Safety Reports Series

No. 91

Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants

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IMPACT OF OPEN PHASE CONDITIONS ON ELECTRICAL POWER SYSTEMS OF NUCLEAR POWER PLANTS

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FOREWORD

An open phase condition (OPC) is a known phenomenon in the power industry and is recognized as having had an adverse impact on the electrical power systems of several nuclear power plants. An OPC may challenge plant safety systems. Operating experience in different countries has shown that currently installed instrumentation and protective schemes have not been adequate to detect this condition and initiate appropriate action.

An OPC may occur as a result of various faults, including circuit breaker poles not opening or closing, or the failure of transformer bushings or line insulators, leading to a loss of circuit continuity. This type of fault creates voltage and current imbalances in electrical power systems that may be detrimental to operating equipment.

An OPC, if not detected and disconnected in a timely manner, represents a design vulnerability for many nuclear power plants. It may lead to a condition in which neither the off-site power system nor the on-site power system is able to support the safety functions.

An OPC in a plant that is operated with equipment important for safety supplied from a common power source can result in the degrading or tripping of redundant equipment, thereby compromising the overall safe shutdown capability of the plant.

This publication provides useful guidance, with a focus on electrical power supply systems, for all personnel involved in the design, manufacture, qualification, operation, maintenance, management and licensing of nuclear facilities.

This publication was produced by a committee of international experts and advisors. Their experience and knowledge was invaluable in providing a comprehensive technical basis for the development of this publication. The IAEA wishes to thank all the participants and their Member States for their valuable contributions. The IAEA officer responsible for this publication was A. Duchac of the Division of Nuclear Installation Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

An open phase condition (OPC) is defined as an open circuit of one or two of the three phases of any power circuit needed for the normal operation of electrical systems. An OPC is a recognized phenomenon that may compromise the operational capability of electrical power systems of nuclear power plants. This condition and the consequences have generally not been considered in the detection and protection schemes in the present design of electrical power systems of nuclear power plants.

An OPC may occur as a result of various faults such as breaker poles failing to open or close, transformer bushings or line insulators breaking and improperly conneced conductors. This type of fault creates a voltage imbalance (and a current imbalance under load conditions) in the electrical power system. The fault condition can be difficult to detect, especially when considering large transformers under no-load or lightly loaded conditions.

When a single or double OPC occurs on the high voltage side of transformers, it is likely that voltages will be regenerated, to some degree, in all phases on the high and low voltage side of the transformers. The magnitude of the voltage and current of each phase is dependent on the configuration and design of the transformers and connected loads in the circuits.

Operating experience has shown that OPCs may be difficult to detect under all operational conditions with existing plant instrumentation and electrical protection schemes, and there is a potential for severe voltage imbalance, resulting in degradation or failure of electrical equipment. In some cases, the inability to detect and disconnect the degraded power source from the safety bus has prevented transfer to a standby off-site power supply or standby alternating current (AC) power source.

A number of events reported up to the time of writing that are listed in Section 6 have involved either single or double OPCs in a plant's electrical power system. These events and their safety significance underline the importance of reliable detection and disconnection of the OPC from nuclear power plant electrical power systems.

Based on the Byron nuclear power plant operating events, the Nuclear Regulatory Commission (NRC) of the United States of America has issued the following publications addressing the design vulnerabilities in electrical power systems: NRC Information Notice 2012-03: Design Vulnerability in Electric Power System [1], NRC Bulletin 2012-01: Design Vulnerability in Electric Power

System [2] and Branch Technical Position (BTP) 8-9: Open Phase Conditions in Electric Power System [3].

In Unit 2 at the Byron nuclear power plant [1], the design vulnerability in the protection scheme of the electric power system prevented the detection of the loss of a single phase between the transmission network and the on-site power distribution system resulting in:

— Unbalanced voltage conditions at redundant safety buses (due to a degraded off-site power supply);
— The tripping of operating equipment, such as essential service water pumps, centrifugal charging pumps and component cooling water pumps;
— The on-site electric power system being prevented from supplying plant safety systems.

This loss of a single phase resulted in a condition in which neither the on-site nor the off-site electric power system was able to perform their intended safety function (i.e. to provide electric power to the safety buses with sufficient capacity and capability to permit the operation of structures, systems and components important to safety) until the operators diagnosed the problem and disconnected the degraded off-site source.

In Unit 1 at the Byron nuclear power plant [1], a failed insulator in the 345 kV off-site power system resulted in a single OPC with a phase to earth fault on the transmission side of the standby transformer circuit. In this event, the fault current was high enough to actuate protection schemes on the 345 kV system. The safety buses experienced a loss of voltage condition after the 345 kV system breakers disconnected the off-site power source. Both standby AC power sources started and energized the safety buses as designed.

In an event in Unit 3 at the Forsmark nuclear power plant [4], on 5 May 2013, the failure of one pole of a 400 kV circuit breaker to open and disconnect the power source from the switchyard caused a double OPC, creating an unbalanced voltage condition. This was not detected by the existing instrumentation or electrical protection scheme owing to low load conditions and, as a result, the electrical protection scheme did not disconnect the safety buses from the faulty electrical system. As a consequence of the OPC, cooling of the spent fuel pool and cooling of the emergency diesel generators was lost until manual action by the plant operators disconnected the power supply from the 400 kV switchyard. After the supply from the off-site grid was disconnected, the cooling systems were manually restored, enabling the standby AC power source to supply power to the safety buses until the OPC in the 400 kV switchyard was resolved and the off-site power from the 400 kV switchyard was restored.

The majority of OPCs in the nuclear power plant operating experience database [5] document events that occurred on the high voltage side of the unit transformer or standby transformer. There is one known OPC event in an on-site power system that occurred owing to a maintenance error. In this case, the standby AC power source generator breaker did not close properly in all poles, resulting in the failure of one phase. This fault was considered a single failure which impacted one safety train only.

1.2. OBJECTIVE

The objective of this publication is to enhance the safety of nuclear power plants by providing technical guidance to address OPC vulnerabilities in electrical systems used to start up, operate, maintain and shut down nuclear power plants. The objective of this guidance is:

- To provide a common technical basis to be considered for OPCs;
- To document aspects of OPCs that are relevant for safety functions of nuclear power plants;
- To outline critical issues which reflect the lessons learned from operating experience and recently performed analysis;
- To outline technical guidelines to analyse plant design protective measures;
- To provide a description of existing practices and design provisions for OPCs that have been implemented at some nuclear power plants;
- To provide measures that can be implemented to upgrade existing plant designs and improve the robustness of plant electrical systems.

1.3. SCOPE

This publication covers relevant aspects of OPCs initiated in the transmission systems or plant electrical systems. It provides details about the methods that can be used to identify vulnerabilities to an OPC in existing protective schemes.

This publication addresses:

- Preventive actions within testing, surveillance and maintenance activities;
- Protective measures such as detection and disconnection of the fault;
- Design provisions for the improvement of existing plant electrical design.

Reference [6] provides recommendations regarding the design of electrical power systems. It recommends performing analyses of electrical power systems for the verification of the design for loss of transmission system elements, including OPCs. This publication provides a detailed technical basis for the concerns about OPCs discussed in Ref. [6] and provides guidance for the implementation of detection and protection schemes.

This publication is intended for all personnel involved in the design, manufacture, licensing, operation and maintenance of electrical power supply systems at nuclear facilities. It provides specific details for utility engineers, operators, managers and personnel responsible for aspects of plant electrical design and operation to better understand preventive and protective measures for coping with OPC events. Finally, it will assist regulators who stipulate requirements for plant systems important to safety.

1.4. STRUCTURE

Section 2 defines the scope of the discussion, that is, which plant states and fault types are to be considered in the publication. Section 3 discusses the effects of unbalanced voltages and currents on electrical equipment and the consequences of an OPC. Section 4 describes the steps for the evaluation of potential design vulnerabilities at existing plants, and experience derived from evaluations that have already been performed. Section 5 provides design provisions to be addressed for those plants vulnerable to OPCs. Section 6 provides information on international operating experience from open phase occurrences. Annex I provides examples of calculations that can be performed to evaluate the unbalanced voltage and current conditions that can result in plant electrical systems. Annex II provides examples of permanent corrective solutions that have been implemented at some plants where an OPC, if undetected, could adversely impact plant safety. Annex III provides a summary of open phase events that have occurred at various nuclear power plants in different countries resulting in the degradation of operating equipment. This safety report provides recommendations for new plant designs and enhanced maintenance and surveillance as well as improved designs for existing nuclear power plants to implement and preclude such vulnerabilities. Annex IV provides examples of the flux paths of different transformer configurations during OPCs. A list of definitions is provided that presents terminology used within the nuclear industry with respect to electrical power supply, and is based mainly on IAEA publications and publications of international organizations.

2. FAILURE MODES AND CONSEQUENCES

Different disturbances can cause unbalanced voltage situations in the three-phase plant electrical power system:

— Short duration voltage imbalances, typically lasting less than a few seconds, occur during short circuits with or without an earth connection (followed by fault clearance) and switching operations such as motor starting and energizing of transformers.
— Voltage imbalances may occur for extended durations owing to various faults, e.g. the failure of breaker poles to close or open and the failure of transformer bushings or the line insulator.
— Long duration unbalanced voltage conditions can also occur owing to unbalanced loading of a three-phase system and to transmission system characteristics.

This publication considers unbalanced conditions caused solely by OPCs.

2.1. CONSEQUENCES OF OPEN PHASE CONDITIONS

An OPC in a three-phase power system typically results in an unbalanced voltage condition. Continued operation for an extended duration with unbalanced voltage conditions can damage equipment as a result of overheating and vibration, or result in the inadvertent trip of electrical equipment and cause a plant transient.

If more than one train of equipment is supplied from a common power source, the unbalanced voltage conditions can result in damage to redundant equipment important to safety — a form of common cause failure.

There is a risk that operators may not be able to respond in a timely manner to prevent damage to multiple pieces of equipment because of a lack of information available from existing measurements, indications and automatic actions.

The operational configuration of the plant or the off-site power source (e.g. switchyard breaker configuration) may result in the unbalanced voltage conditions remaining undetected until:

— The plant loading changes by removing or connecting loads;
— The off-site power source is reconfigured through switchyard breaker operation; or
— A performance abnormality such as load tripping occurs.

If the voltage imbalance levels are low, as a result of the type of fault or transformer winding configuration and earthing, then the degraded conditions can go undetected for a long period of time and may not be identified until the transformer load is increased owing to a change in the plant alignment such as plant shutdown or startup.

2.2. PLANT STATES AND PLANT LIFETIME

All electrical system configurations and loading conditions need to be systematically analysed when assessing and designing the on-site electrical power system to cope with OPCs. The following can be considered, as electrical systems may have unique alignment:

— Each stage in the plant lifetime: design, commissioning, operation and decommissioning.
— Preferred power supply path: electric power from the transmission system to the on-site electrical power system is generally supplied by at least two physically independent circuits or by the main generator during house load operation. This flexibility of power sources permits different plant configurations.
— Standby power sources: the standby AC power source, the alternate AC power source or other similar sources supplying electrical power to essential parts of the on-site power system.
— Each plant state: operational states (normal operation and anticipated operational occurrences). Anticipated operational occurrences include loss of a circuit, transfer to standby off-site power supply and changes in the transmission system network.
— Design basis accident conditions: a design basis accident may result in the operation of high voltage circuit breakers associated with the power plant electrical supply system (e.g. transfer from normal to standby or alternate grid supply). Event sequences which involve the opening or closing of high voltage circuit breakers (which could, therefore, result in an OPC) have to be considered.
— Consequential loss: a transient in the power source or an OPC in the normal power source may result in the loss of operational systems due to unbalanced voltage and current. The loss of operating equipment may result in an accident signal or start safety grade equipment. If the OPC is not disconnected, plant safety may be challenged. This cascading sequence of events has to be evaluated, if applicable.

— Typical loading conditions: loading conditions in the plant states mentioned above. For normal operation, this includes startup, power operation, shutdown, maintenance, testing and refuelling.

2.3. SCOPE OF THE DISCUSSION

The scope of the plant distribution system to be evaluated for OPC vulnerability is generally plant specific as it depends on the design and configuration of the on-site and off-site power system. As a minimum, the consequences of an OPC on the high voltage side of each transformer connecting an off-site power system to the on-site power system need to be evaluated in detail.

For nuclear power plants with the capability to supply house loads from the main generator with a generator circuit breaker/switch, an unsuccessful opening or closing of all poles of the isolation device may lead to unbalanced voltage conditions. This may result in degradation and potential loss of equipment important to safety and may need to be considered.

Although an OPC in the off-site power system is the primary focus of this publication, an OPC in the on-site power system may also need to be evaluated in cases where such an event could impair the safe shutdown capability of the plant.

2.4. TYPES OF OPEN PHASE CONDITIONS TO BE CONSIDERED

The design and analysis of the electrical system need to address, as a minimum, the following aspects:

— Electric power supply from the transmission network to the on-site electric distribution system as supplied by independent circuits: For each independent off-site power supply, the analysis needs to address the loss of one of the three phases on the high voltage side of the power transformer which connects the transmission system to the on-site power system.
— Electric power supply from the main generator (when operating in an island mode) and on-site power systems: The loss of one of the three phases needs to be addressed.
— Loss of two of the three phases in any of the power supply system configurations considered above: A double OPC will have to be considered

in the system under all operating electrical system configurations and loading conditions.
— A high impedance earth fault condition with any of the power systems considered above.

A high impedance system fault has the potential to degrade one phase of the power source in a similar way to an OPC. Protective relaying systems installed for detecting earth faults are sometimes set to trigger an alarm only or have a set point high enough to avoid spurious trips. Typically, high impedance fault conditions without an OPC do not adversely impact operating equipment, but this condition needs to be validated. It is expected that high impedance faults coupled with, or due to, an OPC may be bounded by the analyses considered for an OPC, but this has to be demonstrated for each installation.

3. EFFECTS OF OPEN PHASE CONDITIONS

For an OPC on the high voltage side of a transformer, analytical studies and operating experience have confirmed that voltages can be present in all three phases downstream of the OPC owing to the interaction of magnetic fields in transformers and three-phase loads; in some cases, all three phases on the low voltage winding may have balanced voltages in all phases under no-load or lightly loaded conditions.

In practical applications, the voltage regenerated through the systems depends on:

— Transformer winding, core configuration and rated power;
— System earthing arrangements;
— Transformer loading, size and type of load (e.g. motor or static);
— Properties of cables and overhead lines (capacitance, inductance);
— Location of the open phase.

3.1. OPERATING EQUIPMENT

If the plant electrical loads are supplied from a power source that has an OPC (i.e. a fully loaded power supply system), the unbalanced voltage condition can result in high current flow in at least one of the three phases of the rotating motors.

Typically, this higher than normal current flow actuates the protective schemes, resulting in the disconnection of the loads from the degraded source. However, the magnitude of the current is dependent on the type of transformer and system configuration of the associated feeder circuits and, in some cases, the current flow may not actuate protective relaying. In such instances, the higher than normal current may result in excessive heating of the motor windings and lead to a reduced lifetime.

If the protective scheme actuates and disconnects the associated load from the degraded power source, the safe shutdown capability of the plant may be compromised as the affected component may not be available until manual actions are taken to identify the cause of the trip, reset the protective relaying and close the appropriate breaker.

If the circuit with an OPC is in standby mode or lightly loaded, the low magnitude of current flow in the degraded circuit may not result in sufficient imbalance to actuate any protective device. The OPC may, therefore, go undetected until a change in plant state or a bus transfer to the off-site standby source results in the increasing of the load current in the circuit. Once the circuit has increased demand, the running motors may trip owing to overcurrent protection actuation or sustain winding damage due to heating effects as already explained.

Capacitive charging currents in transmission networks can result in high voltages when the transmission system is lightly loaded. Transformers with an unearthed star point are vulnerable to these elevated voltages on the low voltage side and insulation could be damaged if an OPC were to occur in the system. In summary, during an OPC in which the star point is earthed, negative sequence currents are difficult to detect. Where it is unearthed, there is a risk of damage due to elevated voltages.

3.2. SPECIFIC EXAMPLES OF VOLTAGE IMBALANCE

As already discussed, the effects of an OPC are largely dependent on the location of the fault, and on the design, configuration and loading of the plant systems. The combinations and variations of all postulated conditions are beyond the scope of this publication.

This section provides an explanation of the effects of loading conditions and transformer design and configuration on the voltage downstream of the OPC. The examples provided in this section demonstrate the difficulty of detecting unbalanced voltage conditions due to an OPC.

The discussion in this section is based on a typical configuration of power sources and associated transformers used at nuclear power plants as illustrated in

Fig. 1. A balanced voltage system can be represented with three phasors equal in magnitude and 120° degrees apart, as depicted in the vector in Fig. 2.

Both balanced and unbalanced three-phase systems can be analysed and described using symmetrical components (zero, positive and negative sequence components). Using this method, a quantitative description of the symmetry of a three-phase system can be made. A detailed description of how to perform calculations with symmetric components is given in Annex I.

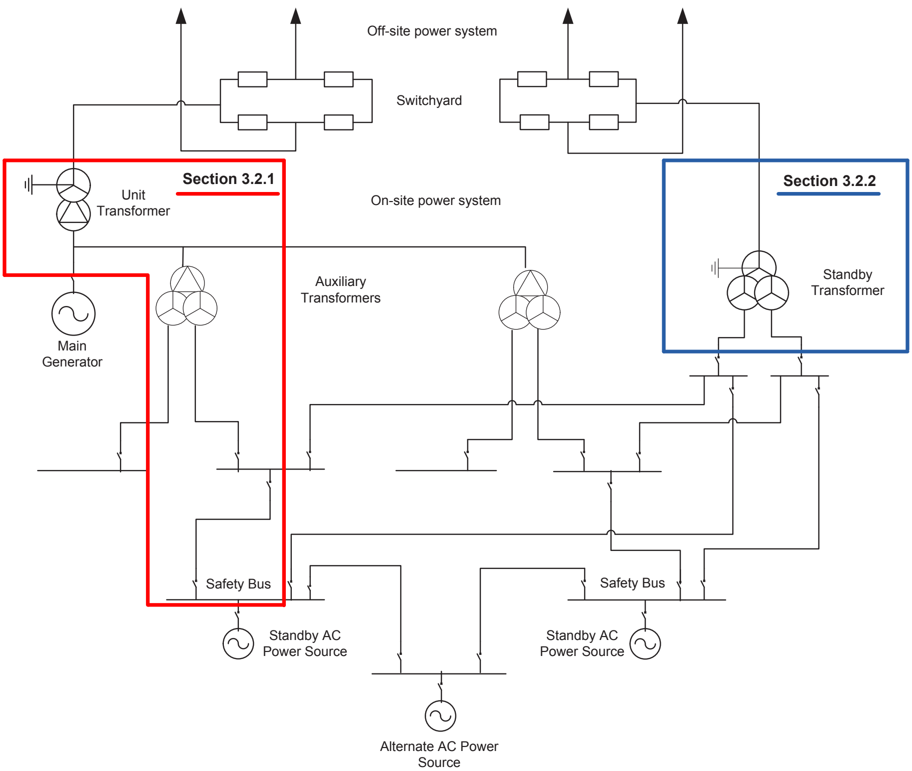

FIG. 1. Typical electrical diagram to illustrate the configuration used in Sections 3.2.1 and 3.2.2.

3.2.1. Lightly loaded system (outage configuration)

Operating experience and simulation results discussed in Refs [7–10] show that an OPC can be difficult to detect. There are multiple elements in the power system that provide mechanisms to generate voltages in the windings of a

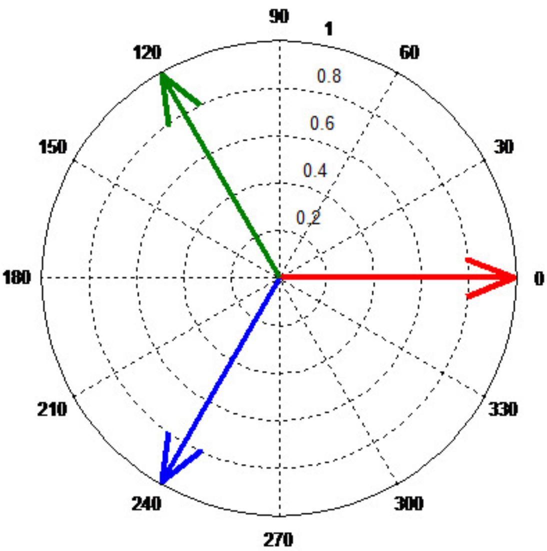

FIG. 2. An example of balanced phase to earth voltages.

transformer with an OPC present. As such, an OPC may remain undetected for an extended duration at plants operating in this configuration.

Figure 3 shows specific simulation results on the safety bus for a single open phase in the 400 kV line to the unit transformer in Fig. 1 during lightly loaded on-site power system conditions, such as may occur during an outage. The single OPC occurs at time equals 0.2 s in the sine wave figure, and the vector figure shows the phase to earth voltages on the safety bus before and after the OPC. Figure 3 also shows that it is difficult to identify all possible kinds of OPC with existing instrumentation and protection relays. The safety bus voltages are more or less identical with and without a single OPC, depending on the transformer vector group, transformer star point treatment and connected loads. During higher loading in the on-site power system, the voltage imbalance will increase.

Figure 4 shows typical simulation results for the same situation as in Fig. 3, but for a double open phase circuit in the 400 kV breaker. The double OPC occurs at time equals 0.2 s in the sine wave figure, and the vector figures show the phase to earth voltages before and after the OPC.

These simulation results show that even if two phases are disconnected on the high voltage side of the unit transformer, a voltage can still be present in all three phases of the low voltage side, although the phase angle and voltage

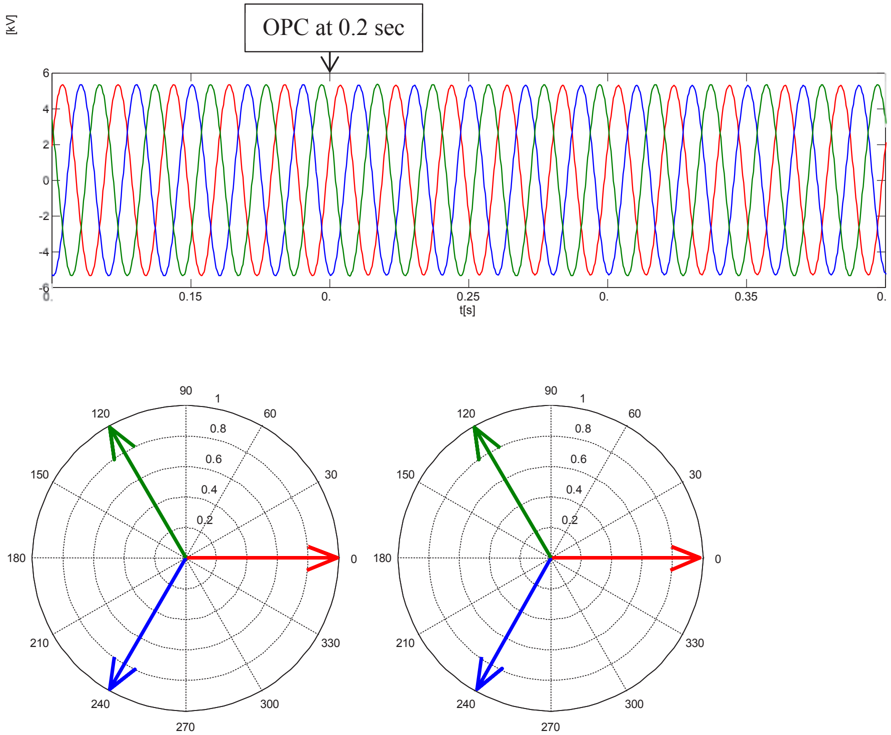

FIG. 3. An example of simulated safety bus voltages and a single OPC in the 400 kV line to the unit. Vector figures prior to an OPC (left side) and after an OPC (right side).

magnitude will be different. Such a situation depends on the transformer and earthing arrangements, and the configuration of the specific plant.

It can be difficult to identify the unbalanced voltage with existing instrumentation and protection relays. However, if not detected in a timely manner, the magnitude of current imbalance can cause damage to the connected electrical equipment.

3.2.2. An unloaded system (with a transformer in standby)

This section discusses the typical behaviour of unloaded transformers during a single and double OPC (see Fig. 1). The single OPC occurs at 0.1 s (1OPC) and the double OPC occurs at 0.2 s (2OPC). The voltage response for different transformer configurations is shown in both sine waves and vector figures. For the calculations, a three-phase, three-limb core type transformer was considered.

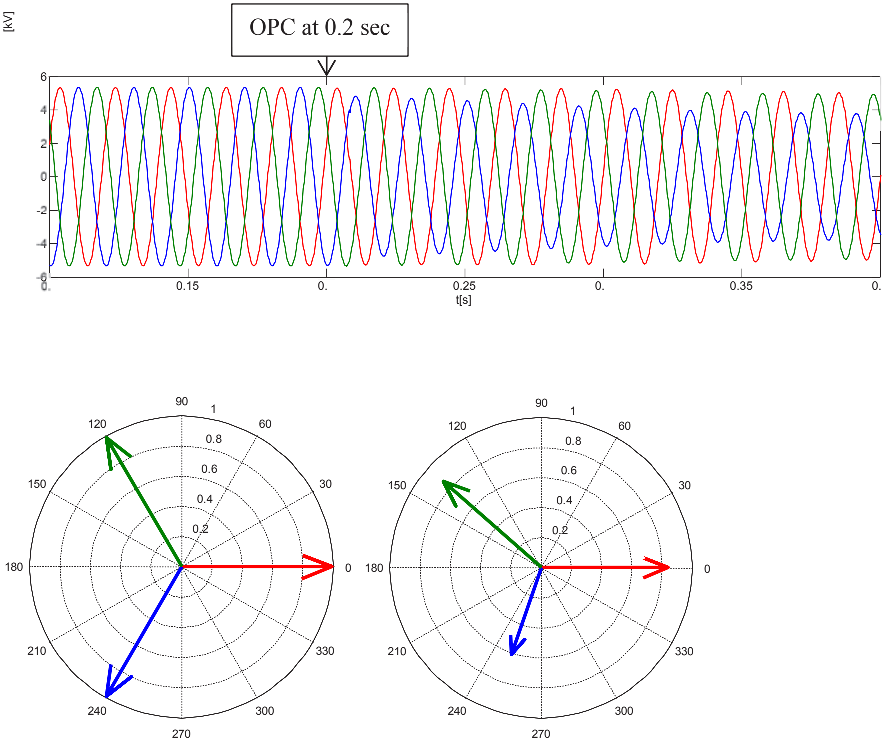

FIG. 4. An example of simulated safety bus voltages and a double OPC in the 400 kV line to the unit transformer. Vector figures prior to an OPC (left side) and after an OPC (right side).

3.2.2.1. Yy0 transformer (high voltage side star point isolated from earth)

Voltages on the high voltage side (downstream of the open phase circuit) of an unloaded transformer with vector group Yy0 are shown in Fig. 5.

Voltages on the low voltage side of an unloaded transformer with vector group Yy0 are shown in Fig. 6. The high voltage side star point is isolated from the earth. With a double open phase, all the voltages on the high voltage side are equal in magnitude and angle, and hence, the voltage on the low voltage side will become zero.

3.2.2.2. YNy0 transformer (high voltage side star point solidly earthed)

Voltages on the high voltage side (downstream of the open phase circuit) of an unloaded transformer with vector group YNy0 are shown in Fig. 7. Clear

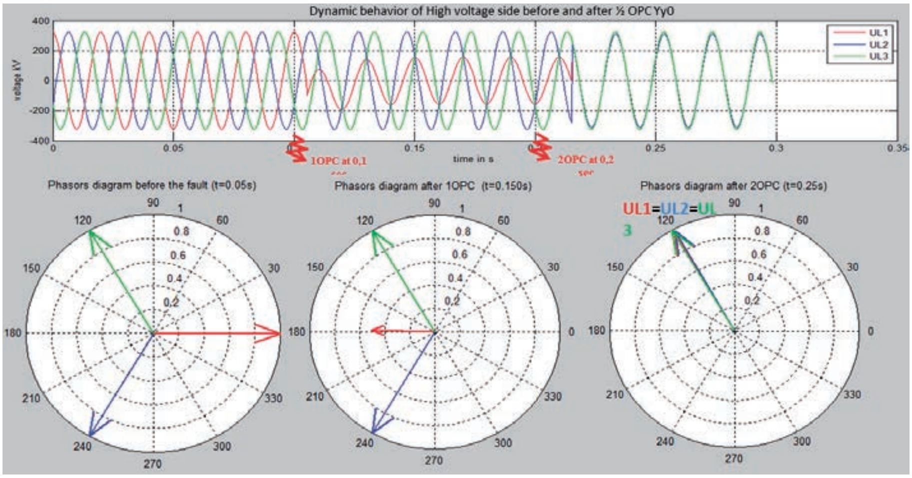

FIG. 5. Phase to earth voltages on the high voltage side of an unloaded Yy0 transformer before and after an OPC.

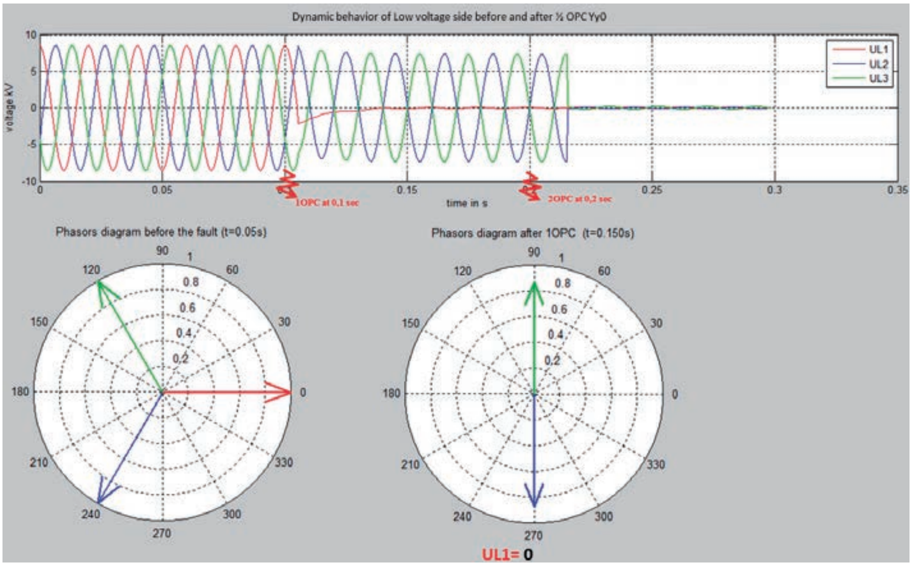

FIG. 6. Phase to earth voltages on the low voltage side of an unloaded Yy0 transformer before and after an OPC.

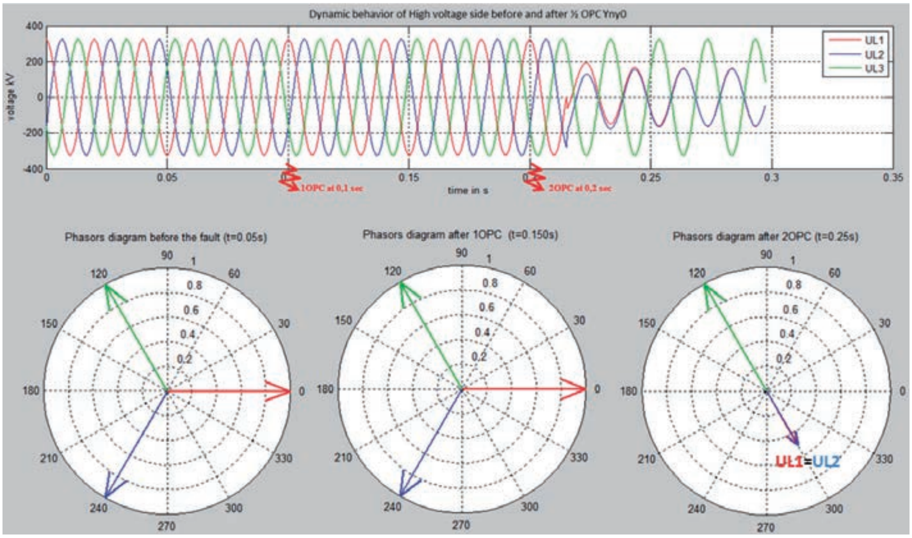

FIG. 7. Phase to earth voltages on the high voltage side of an unloaded YNy0 transformer before and after an OPC.

differences in the voltage are visible compared to the previous transformer configuration as a consequence of an earthed star point on the high voltage side.

Voltages on the low voltage side of an unloaded transformer with vector group YNy0 are shown in Fig. 8.

3.2.3. Power operation

When considering an OPC during power operation, the star point configuration (earthed or not) of the unit transformer is very important. Generally, unit transformers are Y/Δ transformers. For the analysis in this section, it is assumed that the unit transformer star point is either solidly earthed or unearthed.

In general, the following information is important for the results of an OPC for the generator:

- Level of power of the generator and power supply to the grid;
- Technical data of the generator (e.g. reactance);
- Whether a power system stabilizer is installed;
- Technical data of the unit transformer;
- Configuration of star point connection of the unit transformer;
- Length of the line between the transformer and location of the OPC (capacitance, etc.);

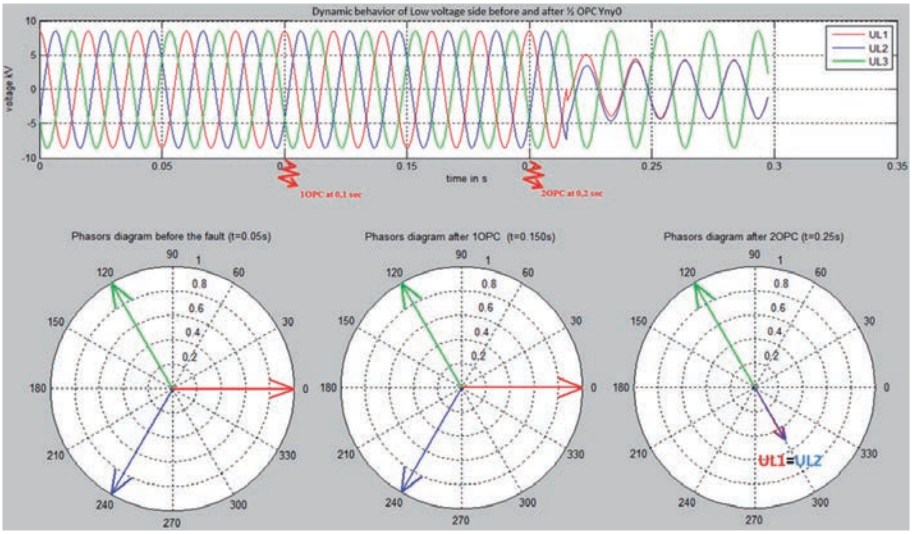

FIG. 8. Phase to earth voltages on the low voltage side of an unloaded YNy0 transformer before and after an OPC.

— Short circuit power of the grid;
— Earth fault factor at the grid connection point (low earth fault factor means a high number of solidly earthed star points in the grid).

In general, a higher power supply of the generator to the grid results in a higher unbalanced current for the generator. This causes greater stress to the affected components but simplifies the detection of the OPC by the unit's protection system. However, it cannot be assumed that the unit protection will trigger fast enough to protect all of the components on the safety buses in the case of an OPC. The two earthing cases are described below.

(a) Unit transformer star point solidly earthed

In the case of a single OPC on the high voltage side of the unit transformer, a power oscillation of the generator on the grid, with an unbalanced load, is likely to occur. A disconnection of the generator by the unit protection system depends on the values reached and on the protection settings. This has to be investigated for every plant or plant type.

The on-site power system is also affected, depending on the connection arrangement and motors in operation. Unbalanced protection of the motors could also be activated in this case.

In the case of a double OPC on the high voltage side of the unit transformer, the generator will become asynchronous with the grid. Generally, the unit protection system will not be able to detect this situation in all cases. Therefore, investigations for every plant or plant type are necessary.

The on-site power system is also affected and protective devices in this system could be activated, depending on the values reached and the protection settings.

(b) Unit transformer star point not earthed

In the case of a single OPC on the high voltage side of the unit transformer, the generator will become asynchronous with the grid. A disconnection of the generator by the unit protection system will not be performed in all cases and has to be investigated for every plant or plant type. The on-site power system will also be affected and protective devices in this system could be activated, depending on the values reached and the protection settings.

In the case of a double OPC on the high voltage side of the unit transformer, no power supply to the grid is possible. This results in a higher generator speed, and high voltages on the main transformer could occur. A disconnection of the generator by its protection system is likely, but has to be investigated for every plant or plant type. The on-site power system will also be affected and protective devices in this system could be activated, depending on the values reached and the protection settings.

3.3. EFFECTS ON ELECTRICAL EQUIPMENT

The unbalanced three-phase voltage system impacts electrical equipment in different ways. This section focuses on the most challenging aspects for typical electrical equipment in the on-site power system.

3.3.1. Induction motors

Unbalanced voltages applied to a three-phase induction motor result in unbalanced currents in the stator windings and introduce a negative sequence voltage. The negative sequence voltage produces a flux rotating in the opposite direction to the rotation of the rotor, producing additional currents and heat. The symmetrical components method used to calculate negative sequence voltage from observed voltage readings of the three phases is explained in Annex I.

The unbalanced conditions result in heating of the motor. Operating experience shows that the temperature rise of the motor, operating at a particular load and with a given magnitude of voltage imbalance, is generally higher than operation under balanced conditions.

A small negative sequence component of the voltage may produce currents in the windings that are considerably larger than those present under balanced voltage conditions, due to the relatively small negative sequence impedance of the motor. The negative sequence current level (I_2/I_1) at operating speed will typically be of the order of 5–10 times the voltage imbalance level (U_2/U_1) (see examples in Ref. [11]).

OPCs are often associated with a reduction of the positive sequence component of the voltage, which causes an increase of the positive sequence components of the currents in the stator if the load under consideration is a constant power load.

Despite the increased current consumption of the motor during unbalanced voltages, the torque will decrease as a result of the reduction in positive sequence voltage. If the voltage imbalance is severe, the torque might not be adequate for the intended function of the motor.

The negative sequence system rotates with twice the line frequency in the opposite direction to the positive sequence system (see Annex I). This causes an oscillating torque of twice the line frequency within the induction motor. A critical torsional speed close to twice the line frequency has to be avoided in order to minimize excitation of impermissible torsional vibrations of the complete shaft system due to the unbalanced voltage.

The full load speed generally reduces when the motor operates with unbalanced voltages because of the higher slip associated with the additional losses.

Where the motor is connected to a pump, the available torque and the heating of the motor are the critical factors. For motor operating valves, the available torque is critical for performing the intended function (open/close). Voltage imbalance may also result in changes in noise and vibration.

According to internationally accepted manufacturing standards [12], a negative sequence voltage component below 1% of the positive sequence voltage component is acceptable for continuous operation. Operation between 1% and 5% negative sequence voltage is possible with reduced power, if the positive sequence voltage is near the rated voltage value. Operation of a motor above a 5% imbalance condition is not recommended and will probably result in damage to the motor.

3.3.2. Converters and battery chargers

Figure 9 shows an example of a power supply to an uninterruptible power system, incorporating direct current (DC) and AC safety loads. The

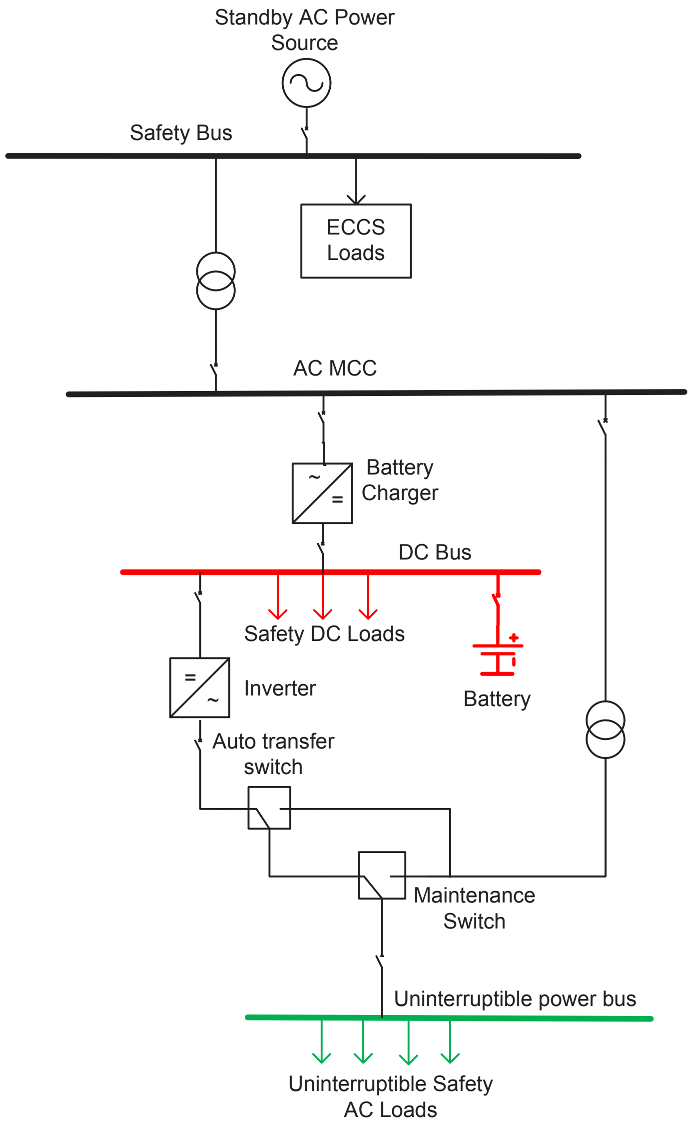

FIG. 9. An example of an uninterruptible AC power supply. DC: direct current.

uninterruptible AC loads are typically supplied from either the DC bus through an inverter (normal supply) or a bypass source.

In cases of unbalanced voltage on the motor control centre AC bus, the uninterruptible AC power system functionality can be impacted. In addition to degrading the bypass source (an undetected failure), the voltage imbalance may cause the rectifier/battery charger to shut down owing to the input voltage being out of tolerance.

Typically, the rectifier/battery charger will restart automatically when the input voltage returns to acceptable limits for a minimum duration. For some designs, the voltage imbalance can trip the rectifier, requiring a manual action to reset the rectifier before the battery is completely discharged.

It is important to ensure that the protection arrangements of rectifiers and battery chargers are consistent with the overall protection philosophy of the whole nuclear power plant, and that the philosophy adequately considers all electrical fault scenarios, including an OPC.

3.3.3. Transformers

Transformers are generally robust electrical components and are subjected to negative sequence current during steady state and transient operating conditions, including during an OPC. The voltage imbalance and negative sequence current is generally not an issue as transformers are designed to operate under non-symmetrical loading conditions for extended durations.

However, if the rated current of the transformer is exceeded due to unbalanced conditions, the heating effect can degrade the life of the transformer insulation and, as such, the loading condition during an OPC needs to be evaluated. It is also noted that cable and transmission line capacitances can impact the voltage observed during an OPC at the transformer terminals when it is in standby mode, e.g. capacitance on the high voltage side can lead to elevated voltages on the low voltage side.

3.3.4. Main generator

The main generator will be exposed to negative sequence current during an OPC which can cause damage to the generator if it is not disconnected in a timely manner. The field produced by the negative sequence currents in the stator will induce current in the rotor with twice the line frequency. This current in the rotor creates heat, which, if it is excessive and persists for a long time, will damage the rotor.

Main generators are, therefore, typically equipped with negative sequence current protection relays. In general, synchronous generators are designed to operate with a negative sequence current equal to the rated current of the machine for some duration. A general operating principle for the protection scheme is according to the following equation:

$$t = \frac{K}{I_2^2} \quad (1)$$

where

t is the time in seconds;

I_2 is the negative sequence current in per unit value;

and K is a constant in seconds which is specific to the machine.

The constant K in Eq. (1) represents the time during which a negative sequence current equal to the rated current of the machine can be sustained without significant damage to the insulation.

Generators are capable of withstanding the effects of continuous small current imbalance. The value is typically between 5% and 10% of rated current. There is also a risk that the main generator will pole slip during an OPC if not properly protected. A pole slip can cause damage to the main generator, and protection relays are typically installed to identify the situation. The existing design of pole slip protection schemes generally focuses on pole slip conditions emanating from short circuits or system perturbations that are not cleared in a rapid manner. The ability of the detection and protection capabilities of installed systems must be evaluated in detail for events such as an OPC.

3.3.5. Protection relays

In operating nuclear power plants, existing protection relays, such as undervoltage, overload, overcurrent and negative sequence, will trip associated breakers for some of the unbalanced voltage situations resulting from an OPC. The protective function depends on the magnitude of the imbalance conditions (voltage and/or current), the consequences of the condition (high or low voltage/current), the trip set point and the selected protection logic.

The undervoltage relays may detect an OPC and initiate transfer to an alternative power source, which is the preferred outcome.

Operating experience has shown that induction motors may be disconnected owing to the actuation of an overcurrent or imbalance protection scheme. The higher current flow during an OPC can result in overheating of the motor windings, resulting in permanent damage. Hence, in most cases, it may be prudent to trip large motors in the event of an OPC. Since an OPC can affect more than one train, multiple redundant systems may be degraded simultaneously. Although tripping of the motors protects the motor from being damaged, the motors and driven loads will be unavailable after the relay actuation because manual actions are needed to investigate, reset protective relays where necessary and operate corresponding breakers. The protective actuations can trigger trips for electrical equipment in redundant systems and thus adversely impact or cause delays in the safe shutdown and post-trip heat removal capability of the plant.

In order to prevent inadvertent operation of protection relays compromising the safety requirements of the plant, the design and operating principle of protection relays has to be understood to ensure that they consistently detect potentially damaging unbalanced phase conditions under all system operating configurations.

3.3.6. Panel meters and metering schemes

Unbalanced voltages and currents may not be accurately reflected in the panel meters and metering schemes. This can mislead operators in their understanding of the situation and result in inappropriate or delayed actions.

3.3.7. Standby AC power source

Depending on, among other things, the type of OPC, transformer configuration, loading conditions and the set points of undervoltage relays installed at the safety buses, the imbalance conditions may not be detected. In this case, the disconnection of the preferred power source affected by the OPC and the energizing of the safety bus from the standby AC power source will not be automatically initiated. As a result, the equipment needed for safe shutdown of the plant may not be able to function satisfactorily.

3.4. POSSIBLE SYMPTOMS OF OPEN PHASE CONDITIONS

To ensure that operators can promptly diagnose and respond to OPCs until longer term corrective actions can be completed, training that includes typical symptoms of an OPC is crucial.

The following list gives examples of symptoms indicative of an OPC:

- Changes in sound level or heat;
- Vibration of equipment;
- A variety of equipment (different/independent systems or trains) starts tripping;
- Loads are not able to start, or when started run for a short period of time before tripping off;
- Unbalanced currents or voltages;

— Lights become darker or flicker (if aligned to the power supply with an OPC);
— Alarms of electrical equipment are triggered (e.g. negative sequence protection, temperature and vibration monitoring);
— Alarms for low voltage;
— Alarms from rectifiers;
— Earth faults might indicate an OPC (an OPC creates zero sequence components, which is equivalent to earth fault behaviour (see Annex I));
— Comparator units within the reactor protection system that monitor all three phases of emergency busbar voltage may initiate an alarm.

It is to be noted that this list does not represent final technical solutions, but rather provides operating personnel with symptoms of an OPC at the plant.

4. EVALUATION OF DESIGN VULNERABILITIES

4.1. INTRODUCTION

Based on the effects of OPCs that have been observed in a number of events to date, it is important that the power plant (licence holder):

— Train plant operating personnel to recognize and respond to an OPC;
— Analyse the design, understand the effects under all operating states and ensure that appropriate protective measures are in place, such that equipment important to safety continues to function as intended.

A review of the plant design, equipment requirements, electrical power system configuration and analysis is needed to obtain a complete understanding of the plant's response under OPCs.

Based on differences in design, various alignments need to be evaluated to assess the impact of OPCs on systems and components. The vulnerability and consequences of an OPC on the equipment needed for plant safety is dependent on several factors that include design and operating practices of nuclear power plants.

The focus of the evaluations is to verify that electrical equipment important for safety will not be prevented from operating or be unavailable to perform its intended (safety) function.

The following sections describe the steps that need to be taken when evaluating a plant for potential design vulnerabilities. The steps have to be performed for all the plant states and conditions discussed in Section 2:

- The magnitude of the unbalanced voltage and current needs to be systematically determined by calculation or simulation (see Section 4.2).
- The existing protection relays and instrumentation response to the unbalanced condition and the consequences thereof need to be determined (see Section 4.3).
- The ability of the electrical equipment to withstand and perform its intended function during the unbalanced condition needs to be verified (see Section 4.4).
- The plant's behaviour and the safety significance of the information obtained from the above points need to be evaluated to see whether the plant is vulnerable to an OPC (see Section 4.5).
- If the plant is vulnerable, the voltage and/or current prior to an OPC is evaluated before implementing permanent corrective actions. It is advised that the evaluation considers steady state and short term disturbances such as a lightning strike, switching surges and transformer energization (see Section 4.6).

4.2. CALCULATION AND SIMULATION

To determine the magnitude of unbalanced voltage and current, a systematic evaluation or simulation study is necessary. The study needs to cover OPCs under all electrical system configurations and loading conditions.

Simulations performed for some nuclear power plants show that the system response to an OPC can be accurately predicted through modelling. Results show that during lightly loaded conditions voltage monitoring alone will not detect all OPCs. It also shows that the system response to an OPC depends on several parameters, for example, the transformer connection and core configuration, loading of the transformer, type of consumer and earthing principle.

4.2.1. Software

Commercial software is available for the calculation and simulation of unbalanced conditions including OPCs in electrical power systems. The limitations and assumptions of the software have to be clearly understood. The results need to be adequately validated. Sections I–7.3 to I–7.7 of Annex I show an example of a calculation method for validating purposes.

4.2.2. Modelling of transformers

The transformer is one of the critical components when modelling an OPC. To accurately simulate the behaviour of the transformer, the appropriate positive sequence, negative sequence and zero sequence impedances of the transformer need to be considered in the model.

These parameters are affected by a number of factors associated with transformer design, including vector group, number of limbs, system earthing, short circuit impedances, magnetizing current and no-load losses.

Annex IV provides examples of the flux paths that can exist within common transformer configurations during single OPCs.

4.2.3. Modelling of loads

All types of load within the system need to be modelled. In addition to transformers, induction motors regenerate voltage within the system during an OPC. For this reason, large induction motors in each plant state have to be modelled in detail.

To accurately predict the behaviour of the induction motor, the appropriate positive sequence, negative sequence and zero sequence (zero sequence if there is a solidly or low impedance earthed system) impedances of the induction need to be considered in the model.

4.3. EXISTING PROTECTION SCHEMES AND INSTRUMENTATION

4.3.1. Protection schemes

The sensitivity of existing protection relays in OPCs, such as overload, negative sequence current and undervoltage, needs to be fully understood.

The measuring principle needs to be taken into consideration as well, such as phase to phase, phase to earth and symmetrical components and whether there is coincident logic, such as ‘two-out-of-two’ or ‘two-out-of-three’. These details are needed to draw the right conclusions regarding the behaviour of protection relays and instrumentation during an OPC.

The configuration of existing protection relays typically includes:

— Overload protection schemes configured to sense current in less than three phases, because overload is normally a symmetrical phenomenon. In a situation with an OPC, the current in one or more phases can be lower than the set value of the overload protection, but, at the same time, current in the remaining phases can be excessive and detrimental to the motor.

— Overload protection schemes that are configured to sense current in all three phases. It should be noted that the logic used by the protective scheme may be configured by the original equipment manufacturer to actuate based on specific conditions, such as overcurrent in two-out-of-three phases or three-out-of-three phases, and the design or operating philosophy may not be clearly delineated in the manufacturer supplied instruction manuals. In such cases, the original equipment manufacturer needs to be contacted, or specific testing needs to be performed to clarify the functionality of the overload protection for unbalanced currents.
— Undervoltage protection that can be configured in many ways, for example, phase to phase voltage, phase to earth voltage, coincident logic between the three phases, and a positive sequence component filter. Operating experience and simulations show that the magnitude of at least one phase to earth or phase to phase voltage can be within the normal operating range, although the voltage imbalance may be excessive.
— Degraded voltage schemes designed to detect low voltage conditions that occur in all three phases. To preclude spurious trips, coincident logic such as two-out-of-three or three-out-of-three actuation schemes are used. As such, these schemes may detect an OPC, but may not actuate or trigger an alarm about the condition owing to the logic used. In addition, positive sequence filters[1] may also mask an unbalanced voltage. It is, therefore, prudent to evaluate the plant specific design of undervoltage detection schemes to establish the adequacy of the protection afforded by existing designs.

4.3.2. Accuracy for measuring channels

Measuring transformers are associated with ratio error and phase displacement errors, and the acceptable error according to manufacturer standards increases for smaller currents and voltages. These errors mean that the primary current and voltage will not be reflected accurately on the secondary side of the measuring transformer. The accuracy of the measuring transformers needs to be considered when evaluating a permanent corrective solution to cope with an OPC.

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[1] The positive sequence filter uses all the phases and creates a kind of average value of all of them, taking the phase angles into account and, hence, masks low values in one or several phases.

The most challenging OPC to identify is the lightly loaded condition, i.e. small currents. Existing transformers are adapted for significantly higher currents than those under lightly loaded conditions. When analysing the detectability of the OPC, i.e. the ability of protection systems to detect it, the accuracy of current transformers needs to be taken into consideration.

The measurement method has to be considered carefully. Voltage measurement has the advantage of measuring the full magnitude of all phasor voltages, since a voltage transformer will be operating closer to its rated value. Current sensing involves the measurement of a small magnitude in comparison with the current transformer rating, hence reducing the accuracy. However, owing to the lower impedance of the negative sequence system, the ratio I_2/I_1 (negative sequence current/positive sequence current ratio) is much easier to measure than V_2/V_1 (negative sequence voltage/positive sequence voltage ratio) for a given asymmetry.

4.4. ELECTRICAL EQUIPMENT WITHSTAND CAPABILITY

During an OPC, energized equipment in the on-site electrical power system is potentially exposed to unbalanced voltage or current conditions.

The equipment upstream of the OPC may not be subjected to damaging conditions and is expected to operate satisfactorily. The rotating and static equipment connected to the buses downstream of the OPC will require detailed evaluation as they will potentially operate under abnormal voltage and current conditions.

The nuclear power plant on-site power system and, specifically, the safety equipment, such as motors, battery chargers/rectifiers, transformers and current transformers, have to be analysed to determine whether they are capable of withstanding the unbalanced conditions.

If the duration or the magnitude of the postulated unbalanced conditions has the potential to degrade safety system performance capabilities, the equipment has to be either disconnected by protective schemes prior to damage or upgraded to withstand the maximum unbalanced conditions.

4.5. EVALUATION OF VULNERABILITIES

Evaluations performed in many plants after the events described in Section 6 have revealed design vulnerabilities for an OPC. When examining the vector figures in Section 3, it is obvious how the transformers and connected loads can reproduce the voltage with both a single and double OPC. This reproduction of voltage downstream of the open phase circuit makes it difficult to detect, and respond to, with the existing configuration of instrumentation and protection relays.

It is advised that all nuclear power plant operators verify whether the existing on-site and off-site power system relay protection schemes have the capability to detect and disconnect an OPC using the information from the activities in Sections 4.2–4.4.

If the verification identifies vulnerabilities, interim measures have to be taken at the nuclear power plant. These may include verifying that the shift personnel have sufficient guidance to promptly diagnose and respond to an OPC, and ensuring that these measures are included in operator training programmes. The symptoms of OPCs have already been discussed in more detail in Section 3.4.

After the implementation of interim measures, the nuclear power plant operator needs to evaluate which detection scheme for OPCs is appropriate for the plant's specific electrical system configuration, and implement this detection scheme in the long run. Where the analysis shows that the timescales for disconnection of an OPC are not consistent with manual operation, automatic disconnection measures will have to be implemented.

4.6. PRE-OPEN-PHASE UNBALANCED VOLTAGE AND CURRENT

A steady state voltage imbalance is usually present in electrical power systems due to:

- Imbalance caused by impedance of the system owing to differences in cable lengths or transformer configurations — on-site or off-site;
- Imbalance caused by minor variations in the design of each phase of large loads — on-site or off-site;
- Unequal distribution of single phase loads between all phases — on-site or off-site.

A transient voltage imbalance occurs in electrical systems due to perturbations caused by events such as switching, large motor starts, transformer energization and lightning strikes. These imbalances do not last longer than a few seconds.

Both long term minor imbalances and short term transients, such as those already mentioned, are considered 'normal' pre-open-phase imbalances and equipment manufacturers design their equipment to operate under pre-open-phase unbalanced conditions.

In order to avoid spurious trips, the magnitude of the unbalanced conditions during normal operation and momentary transient conditions, such as line switching, transformer energization or other perturbations, will have to be established. These conditions are necessary to design the detection and protection set points (time delay and magnitude). Analytical studies and experience indicate that monitoring these conditions at several locations in the electrical power systems provides a better understanding of the development of the set points for the OPC detection scheme.

5. EXISTING PRACTICES AND DESIGN PROVISIONS

OPCs were not explicitly considered in the original electrical power system analysis of almost all existing nuclear power plants and, hence, the configuration of the existing instrumentation and protection schemes may not detect an OPC in a clearly defined way in all plant states. This applies especially for non-power operations, where the lower loads and lack of detection by generator negative phase sequence protection schemes make OPCs less likely to be detected.

Sections 5.1 and 5.2 list examples of possible interim solutions and provisions for permanent corrective solutions, respectively.

5.1. INTERIM MEASURES

To ensure that plant operators can promptly diagnose and respond to an OPC until permanent corrective solutions are implememted, interim corrective measures are recommended. Each plant operator needs to evaluate possible interim measures to diagnose and respond to an OPC.

The following list gives examples of interim measures that can be implemented to diagnose and respond to an OPC:

- Performing walk downs that can detect a visible loss of phase;
- Inspections, by thermography, during routine preventive maintenance inspections of the switchyard to support the early identification of degraded electrical equipment;
- Increasing the robustness of switchyard equipment to minimize the probability of an OPC;

— Aligned normal configuration of safety buses to different off-site sources (only for some plants);
— Periodic surveillance load test of transformers in standby;
— Assignment of a designated operator to monitor safety bus voltage and remotely open breakers in the event of an OPC;
— Aggregation of information (e.g. multiple equipment alarms, trips, vibration, temperature);
— Modification of undervoltage coincident logic from a two-out-of-two to a two-out-of-three configuration to enhance identification of an OPC;
— Alignment of plant voltmeters to ensure that all phases are monitored;
— Enhancement of procedures for verification of the voltages in all phases;
— Enhancement of procedures to provide clear operator directions for the response to an OPC (e.g. alarm response, voltage readings, current readings, motor trips, battery charger trips);
— Procedures for manual bus transfer verified to ensure that three-phase voltages are checked prior to bus transfers and that the bus voltage is checked on the bus voltmeter after the bus transfers;
— Installation of new protection relays in an alarm mode to detect an OPC;
— Training and briefing of operators to recognize the behaviour of equipment associated with an OPC (e.g. voltage readings, current readings, motor trips, sound level, motor vibration, motor temperature and battery charger trips).

Most of the interim solutions can be kept as permanent solutions after implementation of the permanent corrective technical solutions.

5.2. PERMANENT SOLUTIONS

Understanding the behaviour of magnitude and angle of phase to phase, phase to earth, positive, negative and zero sequence voltage and current caused during an OPC is fundamental for the application of corrective detection and protection methods. References [13, 14] are technical papers that include detection and protection methods for OPCs.

The unbalanced voltage primarily impacts the electrical equipment connected downstream of the open phase circuit, while electrical equipment upstream of the open phase circuit is, more or less, unaffected. The unbalanced current affects electrical equipment both downstream and upstream of the open phase circuit.

5.2.1. General

When an OPC has been identified as a vulnerability to the electrical power systems, the following design principles need to be considered:

- — Reliability of OPC detection;
- — Spurious actuation concerns;
- — Prevention of loss of all redundant safety features owing to a failure of the OPC detection system.

Each plant would have to evaluate permanent corrective solutions to diagnose and respond to an OPC. These permanent corrective solutions could be based on an on-line detection scheme to provide a prompt identification of an OPC on off-site power sources.

The design of detection and protection schemes, and any automatic or manual actions are subject to plant specific evaluation of the consequences of an OPC.

The primary objective is to have a reliable scheme. In order to avoid spurious actuation, the pre-OPC imbalances (described in Section 4.6) need to be considered when selecting the protective measures. The use of multiple protection relays from different suppliers in an '*x* out of *y*' logic may increase the reliability of the detection scheme [15].

To ensure the correct operation of the electrical equipment (safety and non-safety), the capability to withstand an OPC (see Section 4.4) needs to be taken into account when selecting set points. The new protective measures need to be coordinated with any existing protection schemes.

In general, an OPC is not postulated to occur on multiple off-site or on-site circuits simultaneously, but it has to be considered whether the grid configuration could allow a single OPC to affect more than one off-site power source simultaneously.

The preferred solution would be to detect an OPC on the low voltage side of the transformers associated with the off-site power sources, as it enables OPCs on high voltage and low voltage sides to be recognized. However, plant specific analysis may identify that not all OPCs can be detected, especially when a transformer is lightly loaded or unloaded. A combination of detection schemes on the high voltage and low voltage sides of the transformers may facilitate a comprehensive solution for all plant operating conditions and plant configurations.

The design of the protective system needs to consider disconnecting only the power source affected by the OPC in accordance with the defence in depth concept.

The testing requirements need to be commensurate with the safety classification of the OPC detection scheme.

5.2.2. Actuation logic

The actuation logic of the implemented permanent solutions may depend on the protected area and plant load.

For example, if a transformer is in standby mode, without a load, an alarm is activated, indicating an OPC in the off-site power system. The OPC, in this case, does not affect any downstream equipment; therefore, the operating personnel has some time to cope with the OPC.

If the transformer is in service mode with a load, an alarm is activated, indicating that the OPC is in the off-site power system. The time to respond to an OPC needs to be evaluated on a plant design basis.

Some plants may conclude that automatic disconnection is not necessary because manual actions are fast enough to prevent impairments of equipment important to safety. Where necessary, automatic disconnection ensures operating equipment is not exposed to an OPC for an extended duration. The alternate off-site or on-site source is then automatically aligned to maintain plant safety.

5.2.3. Solutions on the high or low voltage side of the transformer

Where a permanent protective solution is considered, it will likely involve the measurement of one or more of the following parameters (see examples in Annex II):

— Negative sequence voltage;
— Negative sequence current;
— Magnetization current;
— Zero sequence current;
— Zero sequence voltage;
— Current injection;
— Phase to phase or phase to earth voltage (properly set for unbalanced conditions due to an OPC).

The above list is not comprehensive. Other measurements or combinations of the above measurements can be used as well.

5.3. SAFETY CLASSIFICATION

Reference [15] provides recommendations and guidance on how to meet the requirements established in Ref. [16] for the identification of items important to safety and for their classification on the basis of their function and safety significance. However, categorization and classification have to be determined in accordance with country specific requirements.

6. OPERATING EXPERIENCE

A loss of off-site power event belongs to the group of anticipated operational occurrences that is analysed in every nuclear power plant safety analysis.

The safety standby AC power sources are designed to provide reliable power supply to safety buses in case of a loss of off-site power event, or in case the electrical power is lost to an individual safety bus for another reason.

The design of the on-site power supply system is typically redundant in order to minimize simultaneous loss of AC power to all safety buses.

OPCs have not, in general, been fully considered in the design of nuclear power plants worldwide. Several events over the past few years have shown that the safety of nuclear power plants can be challenged by OPCs (Table 1). A description of the events listed in Table 1 is provided in Annex III with more specific details.

TABLE 1. EXAMPLES OF EVENTS WITH OPEN PHASE CONDITIONS

Year	Nuclear power plant	Description of event
1994	Kalinin Unit 1 (Russian Federation)	Loss of unit auxiliary power and loss of power to essential loads.
1997	Balakovo Units 1 and 3 (Russian Federation)	Loss of unit auxiliary power at two units of Balakovo due to breaker failure in the 220 kV switchyard.
2000	Heysham 2 (United Kingdom)	A single OPC in a 400 kV transmission circuit breaker resulted in a manual reactor trip. The condition was undetected for approximately 2 h.
2005	Koeberg (South Africa)	A 400 kV busbar event.
2005	James A. FitzPatrick Nuclear Power Plant and Nine Mile Point Unit 1 (United States of America)	A single open phase circuit in the 115 kV transmission line caused by a broken busbar connector. The busbar connector failure went undetected for approximately 21 days.
2006	Vandellòs Unit 2 (Spain)	A voltage imbalance detected between the phases of the main generator caused actuation of electrical protection with a subsequent turbine and reactor trip.
2007	Beaver Valley Unit 1 (United States of America)	A single open phase circuit of a 138 kV off-site power circuit caused by a broken conductor in the switchyard.
2007	Dungeness B (United Kingdom)	A single OPC in a 400 kV transmission system breaker resulted in an OPC to station supplies. Several motors tripped on thermal overload over a period of 3 days until the fault was identified.
2011	Ringhals Unit 2 (Sweden)	One pole of the standby AC power source generator breaker did not work properly during a load run test (only affected one safety train).
2012	Byron Unit 1 (United States of America)	A single OPC in the 345 kV side of the station auxiliary transformer due to a failure in an under-hung insulator.

TABLE 1. EXAMPLES OF EVENTS WITH OPEN PHASE CONDITIONS (cont.)

Year	Nuclear power plant	Description of event
2012	Byron Unit 2 (United States of America)	A broken insulator stack for the phase C conductor on the 345 kV power circuit that supplies both station auxiliary transformers caused a single OPC.
2012	Bruce A Unit 1 (Canada)	A single OPC in the 230 kV side of the system service transformer due to a drop line that broke from the baseplate connecting it to the system service transformer.
2013	Forsmark Unit 3 (Sweden)	Human error and a loose cable resulted in a double OPC in the 400 kV breaker. The failure was not detected by the loss of voltage relays. As a result, the standby AC power sources did not automatically start.
2014	Dungeness B (United Kingdom)	A single OPC in a 400 kV transmission system breaker resulted in an automatic main generator trip and manual transfer of station supplies to on-site essential and backup diesel generators.

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Annex I

CALCULATIONS FOR VALIDATING PURPOSES: SYMMETRICAL COMPONENTS

I–1. GENERAL

Unbalanced faults can be: (a) Shunt faults: single line to earth fault, line to line fault and double line to earth fault; or (b) Series faults: single open phase condition (OPC) and double OPC, with or without coincident connection to earth.

The method of symmetrical components resolves the solution of an unbalanced circuit into a solution of a number of balanced circuits. Symmetrical components allow unbalanced phase quantities, such as currents and voltages, to be replaced by three separate balanced symmetrical components. Where 1, 2 and 0 are used they represent positive, negative and zero sequence components (Fig. I–1).

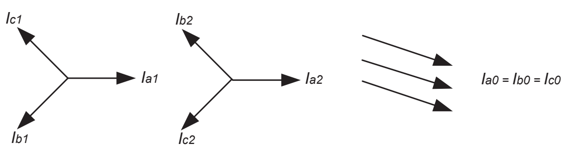

FIG. I–1. Representation of symmetrical components.

Positive sequence components consist of a set of balanced three-phase components with a phase sequence abc. The positive sequence system is the system normally considered in, for example, load flow analysis. Negative sequence components consist of a set of balanced three-phase components with a phase sequence acb. Zero sequence components consist of three single phase components, all equal in magnitude and phase angle.

In a symmetrical system, there is no interaction between components in different sequences; currents of any one sequence may be considered to flow in an independent network associated with that sequence only.

The unbalanced currents, in terms of symmetrical components, are as follows (similar expressions exist for phase voltages):

$$I_a = I_{a1} + I_{a2} + I_{a0} = I_1 + I_2 + I_0$$
$$I_b = I_{b1} + I_{b2} + I_{b0} = a^2 I_1 + aI_2 + I_0$$
$$I_c = I_{c1} + I_{c2} + I_{c0} = aI_1 + a^2 I_2 + I_0 \qquad \text{(I–1)}$$

The operator *a* represents a 120° phase shift and is equal to the unit vector $\boldsymbol{e^{j120}} = -0.5 + j0.866$. The operator a^2 represents a 240° phase shift and is equal to the unit vector $\boldsymbol{e^{j240}} = -0.5 + j0.866$. Figure I–2 graphically visualizes the resolution of unbalanced phasors into symmetrical components in accordance with the previous equations.

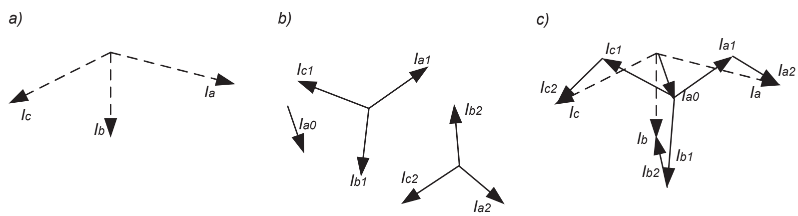

FIG. I–2. Resolution of unbalanced phasors into symmetrical components.

The symmetrical components, in terms of unbalanced currents, are as follows (similar expressions exist for phase voltages):

$$I_1 = \frac{1}{3}\left(I_a + aI_b + a^2 I_c\right)$$
$$I_2 = \frac{1}{3}\left(I_a + a^2 I_b + aI_c\right)$$
$$I_0 = \frac{1}{3}\left(I_a + I_b + I_c\right) \qquad \text{(I–2)}$$

Symmetrical components appear in different types of fault according to Table I–1 (also depending on system earthing). It is, therefore, possible to distinguish between different fault types using symmetrical components.

TABLE I–1. DIFFERENT TYPES OF FAULT FOR SYMMETRICAL COMPONENTS

Three phase to phase short circuit:	Positive sequence
Two phase to phase short circuit:	Positive sequence Negative sequence
Single line to earth fault, double line to earth fault, and OPC	Positive sequence Negative sequence Zero sequence

I–2. SEQUENCE IMPEDANCES

The impedance of a circuit when positive sequence currents alone are flowing in the circuit is called the positive sequence impedance. Similarly, impedance to negative sequence currents is called negative sequence impedance, and the impedance to zero sequence currents is called zero sequence impedance.

Sequence impedance is specific for each unique power system element, transformer, motor, generator, cable, line, etc. Describing the different sequence impedances of the power system elements is out of the scope of this publication.

To analyse the system performance where there is an unbalanced fault, the sequence networks are interconnected at the fault location to represent the interaction between quantities of different sequences due to imbalance created by the fault.

I–3. SINGLE OPEN PHASE CONDITION

A single OPC may be caused by a broken conductor, single phase switching operation or opening of one breaker pole. Figure I–3 shows a section of a three-phase system with phase *a* open between points x and x’. For the single OPC on phase a (Fig. I–3), the boundary conditions are $\Delta U_b = \Delta U_c = 0$ and $I_a = 0$.

The connection of sequence networks in a single OPC is depicted in Fig. I–4.

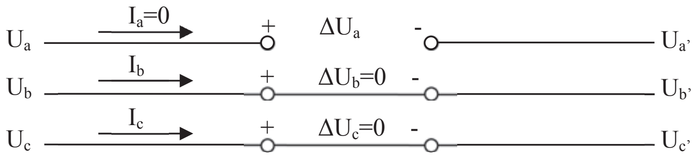

FIG. I–3. Section of a three-phase system with phase a open.

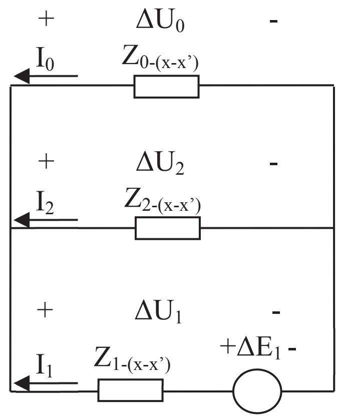

FIG. I–4. Connection of sequence networks in a single OPC.

I–4. DOUBLE OPEN PHASE CONDITION

A double OPC may be caused by the opening of two breaker poles. Figure I–5 shows a section of a three-phase system with phases b and c open between points x and x′. For the double OPC on phases b and c, the boundary conditions are $\Delta U_a = 0$, $I_b = I_c = 0$.

The connection of sequence networks in a double OPC is depicted in Fig. I–6.

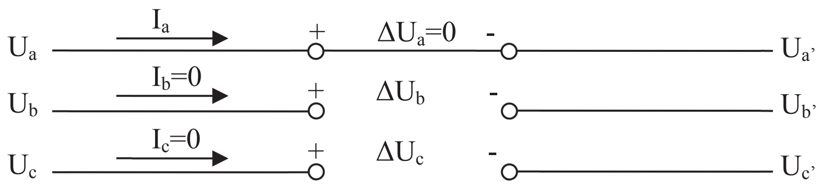

FIG. I–5. Section of a three-phase system with phases b and c open.

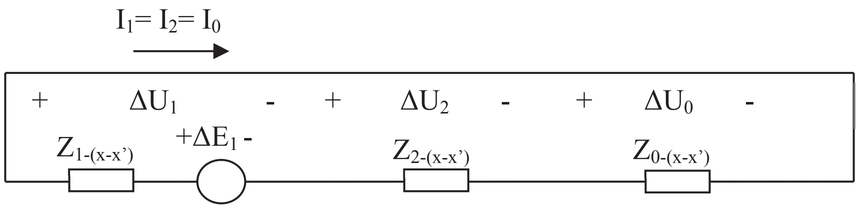

FIG. I–6. Connection of sequence networks in a double OPC.

I–5. GENERAL ANALYSIS

I–5.1. Double open phase condition in unearthed/high impedance earthed power systems

In an unearthed or high impedance earthed system, the zero sequence impedance, $Z_{0\,-\,(x\,-\,x')}$, is much higher than the positive sequence impedance, $Z_{1\,-\,(x\,-\,x')}$, and the negative sequence impedance, $Z_{2\,-\,(x\,-\,x')}$. For a double OPC when the connection of sequence networks is in series, the symmetrical component currents will be identical and very small.

This means that running loads will stop or not be able to start, and that double OPCs are only relevant in loaded solidly earthed or low impedance earthed power systems. Double OPCs are not relevant for high impedance earthed systems because the positive sequence voltage downstream of the open phases will go to zero and that is an already known and analysed condition in the electrical power system.

I–6. CALCULATIONS

I–6.1. Single open phase condition

From Fig. I–4, the symmetrical currents can be calculated according to Eq. (I–3):

$$I_1 = \frac{\Delta E_1}{Z_{1-(x-x')} + Z_{2-(x-x')} // Z_{0-(x-x')}} \tag{I–3}$$

Current division yields:

$$I_0 = \frac{Z_{2-(x-x')}}{Z_{2-(x-x')} + Z_{0-(x-x')}} I_1 \tag{I–4}$$

$$I_2 = \frac{Z_{0-(x-x')}}{Z_{2-(x-x')} + Z_{0-(x-x')}} I_1 \tag{I–5}$$

The voltage drop in symmetrical components across the open phase is calculated by Eqs (I–6 to I–8):

$$\Delta U_1 = \Delta E_1 - Z_{1-(x-x')} \cdot I_1 \tag{I–6}$$

$$\Delta U_2 = -Z_{2-(x-x')} \cdot I_2 \tag{I–7}$$

$$\Delta U_0 = -Z_{0-(x-x')} \cdot I_0 \tag{I–8}$$

The voltage in symmetrical components downstream of the open phase is calculated by Eqs (I–9 to I–11):

$$U_1' = \Delta E_1 - \Delta U_1 \tag{I–9}$$

$$U_2' = 0 - \Delta U_2 \tag{I–10}$$

$$U_0' = 0 - \Delta U_0 \tag{I–11}$$

I–6.2. Double open phase condition

From Fig. I–6, the symmetrical currents can be calculated according to Eq. (I–12):

$$I_1 = I_2 = I_0 = \frac{\Delta E_1}{Z_{1-(x-x')} + Z_{2-(x-x')} + Z_{0-(x-x')}} \quad \text{(I–12)}$$

The voltage drop in symmetrical components across the open phase is calculated by Eqs (I–13 to I–15):

$$\Delta U_1 = \Delta E_1 - Z_{1-(x-x')} \cdot I_1 \quad \text{(I–13)}$$

$$\Delta U_2 = -Z_{2-(x-x')} \cdot I_2 \quad \text{(I–14)}$$

$$\Delta U_0 = -Z_{0-(x-x')} \cdot I_0 \quad \text{(I–15)}$$

The voltage in symmetrical components downstream of the open phase is calculated by Eqs (I–16 to I–18):

$$U_1' = \Delta E_1 - \Delta U_1 \quad \text{(I–16)}$$

$$U_2' = 0 - \Delta U_2 \quad \text{(I–17)}$$

$$U_0' = 0 - \Delta U_0 \quad \text{(I–18)}$$

I–7. NUMERICAL EXAMPLE OF RESISTIVE LOAD

To demonstrate the effectiveness of the calculation with symmetrical components versus real electrical system behaviour, a numerical calculation example is performed in Sections I–7.4 and I–7.5. To eliminate discussions about the adequacy of software, comparison is done between calculations versus measurements performed in laboratory tests in Ref. [I–1].

In the studies described in Ref. [I–1], tests were performed in a laboratory environment. The laboratory setting was built in order to investigate how three-phase transformers respond to OPCs (single and double) on their high voltage side, with respect to various core designs, winding connections, earth connections and load compositions. All transformers in the laboratory test had a voltage ratio of one, which makes it easier to compare parameters on the high voltage and low voltage side of the transformer.

I–7.1. Three-limbed Y/Y solidly/high impedance earthed transformer

The chosen set-up for the calculation in this section is the three-limbed Y/Y transformer in Ref. [I–1]. The transformer is solidly earthed on the high voltage side, high resistive earthed on the low voltage side and loaded with a pure resistive load (Fig. I–7).

The voltages and currents for all three phases were measured on the high voltage side of the transformer, downstream of the open phase circuit. The voltages and currents for all three phases were also measured on the low voltage side of the transformer (Fig. I–7).

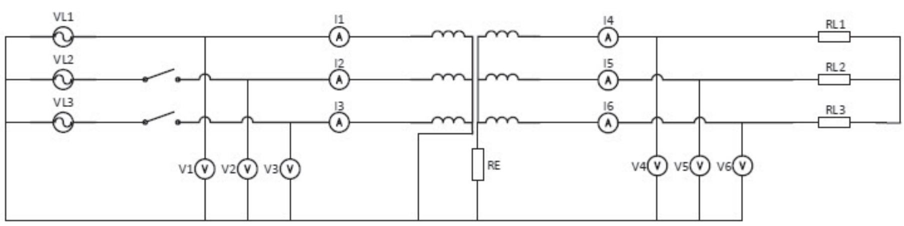

FIG. I–7. Chosen test set-up from Ref. [I–1] for the numerical calculations.

I–7.2. Input data for the calculations

The following input data from Ref. [I–1] and assumptions were used for the calculations.

(a) Grid

The grid is assumed to be infinitely strong, i.e. the impedance of the grid is assumed to be zero; the voltage is 138 V phase to earth [I–1].

(b) Transformer

The positive sequence impedance of the transformer is measured to $0.74 + j0.008$ ohms [I–1]. The negative sequence impedance of the transformer is assumed to be equal to the positive sequence impedance. The zero sequence impedance of the transformer is measured to $0.83 + j3.08$ ohms [I–1]. Magnetizing current is neglected. The voltage ratio equals one.

(c) Load

The load is stated to be 830 W [I–1] and assumed to be 830 W at 138 V phase to earth voltage, which yields $R = (\sqrt{3} \cdot 138)^2 / 830 = 68.83$ ohms per phase.

The negative sequence impedance of the load is assumed to be equal to the positive sequence impedance. The zero sequence impedance of the load is not relevant in this example because of the high impedance earthed transformer that blocks the return path of the zero sequence current.

I–7.3. Calculation of sequence impedances

The grid, transformer and load set-up in the laboratory test, visualized in a single line diagram in Fig. I–8, can be represented by the positive, negative and zero sequence impedances in Fig. I–9.

The low voltage side of the transformer is high resistive earthed and, hence, there is no return path for the current, which means that the only return path for the zero sequence current is through the star point of the transformer.

$$Z_{0\text{-}(x-x')} = (\text{transformer} + \text{grid})\ 0.83 + j3.08 \text{ ohms}$$

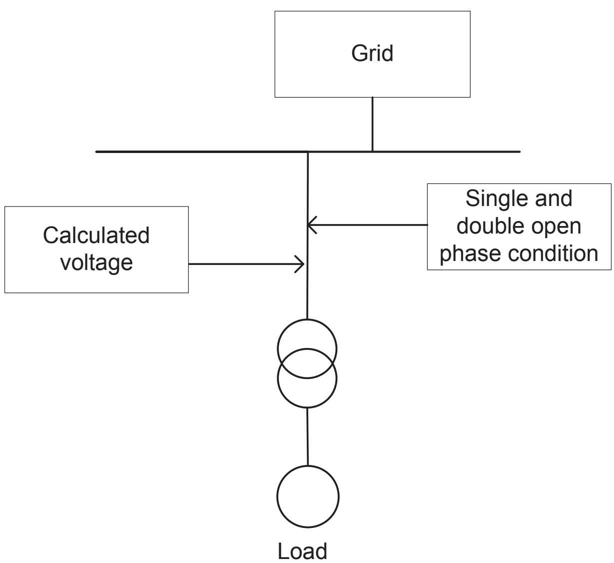

FIG. I–8. Single line diagram for the numerical calculation example.

FIG. I–9. Sequence impedances for the set-up.

Since the positive and negative sequence impedances are equal in this set-up, this implies that $Z_{1\text{-}(x-x')}$ equals $Z_{2\text{-}(x-x')}$.

$Z_{1\text{-}(x-x')} = Z_{2\text{-}(x-x')} =$ (transformer + grid + load) 0.74 + j0.08 + 68.83

= 69.57 + j0.08 ohms.

I–7.4. Single open phase condition numerical example

From Eqs (I–3 to I–5), the symmetrical currents can be calculated as follows:

$$I_1 = \frac{\Delta E_1}{Z_{1-(x-x')} + Z_{2-(x-x')} // Z_{0-(x-x')}}$$

$$= \frac{138}{69.57 + j0.08 + (69.57 + j0.08)//(0.83 + j3.08)} = 1.953 - j0.085 \text{ A}$$

$$I_0 = -\frac{Z_{2-(x-x')}}{Z_{2-(x-x')} + Z_{0-(x-x')}} I_1 = -\frac{69.57 + j0.08}{69.57 + j0.08 + 0.83 + j3.08} \cdot (1.953 - j0.085)$$
$$= -1.923 + j0.168 \text{ A}$$

$$I_2 = -\frac{Z_{0-(x-x')}}{Z_{2-(x-x')} + Z_{0-(x-x')}} I_1 = -\frac{0.83 + j3.08}{69.57 + j0.08 + 0.83 + j3.08} \cdot (1.953 - j0.085)$$
$$= -0.030 - j0.083 \text{ A}$$

The voltage drop in symmetrical components across the open phase is calculated according to Eqs (I–6 to I–8):

$$\Delta U_1 = \Delta E_1 - Z_{1-(x-x')} \cdot I_1 = 138 - (69.57 + j0.08) \cdot (1.953 - j0.085) = 2.1 + j5.8 \text{ V}$$

$$\Delta U_2 = -Z_{2-(x-x')} \cdot I_2 = -(69.57 + j0.08) \cdot (0.030 - j0.083) = 2.1 + j5.8 \text{ V}$$

$$\Delta U_0 = -Z_{0-(x-x')} \cdot I_0 = -(0.83 + j3.08) \cdot (-1.923 - j0.168) = 2.1 + j5.8 \text{ V}$$

The voltage drop in symmetrical components is equal in both magnitude and phase angle, which is expected (see Fig. I–4) concerning the connection of sequence networks in a single OPC.

The voltage magnitude in symmetrical components on the high voltage side of the transformer downstream of the open phase is calculated from Eqs (I–9 to I–11):

$$|U_1'| = |\Delta E_1 - \Delta U_1| = |138 - 2.1 - j5.8| = 136.0 \text{ V}$$

$$|U2'| = |0 - \Delta U_2| = |-2.1 - j5.8| = 6.2 \text{ V}$$

$$|U_0'| = |0 - \Delta U_0| = |-2.1 - j5.8| = 6.2 \text{ V}$$

Only the magnitudes in symmetrical components can be compared with the measurements in Ref. [I–1] because the single OPC is applied in different phases, making the phase angles of the symmetrical components different.

I–7.5. Double open phase condition numerical example

From Eq. (I–12), the symmetrical currents can be calculated as in the following example:

$$I_1 = I_2 = I_0 = \frac{\Delta E_1}{Z_{1-(x-x')} + Z_{2-(x-x')} + Z_{0-(x-x')}}$$
$$= \frac{138}{69.57 + j0.08 + 69.57 + j0.08 + 0.83 + j3.08} = 0.985 - j0.023 \text{ A}$$

The voltage drop in symmetrical components across the open phase is calculated from Eqs (I–13 to I–15):

$$\Delta U_1 = \Delta E_1 - Z_{1-(x-x')} \cdot I_1 = 138 - (69.57 + j0.08) \cdot (0.985 - j0.023)$$
$$= 69.4 + j1.5 \text{ V}$$

$$\Delta U_2 = -Z_{2-(x-x')} \cdot I_2 = -(69.57 + j0.08) \cdot (0.985 - j0.023) = -68.6 + j1.5 \text{ V}$$

$$\Delta U_0 = -Z_{0-(x-x')} \cdot I_0 = -(0.83 + j3.08) \cdot (0.985 - j0.023) = 0.9 + j3.0 \text{ V}$$

The voltage magnitude in symmetrical components on the high voltage side of the transformer downstream of the open phase is calculated according to Eqs (I–16 to I–18):

$$U_1' = \Delta E_1 - \Delta U_1 = 138 - (69.4 + j1.5) = 68.6\angle -1.3 \text{ V}$$

$$U_2' = 0 - \Delta U_2 - = 0 - (-68.6 + j1.5) = 68.6\angle -1.3 \text{ V}$$

$$U_0' = 0 - \Delta U_0 = 0 - (-0.9 - j3.0) = 3.1\angle 73 \text{ V}$$

Both the magnitudes and phase angles in symmetrical components can be directly compared with the measurements in Ref. [I–1] because the double OPC is applied in the same phases.

I–7.6. Measured zero, positive and negative sequence voltage

In Ref. [I–1], the symmetrical component voltages on the high voltage side of the transformer, downstream of the open phase circuit, were calculated from the measured phase to earth voltages.

For a pure single OPC on the high voltage side, the symmetrical component voltages were calculated from the measured phase voltages according to Table I–2.

TABLE I–2. SEQUENCE VOLTAGE HIGH VOLTAGE SIDE, SINGLE OPEN PHASE

Single open phase	V_0	V_1	V_2
Sequence voltage [V]	5.84	135.50	6.11

For a pure double OPC on the high voltage side, the symmetrical component voltages were calculated from the measured phase voltages according to Table I–3.

TABLE I–3. SEQUENCE VOLTAGE HIGH VOLTAGE SIDE, DOUBLE OPEN PHASE

Double open phase	V_0	V_1	V_2
Sequence voltage [V $\angle$ degrees]	2.94 $\angle$ 73.53	67.72 $\angle$ 0.00	69.94 $\angle$ 2.31

I–7.7. Comparison between measured and calculated values

As can be seen in Tables I–4 and I–5, the measured and calculated values correspond very well.

TABLE I–4. SINGLE OPEN PHASE

Single open phase	V_0	V_1	V_2
Measured sequence voltage [V]	5.84	135.50	6.11
Calculated sequence voltage [V]	6.2	136.0	6.2

TABLE I–5. DOUBLE OPEN PHASE

Double open phase	V_0	V_1	V_2
Measured sequence voltage [V ∠ degrees]	2.94 ∠ 73.53	67.72 ∠ 0.00	69.94 ∠ 2.31
Calculated sequence voltage [V ∠ degrees]	3.1 ∠ 73	68.6 ∠ –1.3	68.6 ∠ –1.3

I–7.8. Conclusions on numerical examples

With some assumptions and manual calculations, the behaviour of an OPC can be predicted quite well. The same calculations can also be performed for induction motor loads, but consideration must be given to the different positive and negative sequence impedance of the motor.

If the voltage drop is neglected, the magnitude of the positive and negative voltage is transformed by the voltage ratio through the transformers downstream of the OPC.[1]

A software program is necessary for performing the calculations in a large system but these manual calculations with symmetrical components, including appropriate simplifications, can be used to validate the results from a software program.

I–8. INDUCTION MACHINE EXAMPLE

I–8.1. Equivalent circuit induction machine

Induction machines can be modelled in different ways. The equivalent circuits below are one specific example to demonstrate the concept with symmetrical components for an induction machine type of load.

The equivalent circuit for the positive sequence of an induction machine can be represented by Fig. I–10.

The equivalent circuit for the negative sequence of an induction machine can be represented by Fig. I–11.

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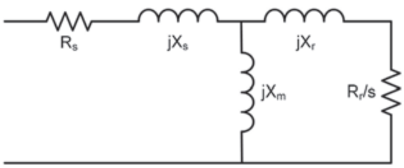
[1] For the positive sequence voltage (the symmetrical voltage normally used), the transformation is obvious. However, the negative sequence voltage is another symmetrical system with a different phase sequence, i.e. the transformation of the magnitude of the negative sequence voltage will follow the voltage ratio of the transformer.

The slip is normally small, which means that the equivalent circuit can be simplified in accordance with Fig. I–12.

Zero sequence components are only relevant if there is a current path available for the zero sequence current in the circuit with the induction machine. Textbooks can be consulted for further details of zero sequence equivalent circuits if needed.



R_s is stator resistance;
X_s is stator leakage reactance;
R_r is rotor resistance (referred to the stator side);
X_r is rotor leakage reactance (referred to the stator side);
X_m is magnetizing reactance;
and s is slip.

FIG. I–10. Induction machine equivalent circuit, positive sequence.

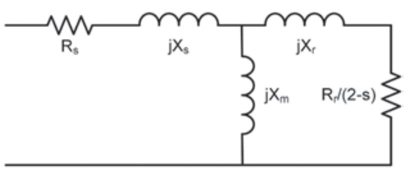


FIG. I–11. Induction machine equivalent circuit, negative sequence.

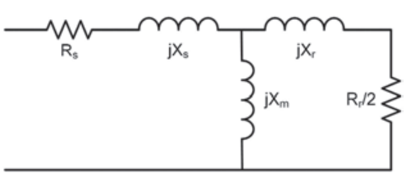


FIG. I–12. Induction machine equivalent circuit, simplified negative sequence.

I–8.2. Numerical example for an induction machine

When performing the calculation with numerical values:

— The numerical data indicated above for the induction machine (or aggregated induction machines) are to be found;
— The load impedances in Fig. I–9 are to be replaced with the equivalent circuits for the induction machine.

The calculations are straightforward and similar to the ones in Section I–7 and because of this are not shown here.

REFERENCES TO ANNEX I

[I–1] CHRISTENSSON, A.E., Transformatorers Beteende vid Fasavbrott i Matande Spänning (2014), http://www.iea.lth.se/publications/MS-Theses/Full%20document/5333_full_document_Transformatorers_beteende.pdf

Annex II

EXAMPLES OF PERMANENT CORRECTIVE SOLUTIONS

II–1. EXAMPLES OF MODIFICATIONS ON THE HIGH VOLTAGE SIDE OF THE AUXILIARY AND STANDBY TRANSFORMERS

The examples cited below may not cover all open phase conditions (OPCs).

II–1.1. Zero sequence current

In an ideal system, the zero sequence current equals zero. In reality, the zero sequence current differs from zero owing to pre-OPC imbalances in the power system. When an OPC occurs in solidly earthed or low impedance, earthed power systems, a zero sequence current of power system frequency appears. The magnitude of the zero sequence current depends on several aspects, such as the loading of the transformers. It is not possible to discriminate all OPCs from pre-OPC imbalances by using zero sequence current measurement.

In some plants, new protection relays are installed using the current transformers in the transformer star point of solidly earthed transformers. The intent is to identify small earth fault currents (zero sequence) arising from an OPC. The set point is chosen low enough to identify a single OPC in a lightly loaded system, but high enough to avoid pick-up for pre-OPC imbalances.

In order not to activate spurious trips, the function is set to alarm mode only. Alarm mode is acceptable if it can be shown that the power supply for the safety power system has enough capacity.

II–1.2. Magnetizing current

In the case of normally unloaded transformers (e.g. standby transformers), the detection of an OPC is generally difficult. The examples in Section 6 show that, in some cases, the OPCs were detected (with existing instrumentation and protection relays) only after a few weeks on unloaded transformers.

A possible solution is to monitor the magnetization currents on the high voltage side of the transformers. Figures II–1 and II–2 show the magnetization currents for undisturbed operation and for a single open phase.

By monitoring the magnetization current, an OPC can be detected at transformers under unloaded conditions. Generally, unloaded standby transformers with the high voltage side energized draw a magnetization current in the range of 50–150 mA.

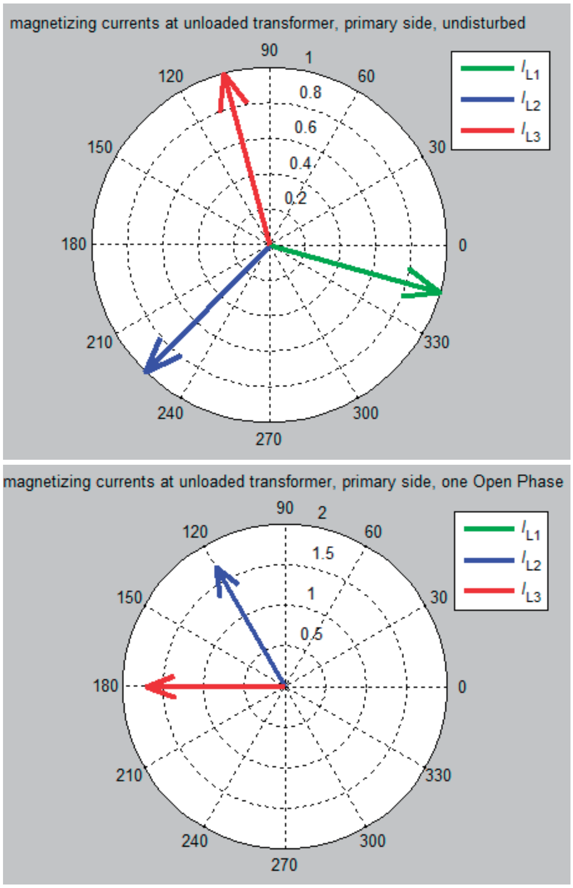


FIG. II–1. Calculated magnetizing current unloaded transformer, without (top) and with (bottom) a single open phase.

Optical current transformers, to be installed over the high voltage bushings of the standby transformer, are able to measure this range of current. With an adequate digital protection relay, the differences between the normal magnetization currents and the magnetization currents in the case of an OPC can be detected and an alarm can be initiated.

Alarm mode is acceptable because it detects the OPC, and the transformer is in standby mode and is not supplying power to the equipment downstream of the OPC. This solution will identify an OPC on the high voltage side of the transformer.

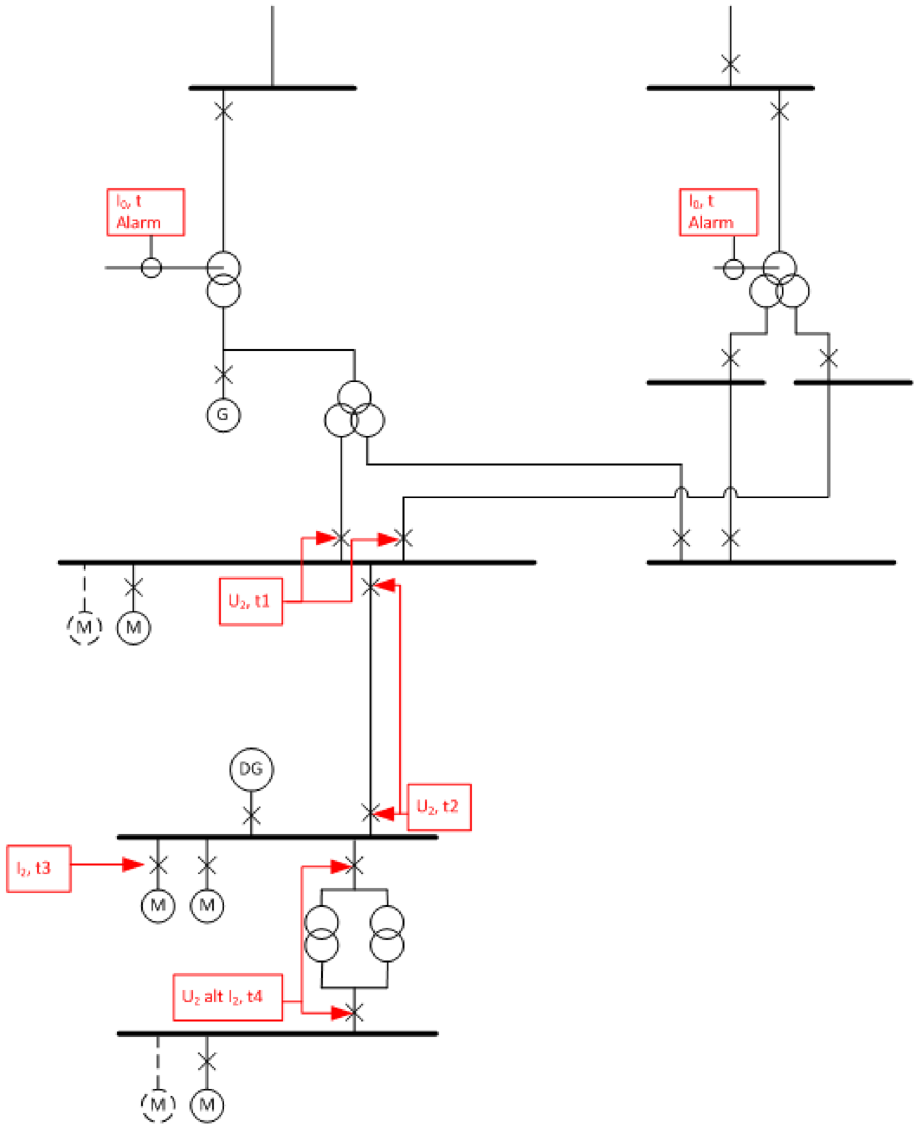


FIG. II–2. Simplified single line diagram showing negative sequence voltage sensing locations and zero sequence current sensing locations.

II–1.3. Injection of a signal onto the star point connection of the transformer

An active method for detecting an OPC of a transformer consists of injecting a signal onto the star point connection of the transformer and monitoring the current flowing in the star point connection on the high voltage side of the transformer.

The injecting system consists of an AC source (the frequency of which is different from the power system frequency) connected to a current transformer along with a current measurement probe and an electronic controller.

The method monitors transformer network zero sequence impedance, where the open phase can increase in impedance from hundreds or thousands of ohms, for a healthy system, to mega-ohms in a system with an OPC. The injection source current decreases significantly in an OPC because of the increase in impedance. This change in the injection source current can be monitored through the star point connection to detect an OPC. There is a detectable change in the star point current when an OPC occurs.

The star point injection method is especially useful for low load and no-load transformer situations. The star point injection method and zero sequence current measurement in the star point connection, in combination, provide a robust detection system.

This solution will identify an OPC on the high voltage side of the transformer.

II–1.4. Advanced microprocessor based solution

Some plants will use a more sophisticated microprocessor based solution. In this particular case, the intention is to use three detection algorithms (these algorithms are developed thorough simulation and modelling work):

— Logic string 1: an open phase with a coincident connection to earth if the zero sequence current exceeds a calculated value — the set point is chosen to detect the condition and avoid false actuation.
— Logic string 2: a single open phase without a connection to earth if one phase current falls to zero; security is achieved by negative sequence and zero sequence current limits to block trip function for downstream[1] faults.
— Logic string 3: two open phases without a connection to earth if two phase currents fall to zero.

All three logic strings are connected to an OR gate and, hence, trips occur according to ‘one-out-of-three’ logic. Before the trip is activated, a time delay is

[1] If current measurement is used for the new permanent solution, it is important to consider unbalanced currents from faults downstream of the measuring location of the permanent solution. Voltage measurements are not so critical for a downstream OPC because the voltage is almost unaffected upstream of the OPC.

introduced. This time delay is coordinated with protection relays in the on-site power system. The trip output is blocked if the phase current is below the detection capability or if the relay diagnostic alarm goes off.

The algorithm parameters are highly dependent on analytical models and are applicable only to certain transformer configurations. This solution will identify an OPC on the high voltage side of the transformer.

II–2. EXAMPLES OF MODIFICATIONS ON THE LOW VOLTAGE SIDE OF THE AUXILIARY AND STANDBY TRANSFORMERS

The examples cited below may not cover all OPCs.

II–2.1. Phase to phase undervoltage on the house load bus in a one-out-of-three configuration

The following solution has been implemented in at least one plant. It utilizes a new protection relay sensing phase to phase undervoltage on the house load bus in one-out-of-three logic (with dedicated set points). If an undervoltage is detected, the circuit breaker from the house load bus to the safety bus will open and thereby de-energize the safety bus. The loss of voltage relay will sense this and the standby AC power source will energize the safety loads per the design basis.

A voltage set point of 85% (of nominal voltage) was chosen based on plant specific simulation results. A 12 s time delay was chosen, in order to have selectivity in relation to all other protection relays. When the loss of voltage relay is activated, this new protection relay is blocked.

The solution will actuate for most harmful OPCs upstream of the voltage transformer, even if there are several transformers in series. Most of the solutions in Section II–1 will actuate for an OPC on the grid side of the transformer; this solution has the potential to detect certain OPCs for off-site power sources.

II–2.2. Negative sequence voltage

In an ideal system, the negative sequence voltage equals zero. In reality, the negative sequence voltage differs from zero due to pre-OPC imbalances in the power system. When an OPC occurs, a negative sequence voltage of power system frequency appears downstream of the OPC in many cases.

The negative sequence voltage will be roughly the same for all voltage levels downstream of the OPC and hence it is possible to identify many of the scenarios with an unbalanced voltage. The voltage is more or less unaffected upstream of the OPC, i.e. there is no risk of spurious activation.

One solution is to measure negative sequence voltage at several locations in the on-site power system and open breakers accordingly (see the simplified single line diagram in Fig. II–2).

Different time delays are needed to achieve selectivity for various fault locations. The shortest time delay is needed at higher voltage levels and the longest time delay at lower voltage levels, because an OPC at higher voltage levels will also affect the protection relays at lower voltage levels owing to the transformation of negative sequence voltage through the transformers. The purpose of the selectivity is to disconnect the open phase as close as possible to the fault location and disconnect as small a part as possible of the electrical power system.

It is not possible to identify all kinds of OPCs with negative sequence voltage measurements, especially those with no, or a very small, negative sequence voltage downstream of the OPC. In this case, additional zero sequence current or measurement of magnetizing current protection relays are needed for completeness. Alarm mode only is the preferred solution for this case, if the withstand capability for the safety power system can be shown to be adequate.

All the set points must be chosen from validated simulation results and the electrical equipment's ability to withstand the unbalanced voltage during the OPC.

II–3. DIAGNOSTIC MEASURES

II–3.1. Vibration measurements

A negative sequence voltage applied to an induction motor will cause an oscillating torque on the shaft of the motor; this oscillating torque makes the motor vibrate.

A vibration measurement on motors is among the solutions that might be used to find an increased amount of vibration for several motors simultaneously, which is a symptom of unbalanced voltage. It is recommended to ensure that historical data are available in a supervisory control and data acquisition system to see sudden changes in vibration that affect more than one motor.

II–3.2. Battery chargers

Using alarms from battery chargers is among the solutions for diagnosing and responding to an OPC. The battery chargers are often equipped with alarm and ‘switch off’ functionality in order to protect the battery charger if the power supply exceeds actual set points.

If several battery chargers send an alarm at the same time, this can be among the permanent solutions that warn the operators about an OPC but, in addition, a protection relay that activates breakers as close as possible to the fault location is needed in order to disconnect the fault and keep all (safety) functions working as intended.

Annex III

DESCRIPTION OF SELECTED OPEN PHASE EVENTS

III–1. KALININ UNIT 1, RUSSIAN FEDERATION, 1994

This section is reproduced from Ref. [III–1] with some modifications. An open phase condition (OPC) occurred at the AT-1-750 autotransformer, with the subsequent generation of a reverse current sequence in the main generator and activation of negative sequence current protection. The main generator and reactor tripped, and a differential protection DFZ-504 actuated which, eventually, led to loss of off-site power at Kalinin Unit 1. The accumulator battery of the common direct current bus lost charging power and the voltage dropped. Two inverters of the uninterruptable power supply disconnected on low voltage, and power was lost to a number of essential loads, part of the main control room information board and communication system, and annunciator panels.

The event was caused by the destruction of a clamp at the autotransformer 750 kV power Phase B which caused a disconnection of a flexible current line of the 750 kV duct bus. The clamp destruction occurred owing to a fatigue-induced fracture of the aluminium plate in the junction between the flexible cable of the duct bus of the AT-1-750 transformer and the arrester. An undesired (early) actuation of differential protection DFZ-504 disconnected off-site power to a unit standby transformer which resulted in the loss of off-site power at Unit 1.

III–2. BALAKOVO UNITS 1 AND 3, RUSSIAN FEDERATION, 1997

This section is reproduced from Ref. [III–2] with some modifications. A single phase short circuit in the 220 kV high voltage side of the Unit 1 circuit breaker in combination with spurious actuation of Unit 3's bus duct electrical protection resulted in the loss of off-site power at Units 1 and 3. The OPC caused a voltage imbalance in the plant electrical system, causing damage to four 6 kV motors and eleven 0.4 kV motors.

The single phase short circuit occurred on the high voltage side of the Unit 1 main transformer, T-1. The short circuit was cleared by protective relays. The main generator of Unit 1 was disconnected. At the time of the short circuit at Unit 1, Unit 3's bus duct electrical protection spuriously actuated, leading to a trip of the main generator of Unit 3. Owing to a design deficiency in the Balakovo principal electrical diagram, both units lost their auxiliary power in this situation, causing a startup of all emergency diesel generators.

While restoring a power supply to the 220 kV auxiliary open switchyard, a single phase short circuit in the high voltage breaker developed again, leading to a loss of off-site power at both units. The single phase short circuit, however, propagated into a two phase earth fault. A spontaneous closure of the Phase A contact in the high voltage breaker occurred during the phase earth faults, leading to asymmetrical voltage conditions propagating into the on-site power supply system.

An undetected earth fault in the current transformer monitoring the Phase B differential protection on the side of the unit transformers 3T-1 and 2 caused spurious actuation of the Unit 3 bus duct protection. As a result, Unit 3 suffered a loss of off-site power condition simultaneously with Unit 1. This earth fault was not detected earlier owing to a design deficiency of differential bus duct protection of Units 2, 3 and 4 that would have allowed detection of the malfunctioning current circuits.

The root cause of the event was attributed to inadequate design of the compressed air supply to the high voltage air operated Unit 1 circuit breaker, thus causing loss of compressed air and spurious closure of the high voltage breaker Phase A contact. The compressed air was supplied from the 0.4 MPa distribution pipe to the control circuit of the circuit breaker. The pipe providing the compressed air from the control circuit to the circuit breaker contacts was U-shaped. This pipe design led to an accumulation of moisture at the lowest point of the compressed air pipe. The layout of the pneumatic valve unit in the circuit breaker air control unit neither provided for removal of accumulated condensate, nor for monitoring of its presence.

III–3. HEYSHAM 2, UNITED KINGDOM, 2000

This section is reproduced from Ref. [III–3] with some modifications. On 30 Dec. 2000, Reactor 8 was manually tripped at 06:25 following a part failure of the blue phase circuit breaker, X890, in the 400 kV substation. The reactor was operating under reduced load conditions while on-load refuelling was in progress. Reactor 7 remained under steady full load conditions (671 MW).

The manual trip was preceded by a period of approximately 2 h of phase imbalance and indications of loss of SF6 pressure in X890. During the event, only two pumps, a condensate extraction pump and a fire resistant fuel pump, tripped on overload. The unit boards were interconnected to the station boards prior to the trip. The cause of the OPC was later found to be a failure of a 400 kV insulator.

III–4. KOEBERG, SOUTH AFRICA, 2005

This section is reproduced from Ref. [III–4] with some modifications. On 11 Nov. 2005 at about 14:00, the switching operations that were conducted in the Koeberg 400 kV transmission yard resulted in the tripping of several transmission lines and the Koeberg generator Unit 2. The event resulted in load shedding of 1326 MW in the Western Cape.

The direct cause of the incident was a latent defect open circuit on the red phase of the 400 kV bus section isolator 1A at Koeberg substation.

The open circuit caused the isolator open state which had not been detected before conducting the switching operation. The correct protocol for closing a circuit breaker on load requires confirmation of the isolator closed state. It could not be determined whether this confirmation had been carried out or not the last time the isolator was operated.

The event analysis showed that the event could have been prevented if the 'risk of trip' assessment had been conducted during the procedure. Detection of typical isolator failures can only be achieved by physical inspections, which unfortunately were not undertaken prior to the switching work on 11 Nov. 2005.

According to the licence conditions, Koeberg has to be able to withstand voltage drops of 30% for 2.5 s. On 11 Nov. 2005, Koeberg Unit 2 failed to island after separation from the 400 kV busbar. The direct cause of the Koeberg Unit 2 trip was the incorrect operation of the rapid power loss protection relay that was not configured correctly.

Owing to a latent commissioning error, the relay's latching circuit was inadvertently set to trip on voltage or current depressions, irrespective of the length of the duration of the disturbance. The incorrect commissioning caused Koeberg Unit 2 to be incapable of islanding when needed.

III–5. JAMES A. FITZPATRICK AND NINE MILE POINT UNIT 1, UNITED STATES OF AMERICA, 2005

This section is reproduced from Ref. [III–5] with some modifications. On 19 Dec. 2005, with the James A. FitzPatrick Nuclear Power Plant and Nine Mile Point Unit 1 operating at 100% power, National Grid (the local grid operator) notified the Nine Mile Point Unit 1 control room (which subsequently informed the James A. FitzPatrick control room) that it had observed abnormal amperage readings (0 A on Phase A, and 50 A on Phases B and C) on the 115 kV off-site power lines and suggested that the readings might indicate an open phase. The James A. FitzPatrick operators walked down the James A. FitzPatrick 115 kV switchyard and observed an open circuit on Phase A of Line 4, caused by a broken busbar connector. The operators removed it from service for repairs, and returned it to service the following day.

An engineering evaluation of the Nine Mile Point Unit 1, James A. FitzPatrick and National Grid data revealed that the busbar connector failure had existed, undetected, since 29 Nov. 2005, and Line 4 had been out of service for approximately 21 days. As a result, one redundant off-site power supply had exceeded the out-of-service time allowed by the technical specification. The cause of the undetected inoperability of Line 4 was inadequate control room indications and alarms at Nine Mile Point Unit 1 and an inadequate surveillance test at James A. FitzPatrick. The James A. FitzPatrick surveillance procedure records 115 kV bus voltages and confirms power availability, via communication with National Grid, but does not confirm that all three phases are intact by monitoring current flow in the 115 kV transmission lines.

III–6. VANDELLÒS UNIT 2, SPAIN, 2006

This section is reproduced from Ref. [III–6] with some modifications. A voltage imbalance was detected between phases of the main generator which caused actuation of the electrical protection with a subsequent turbine and reactor trip. The OPC caused the plant auxiliary transformer (house load) to be fed by two phases instead of three. A current difference in the secondary winding caused alarms due to overloading of the reactor coolant pump and condensate pump motors, without tripping these pumps.

The voltage imbalance occurred owing to a loose connection between the cable and the upper crown of a support insulator of the main transformer Phase R breaker. This fault was caused by the burn-out of the rotating annular contact of the insulator. The unit was shut down for approximately 40 h.

The plant main transformer is made up of three single phase transformers, each one connected to a 400 kV power line (Phases R, S and T). A two column rotating breaker is installed upstream of the connection to the transformer. This high voltage breaker is made up of three independent, identical poles, each constituted by a metallic chassis or bedplate. The insulators, which support the main breaker current line, are attached to the chassis through bearings. At the upper part of these support insulators, there are fittings on which the current line is mounted.

A probable cause of the breaker failure was a destruction of the rotating contact owing to loss of material in the friction zone and subsequent loss of contact pressure, which caused an increase of resistance and, therefore, an increase in the temperature at this point.

The rotating contacts had been replaced not only on the transformer side of the affected breaker, where the entire current line had been replaced, but also on the transformer side of the breakers of Phases S and T, and the plant side of the affected breaker.

Old rotating contacts were disassembled and inspected. It was observed that the Phase S contact had melted in the contact zone between the terminal and the friction fingers. On Phase T, there was significant wear at the connection terminal and the friction fingers, with considerable loss of material. The plant side of Phase R did not show signs of hot spots or friction wear, although the bearing on which the terminal rests was completely destroyed by oxides. Most of the part replacements were performed on the transformer side of all of the breakers.

A contributing factor to the loosening of the cable connection between the rotating contacts and current lines was, most likely, a preferential constant torque towards the side from which it hangs. Furthermore, the action of wind caused the cable to transmit a swing movement, with minor rotations at full load that accelerated the loss of material.

III–7. BEAVER VALLEY UNIT 1, UNITED STATES OF AMERICA, 2007

This section is reproduced from Ref. [III–5] with some modifications. On 27 Nov. 2007, during a non-routine walkdown of the off-site switchyard to investigate line voltage differences, the licensee discovered that the Phase A conductor of a 138 kV off-site power circuit of the Beaver Valley Power Station Unit 1 had broken off in the switchyard. This break occurred between the off-site feeder breaker and the line running on-site to the A train system station service transformer, located inside the site security fence. The terminal broke on the switchyard side of a revenue-metering current transformer/voltage transformer installed in 2006 to track the station's power usage through this line. During normal power operation, no appreciable current goes through this 138 kV line because the unit generator normally powers the station buses (loads). The licensee determined that the break on the 138 kV Phase A had occurred 26 days earlier and, therefore, had not been restored within 72 h as required by technical specifications.

The licensee determined that the root cause of this event was that site personnel did not fully recognize the characteristics of the three-legged Star-G/Star-G Star-G design of the secondary core form transformer. As such, their surveillance procedure did not identify the open phase that rendered the off-site power line inoperable. The surveillance procedure measured phase to phase voltage on the low voltage side (plant side) of the system station service transformer. These phase to phase voltage measurements alone would not identify an open-circuited phase in a lightly loaded power line.

III–8. DUNGENESS B, UNITED KINGDOM, 2007

This section is reproduced from Ref. [III–6] with some modifications. On 14 May 2007, the UK transmission system operator took the Super Grid Autotransformer 1 (SGT1) feeding the 275 kV substation out of service (Fig. III–1). At the time, Reactor 21 was shut down and Reactor 22 was operating at 490 MW.

With SGT1 out of service, the two in-service Dungeness B station transformers, 21 and 23, were being supplied from SGT2.

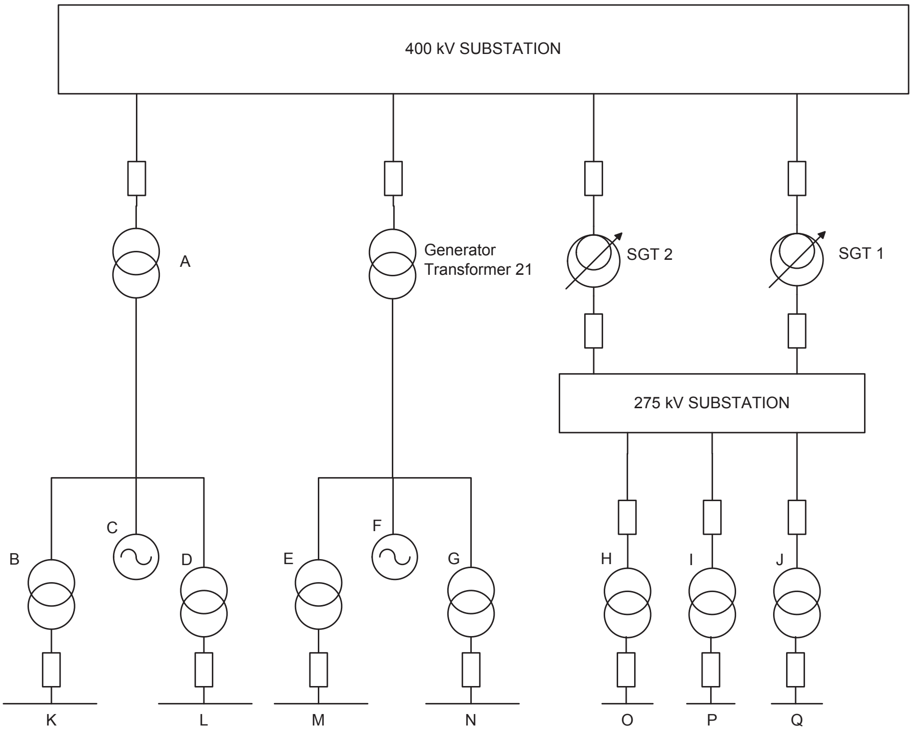
Over the following three days, the station electrical system suffered a series of apparently random voltage motor faults across various voltage levels:

- 21A chiller tripped on thermal overload;
- Cooling water pump 23 tripped on thermal overload;
- Turbine 21 auxiliary lubricating oil pump tripped on thermal overload;
- Active areas supply and extract fans tripped on thermal overload;
- Cooling water pump 21 tripped on thermal overload.

During the fault investigation, voltage measurements were carried out at the 11 kV station boards. Although a small imbalance was noted, the measurements did not indicate a significant supply abnormality — the imbalance being less than 1.6%. The fault had not been detected by voltage measurements as continuity still existed through the secondary circuits and motors connected to the supply. Owing to this and the fact that SGT2 is lightly loaded, the regenerated voltages in the open phase were near to normal.

Investigations by the grid operator eventually confirmed a fault within the high voltage circuit breaker of SGT2, resulting in one phase not fully closing. Normal supplies were eventually restored by placing SGT1 back into service and then removing SGT2 from service.

It was noted that the faulty circuit breaker was returned to service after maintenance on 23 Apr. 2007. It has not been ascertained whether any subsequent switching had taken place since the return to service of the circuit breaker but it is feasible that the fault had been present since that time and had not been detected as the grid is normally run solid (SGT1 and SGT2 in parallel) and the super grid transformers are lightly loaded at less than 6% of their combined rating.



A: Generator Transformer 22
B: Unit Transformer 22B
C: Generator 22
D: Unit Transformer 22A
E: Unit Transformer 21B
F: Generator 21
G: Unit Transformer 22
H: Station Transformer 21A
I: Station Transformer 23
J: Station Transformer 21

K: 11 kV Unit Board 22B
L: 11 kV Unit Board 22A
M: 11 kV Unit Board 21B
N: 11 kV Unit Board 21A
O: 11 kV Station Board 22
P: 11 kV Station Board 23
Q: 11 kV Station Board 21
SGT1: Super grid autotransformer
SGT2: Super grid autotransformer

FIG. III–1. Electrical grid connection for Dungeness.

III–9. RINGHALS UNIT 2, SWEDEN, 2011

This section is reproduced from Ref. [III–6] with some modifications. On 17 Apr. 2011, during a load run test of the standby AC power source (during a refuelling outage), the voltage regulation 'malfunctioned' according to the maintenance personnel. During troubleshooting by the maintenance personnel, several successful synchronizing attempts were performed, without solving the issue with the malfunctioning voltage regulation.

Finally, it was found that one pole of the generator breaker of the standby AC power source did not work properly. The generator breaker failure of the standby AC power source caused a single OPC for the standby AC power source when the breaker was closed and the generator was synchronized in parallel to the system. The on-site electrical power system worked as intended and no other problems were identified.

The generator breaker was replaced and the single OPC was solved. Afterwards, when the breaker was replaced, it was revealed that the vibration of the standby AC power source was significantly lower than during the short periods of operation with a single open phase circuit. Operation with a single open phase gives an oscillating torque and, hence, leads to vibrations in the standby AC power source.

If a loss of off-site power had occurred during such a condition, all of the safety objects in one train would have been affected by the unbalanced voltage from the standby AC power source.

III–10. BYRON UNIT 1, UNITED STATES OF AMERICA, 2012

This section is reproduced from Ref. [III–5] with some modifications. On 28 Feb. 2012, Byron Unit 1 lost its preferred off-site power because the A phase line to the Unit 1 station auxiliary transformers opened, causing a short circuit in the Byron switchyard. The short circuit was isolated, and the 4 kV engineered safety feature buses undervoltage protection functioned as designed. The station auxiliary transformer feed breakers opened and the diesel generators started, as expected, and restored power to the 4 kV engineered safety feature buses. The station auxiliary transformer feeds to the 6.9 kV buses automatically transferred to the unit auxiliary transformer feeds, as expected, and the station auxiliary transformer feeds to the 4 kV non-engineered safety feature buses automatically transferred to the unit auxiliary transformer feed as expected. The 1B emergency diesel generator was already running as part of a planned monthly test and responded as expected, restoring Bus 142.

III–11. BYRON UNIT 2, UNITED STATES OF AMERICA, 2012

This section is reproduced from Ref. [III–5] with some modifications. On 30 Jan. 2012, Byron Unit 2 experienced an automatic reactor trip from full power because of an undervoltage condition on the two 6.9 kV electrical buses that power reactor coolant pumps B and C. A broken insulator stack for the Phase C conductor on the 345 kV power circuit that supplies both station auxiliary transformers caused the undervoltage condition. This insulator failure caused the Phase C conductor to break off from the power line disconnect switch, resulting in a Phase C open circuit. Although the break in the power line may have caused Phase C to earth, the 345 kV circuit does not have earth fault protection and the switchyard breakers did not open.

System description of on-site power system: The Byron Unit 2 on-site power system consists of four safety related 6.9 kV buses, two safety related 4.16 kV buses and two safety 4.16 kV buses. The two 4.16 kV safety buses and two of the safety related 6.9 kV station buses are normally supplied by one of the two station auxiliary transformers connected through one 345 kV off-site circuit. The remaining two safety related 6.9 kV station buses and two safety related 4.16 kV station buses are normally supplied by one of two unit auxiliary transformers when the main generator is on-line.

After the reactor trip, the two 6.9 kV buses that power reactor coolant pumps A and D, which were aligned to the unit auxiliary transformers, automatically transferred to the station auxiliary transformers, as designed. Because Phase C was open-circuited, the flow of current on Phases A and B increased and caused all four reactor coolant pumps to trip on phase overcurrent. With no reactor coolant pumps functioning, control room operators performed a natural circulation cooldown.

Even though Phase C was open-circuited, the station auxiliary transformers continued to provide power to the 4.16 kV safety buses A and B because of a design vulnerability that this event revealed. The open circuit created an unbalanced voltage condition on the two 6.9 kV reactor coolant pump buses and the two 4.16 kV safety buses. The safety loads remained energized momentarily, relying on equipment-protective devices to prevent damage from single phasing or an overcurrent condition. The overload condition caused several safety loads to trip. Approximately 8 min after the reactor trip, the control room operators diagnosed the loss of Phase C condition and manually tripped breakers to separate the unit buses from the off-site power source. When the station auxiliary transformer feeder breakers to the two 4.16 kV safety buses were opened, the loss of safety bus voltage caused the standby AC power sources to automatically start and restore power to the safety buses.

The relay protection scheme is designed with two undervoltage relays on each of the two safety buses. These relays are part of a ‘two-out-of-two’ trip logic based on the voltages being monitored between Phases A–B and B–C of the safety buses. Even though Phase C was open-circuited, the voltage between Phases A–B was normal; therefore, the trip logic was not satisfied. Because the conditions of the two-out-of-two trip logic were not met, no protective trip signals were generated to automatically separate the safety buses from the off-site power source.

III–12. BRUCE A UNIT 1, CANADA, 2012

This section is reproduced from Ref. [III–6] with some modifications. On 22 Dec. 2012, during an outage and operation with the maintenance cooling as the primary heat sink, the maintenance cooling system pump at Bruce A Unit 1 tripped on electrical protection. The operators attempted to restore maintenance cooling using the alternate maintenance cooling system pump, but it failed to start. After several attempts, neither of the maintenance cooling system pumps could run for more than a few minutes before tripping on electrical protection.

Unknown to the operators, a 230 kV drop line to the number one system service transformer broke from the baseplate connecting it to the system service transformer during high winds, resulting in an unearthed single OPC. The operators had difficulty diagnosing the single OPC because there were no other signs of electrical faults on running equipment, and the alarm that indicates a fault on the system service transformer was not triggered because conditions for actuation were not met. It was not until 2 h after the initial maintenance cooling system pump trip, when two main boiler feedwater pumps were started, that the fault alarm for the in-service system service transformer actuated. Once the OPC was discovered, station loads were shifted to a different system service transformer. Maintenance cooling was restored 2.5 h after the event began.

III–13. FORSMARK UNIT 3, SWEDEN, 2013

This section is reproduced from Ref. [III–7] with some modifications. On 30 May 2013, during a refuelling outage, a combination of human error and a loose cable connection resulted in a double OPC in the 400 kV breaker. The failure was not detected by the loss of voltage relays and, as a result, the standby AC power sources did not start (no degraded voltage relays implemented).

The double OPC resulted in a voltage imbalance for the on-site power system. The voltage on safety buses did not drop below the threshold for the loss of voltage relay (measuring positive sequence) starting the standby AC power sources (due to low load conditions). Trains A and B were ready for operation and the standby AC power sources in Trains C and D were ready for operation when the double OPC occurred.

Operating loads equipped with imbalance protection tripped, whereupon, for example, residual heat removal and the cooling chain for the standby

AC power sources were lost. Residual heat removal was lost for 17 min and the temperature in the fuel pools increased by 0.7°C before the operators started the standby AC power sources manually and opened the circuit breakers from the preferred power supply to the safety power system (the standby grid was under maintenance). Manual resetting of imbalance protection was needed when the safety standby AC power sources were supplying safety loads. Some non-safety motors were damaged during the event.

III–14. DUNGENESS B, UNITED KINGDOM, 2014

This section is reproduced from Ref. [III–6] with some modifications. On 27 Apr. 2014, the UK transmission system operator undertook planned switching in the Dungeness 400 kV substation, which is located off both Dungeness nuclear licensed sites. Dungeness B has two advanced gas cooled reactors. The 11 kV station supplies are derived from the 275 kV system via three station transformers (see Fig. III–1). The 11 kV supplies are then used to derive 3.3 kV in support of the essential and backup supply systems. At the time, Reactor 21 was shut down for a statutory outage and Reactor 22 was at normal output power.

During the switching, negative phase sequence alarms for outgoing circuits from the substation were received by the transmission system operator and on the Dungeness B Generator 22 circuit by the power station control room. The transmission system operator followed its own procedures to isolate the last operated equipment and investigate the event. A short time later, the generator tripped on negative phase sequence protection and this intertripped Reactor 22.

Initially, post-trip functions operated normally. However, a few minutes after the trip, a number of low voltage pump motors began to trip on thermal overload protection, affecting post-trip cooling functions.

On Unit 22, the gas circulator's very low speed pony motors and vessel cooling pumps tripped on overcurrent protection. A trip of the auxiliary oil pump on the turbine prompted manual shutdown of the main boiler feed pump and the emergency boiler feed pump was put into service. On Unit 21, the extreme low level in-surge pumps tripped, along with the high speed pony motors on two gas circulators, leaving Unit 21 with no forced circulation or boiler feed for about 15 mins. No significant change in temperature was observed because the reactor had been shut down for several weeks prior to the event and had low decay heat. Despite attempts to reset the protection and restart the motors, they tripped again.

Within 10 min of the trip, a minor voltage disparity (~0.9 kV) was observed between the phase voltmeters in the control room of the 11 kV station board. At this point, the shift supervisor concluded that the grid supplies were insecure, and took action to progressively isolate the station from the transmission system, restoring supplies from the on-site 3.3 kV essential and backup diesel generators. These actions prevented further tripping of electric motors.

Subsequent investigation by the transmission system operator identified that the actual fault was on a 400 kV bus coupler circuit breaker. Once the substation was reconfigured to remove it from use, station electrical supplies were returned to their normal off-site configuration. A post-event investigation determined that one of the breaker poles remained open owing to a maintenance induced defect. It was likely that the failure had gone undetected for a number of months until the switching operation. (Another bus coupler circuit breaker operating in parallel was switched off.)

The station is equipped with 'brown-out' alarms in the control room which operate when the voltage on the diesel generator switchboards decreases by 5% from nominal levels, a level still above the voltage level at which the diesel generators would auto-start. The voltage indications in the control room provide visual confirmation of the voltages on the switchboards and the station operating instructions require operator action. Because of the loading and configuration of the system at the time of the event, these alarms did not initiate.

REFERENCES TO ANNEX III

[III–1] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Plant Operating Experience from the IAEA/NEA International Reporting System for Operating Experience (IRS), Loss of Unit Auxiliary Power and Loss of Power to Essential Loads, IRS No. 6412, IAEA, Vienna (2014).

[III–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Plant Operating Experience from the IAEA/NEA International Reporting System for Operating Experience (IRS), Loss of Auxiliary Power at Two Units of Balakovo due to Breaker Failure in the 220 kV Open Switchgear, IRS No. 71995, IAEA, Vienna (2014).

[III–3] EDF ENERGY, Event report into Heysham 2 reactor trip due to blue phase fault, internal report, 2000.

[III–4] NATIONAL ENERGY REGULATOR OF SOUTH AFRICA, Investigation into the Electricity Outages in the Western Cape for the Period November 2005 to March 2006, NERSA, Pretoria (2007).

[III–5] NUCLEAR REGULATORY COMMISSION, NRC Information Notice 2012-03: Design Vulnerability in Electric Power System, NRC, Washington, DC (2012).

[III–6] WORLD ASSOCIATION OF NUCLEAR OPERATORS, Significant Operating Experience, Rep. 2015-1, WANO, London (2015).

[III–7] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Plant Operating Experience from the IAEA/NEA International Reporting System for Operating Experience (IRS), EDG Failed to Start after Undetected Loss of Two Phases on 400 kV Incoming Offsite Supply, IRS No. 8315, IAEA, Vienna (2015).

Annex IV

TRANSFORMER FLUX PATHS DURING OPEN PHASE CONDITIONS

This annex provides examples of the flux paths that can exist within common transformer configurations during single open phase conditions. This section is reproduced with some modifications with the permission of EDF Energy Nuclear Generation Ltd, UK.

(a) YNd arrangement (three-limb construction, shown in Fig. IV–1):
- $I_A = 0$.
- I_B and I_C return via earth.
- The only core return path for Φ_B and Φ_C is via Limb A.
- V_{wA} and V_{wa} reproduced by Limb A Φ_B and Φ_C.
- Phase A power is supplied by Φ_B and Φ_C.
- Φ_B and Φ_C, I_B and I_C increase by ~50% to supply load on Phase A.
- Power is carried by all three phase windings.
- Low voltage three-phase volts, current and power substantially balanced at light load.
- At heavier load, larger leakage flux on Φ_B and Φ_C will induce proportionally less in Limb A, with increasing voltage and current imbalance on high voltage and low voltage as a consequence.

(b) YNyn arrangement (three-limb construction, shown in Fig. IV–2):
Similar response to that of a delta secondary winding described in (a).

(c) YNyn arrangement (multi-limb or single core construction, shown in Fig. IV–3):
- $I_A = 0$.
- I_B and I_C return to source via earth.
- Φ_B and Φ_C return via a multi-limb or single phase limb and do not induce voltage in w_A.
- Minimal regeneration of Phase A.
- Low voltage operates as a single phase; no low voltage power delivered to open phase.
- Substantial high voltage and low voltage, and current imbalance: large negative phase sequence.

(d) YNd arrangement (multi-limb or single core construction, shown in Fig. IV–4):
- $I_A = 0$.
- I_B and I_C return to source via earth.

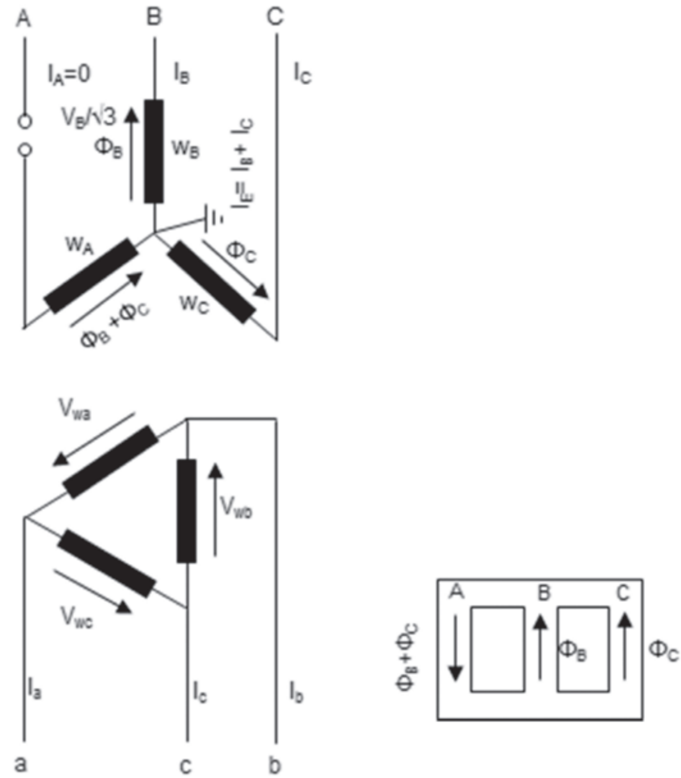


FIG. IV–1. YNd arrangement (three-limb construction).

— w_a has a normal voltage applied across it by phasor addition of V_{wb} + V_{wc}, which reproduces V_{wa}, which in turn regenerates V_{wA} by w_a/w_A interaction, i.e. the lost voltage is perfectly regenerated on high voltage and low voltage windings.

— Φ_B and Φ_C return via a multi-limb or single phase limb and do not induce voltage in w_A.

— Low voltage three-phase power supplied is not affected.

— High voltage power is supplied by the two healthy phases.

— No power is carried by the faulted high voltage or low voltage windings, only excitation current.

— I_B and I_C current will increase by ~50%, adopting a different phase angle to accommodate the additional loading demand of Phase A.

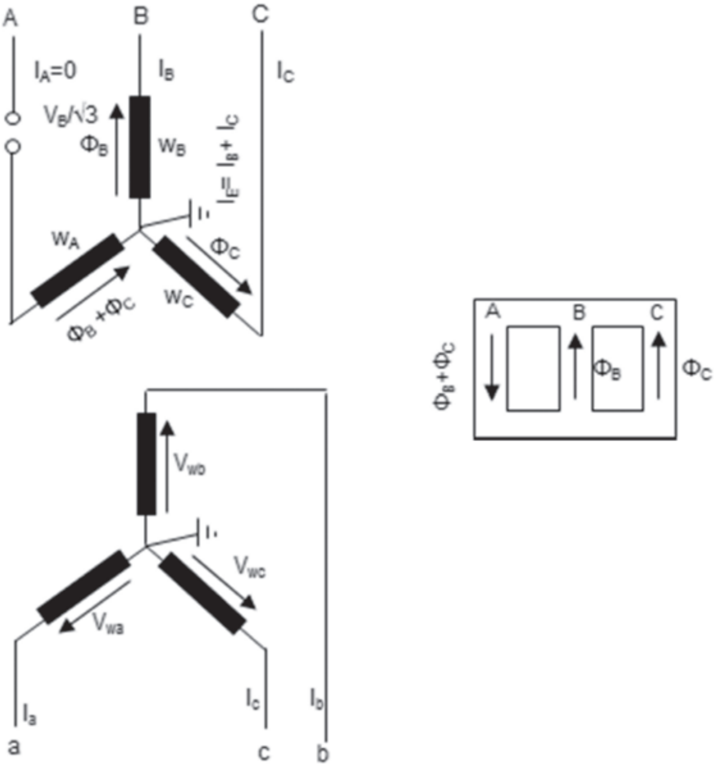


FIG. IV–2. YNyn arrangement (three-limb construction).

- At higher loading, the higher currents produce an increased voltage drop due to winding voltage drop and larger flux leakage, but the voltages remain relatively balanced.
- The above holds true for individual phase units as well as multi-limb core construction.

(e) Dyn arrangement (any limb construction, shown in Fig. IV–5):

- Common among unearthed primary arrangements is that open phase produces substantial unbalanced voltage on both primary and secondary side of the transformer regardless of secondary configuration.
- $I_A = 0$.
- V_{wB} remains unchanged.
- V_{BC} split evenly between W_A and W_C, i.e. 50% each.
- Φ_A, Φ_B and Φ_C are all in phase (zero sequence).

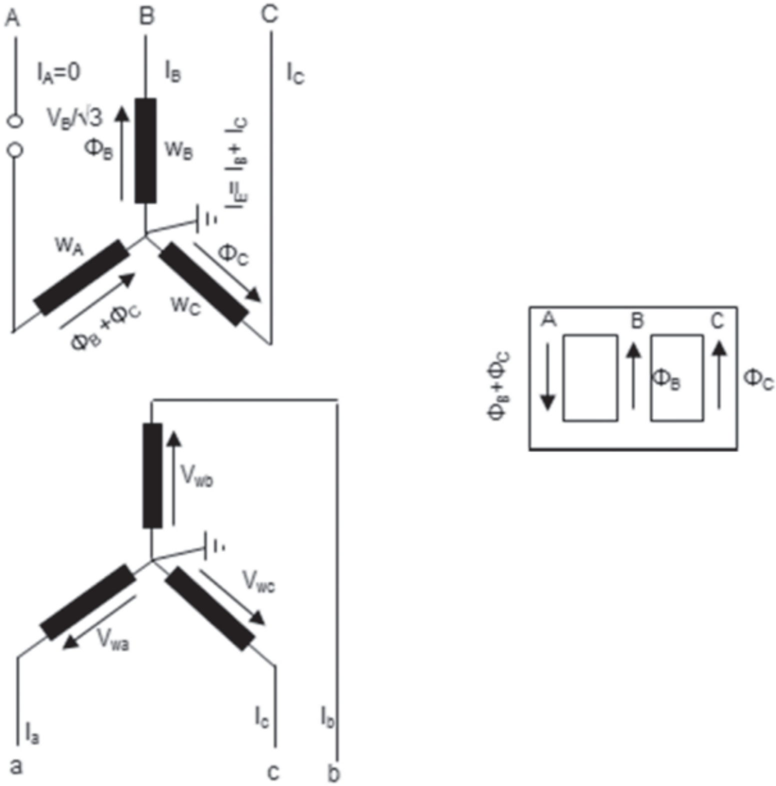


FIG. IV–3. YNyn arrangement (multi-limb or single core construction).

— For a three-limb transformer, the flux return path will be through the air gap, tank, yolk, bolts, etc., leading to larger current, overheating and increased voltage drop.
— For three single phases, or a four or more limb transformer, the 2:1:1 voltage–current relationship would be retained on both the high voltage and low voltage windings.
— All three winding voltages are in phase but unbalanced.
— All three winding currents are in phase but unbalanced.
— The resultant voltage and current imbalance will produce substantial negative phase sequence currents in both the high voltage and low voltage windings.

(f) Yd arrangement (any limb construction, shown in Fig. IV–6):
— $I_A = 0$.
— V_{WB} and V_{WC} are in phase and half the line voltage.

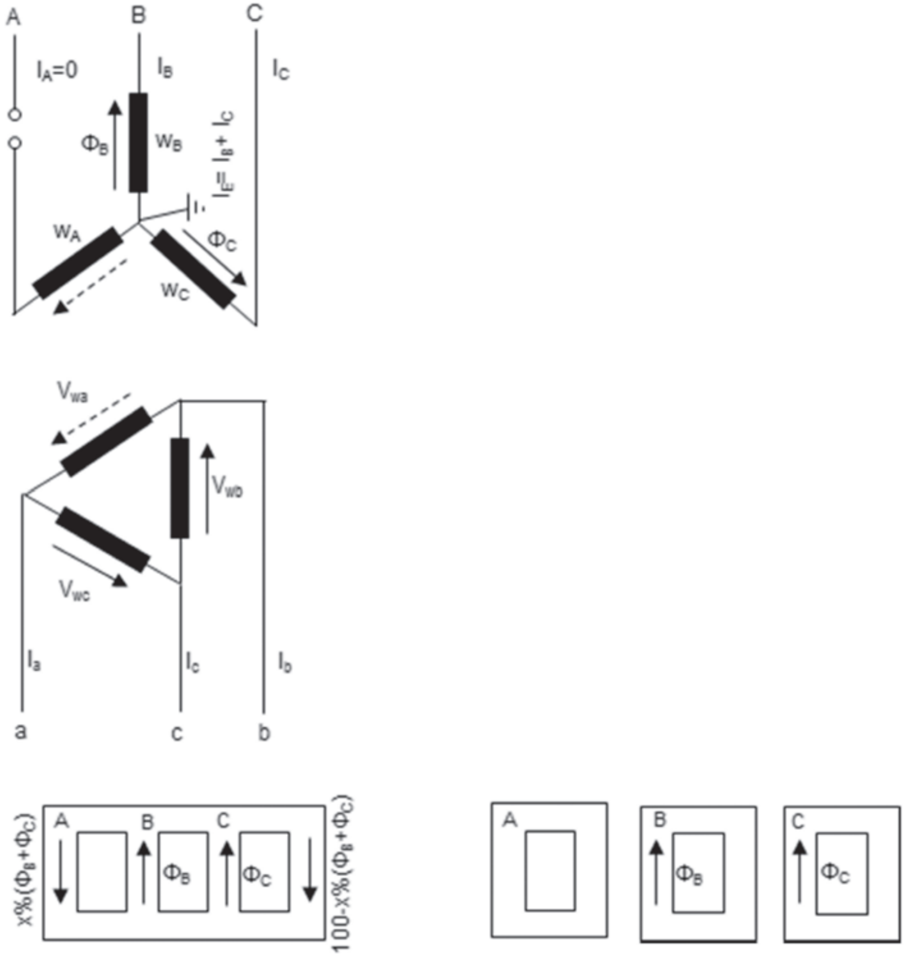


FIG. IV–4. YNd arrangement (multi-limb or single core construction).

— $\Phi_B = -\Phi_C$, such that flux is restricted to Limbs B and C.
— V_{wA} is always zero because V_{wB} and V_{wC} are equal but opposite phase.
— √3/2 times the normal voltage will be generated across w_b and w_c and these are in phase.
— The resultant voltage and current imbalance will produce substantial negative phase sequence voltage and currents in both the high voltage and low voltage windings.

(g) Yyn arrangement (any limb construction, shown in Fig. IV–7):
— $I_A = 0$.
— V_{WB} and V_{WC} are in phase and half the line voltage.

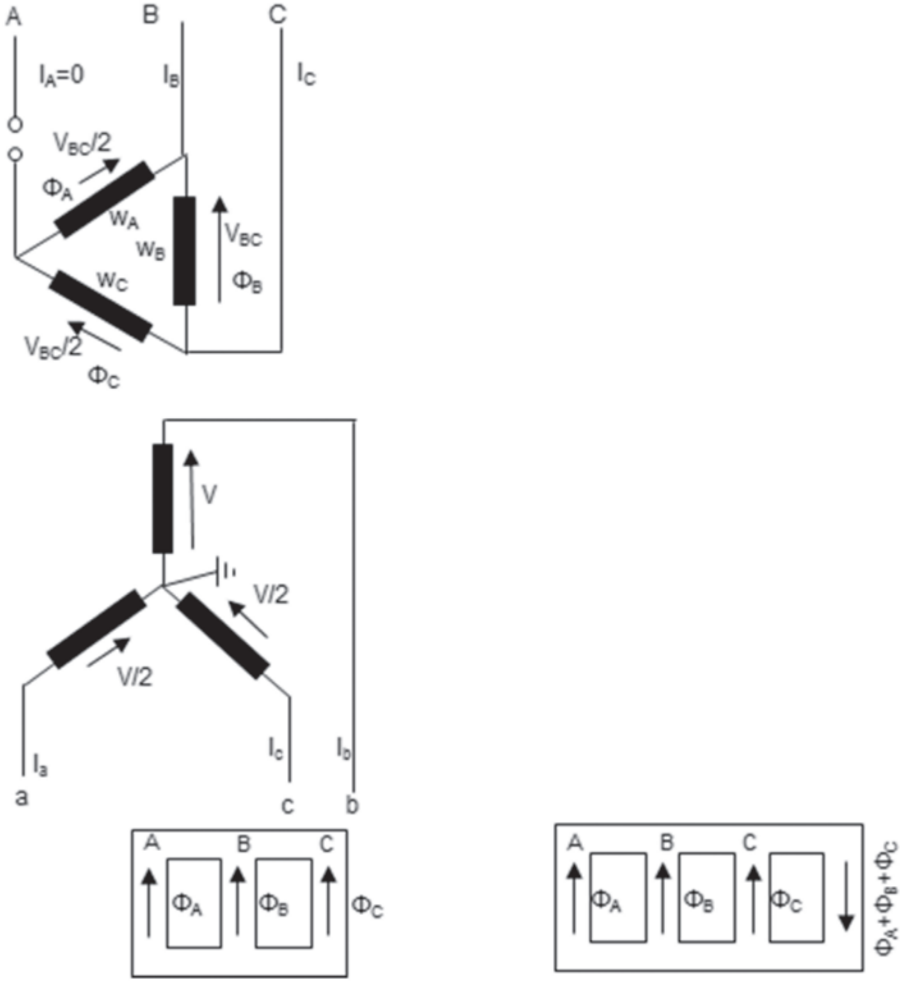


FIG. IV–5. Dyn arrangement (any limb construction).

— $I_B = -I_C$.
— V_{WA} is always zero because V_{WB} and V_{WC} are equal but opposite phase.
— √3/2 the normal voltage will be generated across w_b and w_c and these are in phase.
— The resultant voltage and current imbalance will produce substantial negative phase sequence currents in both the high voltage and low voltage windings.

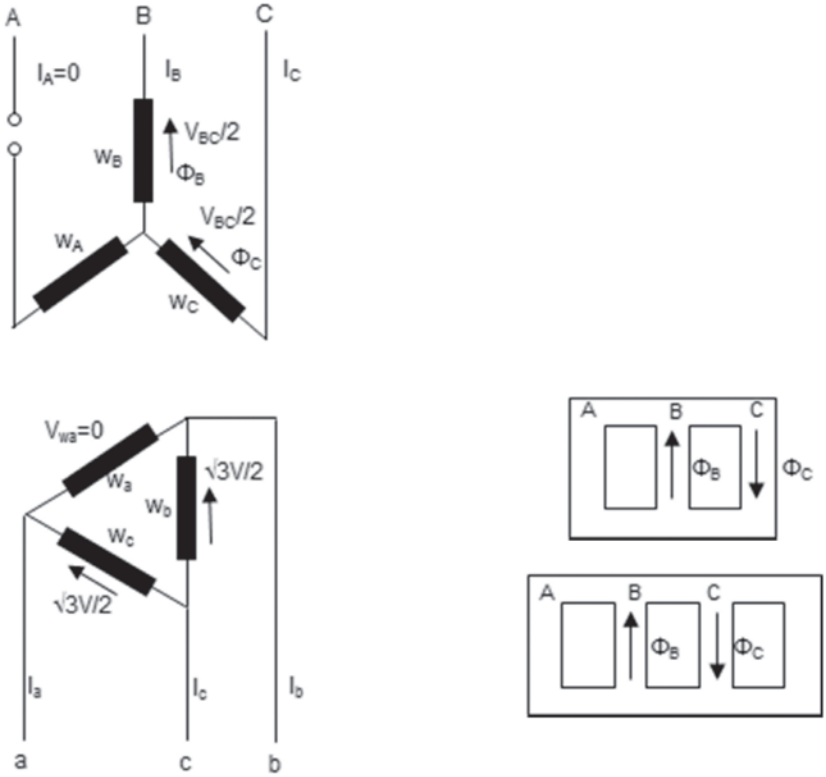


FIG. IV–6. Yd arrangement (any limb construction).

(h) Three-limb autotransformer, shown in Fig. IV–8:

— $I_A = 0$.
— I_B and I_C return via earth.
— The only core return path for Φ_B and Φ_C is via Limb A.
— V_{wA} and V_{wa} are reproduced by Limb A Φ_B and Φ_C.
— Phase A power is supplied by Φ_B and Φ_C.
— Φ_B and Φ_C, and I_B and I_C increase by ~50% to supply load on Phase A.
— Power is carried by all three phase windings.
— Low voltage three-phase volts, current and power are substantially balanced at light load.
— At heavier load, larger leakage flux on Φ_B and Φ_C will induce proportionally less in Limb A with increasing voltage and current imbalance on high voltage and low voltage as a consequence.

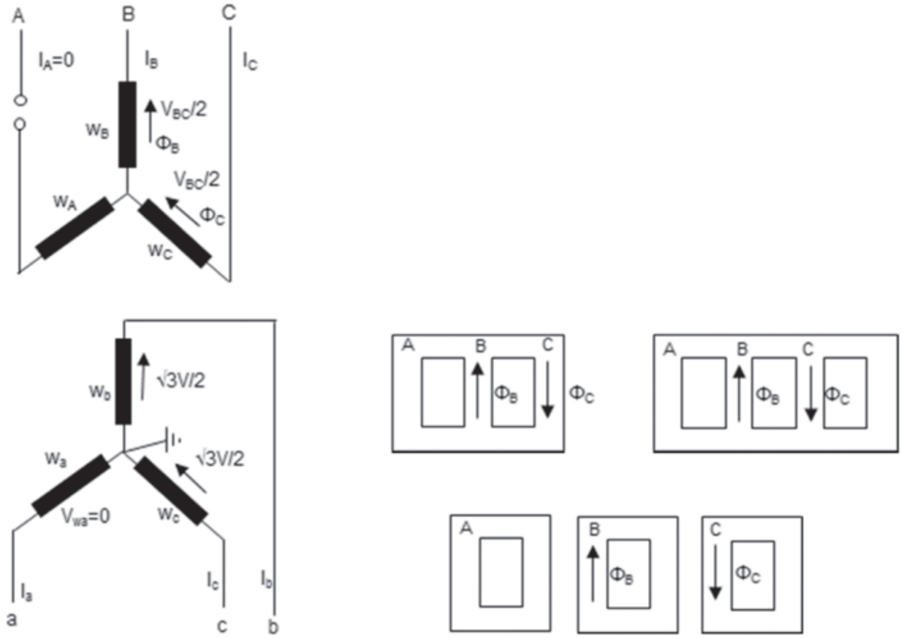


FIG. IV–7. Yyn arrangement (any limb construction).

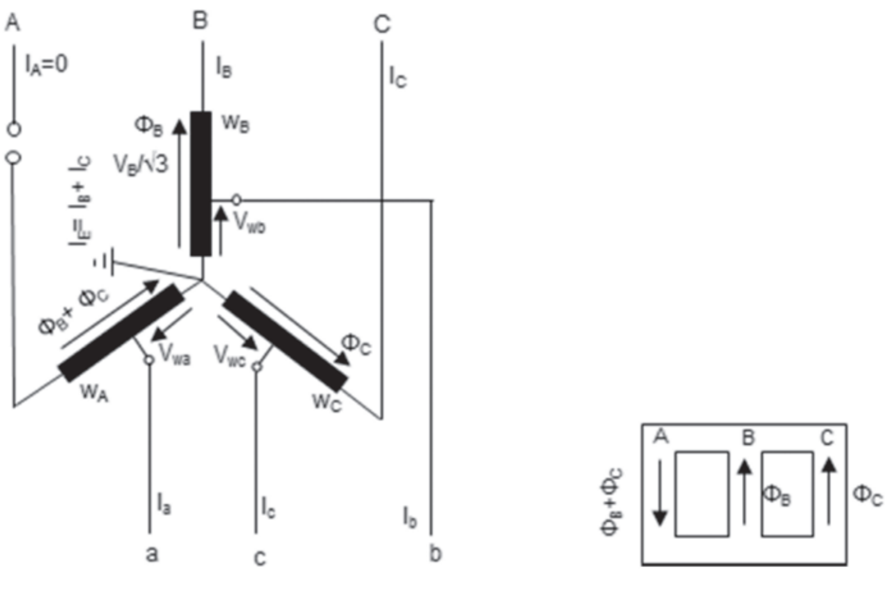


FIG. IV–8. Three-limb autotransformer.

DEFINITIONS

The following definitions apply for the purposes of this Safety Report. Further definitions are provided in the IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection (2007 Edition), IAEA, Vienna (2007): http://www-ns.iaea.org/standards/safety-glossary.asp

alternate alternating current power source. A dedicated power source that could be used as a power supply to the plant during total loss of all non-battery power in the safety power systems (station blackout) and other design extension conditions.

loss of off-site power. Simultaneous loss of preferred power to all safety buses.

negative sequence component[1]**.** One of the three symmetrical sequence components that exists only in an unsymmetrical three-phase system of sinusoidal quantities and that is defined by the following complex mathematical expression:

$$X_2 = \frac{1}{3}(X_{L1} + a^2 X_{L2} + aX_{L3})$$

where a is the 120° operator; X_{L1}, X_{L2} and X_{L3} are the complex expressions of the phase quantities concerned; and where X denotes the system current or voltage phasors.

open phase condition (OPC).

1. An open circuit of one of the three phases of any power circuit needed for normal operation of a nuclear power plant, startup or shutdown of a nuclear power plant or safe shutdown of the nuclear power plant following an accident. An OPC can occur with and without a high impedance earth fault condition under all operating electrical system configurations and loading conditions.

2. An open circuit of two of the three phases of any power circuit needed for normal operation of a nuclear power plant, startup or shutdown of a nuclear

[1] INTERNATIONAL ELECTROTECHNICAL COMMISSION, International Electrotechnical Vocabulary Chapter 448: Power System Protection, Rep. IEC 60050-448, IEC, Geneva (1995).

power plant or safe shutdown of the nuclear power plant following an accident system under all operating electrical system configurations and loading conditions. Transient phase imbalances, such as during the opening or closing of circuit breakers or the operation of auto-reclose schemes on overhead lines, are not considered an OPC.

plant state[2]**.** This can be an operational state (normal operation and anticipated operational occurrences) or accident conditions (design basis accidents and design extension conditions).

positive sequence component. One of the three symmetrical sequence components which exists in symmetrical and unsymmetrical three-phase system(s) of sinusoidal quantities and which is defined by the following complex mathematical expression:

$$X_1 = \frac{1}{3}(X_{L1} + aX_{L2} + a^2 X_{L3})$$

where a is the 120° operator; and X_{L1}, X_{L2} and X_{L3} are the complex expressions of the phase quantities concerned; and where X denotes the system current or voltage phasors.

preferred power supply. The power supply from the transmission system to the safety classified electrical power system.

standby alternating current power source. The electric power supply source located within the nuclear power plant and controlled by the nuclear power plant operators.

zero sequence component[3]**.** One of the three symmetrical sequence components which exists only in an unsymmetrical three-phase system of sinusoidal quantities and which is defined by the following complex mathematical expression:

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[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), IAEA, Vienna (2016).

[3] INTERNATIONAL ELECTROTECHNICAL COMMISSION, International Electrotechnical Vocabulary Chapter 448: Power System Protection, Rep. IEC 60050-448, IEC, Geneva (1995).

$$X_0 = \frac{1}{3}(X_{L1} + X_{L2} + X_{L3})$$

where X_{L1}, X_{L2} and X_{L3} are the complex expressions of the phase quantities concerned, and where X denotes the system current or voltage phasors.

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