SMES PCS TOPOLOGY DESIGN - A CRITICAL COMPARISON OF INVERTER TECHNOLOGIES

C.J. Hawley† and S.A. Gower
School of Electrical, Computer and Telecommunications Engineering,
University of Wollongong

†Corresponding Author

Abstract

The design of Superconducting Magnetic Energy Storage (SMES) Power Control Systems (PCS) can be seen as an evolving technology. PCS designs have adapted to the changes in superconducting coil design and also the availability of refrigeration and switch technology, the most significant of which has been the improvement in available semiconductor switching devices.

One of the pivotal decisions affecting the design of PCS revolves around the inverter, Voltage Sourced Inverter (VSI) vs. Current Sourced Inverter (CSI). As well as the choices made by researchers, there are theoretical considerations to both designs that can be used to match the inverter type to the aim of the project. This paper critically examines available inverter topologies specifically with reference to the University of Wollongong (UoW) SMES requirements.

1. INTRODUCTION

The PCS is an integral part of the design of any SMES system. The PCS must be able detect faults in the mains power then discharge the stored energy in the coil to the load at a controlled rate and within a specified period. It must then recharge the coil from the mains once the fault event has passed.

When choosing the PCS, it is important to take into consideration the type of load that will be supported, and the aims of the system design. This puts into perspective the characteristics that are most important for the PCS.

Major changes to the design of the SMES PCSs began towards the end of the 1980's as High transition Temperature Superconductors (HTS) tapes were becoming available and switching technology was maturing. Since then, PCS researchers have used different topologies depending on the required application and the technology available. However, the reasons behind the decisions, or why a VSI or CSI is chosen has not been adequately discussed. A great deal can be learnt from observing the collaborated evolution of the PCS design. This paper will enable a designer to make educated decisions and see how the characteristics of the PCS affect the operation of a real SMES system.

This paper analyses the possible PCS topologies, and gives a comparison using both literature and theoretical analysis of the characteristics achieved by each design. The paper aims to provide a guide to designing a PCS to match the load requirements.

2. INVERTER TYPE

There are two major design choices to be made when considering the SMES PCS. The first of these is whether to use a VSI or CSI. The SMES coil acts inherently as a current source, so at first glance the choice may seem obvious. However, through examining the historical evolution of the SMES PCS and the theoretical considerations that apply, an informed choice can be made about the inverter type to be used.

2.1 Historical Evolution

In 1988, Wang from the Applied Superconductivity Centre at the University of Wisconsin documented two different methods for controlling the flow of energy in a SMES device [1, 2]. The first method had been built as part of a research project that had been running since 1971. During that time the PCS had been built and tested with the aim to test power-conditioning concepts especially with respect to diurnal load leveling of power systems. The SMES device was built around two 2kJ Low transition Temperature Superconducting (LTS) coils connected in series. The PCS consisted of two 6-pulse thyristor converters, which could be used individually, in series or parallel as needed. The converters were current controlled and fed 3-phase 30kVA transformers to boost the voltage.

In his paper, Wang proposed changes to the existing PCS, so that the amount of reactive power taken or supplied by the SMES could be controlled depending upon the needs of the utility. The new circuit implemented a Gate Turn Off (GTO) bridge with a Pulse Width Modulation (PWM) control algorithm in conjunction with a 6-pulse thyristor bridge. By adjusting the firing angles of the devices the amount of reactive power supplied or taken could be controlled [1, 2]. This design, utilising advances in GTO technology began the interest in implementing VSIs in SMES designs.

The large current involved in Wang's project meant that he was restricted to the use of GTO or thyristor devices. In 1991 Ise documented his testing on a SMES control circuit using cryogenically operated Metal Oxide Silicon Field Effect Transistors (MOSFETs) at Osaka University [3]. The PCS was designed to support a HTS coil carrying only a few amps. The cryocooling of the MOSFETs reduced the circulation losses of the SMES device and the energy was charged/discharged through a voltage controlled chopper circuit [3].

Also in 1991, Kustom, from the Applied Superconductivity Centre published work stating that the VSI GTO circuit had been built and was successful in controlling the reactive power present in the supply [4].

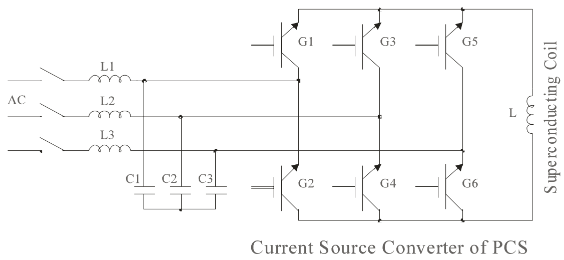
Also at the University of Wisconsin, Lasseter's work compared the use of the CSIs and VSIs [5, 6]. The finding was that both showed very good response to load change and faults, the CSI was easier to control but the VSI allowed better control of harmonic components [5].

In 1993, at the University of Arizona, Karady continued on the development of the PCS in two different directions. Karady and Han designed a 12-pulse GTO inverter and after testing found that it was successful in reducing the system rating and offered independent regulation of the active and reactive powers [7]. Karady cited that Lasseter's designs were not practical for large loads. This was mainly due to the restrictions in GTO capacity making it necessary to current share over multiple bridges, and the increase in switching losses was not acceptable [8]. Karady also developed a 24-pulse thyristor bridge that overcame these problems.

From 1993 till 1996 research, especially by Schoenung, focussed on comparing the costs and advantages of SMES systems to that of equivalent battery Uninterruptible Power Supply (UPS) devices [9]. To further examine the benefits of SMES, in July 1996, a United States Air Force (USAF) funded project successfully adapted a 6MJ LTS SMES coil to a commercially available uninterruptible power module [10]. This project broadened the possibilities of what a SMES device might be interfaced with and the functions that it could perform.

It was also in 1996 that a PCS design using Insulated Gate Bipolar Transistors (IGBTs) was first considered to speed up the response time of the converter [11]. The widespread acceptance and use of IGBTs as fast response switching devices lead to a whole new round of designs, replacing the GTOs with the new semiconductors. In 1998 Casadei, published his design and chose the VSI topology over CSI for a 3-phase system [12]. His reasoning was that CSIs were the best solution to transfer reactive and active power to the network, but VSIs handle low order harmonics better and can be used as a shunt active filter [12].

From 1999 till 2002, there have been multiple adaptations of the two PCS systems proposed by Lasseter: the CSI topology and the VSI topology (with the GTOs or thyristors replaced by IGBTs). All of these designs were variants of the two basic circuit topologies that are shown in Figure 2.1.



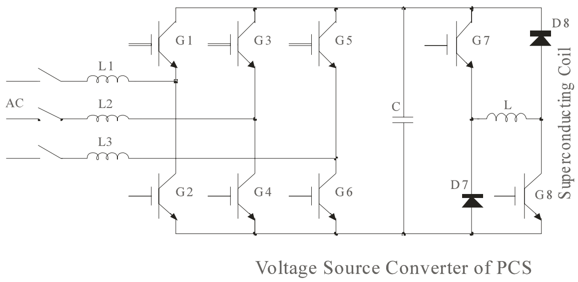


Figure 2.1 Comparative circuit diagram of CSI and VSI topology [13]

Very few of these designs adopted the CSI topology, but there were some exceptions. Jiang chose the CSI topology for a joint project between the Chinese Ministry for Education, Tsinghua University and the Chinese Academy of Sciences [14]. The project was to build a 20kJ LTS SMES device to study the applicability to utility and customer power applications. Jiang reasoned that the CSI was able to supply a higher level of reactive power and has smaller ripples on the superconducting coil, implying lower AC losses. The intended high power application of the project meant that the ease with which CSIs can be paralleled to cater for higher currents was a large advantage. To reduce the disadvantage of high harmonic content, Jiangs design implemented a 12-pulse IGBT bridge to eliminate lower order harmonics [14].

Most of the other projects from 1999 onwards chose to adapt the VSI topology. Amongst these projects, Huazhong University of Science and Technology in China, did extensive testing and refinement of 3-phase VSI PCS, and acknowledged the existence of the CSI configuration [15]. The main aims of the project were to develop a PCS for a SMES device that had a high current stability, quality and efficiency and the ability to transfer reactive power in a bi-directional manner. However, no specific reason for adopting the VSI topology was cited.

Other projects working to improve the PCS circuit were undertaken at the Virginia Polytechnic Institute and State University, who developed a 3-level VSI chopper configuration [16], and Fuji Electrics R&D who designed a novel unity power factor circuit [17]. These designs, all incorporated bi-directional power flow attached to 3-phase mains and helped improve the efficiency and cost effectiveness of the PCS.

In 2000, ACCEL Instruments, Germany, published their designs for a 2MJ LTS SMES device with a PCS adapted from a commercially available UPS [18]. This followed the thread of the USAFs 1996 work to improve the functionality of the SMES. Tel Aviv University, Israel also published plans in 2002 to build an electronic interface between SMES coils and the UPS electronics so that the coils could be used to replace the batteries as a storage element in UPS devices [19]. Finally, the Korean SMES project has taken this one step further by beginning design and building of a 3MJ LTS and a 200kJ HTS SMES device. The PCS for these coils will act as a UPS, active harmonic filter, a power system stabilizer and a peak load compensator. The Koreans plan to build these systems by 2004, when testing will begin [20].

2.2 Theoretical Examination

As well as the choices made by researchers, there are published theoretical comparisons to both designs that can be used to match the inverter type to the aim of the project.

A CSI behaves in the opposite way to a VSI, the current is controlled, whilst the voltage is varied to satisfy the loads needs. To make this possible a large inductance is placed on the primary side to oppose changes in DC current [21]. In a PCS the SMES coil would represent the inductance. Similarly, the advantages and disadvantages of CSIs and VSIs are the inverse of each other. Figure 2.2 summarises the features of inverters as compiled by Brumbach [21].

Features	Variable Voltage Inverter with Phase Control	Variable Voltage Inverter with Chopper Control	Current Source Inverter with Phase Control	Current Source Inverter with Chopper Control	Pulse Width Modulation
Open Circuit Protection	YES	YES			YES
Short Circuit Protection			YES	YES	
Ability to Handle Oversized Motors			YES	YES	
Ability to Handle Undersized Motors	YES	YES			YES
Multiple Motor Applications	YES	YES			YES
Low Speed Torque Applications	YES	YES	YES	YES	
Requires High-Speed Switching Devices		YES		YES	YES
Battery Operation		YES		YES	YES
Regenerative Operation	YES		YES		
Low Speed Efficiency	GOOD	GOOD	GOOD	GOOD	MEDIUM
Complex Control Circuit	MEDIUM	MEDIUM	MEDIUM	MEDIUM	HIGH
Size and Weight	MEDIUM	MEDIUM	HIGH	HIGH	LOW

Figure 2.2 Table of comparison of inverter features [21]

In 1998, a joint project by the University of Nevada, Siemens and Aalborg University in Denmark, to build a hybrid inverter combining the benefits of both a VSI and a CSI was begun. As part of the project they produced a set of papers comparing the features of both inverter topologies [22, 23]. They are summarised in the following tables:

VSI Advantages	VSI Disadvantages
Simple and Robust	High switching frequencies
Easy to control in the feed-forward voltage or feed-back current mode	Large switching losses
Wide ranges of frequency and magnitude of the fundamental output voltage are attainable	Conducted and radiated electromagnetic interference
PWM allows direct control of magnitude and phase of output space vector	Hazardous over-voltages in long cables
	Accelerated deterioration of insulation and bearings in supplied motors

Figure 2.3 Advantages and disadvantages of VSI

CSI Advantages	CSI Disadvantages
Can transfer power in both directions	The inductance slows down response to current magnitude control commands and can cause over-voltage if the current path is broken
In square-wave mode is more efficient than a PWM VSI	Has square wave output current waveform
Power circuit is simpler and more robust than the VSI	High level of low-order harmonics
Lack of freewheeling diodes, the large dc-link inductance and the current control in the rectifier results in inherent protection from over-currents	When supplying a motor, can cause voltage spikes in the stator leakage inductance
Can transfer power in both directions	PWM CSIs are large and costly, and they lose their efficiency advantage over VSI

Figure 2.4 Advantages and disadvantages of CSI

3. PCS CONFIGURATION

The second major design decision is the use of either a parallel or series configuration for the PCS. The basic topologies are shown in Figure 3.1.

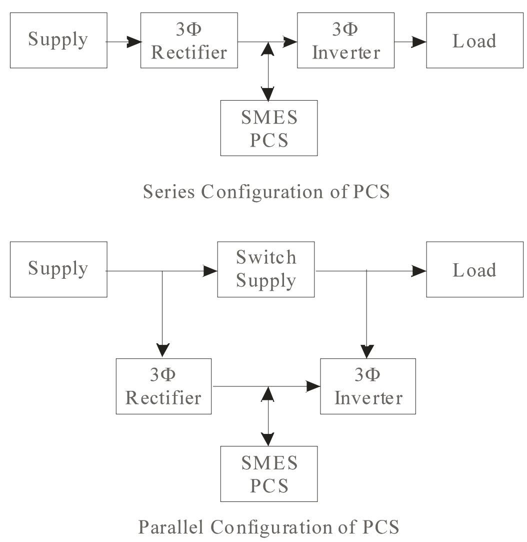


Figure 3.1 Series and Parallel configuration block diagrams of a PCS

The advantages and disadvantages of each system is much more self-evident than that of the inverter choice.

The parallel configuration benefits from the fact that the SMES system sits idle for long periods between events. Hence the devices used for the rectifier and inverter need to only be rated to perform during the event time (<1s). It can also be attached to an existing main supply, without the need to disturb the already installed equipment. However the fault detection and switch control system required for this configuration is very complex. The control algorithm almost needs to pre-empt a fault to effectively mitigate it.

The series configuration does not require the complex fault detection, and needs only to maintain the voltage on the DC bus. It also provides the advantage that the mains supply is passed through the inverter so any distortion of the supply up-line can be removed by the system.

4. SPECIFYING SMES FOR A LOAD

4.1 SMES Design at UoW

The overall design for the SMES project at the UoW is a combination of the series configuration with a VSI. The series configuration was chosen mainly due to the lower complexity of fault detection and switching algorithms as well as the ability to remove distortion from the mains supply.

The VSI was chosen over the CSI, not only due to the reduction in lower order harmonics, but also because of the faster response time achieved by having the intermediate capacitance rather than relying on the inductance to deliver energy immediately.

The circuit in Figure 4.1 represents the final system layout.

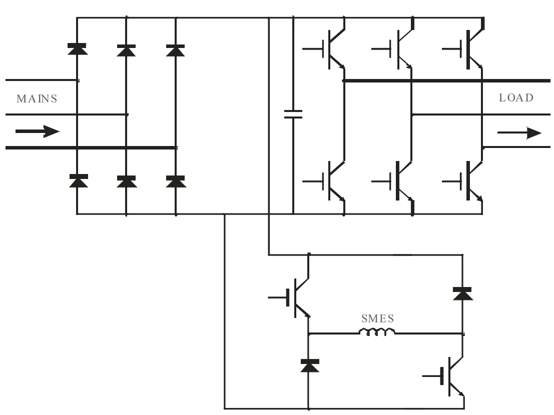


Figure 4.1 SMES Circuit Diagram

5. CONCLUSION

The advantages of different inverter technologies and parallel/series systems have been discussed. It was determined that for our design a series configuration with a VSI would be implemented.

The series configuration reduces the complexity of the control electronics required and also reduces the number of switches needed. If the SMES is in series with the supply then it also means that any disruptions to power quality, such as harmonics, closer to the supply can be rectified by our system. The VSI was chosen over a CSI mainly due to the faster response time and the cleaner waveform produced.

It can be concluded that CSI topologies have been implemented mainly to supply very large loads where high current rated devices of sufficient switching speeds to implement a VSI are unavailable. However these topologies are still appropriate for applications where constant current control is required.

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