circuit passes to the regenerative heat exchanger where it is cooled by feed water return flow to the primary circuit. After that, it is cooled in the auxiliary heat exchanger down to 40–55ºC.

After cooling, the bleed coolant is purified in the low pressure water purification system. After purification, the coolant flows to the feed water de-aerator for degassing from which it is returned to the primary circuit by feed water pumps through the hot side of regenerative heat exchangers. Under normal operation conditions, only one train of feed water pumps is in operation. Control valves provide feed and bleed flows in the range 30–60 t/h.

Part of the feed water goes to MCP sealing. The pressure head of the feed water pumps is about 2.0 MPa higher compared to the MCP outlet pressure head. The MCP sealing flow is about 2 m^3/h for each MCP.

III.2.7. Secondary circuit

The secondary circuit of the WWER-1000 includes four steam generators, steam isolation valves and steam discharge valves, main steam header, turbine, condensers, feed water heating system, and feed water supply system.

The steam formed in the steam generators is collected in the main steam header and distributed to a number of consumers. Under normal operation conditions, most of the steam flow goes via turbine governor valves to the high pressure cylinder of the turbine. Steam exiting the high pressure cylinder enters the separator to remove extra moisture. After the separator, steam passes to the re-heater where it is heated and enters the low pressure cylinders. Each of the low pressure cylinders is connected to a separate condenser, where steam is condensed by flowing over tube bundles through which cooling water is circulated. Starting from the condenser, the condensate is pumped through low pressure and high pressure reheating heat exchangers respectively, in which it is heated by extraction steam from the turbine. Then the condensate goes to the de-aerator in which all non-condensable gases are removed. Finally, the feed water is pumped to steam generators by feed water pumps.

III.3. REACTOR CONTROL AND PROTECTION SYSTEM

Regulation of reactor power and control of the fission chain reaction is carried out by two systems adjusting reactivity that are based on different principles:

- Insertion of solid absorbers — control rods system;
- Injection of liquid absorber — boron regulation system.

Reactivity regulation is based on changing the position of the control rods and on changing the boron concentration in the primary circuit coolant.

The reactor control and protection system includes the:

- Control rod system;
- Neutron flux monitoring system;
- Emergency protection system;
- Preventive protection system, including power limiting regulator;
- Control rod position monitoring system;
- Control rod individual and group control system;
- Technological parameter transmitters;
- System for processing signals and data from technological parameters transmitters.

III.3.1. Control rod system

The control rod system is intended for:

- Maintaining a critical state at a stationary power level and control of power release distribution in the core;
- Changing reactor power;
- Providing preventive and emergency reactor protection.

In a WWER-1000, there are 61 control rods. Each control rod consists of 18 absorber elements, which move inside fuel assemblies in special channels and have individual drives.

All control rods are subdivided into 10 groups (banks). The number of control rods in a group and the velocity of movement are chosen so that maximum differential efficiency should be more than 0.035 $ß_{eff}$/cm and the reactivity introduction rate in the process of withdrawing control rods should be less than 0.07$ß_{eff}$/s, where $ß_{eff}$ = efficient fraction of delayed neutrons.

When the reactor is operating at rated power, all groups of control rods are in the topmost position above the core, except for group #10, which is work group. Typically, it is located at a height 70–90% from the bottom and serves for compensation of small changes of reactivity due to variations of temperature, boron concentration, and electric load.

Control of sparse power release distribution in the core is performed by the control rod group #5. It is used for maintaining power release non-uniformity in designed margins and for stabilization of field shape in manoeuvring regimes according to the algorithms of reactor control for xenon transients.

All control rods are used for emergency protection and preventive protection. When the emergency protection signal occurs, all control rods are dropped into the core and reach the lowest position in less than 4 seconds.

After signals of preventive protection occur (they can be of various types), groups of control rods are sequentially moved down in the core with work speed, or one group can be dropped for fast decreasing of reactor power, or prohibition of control rods moving up is implemented. Control rod positions are displayed on panels in the control room.

Positions of all control rods are displayed on the control rod position panel, while the position of the particular selected control rod bank is displayed on the individual control rod bank position indicator.

Any control rod bank can be selected for automatic or manual power control. This is done with the help of the control rod bank selector.

III.3.2. Boron regulation system

The boron regulation system is intended for compensation of slow reactivity changes and maintaining the reactor critical state during transients concerned with xenon poisoning, and during reactor startup and shutdown.

In normal operation regimes boron regulation provides:

– Compensation of slow reactivity changes associated with fuel burnup and xenon transient processes;
– Compensation of reactivity increase during xenon decay and cooling down of the reactor;
– Required subcriticality during core refuelling and planned maintenance work.

Boron regulation can also be used for changing reactor power. The absorption capabilities of boron regulation were chosen taking into account the requirements:

– To compensate the full reactivity in the cold state;
– To provide subcriticality not less than 0.05%, without taking into account control rods.

This requirement is satisfied when the boron concentration in the coolant is 2.8 g/kg (16g/kg of boric acid). The boron regulation system permits changing boron concentration at a rate of about 15–20% per hour from the rated concentration. Combination of boron regulation with the control rods improves manoeuvring characteristics of the reactor.

III.3.3. Neutron flux monitoring system

The neutron flux monitoring system (on WWER reactors it is called AKNP) is intended for monitoring neutron flux and determining neutron power and reactor period. It provides comparison with set points for neutron power and reactor period, generates signals for the control and protection system, for the power limiting regulator (ROM), and for the control room panels.

The neutron flux monitoring system consists of the subsystems for:

– Control and protection;
– Core refuelling;
– Standby control panel.

The neutron flux monitoring system for CPS provides permanent monitoring of neutron flux beginning from the reactor subcritical state and at all power levels. The system consists of two independent trains, each having its own detectors in adjacent channels of ex-core ionizing chambers. The range of measurements is subdivideed into three intervals: source range, intermediate range and power range, where:

– Source range $(1.0\times10^{-7}–0.1)\%\ N_{nom}$ / $(3.0\times10^{3}–3.0\times10^{9})$ neutron/s·m^2;
– Intermediate range $(1.0\times10^{-3}–100)\%\ N_{nom}$ / $(3.0\times10^{7}–3.0\times10^{12})$ neutron/s·m^2;

– Power range (0.1–120)% N_{nom} / (3.0×10^9–3.0×10^{12}) neutron/s·m^2.

AKNP provides monitoring of the reactor period in the interval from 10 to 200 sec.

III.3.4. In-core instrumentation

Neutron flux measuring channels (NFMCs) are intended for monitoring neutron flux in radial and axial directions in the reactor core. The NFMC assembly is for neutron flux measuring instruments installed in a protective cover.

The NFMC assembly is placed within the fuel assembly central tube and guiding channel of the protective tube block. In the upper part of the NFMC, an electric connector with a signal cable is mounted. Signals from direct-charge sensors made of rhodium are transmitted to measuring instrumentation.

The total number of NFMC assemblies in the WWER-1000 reactor core is 64. Signals from the 64 NFMC assemblies give representative information on the neutron flux density distribution in the core in the axial and radial directions.

Besides neutron flux transmitters in the in-core measuring system, temperature monitoring transmitters are used, 91 of which are installed at the outlet of 91 fuel assemblies. Their readings are used for determination of individual fuel assembly power and for precise determination of reactor thermal power.

III.3.5. Control and protection system operation

For reactor protection and control, the following systems are used: AKNP, ARM, ROM, URB, AZ. All of them adjust the reactivity via control rod systems.

All control rods are subdivided into ten groups (banks), having six control rods in each group, except for group No.5 which consists of seven control rods. Control rods can be moved individually and in groups. There are predefined sequences of control rod movement by groups: ‘up’ — from lower number to higher number, ‘down’ — from higher number to lower number.

Electromagnetic forces suspend control rods above the reactor core. When an emergency protection signal occurs (in WWER it is called an AZ signal) all control rods drop down. The power supply to the electromagnetic locks is cut off, so the control rods drop down by gravity force in less than 4 seconds.

The preventive protection system is intended for generation of signals for prohibition of increasing power or for reducing power to the safety margin. The preventive protection system may generate commands for:

– Sequential movement of control rod groups with normal speed until disappearance of signal that some parameter exceeded set margin;
– Prohibition of increasing power level until disappearance of signal that some parameter exceeded set margin;
– Drop down of one group of control rods.

When preventive protection of level #1 signal occurs (in a WWER it is called a PZ-1signal), groups of control rods are moved down with speed 2cm/s in standard sequence until the PZ-1 signal disappears.

When preventive protection of level #2 signal occurs (in a WWER, it is a called PZ-2 signal), plant automation prohibits withdrawing control rods, i.e. it is prohibited to raise reactor power until PZ-2 signal disappears.

Preventive protection is also carried out by the reactor power reducing and limiting device (ROM). Functionally, it is a component of the PZ-1 system. The permitted reactor power value is programmed as a function of several parameters. Reactor power is restricted depending on the number of main circulation pumps currently in operation, the number of feed water pumps (FWP) currently in operation in the balance of plant (BOP) system, the grid frequency and a number of other signals. Decrease of reactor power is carried out by movement of the selected work group of control rods down with normal speed.

ROM generates a signal for restriction of reactor power in the following cases:

– 102% N_{nom} when 4 MCPs and 2 FWPs are in operation;
– 69% N_{nom} when 3 MCPs and 2 FWPs are in operation;
– 52% N_{nom} when 4 MCPs and 1 FWPs are in operation;
– 52% N_{nom} when 2 MCPs in opposite loops and 2 FWP are in operation;
– 42% N_{nom} when 2 MCPs in adjacent loops and 1 FWP are in operation;
– 7% N_{nom} when both FWPs are not operating;
– Main circulation pump electric power supply frequency is less than 49 Hz.

In the case that the MCP electric power supply frequency is less than 49 Hz at 3 of 4 sections of power supply, a factor 0.9 is applied to the above margins.

Reducing reactor power is carried out to 2% lower than the predefined power level.

The automatic regulator of reactor power (in WWER it is called an ARM) is intended for maintaining reactor power corresponding to the turbine-generator power and according to signals from the neutron flux monitoring system (AKNP). The automatic regulator of reactor power can be set in the following two operation modes:

– Mode of maintaining constant pressure before turbine regulating valves in the range 10–102% N_{nom} (mode 'T');
– Mode of maintaining constant neutron power in the core in the range 3–102% N_{nom}. (mode 'H').

The automatic change to mode 'T' is carried out in case of:

– Neutron power rise 2% above the prescribed value;
– Generation of any PZ signal.

The automatic change to mode 'T' is carried out when the pressure in the main steam collector exceeds the set value by 0.2 MPa.

Prohibition for increasing reactor power by ARM is introduced in the case when:

– Neutron power reaches 102% from rated value;
– Reactor period is less than 40 sec.

In WWER reactors there is also specific protection, namely the rapid power change to lower power value (in WWER it is called URB) — reactor runback.

URB actuates while the reactor is operating at 75% N_{nom} when there is:

– A trip of 2 of 4 operating MCPs with delay 1.4 sec — reactor power is reduced to 50% N_{nom} if tripped MCPs are in opposite loops, and to 40% N_{nom} if tripped MCPs are in adjacent loops;
– A trip of 1 of 2 operating FWPs (closing of FWP stop valves or reducing steam pressure after regulating valves to set point) — reactor power is reduced to 50% N_{nom};
– Turbo generator load reduction to zero (disconnection of generator from electric grid) — reactor power is reduced to 40% N_{nom};

– A disconnection of turbine by steam (closing of two turbine stop valves) – reactor power is reduced to 40% N_{nom}.

Until the inserted control rod group is withdrawn, these power margins should not be exceeded. Rated positions of control rods should be restored within three hours. If this is not possible, hot shutdown of the unit should be carried out.

III.4. SAFETY SYSTEMS

Safety systems of WWER-1000 include a number of special systems which do not take part in normal plant operation and the systems having safety devices as the integral part of each system.

Safety systems are poised to act. In the case that the processes, control systems, and operators cannot keep operation parameters in the prescribed limits, these systems start acting.

The emergency core cooling system includes a high pressure part which is intended for fast feeding of boron concentrate in the reactor when reactor pressure drops below 5.9 MPa.

Boron concentrate (16 g/kg of boric acid) at temperature of about 60–70°C is delivered to the reactor from high pressure tanks via four independent trains. Within the first 30 minutes no actions of reactor operator are needed. For delivery of coolant to the reactor, the energy of compressed nitrogen is used. There are fast acting stop valves for prevention of nitrogen ingress in the reactor.

The primary circuit over-pressure protection system protects the reactor vessel, pressurizer and primary circuit equipment from pressure rise over specified limits. It includes steam discharge valves on the line from the pressurizer to bubbler-condenser, and a safety membrane. The pressure in the primary circuit should not exceed the nominal value by more than 15%. In case the pressure in the pressurizer rises, the coolant is dumped from the pressurizer to the bubbler through a relief valve. The steam is condensed in the bubbler, and the condensate is pumped out of the bubbler to maintain a constant level in it. If the pressure in the bubbler rises above the safety limit, the membrane breaks and the excess pressure is released to containment. A control valve permits primary circuit pressure to decrease to any defined value by operator command. Set points for impulse valves that are fully open are from 18.5–19.2 MPa, and from 17.0–17.5 MPa for fully closed.

The secondary circuit over-pressure protection system includes steam discharge valves to the atmosphere and to condensers, and quickly actuating safety valves. Under normal conditions, the steam flows to the turbine via governor valves. The opening of the governor valves alters steam flow to the turbine, varies turbine load, and affects the steam pressure in the main steam header and steam generators. If the pressure rises above the specified value, the steam discharges into atmosphere and limits the steam pressure rise. If the pressure rises further, the steam discharge valves to condensers open and the steam bypasses the turbine to the condensers. If after that the pressure is still too high, the safety relief valves open to ensure that the steam pressure does not exceed the safety limit.

REFERENCES

[1] The protocol decision 14 “On Approval of the Concept for Ensuring Energy Security in the Republic of Armenia” of the Republic of Armenia Government session No. 50, of 22 December 2011.

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, IAEA-TECDOC-1575, IAEA, Vienna (2007).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Information System, IAEA-TECDOC-1613, IAEA, Vienna (2009).

[4] SUBBOTIN, S., DEPISCH, F., KHOROSHEV, M., TSIBULSKIY, V., International Conference on Nuclear Engineering “ICONE 14”, DESAE (Dynamic Energy System-Atomic Energy), Integrated Computer Model for Performing Global Analysis in INPRO Assessment Studies, 17-20 July 2006, Miami, Florida, USA.

[5] IPF Batch Power Flow (BPF) User’s Guide, User Publication , Interactive Power Flow Program, Planning Methods Section, System Planning, Bonneville Power Administration, P.O. Box 3621 — TEOS, Portland, OR 97208, (5 November 2001).

[6] “ENERGY SECTOR DEVELOPMENT STRATEGIES IN THE CONTEXT OF ECONOMOC DEVELOPMENT IN ARMENIA”, Approved by the Government of Republic of Armenia at June 23, 2005 session, No. 1 resolution of No. 24 protocol.

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, “Energy and Nuclear Power Planning Study for Armenia”, IAEA-TECDOC-1404, IAEA, Vienna (2004).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Human Resource Needs for a New Nuclear Power Plant: Armenian Case Study, IAEA-TECDOC-1656, IAEA, Vienna (2011).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning Costs of WWER-440 Nuclear Power Plants, IAEA-TECDOC-1322, IAEA, Vienna (2010).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Fundamentals Relating to Radioactive Waste Managements, IAEA Safety Standards Series No. 111-F, IAEA, Vienna (1994).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Developing Multinational Radioactive Waste Repositories: Infrastructural Framework and Scenarios of Cooperation, IAEA-TECDOC-1413, IAEA, Vienna (2004).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from Nuclear Energy System Assessments. Using the INPRO Methodology. A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1636, IAEA, Vienna (2009).

LIST OF ABBREVIATIONS

AGR	–	advanced gas-cooled reactor
AKNP	–	neutron flux monitoring system in WWER reactors
ANPP	–	Armenian nuclear power plant
APS	–	Armenian power system
ARM	–	automatic regulator of reactor power in WWER reactors
AZ	–	emergency protection signal in WWER reactors
BOP	–	balance of plant
BWR	–	boiling water reactor
CCGT	–	combined cycle co-generation turbine
CHP	–	combined heat and power
CPS	–	control and protection system
DESAE	–	Dynamics of Energy System of Atomic Energy
EFPD	–	effective full power day
FP	–	fission products
FWP	–	feed water pump
GCR	–	gas-cooled reactor
GDP	–	gross domestic product
HLW	–	high level waste
HM	–	heavy metal
HPP	–	hydro power plant
HVL	–	high voltage line (overhead line)
I&C	–	instrumentation and control
INPRO	–	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	–	innovative nuclear power system
IPF	–	Interactive Power Flow
LLW	–	low level waste
MA	–	minor actinides
MAED	–	Model for Analysis of Energy Demand
MESSAGE	–	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MCP	–	main circulation pump
NE	–	nuclear energy
NES	–	nuclear energy system
NESA	–	nuclear energy system assessment
NFC	–	nuclear fuel cycle
NFCSS	–	Nuclear Fuel Cycle Simulation System
NFMC	–	neutron flux measuring channel
NORM	–	naturally occurring radioactive material
NPP	–	nuclear power plant
OHL	–	overhead line
PFP	–	Power Flow Program
PHWR	–	pressurized heavy water reactor
PRIS	–	Power Reactor Information System
PSAP	–	Power System Analysis Package
PV	–	photovoltaic system
PWR	–	pressurized water reactor
PZ	–	preventive protection signals in WWER reactors
R&D	–	research and development
RBMK	–	graphite-moderated nuclear power reactor

ROM	–	reactor power reducing and limiting device
SIMPACTS	–	Simplified Approach for Estimating Environmental Impacts of Electricity Generation
SNF	–	spent nuclear fuel
SS	–	substation
SWU	–	separate work units
TACIS	–	Technical Assistance Programme for the Commonwealth of Independent States
TPES	–	total primary energy supply
TPP	–	thermal power plant
TSP	–	Transient Stability Program
ULS	–	under-frequency load shedding
UOX	–	uranium oxide (nuclear fuel)
URB	–	rapid power change to lower power value in WWER reactors
WWER	–	water-water energy reactor

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