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Power Electronic Converters in Particle Accelerator Applications: A Review

Moataz EL SIED*¹, Amrane OUKAOUR², Jean-François BOUTEILLE³

¹Electrical power and machines departement, Faculty of engineering, Helwan University, Egypt

²LUSAC laboratory, University of Caen Normandie, Cherbourg, France

³Electrical Power Quality & Converter Supplies, European Synchrotron Radiation Facility (ESRF), Grenoble, France

RESUME - In particle accelerator (PA) applications, a continuous, reliable, efficient and sustainable power supply solution is required. This supply should guarantee the availability of high power quality through reliable and high energy efficient power electronic stage. This paper presents a review on different power electronic converters for particle accelerator applications and provides an account of research in areas related to main power converters' topologies, operating modes control systems, fault detection and isolation methods and reliability analysis. The paper can be also considered as a guidance to assist in the power converter selection process of the next generations of particle accelerators.

Key words—particle accelerators, power converters, power supply, DC-DC converters, AC-DC converters.

1. INTRODUCTION

At the turn of the century, research into the structure of matter, medical instrumentation, electronics, aero-space, deep sea exploration, and complex particle-physics were advancing rapidly and particle accelerators could be considered as the major driving forces in the development of these research fields [1]. In particle accelerators, power converters (PCs) have always been closely associated and play a crucial role to drive the magnets with different power, voltages and frequencies and allow a better usage of the magnetic components. For every new generation of accelerators, the improvements in the beam quality impose new and more severe requirements on PCs [2].

Recently, research efforts on PCs have been focused on finding topologies that could offer improved conversion efficiency, high power quality (power factor close to unity and low harmonics distortion), high reliability, good dynamic performance (high accuracy in the magnet's current tracking) and power density for the accelerators [3]. These necessary requirements could be reached due to the advances in converter architecture, the power management optimization, the new thermal management techniques, the huge development in switching semiconductor devices and the appearance of new semiconductor technologies such as the silicon carbide (SiC) and the gallium nitride (GaN) [4].

This paper highlights and illustrates the evolution of power electronic converters that have been used in particle accelerators applications.

Firstly, the paper will present the requirements that should be considered in designing PCs. Secondly, a review about principle schemes and operation of different power converter topologies, will be explained. Three main topologies will be considered: Linear power converter, line-commutated thyristor power converter and switched-mode power converter. Finally, the existing control methods, fault detection methods, reliability analysis and maintenance strategies that have been used for PCs in particle accelerators applications will be discussed.

2. MAIN POWER SYSTEM DESCRIPTION

Main power system for particle accelerators should consist of mains utility grid, energy storage unit (ESU), diesel generator and load and supply breakers as shown in **Fig. 1**. May be renewable sources can be added if necessary. In normal operation, the grid utility should supply the load requirements and ESU can protect the electrical load from power quality problems eliminating harmonics, flicker, voltage spikes and sags.

During mains utility failure (small period/ 2-3 seconds), depending on ESU capacity and load power, the ESU should maintain the power supply at the precise voltage and frequency. Under long interruption period, the load will be automatically transferred to diesel gen-set. In case of surplus power, the diesel can charge again the ESU. Once the mains utility returns, the ESU will safely transfer the load back to the utility and be ready to act again. In **Fig. 1**, the PCU of load demand will include the different power converter topologies to supply different magnets, RF, vacuum and cooling pumps, digital equipment and some auxiliary loads. In the next sections, the paper will focus on different power converters topologies which are used to supply magnets.

3. POWER CONVERTERS TOPOLOGIES FOR PARTICLE ACCELERATORS

In this section, principle schemes of power converter topologies will be explained and their performance and suitability of application will be compared. Three main power converter topologies are considered:

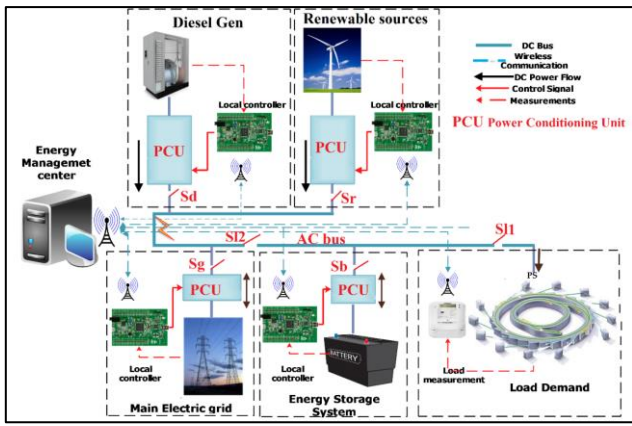


Figure 1: Mains Power System

3.1. Linear Power Converters

This power converter is used to supply dc magnet through AC transformer, auto transformer, uncontrolled rectifier, passive filter and voltage regulator as shown in Fig.2. AC transformer is used for isolation while auto-transformer is used to adjust AC voltage. Then the diode rectifier, LC passive filter and series regulator are used to obtain DC voltage. The series regulator has transistor bank working in the linear region to regulate the output DC voltage. Such kind of power converter has low noise since there are no controlled switching devices. On the other hand, it has big size and low efficiency due to linear mode of regulation.

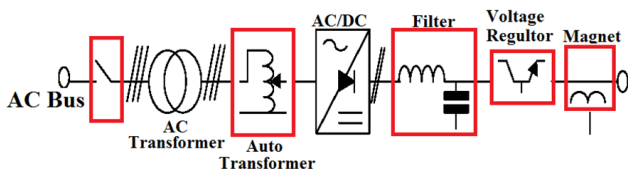


Figure 2: Linear power converter

3.2. Line Commutated SCR Power Converter

The basic structure of this power converter is very simple and reliable. It includes an input AC transformer, full control rectifier based on SCR (Silicon controlled rectifier) and a LC network to compensate the output voltage. A simplified schematic diagram of a three phase 6 pulses for low power is shown in Fig. 3.

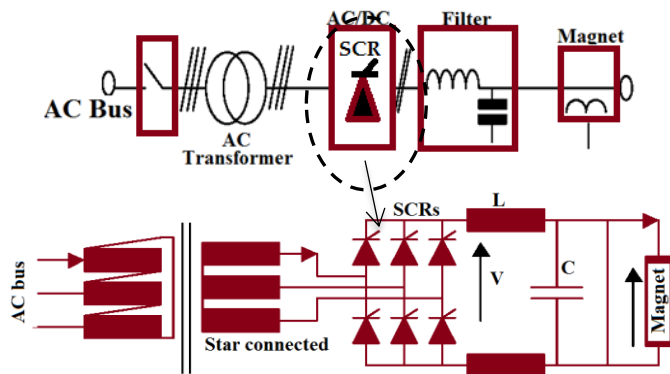


Figure 3: Three phase-six pulses power converter

The harmonics and ripples of this converter can be improved using 12 pulses topology (Fig. 4) due to the 30 deg phase shift between the two bridges of the secondary winding of AC transformer. In addition, the filter size can be reduced based on the harmonics improvements.

On the other hand, it has poor power factor which is depending on the firing angle of SCR. This will require additional costs for power factor correction unit. Moreover, large and heavy magnetic elements such as transformers and chokes could make it unsuitable for low power applications.

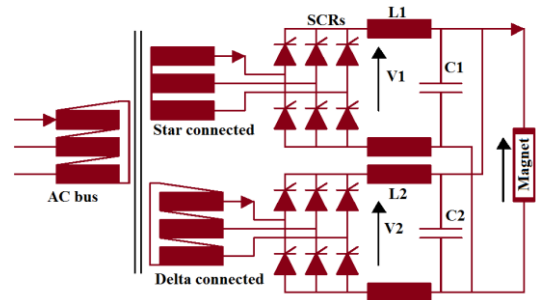


Figure 4: Three phase-twelve pulses power converter

3.3. Switched-Mode Power Converter (SMPC)

The switching mode power converters are proposed to decrease the power dissipation, and hence increase the overall efficiency. There are two main types of such kind of converters; non-isolated and isolating power converters.

3.3.1. Non-Isolated SMPC

The non-isolated power converter topology is used to supply dc magnet through uncontrolled rectifier, DC chopper and passive filter (Fig. 5). The key element of this topology is the DC chopper which can be configured in different schemes such as buck, boost, buck-boost and cuk. The configuration of DC-chopper could be selected based on the desired output voltage. Normally, dc-dc converter should work with duty cycle range between 0.1 to 0.9. A non-isolated power converter based on buck dc-dc converter is shown in Fig. 6. In high power applications, two or more converters can be connected in parallel as shown in Fig. 7.

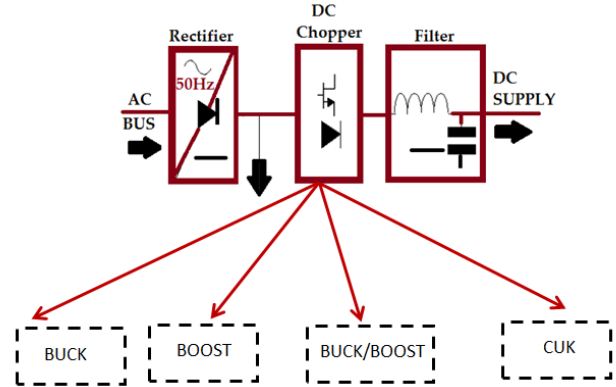


Figure 5: Non-isolated switching mode power converter

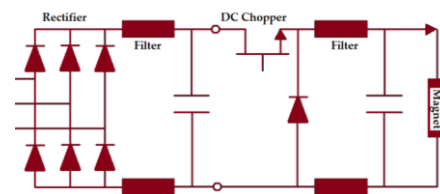


Figure 6: Non-isolated switching mode power converter based on Buck dc-dc chopper

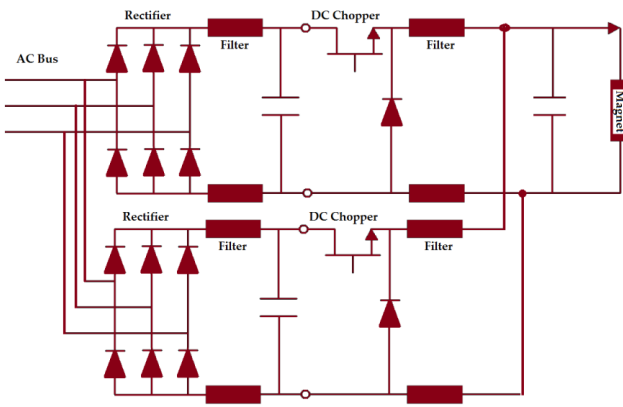


Figure 7: high power non-isolated switching mode power converter

3.3.2. Isolated SMPC

In this section, the isolated power converter topology is used to supply dc magnet through uncontrolled rectifier, inverter, HF transformer, HF rectifier and passive filter as shown in **Fig. 8**. Isolated DC-DC converters have high output voltage ratio, high isolation (barrier) voltage from several hundreds to thousand volts depending on the type of standard. They have also strong noise and interference blocking capability thus provide the load with a cleaner DC source which is required by many sensitive loads.

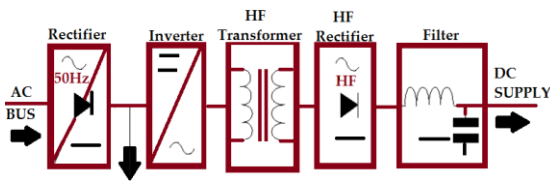


Figure 8 : Basic topology of isolated SMPC

On the other hand, these converters have bigger size and higher cost compared to non-isolated SMPC. More topologies are proposed using isolation principal such as fly-back, forward, push-pull, dual active bridge (DAB) [5]. The isolated DAB can be considered as the most promising topology among isolated SMPC as the control system of the two bridges can be controlled simply by square wave or PWM signals. A delay between the control of the first bridge and the second bridge can determine the amount of power that passes through the converter. The power rating could be also increased by connecting multi-converter in parallel (**Figs. 9-11**).

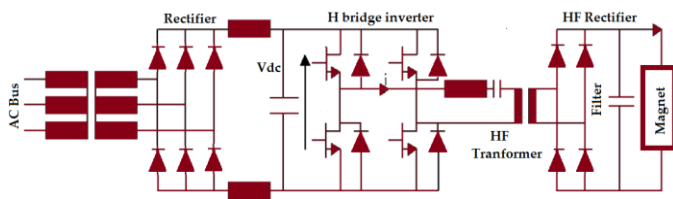


Figure 9: Unidirectional isolated DAB

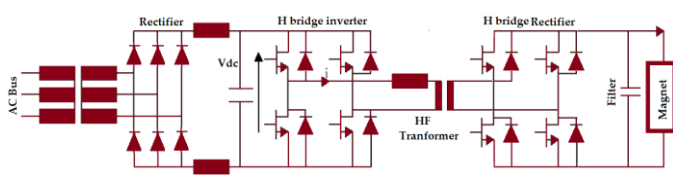


Figure 10: Bi-directional isolated SMPC (Dual active bridge)

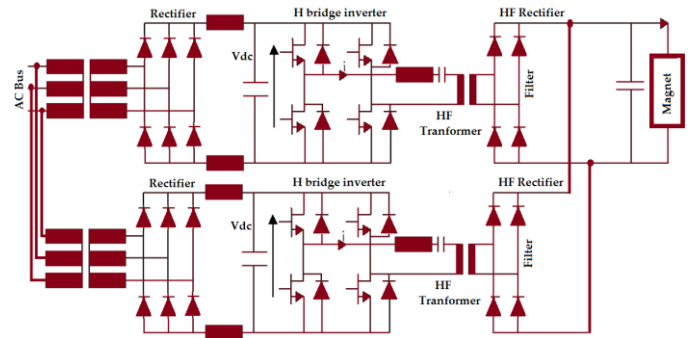


Figure 11: High power isolated SMPC

4. SWITCHING MODES OF POWER CONVERTERS

In this section, principle operating modes of different SMPC mentioned above will be explained. These converters can be operated in two main modes as follow:

4.1. Hard-Switching operating mode

Hard switching mode refers to the stressful switching behavior of the power semiconductor switch as shown in **Fig. 12**. During the turn-on and turn-off processes, the power semiconductor switch should withstand high voltage and current simultaneously, resulting in high switching losses and stress [6]-[7]. In addition, the stray inductive and capacitive components in the power circuits and power devices can cause also considerable transient effects, which in turn give rise to electromagnetic interference problems. Snubber circuits could be added to the power circuits to limit the dv/dt (**Fig. 13 right**) and di/dt (**Fig. 13 left**) applied on the power devices. This will lead to reduction in the switching loss and stress. Another solution is to use soft switching mode which will be discussed in the next section.

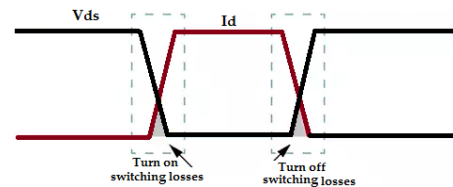


Figure 12: Hard switching voltage and current signals

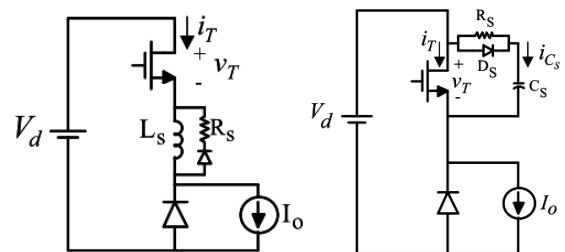


Figure 13: Turn on and Turn off snubber circuits [6]

4.2. Soft-Switching operating mode

The soft switching mode is related to the switching strategies that result in zero-voltage and/or zero-current switching. This operating mode has several advantages such as; low conduction and switching losses, low EMI and allow operation with high switching frequency. Soft switching modes can be classified into three strategies based on the controlled signal as follows:

4.2.1. Zero voltage switching converters

The idea of this strategy is to control switch voltage to be zero during turn on before gate voltage is applied as shown in **Fig. 14**. A parallel capacitor as a loss-less snubber can be used during off period as shown in **Fig. 15**.

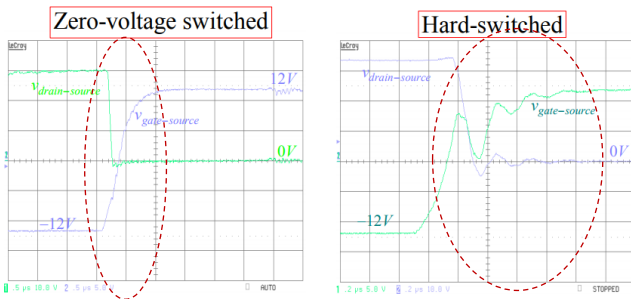


Figure 14: ZVS mode versus hard switching [6]

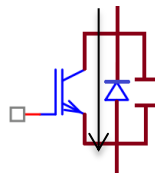


Figure 15: C-Snubber circuits during off state

4.2.2. Zero current switching converters

The control strategy of this converter is to control the switch current during turn off switching to be zero before the gate voltage is removed. The scheme of the power switch during on state using series inductor to make a low loss transition is shown in **Fig. 16**.



Figure 16: L-Snubber circuits during off state

5. POWER CONVERTERS CONTROL METHODS

Electromagnets for particle accelerators require a high current and a high performance power converter for PSs [8]-[10]. These converters should be capable to carry bidirectional current, and they are required to track a known reference with a very high accuracy. Commonly used control topologies in this application are:

5.1. Voltage control

The output voltage of PS is measured and compared with a reference or set-point to generate an error signal. Then, this signal will be applied to the input of a compensation $C_V(s)$ which can be implemented using PI or PID type block. The output will be the duty ratio that will be compared with a carrier waveform to generate the required PWM signal as shown in **Fig. 17**. In this control mode any change in the source or the load is detected only after it has propagated to the output.

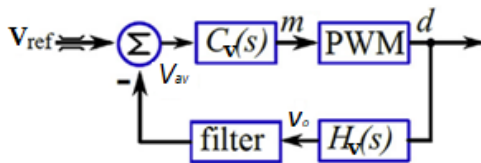


Figure 17: Voltage control loop

5.2. Current control

The output load current of PS can be measured and compared with a reference or set-point to generate an error signal as in the voltage control (**Fig. 18**). In this control mode, the power supply can be controlled to work as a current source.

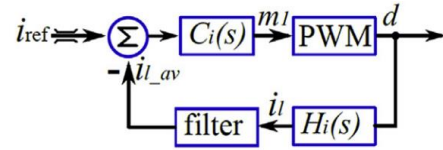


Figure 18: Current control loop

5.3. Voltage and Current

In this application, current and voltage reference values are dependent and they specifically require knowledge of the load. To overcome this obstacle, two loops of control are normally arranged, the outer loop manages the output voltage error by generating the necessary current reference whilst the inner loop makes the converter to act as a current source as shown in **Fig. 19**.

For all control methods mentioned above, the compensators could be implemented using classical like PI or PID or adaptive. Adaptive control like sliding mode control (**Fig. 20**) is essential in case of the parameters of the plant dynamics are unknown and/or change in time. Adaptive control covers a set of techniques, which provide a systematic approach for automatic adjustment of the control signal or parameters in real time, in order to achieve or to maintain a desired level of the system performance.

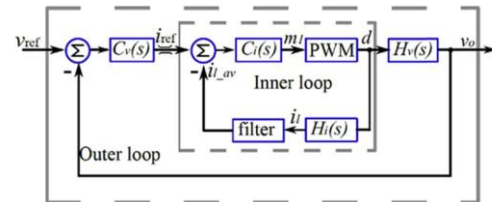


Figure 19: Voltage and current control loop

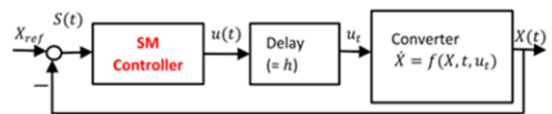


Figure 20: Sliding mode control loop for dc-dc converter

6. POWER CONVERTERS: FAULT DETECTION, ISOLATION AND IDENTIFICATIONS

In recent years, fault detection and isolation (FDI) systems have been successfully applied in many kinds of technical processes to improve operational reliability and safety. It is considered an important and challenging problem [11]. Although particle accelerators systems are built with high level of redundancy to tolerate hardware and software faults, a robust fault diagnosis system should be used to monitor and assess its power converters [12]. A very high-level redundancy design coupled with a robust fault diagnosis scheme would be required to ensure that such systems can meet the reliability and the safety requirements of particle accelerator operations.

The most popular fault detection and isolation (FDI) methods were introduced in the literature over the last decade for power converters in particle accelerator applications such as:

6.1. Model based method

In this method, the system input $u(k)$ and output $y(k)$ should be measured. Based on these measurements, process parameters are estimated and compared with a nominal parameter set. The difference, or residual, is used as a fault indicator. This method requires very accurate mathematical model of the supervised. Many approaches can be found in the literature [13-15] for designing model based fault detection.

6.2. Signal based method

This method is proposed for fault detection based on analysis of the measured output signals $y(k)$. Signals may be analyzed using: time-domain methods (e.g. correlation, mean-change), frequency domain methods (e.g. Fast Fourier Transform, FFT), or more sophisticated methods including time frequency or wavelet analysis. Decision should be made based on the normal process behavior knowledge or on some faulty behavior knowledge. Signal-based fault detection methods are particularly interesting for electrical faults detection [16]. A method for fault detection and isolation is proposed in [17] and applied to inverter faults in multi-phase drives. This method is implemented based on the unbalance of the phase currents and their instantaneous frequency. The faults under consideration were: open-phase faults and open-switch faults.

6.3. Data based method

This method can be used if the process has a complex analytical model and the regular signal analysis approach doesn't yield a reliable FDI scheme [18-19]. This method has advantage compared with the aforementioned methods because it doesn't require any knowledge about the system parameters. A classification of the sampled data is carried out based on extracted features. This method is always using artificial intelligence approaches such as: neural network or fuzzy logic or combination between both of them.

7. POWER CONVERTERS RELIABILITY ANALYSIS

Power electronics presents special challenges for reliability analysis which can help to understand the main causes of failures, downtime, and cost and how to reduce them [20]. This part presents the reliability analysis process of power electronics based on data maintenance. In this method, it is recommended that the power converter users should collect maintenance data in order to answer questions such as:

- Which failures are costing the most?
- When are most of the failures occurring?
- Which failures are causing the most reliability problems?
- Which pieces of equipment are causing the most problems?
- How much would the system reliability improve if a certain component never failed?

Then, the maintenance data should be stored in Table using date, time, equipment ID, Failure mode ID, down time and repair cost. Of course, the more detail desired, the more difficult the data collection will be. Finally, the analysis process should be used in a series model which considers that every failure can cause downtime. The data base should

include at least MTBF, availability, downtime (per failure or per year), and cost (per failure or per year). It is straightforward to calculate these metrics once the data is in the right form. A simple way is to normalize this data and plotted together as a Pareto chart from greatest to least which quickly shows which failure modes cause the most reliability problems. In addition, combining all sources of failure data provides clear image about which are most of the failures occurring and information about the properties of each failure mode.

8. CONSIDERATIONS AND RECOMMENDATIONS IN DESIGNING POWER CONVERTERS FOR NEXT GENERATION OF PARTICLE ACCELERATORS

This section will present the most important factors that should be considered when designing a power converter for particle accelerators applications such as output voltage and current as well as the electrical and physical environment that the equipment will operate in. In addition, it is necessary to know its functional modes [21]-[23].

8.1. Desired outputs (specifications)

In applications such as particle accelerators, it is necessary to know the desired output voltage and current. These values will help to select the suitable converter, control parameters and the output configuration. For example; the output configuration of PSs is generally adopted when high output current or voltage are required. When placed in parallel, multiple PSs may come with different current ranges but should have with the same output voltage range. On the other hand, the series configuration of multi PSs should be used to increase the output voltage rating.

8.2. PS Control mode and stability

The control system is needed to ensure that the established magnetic flux drives the particles accurately during all the time length of the experiment. The control mode of PSs can be configured into of full analog, full digital and hybrid (part analog and part digital). Indeed, the digital control is preferred as it has several advantages such as flexibility, easy configuration, long-term stability and reconfiguration of the system compared to the analog control.

8.3. Transient response

Knowing the load profile, current and voltage, during transient and steady state as shown in **Fig. 21** can helps in the selection of the PS and its PCs which could react and cope with fast changes in the load current. The PS should decrease output voltage ringing using robust voltage control loop when the load current changes rapidly over a large range in a short period of time. Another solution is to use a large output filter with cut-off frequency to limit the output ripple. This solution is not preferable as it may make the supply response too slow to react at fast load changes.

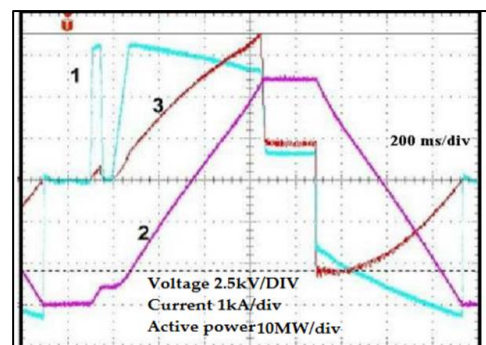


Figure 21: Current, voltage and power profile of PS chronograms [1]

8.4. Efficiency

PS efficiency can be considered as the most important issue in the design of a PS, since there is almost an effort to select a suitable semi-conductor device technology, converter topology, and cooling system. Advances in semiconductor technology have always been the major thrust behind efficiency and power density improvements in power conversion circuits. Recently, the superior electrical characteristics of SiC MOSFET and GaN technologies make them very good candidates to replace Si-devices and design a high efficient PS [4]. The advantages of these devices are; small on-resistance at high voltage rating, allow the operation with higher switching frequencies at high power rating, low conduction and switching losses and hence high efficiency characteristics.

8.5. PS filters

It is well known that the PSs should have output filters with large capacitors to decrease the ripple and noise level of the output voltage. In addition, typical filters should be also employed to suppress Electro-Magnetic Interference (EMI) including common mode and differential mode inductors. The common mode inductors is a good solution as it could offer high impedance to high-frequency noises, absorbing it and then dumping it to ground through low impedance capacitors

8.6. Transformers and inductors

The correct designing and sizing of inductor and its core type in the PS application gives a key contribution to increase the reliability of the PSs. This issue can limit high voltage spikes, and core saturation problems.

CONCLUSION

In this paper, an overview of the technologies and topologies that should be considered in power converters when designing power supplies for particle accelerators applications have been presented. The power converters' operating modes were also considered, followed by an overview of common control methods used in power converters. Then, the paper has introduced different fault detection methods that can be used for to detect and isolate any fault in the system. Finally, the reliability analysis of power converters has been mentioned to show how we can increase the power system reliability and decrease downtime and reduce maintenance cost.

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