A Regulated Power Supply for Accelerator Driven System

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Abstract. This paper discusses a regulated high voltage power supply (RHVPS) developed for accelerator driven systems to drive a klystron. The RHVPS uses a large no. of small voltage choppers. These choppers are switched in tandem by a novel technique to regulate output voltage. Various parts of the system are novel. The front end is a pair of transformer with 40 secondaries each. Each secondary feeds a switched power module (SPM) which has a rectifier-filter unit followed by an IGBT switch to get 1.3 kV. All 80 SPMs are connected in series. The final output is taken from the two end SPMs. A central controller uses voltage sample from each SPM and generates switching pulses for each IGBT switch. IGBTs of all SPMs are switched with a fixed phase lag from each other, resulting in purely constant voltage with ripple limited to one SPM voltage. The frequency of ripple is high and can be filtered out with a simpler filter. The system can turn off for protection of the load in less than 2 microseconds, the essential attribute for a power supply to be used with klystrons. The results of wire burn tests measure the low stored energy at fault turn off (less than10 J). The power supply (rated for 100 kV at 2.5 MW) will be used for a continuous duty with the klystron for accelerator driven system at BARC (India). A power supply giving 80 kV, 75A is being used with an accelerator system for extraction of beam along with a Neutral Beam Injector. This paper discusses the technology and experimental results of the system. It also discusses various other options with similar power supply.

1. Introduction

A high voltage power supply is an essential component of a RF driven accelerator. High power tubes like klystron needs a high voltage power supply with stable operating voltage and low ripple. Regulated High Voltage Power Supply (RHVPS) for use in the Accelerator Driven Systems (ADS) at BARC, Mumbai, India uses a 100 kV, 25A power supply.

Traditionally, RHVPS at few megawatts capacity for continuous duty applications were built with a series tube to regulate the pre-regulated and filtered output of a HV converter. The tube serves as a disconnecting switch to protect the RF tube as well. However, regulator tubes in MW rating and for continuous operation have poor efficiency (and consequently more thermal management). In any case, the tubes are customised and considerable R&D effort is necessary for its development.

Over the last two decades, fast semiconductor power devices are replacing the tetrode tubes. With more computing power available at lesser cost and compact form, it is now possible to realise complex control functions to connect a multitude of switches to build high voltage power supplies with better performance. The following description of high voltage power supply uses Pulse Step Modulation (PSM) technique [1]. This architecture for obtaining high voltage is an adaptation from the same modulation technique used in high power AM amplifiers.

2. Power supply topologies

TABLE I: COMPARISON OF HIGH VOLTAGE POWER SUPPLY TOPOLOGIES.

Parameters	Solid State PSM Topology	Tetrode Tube Topology
Losses	typically 3 %	6 to 20 %
Ripple	0.5 %	3 %
Auxiliary efforts	very less	high (mounting, cooling)
Range of control	0 to 100 %	80 to 100 %
Harmonic contents	negligible	high
Reactive power	high (p.f. =0.9)	low (p.f. = 0.6)

Table I compares these two topologies on some key parameters. For the PSM topology (fig.1) using multitude of low voltage isolated switched power modules (SPMs), all major components are standard and commercial items. Here too, the series switches (S_1 to S_N) control the output voltage. The topology does not need a separate switch to disconnect the load. The digital control system controls the array of switches according to the PSM (pulse step modulation) switching matrix. The output voltage is maintained constant by a feed-forward control system. This topology also provides sufficient redundancy in case of failure of few SPMs. The output ripple voltage is of relatively high frequency (a few hundreds of kHz) for these power supplies as compared to the 12 or 24 pulse ripple in a series regulator tetrode tube type power supply. The output side filter size is smaller and hence stored energy in the system is greatly reduced. This makes it a suitable for use in klystrons, gyrotrons and NBI power sources as it is mandated that RHVPS should have low stored energy (less than 10J to avoid arcing at the time of fault) in these applications.

TABLE II: SPECIFICATIONS FOR RHVPS USED FOR ACCELERATOR DRIVEN SYSTEM.

Parameters	Values
Output	0-100kV, 25A
Regulation	1 %
Ripple	0.5 %
Duty	Continuous
Rise time	~10µS
Turn off time	>2µS
Fault energy	< 10 J

Table II summarises specifications of RHVPS for using with ADS.

3. Description of RHVPS

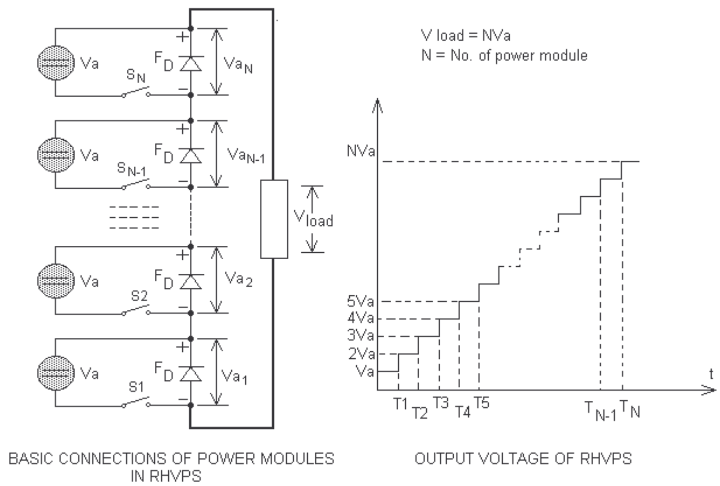

Fig. 1, Basic Scheme for PSM Based Accelerator Power Supply.

The basic scheme can be explained with the help of fig.1 and 2. Here, the N no. of independent voltage sources (Va) are connected to power supply output by series switches S_1 to $S_{N,}$ which are controlled to be ON and OFF by a controller. It may be noted that switch ON/OFF times are in the range of microseconds or even less.

As shown in fig. 2, the operation of the basic PSM technique involves switching of the required number of switched power modules (SPMs which are identical and isolated). Each SPM in the chain of stack is switched on with the required duty cycle. Fig. 2 shows the generation of output voltage V_{load} for the case of 5 SPMs connected in series, The 5 SPMs being switched in a manner shown by their output voltage pattern V1 to V5. The switching of each SPM is controlled in a cyclic fashion to equalise the average loading of all SPMs. This facilitates use of identical SPMs. Naturally, the output shows the characteristics of both PSM and PWM (pulse width modulation). The output waveform is DC with ripple voltage of Va (peak to peak) and ripple frequency of N times SPM switching frequency (f_{MS}). If N=80 and f_{MS}=5kHz, ripple frequency is 400kHz. A relatively small filter with low stored energy is sufficient to filter this output to an acceptable level. The average output is 2.5 Va, (half of 5Va) since the duty cycle considered here is 50 %. The power supply with interconnection of

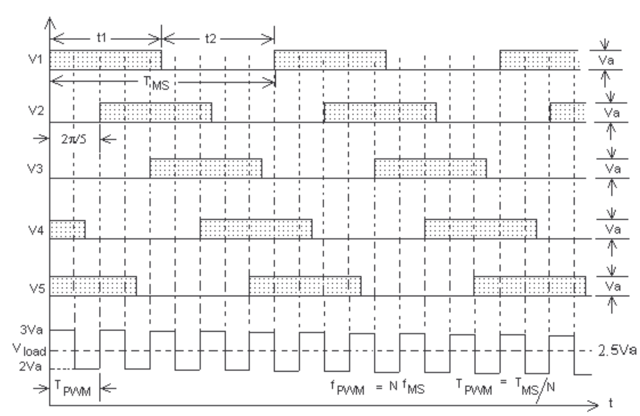

Fig. 2. Output Voltage with PSM and PWM for 5 SPMs.

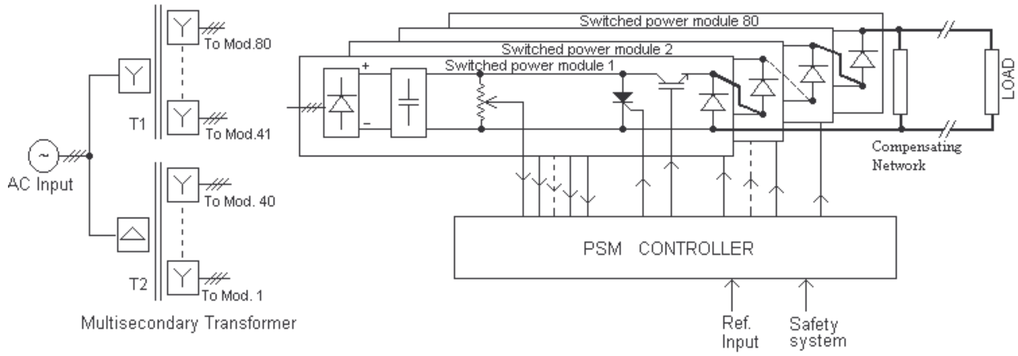

Fig. 3, Solid state high voltage power supply using PSM.

its main elements is shown by schematic in fig. 3. The different elements of such a power supply are:

-Multisecondary transformers T_1 and T_2 (with 40 isolated secondaries),

-Switched Power Modules (Thyristor crowbar and IGBT switch followed by unregulated - rectifier/filter) and the HV Rack Structure,

-PSM controller,

-Output filter/ compensating network, and

-Auxiliary systems (for safety, insulation, cooling etc.)

3.1 The multisecondary transformers

In the present design two multisecondary transformers are used for obtaining 12-pulse configuration of the DC output and input lines. These transformers are cast resin type. Each of the transformers has a single 3-phase primary and 40 nos. of 3-phase secondary windings. Each secondary winding is isolated from each other and the primary winding. Each secondary winding feeds one SPM (fig. 3). The output of the SPM is connected in series to other SPMs in the stack, each secondary experiences the same load.

The secondary winding connected to the SPM placed near the live (+ve or –ve) end of the output is subjected to the rated DC voltage of RHVPS. Consequently, the secondary windings are to be isolated for the DC voltage to which it is subjected. Depending on the disposition of the secondaries with respect to each other, the insulation requirement of secondary varies. As such, the secondary windings can have graded or uniform insulation. However, the phase to phase insulation is normal.

The inter winding capacitances have direct bearing on dielectric current (at switching frequency) and the transient performance of the RHVPS. An estimate of these parameters should be used for the design.

In the present design, resin cast transformer winding is used for indoor installation. Oil filled transformers were used in an earlier version, but accommodating large number of HV bushings is a difficult issue considering leaks that may occur from them.

3.2 The switched power modules

There are 80 switched power modules (SPMs) arranged in a stack for series connection. These are the equivalent of the voltage sources shown in fig. 1. The SPM works with the local reference voltage which is one SPM voltage. The design of the electronics is conventional,

except for static discharge considerations. These are switched ON and OFF at a duty cycle of a maximum of 95% at a frequency of 5 kHz. The duty cycle control and adequate derating of the switch devices allows using simpler cooling method. Also, the power supply operates at rated load with high reliability for long time. The input AC is controlled (with resistive-soft charge circuitry) by a controlled switch for charging the capacitor bank relieving the input transformer from high turn-on inrush current point of view. The 3-phase unregulated rectifier-filter section stores enough energy for a very fast turn ON (~few µS) of the output. The bleeder resistors are used for a safe discharge of the stored energy.
The switch section is made of an insulated gate bipolar transistor IGBT) with an inbuilt diode by-pass element. The commutation from the diode path to the IGBT path (and vice versa) is free from oscillations by making a stray free construction. To ascertain this, stray elements of the circuit need to be small. IGBT as a switching element fulfils the requirement of fast turn ON/OFF times in the range of few microseconds. There is a crowbar circuit for clearing fault by opening input side contacts and isolating the SPM if the IGBT fails during operation. In this case, diode at SPM output continues carrying load current, bypassing the SPM. Bypassing of the SPM during operational period does not result in any change at power supply output because of the instantaneous modification carried out in PSM and PWM switching pattern.
SPM draws its control power from an auxiliary supply. It has an independent safety system for overload, input undervoltage, output short circuit, switch failure and usual protections for the semiconductors. It has the following control interfaces.

1. IGBT trigger input at 5kHz switching frequency and variable duty cycle pulses from the PSM controller.
2. Stage voltage measurement (analog, sampling rate ~ 100 kHz).
3. Crowbar trigger input.

All these links are through fibre optic cables for HV isolation. Each SPM contains the receiver/transmitter for the optical signals and other necessary electronics.

3.3 The PSM controller

The control system (fig. 4) is a digital system which performs two basic purposes,
1. Generate PSM control signals for each of the SPM and,
2. Supervise general safety system and provide control parameters

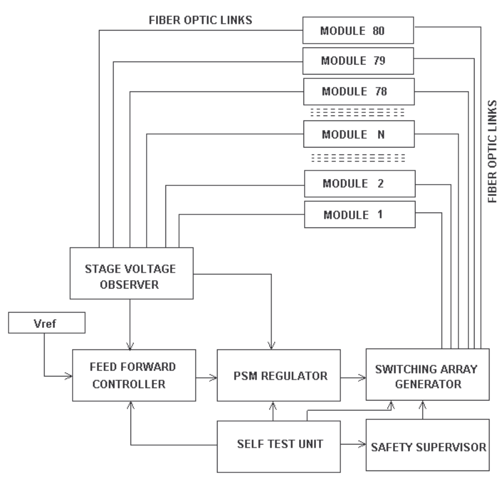

Fig. 4, Control System for Accelerator Power Supply.

The hardware is PC based and dedicated electronics for generating IGBT trigger signals. The software is dedicated to the functional requirements.
The major functions of the control system are:

1. Reading stage voltage data for each SPM
2. Reading reference inputs and run the feed-forward control algorithm
3. Generate the PSM pattern signal to IGBTs in SPM
4. Allow corrections in duty cycle in case of missing/faulty SPM
5. Emergency trip of the system in case of fault and safety system failure

3.4 Output filter

The RHVPS output is connected by a HV cable to the load. Depending on the parameters of the load, transmission line and the system performance requirements, the output need to be filtered, a network for filtering is an RLC series-parallel network (not shown in schematic) for specific transient/dynamic performance operating at the output voltage of the RHVPS.

3.5 The auxiliary systems

The main heat dissipating parts of the system are the semiconductors and transformers which are spread over a large volume. At about 97% overall efficiency, the system dissipates about ~75kW, at continuous operation. Forced air cooling is used for the SPMs, and transformers.
For test of the system (and to be used for troubleshooting in future) a full powered resistive dummy load for 1 Sec. duty is used. A short duty load bank is good enough to verify all electrical parameters of the system.
The safety system involves safety for human and equipments. Interlocks for start/run/stop, etc. are provided to the controller for safe operation. Most of the safety signals are hard-wired with computerised backup supervision.
Ground switches are also provided at output for safe access to the system for maintenance. Fast protection for current is provided which acts in <1µS to block the triggering pulses to all IGBTs in case of a fault.

4. A System used for Neutral Beam Application

An RHVPS system rated 80kV, 75A was developed for the Neutral Beam Application in the Tokamak program [2] [3]. This system used oil cooled transformers and forced water cooled IGBTs, photographs can be seen in fig. 6 & 7. Some operating waveforms are shown in fig 8 to 11. Fig.8 is a 70A current pulse at output which has a flat shape on top with an acceptable regulation figure. Feed-forward control does not allow oscillations at turn on. Fig.9 shows a ripple on output well below 1%. This system used a special control mechanism for a two fold ramp start-up (fig.10) which helps a transient free turn on for equipments.

Fig.11 is the waveforms from wire burn test where the system is characterised for fault energy. In this case a short circuit was created through a 10 Joule rated wire which did not fuse and the RHVPS was turned off by electronic protection (IGBTs OFF). A small rise in output current is detected and the IGBTs are blocked within ~µS, limiting the peak current to <150A.

Fig. 6, RHVPS with switched power modules in rack.

Fig. 7, Multisecondary transformers.

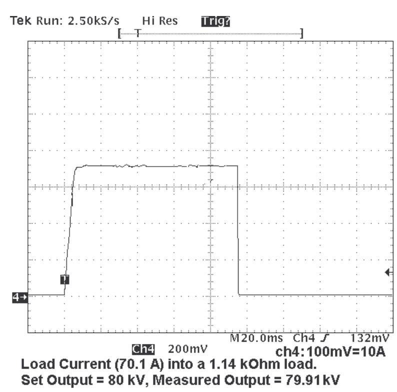

Fig.8, RHVPS output.

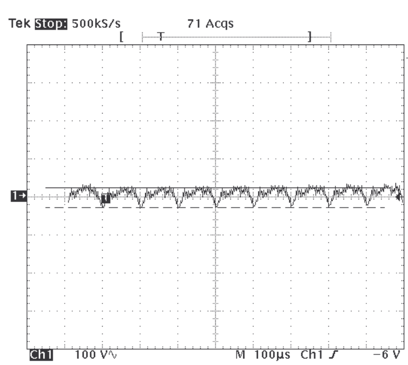

Fig. 9, Output voltage ripple.

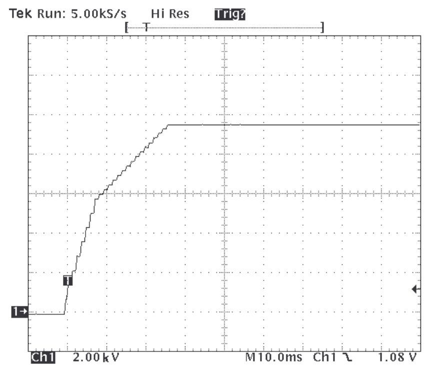

Fig. 10, Variable ramp start-up

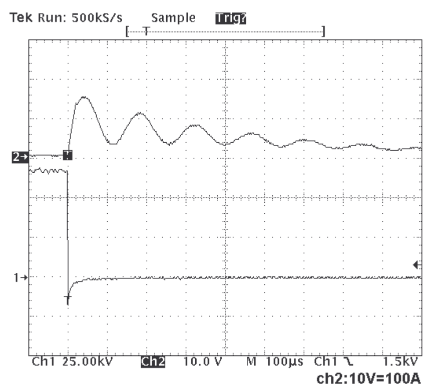

Fig.11, Wire burn test result.

5. Summary

High voltage power supplies built around the PSM topology are suitable for continuous duty, controlled HV power requirements with fast dynamics. These are the most efficient power supplies for the given range of power and voltage. They can be configured for modulating outputs for alternative applications as well. Fast turn ON and turn OFF capabilities with small stored energy (for feeding a fault) are features which makes it very competitive for use with high power RF tubes.

References

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[2] U.K.Baruah, P.J.Patel, et.al., "Power Supply System for 1000 S Neutral Beam Injector", Presented at Symposium on Fusion Engineering, 1997.

[3] Indian patent no.:206556, Title: A regulated High Voltage Power Supply