CONTROL AND OPERATION OF SMES AND SMES/PV SYSTEMS

by

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(ABSTRACT)

Applications, converter topologies, and control schemes are examined for superconductive magnetic energy storage (SMES) systems. Diurnal load leveling for electric utilities and compensation for fluctuations in photovoltaic (PV) power generation are the primary applications discussed.

It is demonstrated that a SMES system implemented with standard AC/DC converters offers energy storage capacity large enough, and dynamic response fast enough, to compensate for PV fluctuations due to changes in weather conditions. The method of control is developed so that the charging and discharging of the SMES system are changed in response to PV fluctuations, and the combined SMES/PV power output is smooth and controllable.

An innovative control scheme is introduced for SMES that can simultaneously regulate real power and voltage independently without hardware modifications to the

standard AC/DC bridge arrangement normally used for coordinated control of real and reactive power.

The combination of SMES and PV systems could benefit from DC/DC converters that take advantage of the DC nature of both. It is established that DC/DC converters can respond with sufficient speed to handle variations in PV power. A converter topology is devised where two DC/DC converters in cascade effectively maintain a PV array at its maximum power point and simultaneously control a SMES system to compensate for PV fluctuations.

An alternative cascade configuration of an AC/DC converter with a DC/DC converter is proposed that could significantly reduce the reactive power requirements and improve the operational characteristics of a large scale SMES system connected to the utility grid.

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Following the relatively recent advancements in high temperature superconductor research, greater thought has been given to the possible applications of superconductors at any temperature. One area of investigation is superconductive magnetic energy storage (SMES). SMES is already being considered or tested for a wide range of potential uses, including: diurnal load leveling (peak shaving) for electric utilities, power system stabilization, stabilization of DC transmission lines, damping of subsynchronous resonance on AC transmission lines, reactive power compensation, pulse power supplies for fusion research facilities, nuclear magnetic resonance imaging, and energy storage for space systems. Further improvements in high temperature superconductors could make SMES even more desirable for current uses, make feasible a number of applications that are at present only theoretical, and even instigate development of entirely new uses never thought of before.

SMES is attractive in each of the applications mentioned because of one or more of its salient features: high round trip energy storage efficiency, fast dynamic response, little cyclic degradation, high energy density, and long lifetime. For example, high round trip efficiency and long life are crucial for diurnal load leveling for utility applications where other storage schemes have significant electrical losses and maintenance costs. In space applications, high efficiency and negligible cyclic degradation of the energy storage capacity would permit a reduction in the size, weight, and cost of the power supply system. High energy density and fast dynamic response are the most important aspects for fusion reactor research where other methods are incapable of either storing enough energy or delivering it quickly enough.

Though so many of its features are appealing, implementation of a SMES system presents a number of engineering challenges, including: cryogenic containment, magnetic shielding, structural support, and electrical power conversion. A cryogenic container (or dewar) must separate the extreme cold of the superconducting material from ambient temperature because even the highest superconductor cutoff temperatures are far from room temperature. The strong magnetic fields generated by large scale storage must be shielded to protect humans, wildlife, and sensitive equipment. SMES produces very strong radial forces; coils carrying high currents push outward as if attempting to straighten themselves, so hefty structural support is needed to prevent that from occurring. Due to the DC nature of both superconductivity and magnetic energy storage, SMES systems cannot interface directly with the standard AC power grid; power generated as AC must be converted to DC for storage, and the DC stored must be converted back to AC for transmission.

Even assuming these engineering challenges can be overcome, there are still operational drawbacks to be faced. Because no containment vessel is perfect, the continued operation of a superconducting system requires a marginal amount of refrigeration power to be supplied continuously. Plus, the necessary AC/DC conversion requires a supply of reactive power and inserts troublesome harmonics on both sides of the circuit.

1.2 Objective and Scope

With the field of SMES so large and diverse, it would be impossible to address within the scope of this work all of the issues involved or solve all of the challenges that remain. As the title suggests, the emphasis of this work was the combination of SMES and PV systems. However, that was not the initial direction of the research, just the final result. The potential of high temperature superconductors, the possibility of diverse applications, the relatively early stage of SMES development, and the promise of great benefits led to an examination of a wide range of issues. The scope of the study was then narrowed to a few related topics where a reasonable amount of effort could still provide significant results. Any contribution that could increase the probability of practical SMES implementation was pursued.

The first area of investigation was a search for applications that could benefit from SMES, make SMES more attractive, or that combined with SMES could become feasible even though the separate applications were not. Both small scale (electric vehicles) and large scale (photovoltaics) applications were examined in this portion of the study.

The second area of inquiry was converter topologies and connections suitable for a variety of applications. A connection of a SMES system with PVs could benefit from a DC/DC converter topology that takes advantage of the DC nature of both. If a SMES system is connected to a DC transmission line, there are difficulties associated with the conversion between the high-voltage/low-current combination of HVDC and the low-voltage/high-current of SMES. A significant challenge for utility scale SMES is the conversion process between the direct current of SMES and the alternating current of the standard utility grid. A configuration optimized for the specific connection of SMES to the AC grid could remove some of the hindrances.

Finally, control schemes for SMES must account for its unique features; it is not a typical electrical storage device. It requires full current to be flowing through the coil whether transferring energy or simply storing it, so a current path must always be provided (either through the power converter itself or through a bypass switch) even when no real power is being transferred. Any method for control needs to allow for charging, discharging, and circulating modes as well as the transitions among them.

These areas of applications, connections, and control are related because new applications may require new connections and control schemes to be practical. Specifically, the work combining SMES with PVs involved all three. The potential impact of this work is that by making use of the results presented here, certain applications for SMES may become attractive enough to be attempted; they might cross the threshold over to being implemented.

1.3 Organization

This thesis is organized into six chapters followed by the bibliography. Chapter 1 is a brief introduction into SMES and defines the scope of the work. Chapter 2 is a more detailed explanation of SMES, organized by topics, and includes an extensive review of what is found in the literature. AC/DC conversion, as it applies to SMES, is covered in Chapter 3. Chapter 4 discusses configurations and control schemes for DC/DC conversion, especially a SMES system connected to photovoltaic systems. A new cascade connection of AC/DC and DC/DC converters is explained in Chapter 5. Chapter 6 draws conclusions from the work and makes suggestions for further research. The bibliography has entries organized by topics that correspond to the literature review in Chapter 2.

CHAPTER 2

LITERATURE REVIEW

This chapter gives an overview of SMES and discusses the technology, circuits, switches, and control related to SMES that have been reported in the literature. It is clearly not a primer for all of the topics discussed, but instead attempts to show the reader how these areas relate to SMES. More than just a simple review of the literature or a summary of work that has been done, it also includes critical analysis of that information and suggestions of where potential improvements could be made. How future advances and practical considerations might improve the chances for a SMES system being built is explained, and a framework is provided for the discussion of this work and its contributions. In particular, AC/DC and DC/DC circuits and control that are applicable to SMES are examined in detail.

2.1 Basic Characteristics of SMES

2.1.1 Zero Resistance

The appeal of SMES systems derives from the attributes of superconductors themselves. Superconductors exhibit several distinct electrical and magnetic properties that are useful in various applications, but the most distinguishing characteristic of superconductors is the one inherent in their name – the ability to conduct electrical currents exceptionally well. All conductive materials experience a decrease in resistance when their temperature is reduced, but these materials demonstrate unique behavior; their resistance drops to zero at a cutoff temperature. Above that critical temperature (T_c), the superconductor returns to its normal state of conductivity. The normal state can also be brought on if the current or magnetic flux exceed characteristic limits. These two parameters are referred to as critical current density (J_c), and critical magnetic flux density (H_c). It is important to note that these three critical values are not independent from each other; there is actually a complex relationship among temperature, current, and magnetic flux. A superconductor cannot reach maximum temperature, current density, and magnetic flux density simultaneously. Being near the maximum cutoff of one reduces the range of the other two. For example, the highest values for J_c are attained when the temperature is well below T_c and the magnetic flux density is well below H_c.

SMES systems take advantage of this phenomenon by combining it with the energy storage potential of inductors. The magnetic field of an inductor stores energy proportional to the direct current squared ($E = 1/2\ LI^2$), and the power exchanged is the product of the direct voltage across the inductor and the current through it ($P_d = V_d I_d$). The resistance of normal conductors quickly dissipates the energy, but superconductors allow the current to be maintained without loss. When the current is low, the amount of energy stored is low, and the power rating is also reduced. When the current reaches zero, so do the energy stored and the power capacity.

2.1.2 Direct Current

SMES operates with direct current. Alternating currents flowing in superconductors experience energy loss due to an effective AC resistance. Inductive (magnetic) energy storage is also inherently direct current. An alternating voltage (sinusoidal or otherwise) applied to the inductor produces no net effect on the energy stored; energy stored in the inductor during one portion of the cycle would be returned to the circuit during the remaining portion of the cycle. Therefore, any connection to the AC utility system requires AC/DC power conversion.

2.1.3 High Current, Power, and Energy Density

Superconductors can carry extremely high currents because they are not subject to the resistive heat generated in normal conductors, and they typically exhibit very high values of current density [A-19]. They can also deliver high power, essentially limited only by the power rating of their converter. Related to their current and power handling capabilities, superconductors can achieve rather high energy densities as well. Superconductive coils can attain energy densities comparable to, or even better than, other energy storage options, such as capacitors, flywheels, or batteries [A-14].

2.2 Factors Favoring Large Scale Applications

There are a significant number of factors that tend to favor large scale applications for SMES. First of all, there are factors that depend on the application itself. For leveling a utility load, a SMES system must exceed a minimum size to have any worthwhile impact [B-3]. The same is true for reactive power compensation or the damping of subsynchronous resonance on AC lines. A substantiating factor is that a SMES system of sufficient size could perform all three of these functions simultaneously [A-7].

A large SMES system is also necessary to provide a reasonable scale for peripheral equipment that includes the refrigeration system, converters, and transformers [B-3]. Further, the larger a SMES system, the greater advantage it can take of economies of scale. Under normal operating conditions, the overhead cost of refrigeration is proportionally lower for large-scale systems. The refrigeration demand is virtually independent of the state of charge of the system, but is instead proportional to the surface area of the cryogenic container. In comparison, the energy stored is proportional to the volume of the superconductor, and the energy density is proportional to the radius of the coil (with constant aspect ratio). Therefore, for a solenoid with a given aspect ratio, the ratio of volume to surface area, (and therefore, the ratio of energy stored to energy lost through heat transfer), increases with the size of the SMES system [A-2].

Finally, due to the substantial start-up costs of a SMES system, the break-even size where SMES becomes financially more attractive than its alternatives is typically very large

[B-3]. All of these issues would tend to make a single large SMES system more attractive than a set of smaller systems, whether distributed or centrally located.

2.3 Factors Favoring High Current

Largely independent of the factors that favor large size are the factors that favor high current. The amount of energy stored goes up proportional to the square of the current while only linearly proportional to the inductance ($E=1/2\ LI^2$). For a given power rating, a higher current allows a correspondingly lower voltage, which reduces the voltage differential between the SMES system and its surroundings. This feature is especially important with a conductive dewar where high-voltage arcing between the superconductive coil and the container wall could be catastrophic.

High current, however, is not necessarily ideal; there are some reasons to prefer lower current. Higher current leads to: stronger radial forces exerted on the containment structure; higher resistive losses in the joints of the superconducting wiring, the transitional area between cryogenic and ambient temperatures, and the normal transformer windings; higher losses due to the forward voltage drop in the switches; and greater commutation overlap, which limits the range of control possible and increases the consumption of reactive power.

2.4 Classifying SMES Systems

The diverse designs and applications of SMES systems lead to a wide range of criteria for classifying them. The following paragraphs specify some of the ways that systems can be grouped. One way of distinguishing among different SMES systems is the comparison between the input and output power ratings. A system for load leveling that operates continuously, or nearly so, has an effectively equal power rating for input and output, whereas a system for pulsed power operation has a relatively small input power rating and an extremely large output one. The latter arrangement is typical of power supplies for Strategic Defense Initiative experiments and fusion power research [A-30]. Such systems will typically be charged gradually by a power supply operating at its full capacity. They tend to store their energy for relatively short periods of time and then discharge it very quickly. The purpose of such a system is to generate pulses of power much more narrow in duration and intense in strength than could be achieved with other techniques.

2.4.1 Energy Storage vs. Magnetic Field

Magnetic energy storage and magnetic fields are inextricably linked, but systems can be designed stressing one purpose or the other. An inductor storing a large amount of energy might not produce an especially high magnetic field, and one designed to yield a high magnetic field might not store a great deal of energy. High magnetic fields are most often associated with magnets for physics research or medical diagnosis; superconductors are used because magnets made with normal conductors are unable to achieve a magnetic field either strong enough or uniform enough [P-2].

2.4.2 Power Rating vs. Energy Storage Capacity

Another comparison related to input and output power ratings takes the overall energy storage capacity into account as well. The relationship between the power rating and the energy storage capacity gives an indication of the time frame involved in operation. For example, a system designed exclusively for diurnal load leveling would need to have sufficient energy storage capacity both to charge and discharge at the rate required by the utility grid for the period of a day. The loading of a utility varies quite drastically during each day and from one day to the next; however, the duration of peak demand is generally shorter than the time of off peak demand. This asymmetric characteristic of utility load curves integrates quite well with the inherent features of SMES. The SMES system can only charge or discharge at its full power capacity when it is carrying full rated current; conversely, when its current and stored energy levels are at their rated minimum, the available power is greatly reduced as well. The fully charged state would typically be reached at the end of off peak hours, just in time for discharging at full capacity during peak hours. When those peak hours are over, and the SMES system begins recharging from a low state of energy and current, its diminished capacity to charge would not be a disadvantage to its operation because it would have a long time during off peak hours to recharge slowly. A utility sized system designed to level fluctuations in load over time periods longer than a day would require an energy storage capacity substantially greater than one designed exclusively for diurnal load leveling. At the other extreme of the relationship between power rating and energy storage capacity would be a pulsed power system where the full energy storage capacity could be discharged in milliseconds.

2.4.2.1 Current and Voltage Ratings

The current rating is chosen primarily on the basis of the desired energy storage capacity and the inductance of the coil. The voltage rating is then derived from the desired power rating and the marginal operating current. Because $P_d=V_dI_d$, the full rated power is only available at full rated current. If the level of charge is lower, the power attainable is also lower.

For practical power ratings and energy capacities being considered for utility load leveling, the voltage and current requirements don't correspond well with the available semiconductor switch technology; thyristors have voltage ratings of several thousand volts and current ratings of a few thousand amps [R-4]. However, the ratings being proposed for utility scale use are a few thousand volts and hundreds of thousands of amps.

2.4.3 Switches at Ambient or Superconducting Temperature

In any SMES application, the power conditioning system is crucial for getting the energy in to and out of the superconductor at the right time and under the right conditions. Many different control circuits have already been built or proposed, but they can be classified first into two categories: those that execute the control under superconducting conditions, and those that have the control circuit under normal conditions. These two general types can be further subdivided.

2.4.3.1 All Superconducting System

Systems that operate entirely under superconducting conditions make use of superconducting transformers and superconducting switches (cryotrons) [Q-7]. Low inductance transformers can have a high turns ratio without introducing a large leakage reactance. To reduce their inductance, these transformers usually have an air core, though that feature also reduces their coupling coefficient. A great advantage of this arrangement is that all of the high current is in the superconductive state only. The primary side of the transformer can put in (or take out) power at high voltage and low current. Therefore, ohmic I^2R losses can be greatly reduced. A disadvantage is that the input waveform must be carefully shaped; a regular sinusoidal input is not suitable for this type of circuit operation.

2.4.3.2 Superconducting Switches

Cryotrons can be activated either thermally or magnetically [Q-4]. The thermal type is smaller but slower. When in the normal state its temperature is above the critical temperature, and it must be cooled to return it to the superconducting state. That cooling takes time, and it introduces heat at the cryogenic temperature. The amount of heat, however, is relatively small when compared to the heat from the high-current superconductive-to-normal interface that is required if the cryotron is not used. Magnetically activated switches are faster because a change in magnetic field can be made quicker than a change in temperature. Furthermore, the magnetic type does not inherently introduce heat at the cryogenic temperature, though it is bulkier than the thermal type. At present thermal switches are limited to frequencies below the 60 Hz necessary for direct interaction with standard AC power transmission [Q-15]. That situation could improve as superconducting materials with both higher current density and higher normal resistivity are developed.

2.4.3.3 Switches at Ambient Temperature

Power conditioning systems that operate at ambient temperatures in their normal state make use of typical high power switches such as thyristors. These switches must be able to handle all of the current that flows in the superconductor itself. This fact makes it necessary to use rugged (and expensive) switches. Furthermore, this current flowing through normal wires and switches introduces higher ohmic I^2R losses. Because transformer windings have leakage reactance, commutation cannot take place without overlap. This overlap adds loss and reduces the average output.

2.4.4 Method for Circulating Current

Systems that are entirely at cryogenic temperatures also allow the use of a persistent mode switch so that once energy is stored, it can be left untouched for a long period of time. This advantage, however, is not as important as it may seem because there are invariably small losses in the circuit (due to imperfect joints for example) that limit the time that energy can be stored in the persistent mode. Before very long these losses can dissipate a significant portion of the total stored energy.

The decision about the method for circulating current depends primarily on the expected length of time for storage and the size of the system. Situations that require quick or frequent transitions between operational modes are not suited for a persistent mode switch. Likewise, for very large scale applications a persistent mode switch is not practical. Both of these factors suggest that utility scale implementations would probably not use a persistent mode switch at all. The connection through a 6-pulse or 12-pulse bridge to the external utility grid provides a current path, allows continuous AC/DC conversion, and permits the transition between charging and discharging or circulating mode to be made with a minimum of delay.

2.4.5 Control Scheme

Different control schemes and strategies also distinguish among SMES systems and depend on the intended purpose for the application. The first differentiating factor is which parameters are regulated; real power (P), reactive power (Q), voltage (V), stability, resonance, etc. Some techniques might regulate two or more parameters simultaneously, such as P and Q or P and V. Simultaneous P/Q control would be desirable for utility scale systems and can be implemented in several ways [K-1 through K-14]. The actual technique for implementing that control scheme, such as proportional-integral-derivative (PID), Dahlin, or finite time settling control (FTSC) can also distinguish among systems.

2.4.6 AC vs. DC Source and Load

Whether the energy source provides an alternating or direct current is perhaps one of the most significant distinguishing factors among SMES systems. In most cases it is also related directly to whether the load is AC or DC, though there are instances where the source and the load are of different types. A case where both the load and the source are of the same type is the AC interface with the standard utility grid. DC sources would include photovoltaic systems (whether terrestrial or space-based), magneto-hydrodynamic (MHD) systems, and connections to high voltage DC (HVDC) distribution systems. DC loads, in turn, could range from space systems or other remote sites, to electric vehicles or other mobile uses, to pulsed power supplies. Generally the only AC loads will be in those instances where DC to AC conversion is necessary for distribution on AC lines. If the load is itself DC and is located near enough to the SMES system that AC transmission is unnecessary, then the redundant AC/DC conversion could be avoided.

2.4.7 AC Options

2.4.7.1 Frequency and Phases

When the load and the source are both DC, the only electrical parameters that are truly important are the voltage and the current, from which the power rating can also be derived. For an AC connection, whether source or load, there are many more salient features to be considered. One of primary importance is the frequency of operation. Generally the standard would be the frequency of the utility grid: 60 Hz in the U.S.; 50 Hz in Europe. A higher frequency AC distribution system could be considered for space applications. A related issue would be whether the AC to DC converter operates its switches at the AC frequency or at a substantially higher frequency using pulse width modulation (PWM). Also to be decided are the number of phases – three phases being the standard for AC distribution systems that allows standard balanced transformers. However, in unique applications some other number of phases might be considered [E-7, L-2, L-15].

2.4.7.2 6-Pulse Bridge

For 3-phase systems that use standard balanced transformers, there are a number of bridge converter and transformer connection combinations available. The standard method of connecting a balanced 3-phase AC system to a DC system is the 3-phase 6-pulse (Graetz) bridge converter.

A great advantage of this type of converter is that it can interface very nicely with the regular utility 60 Hz (or 50 Hz) sinusoidal input. Some configurations use multiple bridges in series or parallel; some use bridges fed by different transformer winding arrangements; and some use different commutation methods, but the basic circuit is still the same [E-1 through E-35]. The design decisions and the performance tradeoffs, however, make these differences crucial.

2.4.7.3 12-Pulse Bridge

When two such bridges are connected in series on the DC side, they form an effective 12-pulse bridge, which doubles the frequency of the ripple on the DC side and removes the lowest frequency harmonics on both sides of the bridge. It also permits the bridges to have different firing angles, enabling a more versatile control scheme. The necessary 30° phase shifts between the two 6-pulse bridges in a 12-pulse bridge configuration are easily generated by a combination of transformer connections with the same wye or delta connection on one side and the opposite wye or delta connection on the other. A wye connection provides a common ground, and a delta connection provides a path for third harmonic currents. The most common of these combinations is a wye-wye with a wye-delta, but the proper phasing can also be generated by a combination delta-delta and delta-wye connection.

The 12-pulse converter is operationally superior to the 6-pulse, and use of a true 6-pulse bridge is generally for experiment only [E-17]. Some have suggested going as far as using an 18-pulse bridge [E-25] to reduce harmonics and provide still more versatility to the control scheme, but its advantages compared to cost and complexity are questionable for a large-scale application. It is rarely used because of the special transformer windings necessary to generate the correct angles between the phases.

2.4.7.4 Series and Parallel Connections

Though most systems in the literature use 12-pulse operation of 6-pulse bridges connected in series [see A-6, B-6, C-7, D-8, and E-8 for examples], parallel connections are mentioned [B-2, E-19], and one system cited is switchable between series and parallel [A-11]. However, all of the ones in series are either for small scale testing of SMES or are for HVDC terminals. Both of these applications have relatively low current. Practical SMES systems will operate at very high currents and will require parallel thyristors and/or bridges [E-17]. With parallel operation of bridges offset by 30°, an interphase reactor is necessary at the output.

Using AC/DC bridges to convert from a low-voltage/high-current AC side to a high-voltage/low-current DC side is relatively simple because AC/DC bridge converters connect quite well in parallel on the AC side and in series on the DC side. In contrast, connections in series on the AC side and in parallel on the DC side are rather difficult. Unfortunately, it is the latter connection that is strongly desired for typical SMES configurations. High voltage and low current on the AC side: 1) corresponds well with the typical high powered AC utility grid; 2) makes appropriate use of standard switch technology such as thyristors; and 3) its low current has the advantages of lower resistive (I^2R) losses, lower losses in the switches, and lower commutation overlap. With extremely high currents envisioned for the DC side, the advantages of a parallel connection are obvious. With a number of converters in parallel, none of them has to carry full rated current at any time, whereas a series connection on the DC side requires that a number of switches carry full rated current at all times. Further, for a given power rating, higher current corresponds to lower voltage, so a series connection on the DC side becomes unnecessary. The challenge of achieving high current and low voltage on the DC side will be addressed extensively in Chapter 5.

2.4.7.5 Artificial Commutation

The use of 12-pulse bridges is widespread, and their shortcomings are well-known. A number of methods exist for minimizing the adverse effects from reactive power consumption and harmonic generation, such as static var converters, switched capacitor banks, synchronous condensers, and harmonic filters. However, these devices are relatively expensive, and the extremely high currents anticipated for large-scale SMES could consume enormous quantities of reactive power. One attractive way of overcoming the bridge converter's inherent need for a supply of reactive power is the use of artificial commutation. Such a scheme, where the switches in a bridge can be fired to lead the current instead of lagging it, allows the operation of the bridge in all four quadrants of the complex power plane.

When one 6-pulse bridge in a two bridge 12-pulse configuration is connected as a naturally commutated converter (NCC), and the other bridge is connected as an artificially commutated converter (ACC), the hybrid converter, as it is called, permits operation in all four quadrants of the complex power plane [F-8]. That ability allows a great deal of flexibility in control, and a system that can deliver, as well as absorb, reactive power represents an advantage in regulating a transmission line. The hybrid converter is an attractive arrangement: it has the capability to interface well with a 3-phase system; it can handle both high current and voltage; it can be implemented with different switch components depending on the specific system power requirements; it does not need additional reactive power compensation; the two individual bridges of the converter can be controlled independently so that nearly any combination of real and reactive power can be attained within the limits of the converter's full rated power; the two can be adjusted to transfer zero real power so that a persistent mode switch is unnecessary to hold a charge; and the control methods are simple and well established.

The hybrid converter, though an elegant engineering solution to a real life problem, is not used as commonly as one might expect. The reason is because of the substantial cost of implementing an artificial commutation scheme and the inherent operational drawbacks of all of the artificial commutation schemes devised up until now. The additional costs include gate turnoff thyristors, large high-current capacitors, and shunting networks. The operational drawbacks include increased harmonics from operating the two 6-pulse bridges at different firing angles and the limited reduction in commutation overlap due to the leakage reactance of the transformer secondary windings. Capacitive commutation has the disadvantage that the capacitors must be able to handle temporarily all the current flowing through the switches. Magnetic (inductive) commutation may have potential for improving that situation, but it has its own inherent disadvantages. It needs additional transformers; it complicates control; and it introduces extra inductance in the commutation path which slows the commutation process. A better artificial commutation scheme would be a significant contribution to this field of study. There are fundamental limits to how quickly the secondary current can be switched from one phase to the next, but there is no theory that eliminates the possibility of a more desirable artificial commutation scheme in the future. Artificial commutation is a relatively mature field in both theory and technology, and rather extensive research has already been done. Though substantial progress has been made, it still does not enjoy wide-scale use.

2.4.8 Scale

The scale of a SMES system is another characteristic that can distinguish it from other systems. Superconducting magnets for medical diagnosis or physics research can be quite small, and in fact, can often be dwarfed by their own peripheral support equipment. At the other extreme, very large scale systems for leveling utility loads over periods longer than a day have been suggested as large as 5 GWh [A-31]. However, before such a mammoth project would be undertaken, significantly smaller systems will most likely be built. These smaller systems would still be quite large compared to anything built so far.

No discussion of practical SMES systems and the work that has been reported in the literature could be complete without mention of the 30 MJ system designed and built in Tacoma, WA by the Bonneville Power Administration (BPA) [D-1 through D-10]. The experience and practical considerations derived from its design, construction, and operation have been invaluable to the progress of SMES research as a whole. With a 30 MJ storage capacity, it is still the largest SMES system built to date. The BPA system was not designed for load leveling, but for damping oscillations on the Pacific Intertie DC transmission line. Its energy storage capacity is very small compared to its rated power. The coil can be completely charged or discharged in a few seconds. SMES systems for load leveling would have an energy storage capacity equivalent to at least several hours at rated power.

The pioneering work at the University of Wisconsin and its proposed Engineering Test Model (ETM) also cannot go unnoticed [see A-1, A-4, A-33, B-3, and B-22 for examples]. Both of these programs have advanced the state of knowledge and research on SMES significantly, and the number of articles cited in the bibliography that follows are an indication of the impact they have had. It is noteworthy that a substantial number of the other articles cited in the bibliography also reference many of those very same articles.

2.4.9 Applications

The range of applications that SMES systems are considered for filling are just as diverse as the range of their scales. The set of applications given most consideration during the course of this work involves enhancements to, or improvements in, large-scale operations. The most likely candidates for building such a large system are electric utilities. A block diagram of a basic SMES system configured for utility use is shown in Figure 2-1. The factors that favor large storage capacity, power, and current, as well as the extremely high estimated initial cost for the construction of a SMES system reduce the chances for a small-scale system. Furthermore, utilities could make the most use of the attributes SMES has to offer; could justify the capital outlay (based on the economic return when compared to alternative energy storage systems); could gather the necessary capital investment; and are financially stable enough to reap the long-term financial benefits of its operation.

2.4.9.1 Diurnal Load Leveling

There is already a specific need that SMES could fill for utilities. The daily fluctuations in load require substantial amounts of spinning reserve to handle the demand. Plus, at peak demand, the last incremental power generated is quite often the most expensive. To compensate, a number of utilities have built pumped-hydro storage systems where hydroelectric facilities are used to pump water uphill during off-peak hours using relatively inexpensive power, then are operated in normal generator mode during peak demand. Though this system is very inefficient, it is still cost effective because the difference in price between the least and most expensive power generation methods is so great. The greater efficiency of SMES could make it a reasonable alternative to pumped-hydro and make utilities more efficient and less costly in the long run.

To compete with pumped-hydro storage, the incremental value of power returned to the system during peak load must be greater than the incremental cost of generating that power at off-peak time and storing it in between. The cost of a SMES system is almost entirely its design and construction. Its costs of operation are minimal, and it requires little maintenance; its primary machinery is peripheral equipment. Because the system is efficient, there is little loss associated with its use.

2.4.9.2 Reactive Power Compensation

A SMES system designed primarily for diurnal load leveling could also be controlled to regulate reactive power consumption without additional exchange of real (?) power [K-1 through K-14]. A SMES system can be considered effectively as a current supply which can be controlled to cause the current to lag the voltage by varying amounts. If capacitor banks supply sufficient reactive power for the SMES system, its control scheme can adjust the firing angles of the bridges to maintain reactive power fluctuations at a minimum.

2.4.9.3 AC System and HVDC Line Stability

A SMES system capable of exchanging large quantities of real and reactive power very quickly can be controlled to provide added stability to the overall AC utility system [C-1 through C-16]. (When stability is mentioned in conjunction with HVDC systems, the reference is made to the stability of the HVDC line.) Whether referring to the stability of an AC system or a HVDC line, a SMES system can provide an added measure of stability unavailable from other sources. Its versatility of control and very fast dynamic response allow an almost instantaneous adjustment to real power, reactive power, voltage, or a combination in response to the present conditions.

The system built by the Bonneville Power Administration is an example of SMES being used to damp subsynchronous resonance on the Pacific Intertie [D-1 through D-10]. The control of the system is adjusted below 60 Hz in response to measured line variations.

2.4.9.4 Multiple Uses

If a SMES system is built large enough for diurnal load leveling, it could potentially be used to perform all of these functions simultaneously. The operational control schemes for these functions can be essentially independent of each other. For example, within a (?) certain range, reactive power can be regulated without affecting real power. Similarly, the adjustments necessary to bolster stability do not exclude regulation of real and reactive power.

2.4.10 Assorted Options

2.4.10.1 High Field Magnets

Some applications that use superconducting magnets do not explicitly make use of their energy storage features. Instead they take advantage of the fact that superconducting magnets can achieve higher magnetic flux density and a more uniform field than conventional electromagnets. This feature is important for nuclear magnetic resonance imaging (NMR or MRI) machines for medical diagnosis and devices for high magnetic field scientific research [Q-13].

2.4.10.2 Fusion Reactors

Superconducting magnets have been considered for obtaining the magnetic containment forces necessary for Tokamak fusion reactions, while superconducting magnetic energy storage is a candidate for providing the energy pulses needed to fire such reactions [A-9]. Fusion reactors as well as laser weapons for the Strategic Defense Initiative might use SMES as an intermediate stage between a continuous power supply and a pulsed load.

2.4.10.3 High Temperature Superconductors

The development of higher temperature superconductors could make feasible a number of applications that are at present only theoretical, and they could be used in various ways in conjunction with low temperature superconductors. High temperature superconductors have been suggested for use at the interface between cryogenic and ambient temperature regions. If used for the superconductive-to-normal electrical connections they could reduce the heat loss at cryogenic temperatures. If employed as part of the dewar, higher temperature superconductors could possibly provide structural support, cryogenic containment, and magnetic shielding.

2.5 Electric Vehicles

Attention was given to electric vehicle (EV) research because that was an early motivation for this study, and it fit the desired criteria mentioned in the objective; it is the kind of application that could benefit substantially from a better energy storage system. The less than favorable results are included for completeness and because they provide a contrast to the later section on photovoltaics – one a failure, one a success.

2.5.1 Electric Vehicle Potential

EVs have been studied for many years because of their obvious advantages of operation: reduction of dependency on oil, reduction of pollution (both air and noise), and potentially cheaper fuel costs [O-11]. However, the difficulties of making electric vehicles to compete with gasoline- and diesel- powered ones have kept them from being widely used. For most applications, using current technology, EVs have distinct disadvantages when compared to gasoline-powered vehicles.

2.5.2 Weight

EVs are heavier than conventional types; the power trains alone for the two systems are of comparable weight (motor + controller + transmission vs. engine + transmission). Therefore, the energy storage method, or fuel supply (i.e., batteries for EVs), are additional weight, typically ranging from 500 to 1000 lbs. This extra weight requires more structural support which further increases weight. Excessive battery weight and volume reduce the potential payload of passengers and cargo for EVs [0-5].

2.5.3 Operational Drawbacks

Even allowing for lower payloads and large battery capacities, EVs are severely restricted by power and energy demands on the batteries. Acceleration is very poor (sometimes unacceptable for entering high speed traffic such as interstate highways) due to power output limitations of batteries. Top cruising speed, as well as gradeability (the ability to climb an incline), are also adversely affected. The limited energy storage of batteries makes maximum driving range short, often too short for the demands of many drivers [O-5].

2.5.4 Batteries

The difficulty with range is worsened by peculiarities of batteries. They cannot be discharged of their full capacity (typically no more than 50%) without causing permanent damage. Plus they must be recharged slowly (usually at least 6 hours for a full charge) where a charging system is available [O-12]. This is in sharp contrast to the conventional gasoline tank which can be run down to empty and then refilled in just minutes virtually anywhere.

2.5.5 Reliability

EVs are also less reliable than conventional vehicles. Gasoline-powered cars have enjoyed decades of healthy competition in the marketplace, whereas EVs have not. Furthermore, electrochemical systems (batteries) are inherently more troublesome than mechanical (transmissions) or electrical systems (motors and controllers) [O-10]. Battery degradation (often as much as 40% of total capacity over useful lifetime) and battery failure account for the most problems of reliability [O-12].

2.5.6 Costs

Energy costs for EVs have the potential for being lower than for internal combustion engines (I.C.E.s) because of the relative prices of utility-supplied electricity and gasoline. However, "operating" costs for EVs are actually much higher than for I.C.E.s because of maintenance and batteries. Maintaining and replacing batteries combine for more than 50% of total EV operating costs [O-12]. Batteries are also a significant part of start-up cost, making EVs more expensive than conventional cars [O-5].

2.5.7 Opportunities for Improvement

It is doubtful that major advancements will be made to reduce significantly the power/energy requirements for EVs considering the level of research and development. Rolling friction and aerodynamic drag, as well as structural weight, have already been greatly reduced. Furthermore, any additional advances for EVs in these two areas will also benefit gasoline-powered cars, and therefore, will not help EVs in a competitive sense. Motors and transmissions are already very efficient, so breakthroughs in design could only improve efficiency to a marginal degree. Therefore, the greatest need (and also greatest opportunity) for EV development is the energy storage system [O-12]. Batteries are the primary problem for EVs: they are a great expense; they are heavy; they limit acceleration and range; and they are unreliable. The possibility of replacing the batteries of EVs with a SMES system was investigated. The practicality of using SMES for EVs was considered based on ability of SMES to meet the power and energy requirements for current EVs.

The state of electric vehicle development was examined. If future research is considered, improvement may be possible in areas other than energy storage, but these areas would not contribute substantially to reducing the energy requirements. Therefore, the limits that now exist must be expected to remain essentially the same. The following data values are considered "typical" for a small (subcompact) two-passenger commuter vehicle [O-5, O-14]. Numbers are approximate and are intended to be bounds; all rounding done was upward so that the results are conservative. No attempt was made to compensate for the variability of terrain; it is still assumed that electric vehicles will find primary use in commuting passengers over relatively short distances.

Table 2-1. Typical Parameters for Current Electric Vehicles

Minimum payload	130	kg
Fixed structural weight	1000	kg
Minimum peak acceleration power	23	kW
Rolling friction	1	% of weight
Aerodynamic drag	1	% of weight
Force needed to cruise at highway speeds	250	N
Energy (at wheels) to cruise 100 km	25	MJ
Efficiencies:		
Motor and controller	85	%
Transmission and differential	95	%
Total	80	%
Total energy requirement	30	MJ / 100 km

2.5.8 Mobile Feasibility

Unfortunately for mobile applications, a 30 MJ superconducting storage device would be huge. In fact, its energy storage capacity would match the largest SMES system yet built – the BPA facility. Its superconducting coil and cryogenic container unit measure 2.7 m (9 ft) in height and 3.9 m (13 ft) in diameter; in addition, its peripheral equipment is housed in a trailer-sized building [D-5]. Though the BPA system's design was not necessarily optimized for least volume or weight, a SMES unit (coil and refrigeration equipment) even a tenth of the size of the BPA system could not fit in an electric vehicle. It is also important to note that the weight of the SMES system was not considered in determining the energy needs for an EV; the 30 MJ requirement corresponds to an energy storage device that weighs nothing. Any weight that the device adds to the vehicle will in turn increase its energy needs. It should be clear that a SMES system could not store enough energy to move an electric vehicle with passengers and cargo, let alone move itself.

There may be potential for greatly reducing the size of the storage device, but it will require superconductors that can handle higher energy density and a magnetic structure that can take advantage of that. Higher critical temperature (T_c), higher current carrying density (J_c), and higher magnetic flux density (H_c) will all be required for superconductors to achieve energy densities high enough for mobile use. There is no evidence to conclude that such values are theoretically impossible, but the current state of superconductive energy storage is orders of magnitude away from vehicular applications.

Furthermore, energy density is not the only factor involved in making SMES systems large. Metals used for low temperature superconductors and ceramic materials used for high temperature superconductors are very heavy. Plus coils are wound with a redundant normal conductor such as copper or aluminum to carry the current when the coil is returned to normal temperature. Cryogenic containment, magnetic shielding, and structural support also add weight and volume.

2.5.9 Space

Though mobile applications for SMES would generally not be considered feasible, one possible exception could be energy storage in space where a number of factors are kinder to SMES. Of course size and weight are still very important in space, but they are not necessarily the only criteria considered. Reliability of operation for an extended period of time without maintenance is also crucial. For example, a SMES system might be preferred over a smaller competing battery option. It must be further noted that some energy alternatives available on earth, such as spinning reserve or pumped-hydro, are obviously not an option in space. The cold background temperature of deep space goes toward absolute zero, so cryogenic containment might not present the same difficulties that it does on the ground. With proper shielding against radiation from the sun, the heatsink of deep space might be enough to maintain the coil in its superconducting state. Furthermore, space reliable equipment is already shielded from magnetic interference, so there could be less danger to equipment from the possible environmental effects of strong magnetic fields. The potentially negative effects of magnetic fields on humans or animals is not likely to be a factor in probable space scenarios. Spaceflights which can support living subjects are constrained to be short-term and utilize other energy sources without the need for long-term storage from SMES, whereas long-term spaceflights, which could benefit from the features of SMES, cannot support living creatures.

2.6 Photovoltaics

Photovoltaic (PV) power supplies are already the most prevalent source of electrical power in space applications and are becoming more common in terrestrial uses. The abundance of sunlight in space and in certain geographical areas on earth makes PVs attractive sources of energy. The fact that PVs generate electrical power directly without any intermediate step eliminates the need for electromechanical or electrochemical conversion schemes that are necessary for other energy sources. Using sunlight obviously incurs no fuel cost and little operational cost, so the amount of power available for a given capital investment is the deciding factor in determining the economic benefit of PV use. As technology continues to increase the efficiency and reduce the initial cost of PV installations, they should continue to widen their appeal.

2.6.1 Limited PV Penetration

The usefulness of a large scale PV installation connected to the AC utility grid, however, is severely limited due to the natural fluctuations of sunlight. A PV system is simply not dependable as a continuous energy source and cannot be controlled to deliver power when it is needed. If PVs were to provide a substantial portion of a utility's total power generation (often referred to as penetration) the quantity of power provided by the PV system would not allow for an equivalent decline in the amount of spinning reserve capacity required by the system. In fact, a PV system would not necessarily provide any reduction in spinning reserve requirements at all. The PV system introduces fluctuations in the power supply that will not always coincide with fluctuations in demand. Therefore, a substantial penetration of a utility system by PVs would actually increase the need for spinning reserve [N-9].

2.6.2 Combination of SMES and PVs

The advantages of SMES and PV technology could be enhanced by the combination of the two. The potential benefit to a utility of a combined SMES/PV system is greater than the sum of the benefits from each system used separately. PV power generation, being weather dependent, introduces sharp fluctuations in power delivered and causes difficulty in system control as well as power dispatch. These technical difficulties are major impediments to large-scale use of PV power. However, a SMES system could enhance PV utilization without any increase in its size or complexity and still perform load leveling. A SMES system could store the energy supplied by the PVs that exceeds the load requirements, supply power when PV output is insufficient, and at the same time compensate for sharp fluctuations in PV output so the load would not be affected [N-30]. With SMES support, the prospect for large-scale use of PV generation could be greatly improved.

2.7 Engineering Challenges

2.7.1 Cryogenic Containment

For small-scale superconductive systems, cryogenic containment and refrigeration are of great concern and can be a substantial portion of the overall cost. The construction, maintenance, and operational costs for a large-scale cryogenic system are relatively fixed. Due to the complexity of their refrigeration systems and the costs of operating them, a liquid nitrogen system would be preferred over liquid helium. However, at present there is no high temperature superconductor with the necessary characteristics of high current carrying density and malleability to be used as the primary conductor in a large-scale SMES system. If suitable high temperature superconductors with the necessary traits are developed in the future, it is still quite likely that a large-scale system would operate at liquid helium temperatures. The maximum temperature, current carrying density, and magnetic flux density of a superconductor do not occur at the same point. The maximum cutoff temperature occurs at low current and low magnetic flux; the maximum current carrying density coincides with lower temperature and low magnetic flux; and the maximum magnetic flux corresponds to low temperature and low current. Even if a superconductor had a cutoff temperature higher than the temperature of liquid nitrogen, maintaining it at the temperature of liquid helium would allow a much greater current and magnetic flux. Therefore, with the low temperature superconductors available at present that can already carry the currents envisioned for SMES systems, it is unlikely that the development of high temperature superconductors will soon have a substantial impact on utility scale uses of SMES [A-40].

2.7.2 Magnetic Shielding

Strong currents flowing in the windings of the solenoidal coils produce strong magnetic fields. Coil configurations have been proposed that reduce the level of stray magnetic fields and the strength of radial forces, but these arrangements also reduce the amount of energy stored. Coils of the size envisioned for large-scale SMES applications could potentially produce magnetic fields strong enough to be a hazard to humans and wildlife. The greatest field strength occurs at the center of the solenoid and extends along its axis perpendicular to the ground. With such an arrangement, sufficient protection could be provided by simply surrounding the SMES installation with a fence and prohibiting any activities within its boundaries. One notable exception to the prohibition against anything inside the fence would be the possible placement of large-scale PV arrays inside such a fence perimeter [N-30]. Photovoltaic cells do not seem to exhibit any significant adverse reaction to the presence of large magnetic fields, and locating them at the same site as the SMES system could make more productive use of the large tracts of land necessary for each.

2.7.3 Structural Support

The radial magnetic forces generated by strong currents in solenoid windings push outwardly from the axis of the solenoid. For large-scale SMES applications, these forces would be so strong that only a few options for providing the necessary structural support are economically feasible. The most likely candidates being considered at present are the burial of the coil in bedrock and the construction of containment walls using fiberglass epoxy composites [A-13].

2.8 Bibliography

The bibliography is not an exhaustive list of literature available on all topics related to SMES, but it is an extensive one and the result of a thorough search of those topics. Because of its size and the amount of work that went into assembling it, it is organized primarily for the purpose of providing the interested reader with a starting point for conducting a similar literature search. It is not arranged in the sequence that works are referenced in the text; nor is it ordered by the perceived importance of the sources. Instead it is sorted by topics and, when appropriate, by subtopics. Within each group the individual sources are listed chronologically. This structure provides the reader easy access to the most recent work done in a specific area. Furthermore, since so many of these sources refer to other ones within this bibliography, a chronological listing provides the easiest access to those works which are likely to reference earlier ones. Where several references could have been footnoted for providing the same details, only the earliest one is noted in the text.

The sections are labeled A through U, and the sources are numbered separately within each. The first category includes references that provide an overview of SMES or cover a number of diverse topics. The remaining ones, as outlined below, cover the areas of applications, converters, control, potential applications, and components. A number of sources could have easily been placed in several sections, but to remain consistent with the overall arrangement, only one was selected. In a few cases, a book was included if it contained several papers that were listed individually.

The last three sections are unique; they are lists of references that were not used in the preparation of this thesis, but could possibly be of value for someone else conducting research in these areas. The first of these categories includes internal reports of research institutions, reports that are available to a limited distribution, articles from obscure periodicals, proceedings of obscure conferences, patents, theses, and dissertations. The second set of references appear in languages other than English. The third set is a collection of references that were released or found after the initial literature search was conducted, but were not considered vital to this work. An example would be papers concerned with further advances in the area of high temperature superconductors; such efforts are certainly important, but even substantial strides in that field would not yet have an impact on the work described here, nor the conclusions reached. A type of source included in the earlier references, but not included here, is electric vehicles; the initial study determined that any improvements in EV technology would have no bearing on the area of SMES for mobile applications, so further investigations into EV sources stopped. Any papers from the time period following the original literature search that contained information deemed relevant to this thesis were included in the other sections. In particular, research into control schemes for SMES was followed closely because new developments could have been directly applicable to this effort.

A. SMES Overview

Applications

- B. Utility Load Leveling
- C. System Stabilization
- D. Bonneville Power Administration

Converters

- E. AC/DC Bridges
    - F. Artificial Commutation
    - G. High Voltage DC
- H. DC/DC Switched-mode Converters
- I. Novel Conversion Schemes

J. Control

- K. Simultaneous P/Q

- L. Two Inductive Coils
- M. Digital Control

Potential Applications

- N. Photovoltaics
- O. Electric Vehicles

Components

- P. Superconductive Coils and Conductors
- Q. Superconductive Rectifiers and Switches
- R. Semiconductor Switches

Unique

- S. Unusual
  - Special Reports
  - Obscure Periodicals
  - Obscure Conferences
  - Patents
  - Dissertations
- T. Foreign Language
- U. Newest

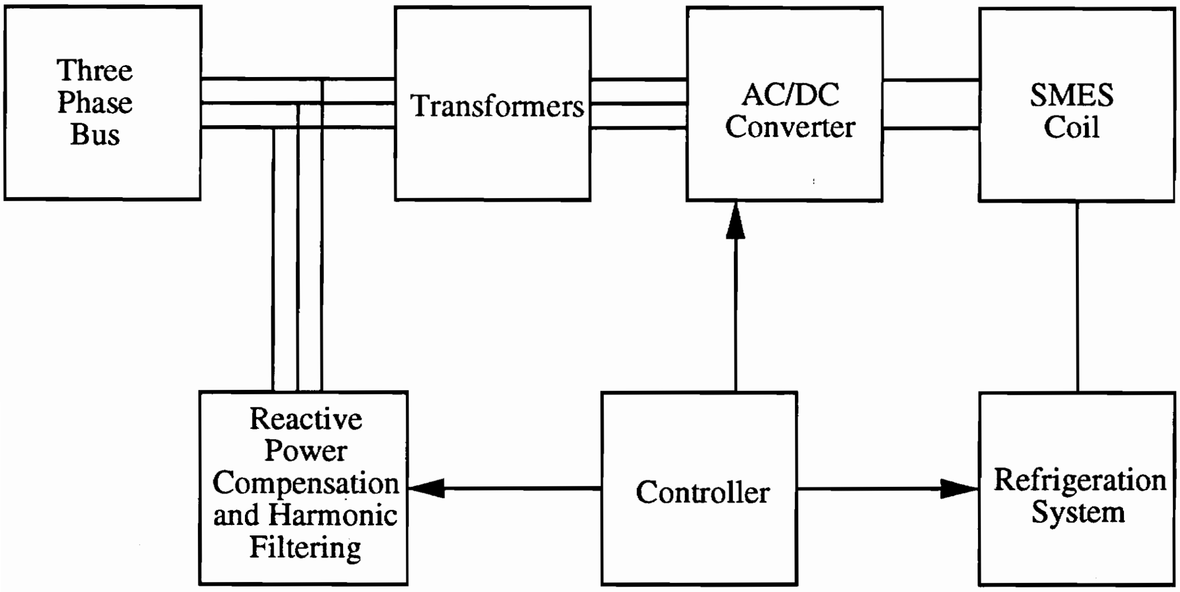


Figure 2-1. Block Diagram of Basic SMES System

CHAPTER 3

AC/DC INTERFACE

3.1 Background

Large scale SMES systems that have been proposed for utility load leveling require power conversion between the direct current of SMES and the alternating current of the 3-phase utility grid. This chapter discusses the control of AC/DC power processing systems for general SMES applications and the operation of a SMES system combined with PVs. The control aspect focuses primarily on simultaneous regulation of power and voltage, and the operational section concentrates on the capacity of SMES to compensate for PV power fluctuations.

The primary feature necessary for any circuit intended for utility scale applications is the ability to interface with the regular 60 Hz 3-phase power distribution network. To be useful as an energy storage device it obviously must be able to transfer energy in both directions – absorbing power when charging and delivering it when discharging. The system should be able to handle both high current and high voltage so that it can be used under extreme conditions or operate in modes that fulfill different roles. Preferably the design would be technology independent – able to be implemented with various external switch components. Finally, the control circuit should be as versatile, reliable, efficient, and inexpensive as can be reasonably attained.

The potential applications for this type of converter are numerous, but three will be examined in more detail here. The first is the one that gets the most attention in the field of SMES research – utility load leveling. That is the most likely area for large scale implementation of a SMES system. The other two are related to it because they are actually peripheral functions that could be served by such a utility scale system. Compensating for PV fluctuations could be performed by the SMES system as part of its load leveling objective. At the same time, regulating the bus voltage could be incorporated into its control scheme.

3.2 AC/DC Bridge Converters

3.2.1 Advantages

The 3-phase AC/DC 6-pulse (Graetz) bridge converter, as shown in Figure 3-1, has become the standard for SMES because it is inherently well suited for inductive energy storage. The design of the circuit and arrangement of its switches matches it with the unidirectional current of an inductor. Its ability to operate with positive and negative bipolar voltage allows bidirectional flow of power. The switching sequence of the phases always provides a continuous path for the flow of the inductor current which cannot be interrupted.

3.2.2 Drawbacks

There are also a number of drawbacks to these AC/DC converters. Their operation generates harmonics on both sides of the circuit; commutation overlap prevents the instantaneous switching of current from one phase to another; and the lagging power factor requires a supply of reactive power.

3.2.3 6-pulse Operation

The 6-pulse bridge can operate in two quadrants of the complex power plane as shown in Figure 3-2. In this figure and all figures that follow, the passive convention is used – power is considered positive when absorbed by the SMES coil (charging) and negative when being delivered (discharging). The current is always positive, and the voltage ranges from positive to negative depending on the firing angle of the switches. The relationships among the parameters are governed by the equation [G-8]:

$$V_d = \frac{3\sqrt{3}}{\pi} E_m (\cos \alpha) - 6 f L_c I_d$$

The direct current I_d is determined by the state of charge of the inductor; for expected power and energy ratings, I_d changes very slowly. Holding the current constant simply holds the charge. The direct voltage V_d is a function of the firing angle α and the amplitude of the voltage E_m on the secondary side of the transformer. Maintaining a constant direct voltage steadily charges or discharges the system depending on the voltage polarity. Constant power exchange is only possible over a reduced range because both I_d and V_d have limits, and I_d cannot be changed quickly.

3.2.4 12-pulse Operation

Two 6-pulse bridge units connected as shown in Figure 3-3 make up a 12-pulse configuration which allows the two 6-pulse bridges to be operated with independent firing angles. The range of operation in the complex power plane is extended as shown in the diagrams of Figure 3-4 where the vectors representing the complex power associated with each bridge are added.

For a single value of SMES current, if one of the two 6-pulse bridges is restricted to the minimum or maximum α (at the extremes of the gray arc in Figure 3-4a) and the other bridge is allowed any α, the range of possible operating points becomes the two black arcs in the diagram. If the first bridge is then permitted any of the α's along the gray arc, the operating range fills the shaded region of Figure 3-4b. Since the SMES current will most likely change slowly, the limits associated with a single value of current are the expected operating conditions over short periods of time. Within the shaded region of Figure 3-4b, a horizontal line represents the range of P associated with a given steady Q, and a vertical line shows the possible values of Q for a given P.

For any possible SMES current, as could be expected over long periods of time, the operating range of the 12-pulse bridge expands even more. For example, for a single value of current half that of the original current assumed in Figure 3-4b, the corresponding operating range is the smaller shaded region added to Figure 3-4c. When all values of current are allowed, the operating range fills the shaded region of Figure 3-4d.

It is important to remember the restrictions placed on this arrangement. First of all, the transformers for the two bridges must be connected differently to generate the necessary 30° phase shift between the two bridges. Secondly, the bridges must be connected in series on the DC side if they are to have different firing angles; a parallel connection with an interphase reactor is only possible if the firing angles match each other. Thirdly, though independent firing angles permit a wider range of control, the benefits of 12-pulse operation are lost; the magnitude and frequency of harmonics revert to those of the 6-pulse bridge.

3.2.5 Artificial Commutation

With natural commutation, whether the real power transfer is positive or negative, the current always lags the voltage so the converter always consumes reactive power. If the 12-pulse bridge is augmented to provide artificial commutation for one of the 6-pulse bridges, the range of operation expands to that shown in the diagrams of Figure 3-5. For a single value of current, if the naturally commutated bridge is held at the minimum or maximum α, and the artificially commutated bridge is allowed any α, the operating range is the outline of the two black circles in Figure 3-5a. For any α in the first bridge and any value of current, the operating range extends to the shaded region of Figure 3-5b. Within a limited range, the converter can be regulated to maintain a steady Q, consume no Q, or even supply Q to the network.

Though artificial commutation is attractive for several reasons, it is not often used for large scale applications because of complexity and expense. Even without artificial commutation, independent firing angles for the two 6-pulse bridges allow simultaneous P/Q control over a limited range within the first two quadrants of the complex power plane.

3.2.6 Series and Parallel Connections

The expected scale of SMES applications would combine very high current with relatively low voltage. For the estimated values of voltage, individual thyristors are adequate. However, the current would be too high for single thyristors; such a system would require a number of switches and/or bridges in parallel. The most likely arrangement would be multiple bridges operated in parallel.

3.2.7 α Control

The most fundamental distinction among the various possible control schemes for 12-pulse bridges is whether the individual 6-pulse bridges are operated with equal or unequal α firing angles. Equal α's offer the least freedom of control; P and Q are tightly coupled, so a change in one produces an unavoidable change in the other. It does, however, produce the lowest magnitude harmonics, and they begin at a higher frequency.

Unequal α's allow more versatile control, including extension to simultaneous P/Q or P/V modes. However, once the α's are no longer identical, balanced 12-pulse operation is lost; the harmonics produced are the same as two independent 6-pulse bridges. They are of greater magnitude than those for equal α control, and they begin at lower frequencies.

3.3 Combined SMES with PVs

One objective of this work was to establish that current SMES systems could be expanded in their usefulness without substantial hardware modifications. A prime example is the combination of SMES with PVs. PV arrays are completely dependent on the amount of solar radiation incident on their surface. In space PVs are darkened at regular intervals when the earth eclipses the sun. On earth PVs are subjected not only to the darkness of night, but also to the intermittent blockage of the sun by clouds. In both situations PVs need a reliable energy storage system to compensate during periods of reduced or nonexistent PV output. A PV array alone would introduce sharp fluctuations in the supply to the utility grid. Though at times it might supply a large quantity of power, it would not reduce the need for spinning reserve by the same amount because of its intermittent nature.

Addition of a SMES system alone would perform daily load leveling for the entire system but would not be using its full potential. It can also perform the function of enhancing PV utilization without any increase in its size or complexity.

3.3.1 Computer Simulations

For such an arrangement to be viable, SMES must exhibit the ability to compensate for power fluctuations of the magnitude and rate expected from PVs. To demonstrate that capacity, computer simulations were conducted on a model SMES/PV system using the Electromagnetics Transients Program. To make the results as realistic as possible, the representative SMES model was based on the actual BPA system, along with its transformer and switch configuration [D-1 through D-10]. See Table 3-1 for details. To be conservative, and to show meaningful results within a reasonable simulation time, the PV fluctuations simulated were approximately 500 times faster than the fastest changes ever expected from weather variations [N-13]. (?)

3.3.2 Control Scheme

How are PV, SMES and dc bus connected ?

The control scheme was based on adjusting a single α firing angle of the 12-pulse bridge converter in response to variations in the system power demand and fluctuations in the PV power supply. The initial equal α control is a subset of the block diagram shown in Figure 3-6. The inclusion of a steady Q mode in the diagram was to show how this simple

Table 3-1. Parameters for BPA SMES System

Bus voltage (RMS)	13.8	kV
Superconducting coil	2.6	H
3-phase transformers (each) (Δ-Δ, Y-Δ):		
Primary voltage	13.8	kV
Secondary voltage	0.925	kV
3-phase rating	6	MVA
Short circuit impedance	8.8	%
AC/DC converters (each):		
Maximum direct voltage	2.4	kV
@ α firing angle	5	°
Minimum direct voltage	-1.9	kV
@ α firing angle	140	°
Rated direct voltage	1.25	kV
Rated direct current	5.5	kA
Overall converter rating	6.875	MVA
Total losses (@ 5 kA coil current)	300	kW

control approach could easily incorporate simultaneous P/Q regulation. No computer simulations were conducted that explicitly demonstrated P/Q control because so much has already been done by others on that topic. The voltage regulation portion of the block diagram will be explained later.

The desired SMES power ($P_{difference}$) is calculated from the measured value of PV power (P_{PV}) and the assumed power demand signal (P_{demand}). From that power difference and the measured value of bus current (I_{bus}), an α firing angle is calculated. That α is adjusted by an error signal (P_{error}) derived from the actual power measured at the bus (P_{bus}) and the desired SMES power ($P_{difference}$). (?)

The feedback loop based on that error signal was designed using simple proportional-integral-derivative (PID) control. The purpose was not to develop a new or more suitable control method, but to demonstrate the suitability of SMES to compensating for PV fluctuations. More elaborate feedback control algorithms could potentially be employed to optimize performance, but even this simple method has exhibited the ability to handle the magnitude and rate of change effectively.

3.3.3 Simulation Results

In the simulation scenario shown in Figure 3-7, the PV power output increases with fluctuations during the early daylight hours. Assuming a relatively low load demand at the time, only half of the PV generated power is supplied to the power system. The other half is absorbed by the SMES in charging mode. When the PV power rapidly drops to zero, as it could during the arrival of a cloud front, the SMES system changes its operational mode from charging to discharging very quickly (in less than 0.2 second) so that the combined power from the SMES/PV system remains at the level desired. When the PV power rapidly increases from zero to a high level of power output, the SMES quickly changes from discharging back to charging. The total SMES/PV power supplied to the system stays at the desired level throughout the simulation and is not affected by the PV fluctuations. The SMES system can readily handle the rapid changes in PV power, and the transitions between the charging and the discharging mode are smooth. Since the SMES system can readily handle these unusually severe situations, it can be concluded that under normal conditions the fluctuations in PV power can definitely be smoothed out by SMES response.

Note also the reactive power curve shown. Probably the most important feature is how much reactive power is consumed. Though the real power reaches a magnitude of only 10 MW (both positive and negative), the magnitude of the reactive power stays near 20 MVAr throughout the simulation. The peaks in Q correspond to the transitions between positive and negative P. The gradual increases in Q are associated with periods of steady positive P (SMES charging) where the SMES coil current is increasing; the increase in current expands the operating circle in the complex power plane shown in Figure 3-2. In the same manner, the gradual decreases in Q are associated with periods of SMES discharging where the coil current is decreasing.

The results shown demonstrate that SMES using equal α control can compensate for the fastest PV power supply fluctuations expected and beyond. A limited test like this is certainly not sufficient proof that SMES can meet all the requirements of such a system, but it does confirm that SMES exhibits the versatility of control and speed of response necessary to handle PV fluctuations. The ability of SMES to track the desired variations in real power establishes SMES as a legitimate prospect for PV compensation. The corresponding high level of reactive power consumed, however, is a clear indication that this arrangement is far from ideal.

3.4 Simultaneous P/V Control

A significant amount of research has been done in the area of simultaneous P/Q control using 12-pulse bridges and SMES. Such an arrangement, in conjunction with a supply of reactive power (e.g., from a capacitor bank) allows operation with a combined minimal flow of reactive power and minimal fluctuations. Figure 3-4 shows the range of real power possible while maintaining zero overall reactive power for a given value of reactive power supply. Within that range, SMES can regulate the real power very quickly. For relatively slow changes, the steady supply of reactive power supply can be adjusted.

Under most circumstances, the primary purpose of P/Q control for SMES is to reduce the adverse effects of reactive power consumption inherent to operating the bridge converter in the naturally commutated mode. The unequal α control scheme for the 12-pulse converter simply maintains the reactive power absorbed at a steady level. The supply of reactive power still comes from external devices such as capacitor banks or static

VAr controllers. However, the speed and versatility of unequal α control give SMES systems the ability to respond to external utility system parameters more effectively than some other options. The two firing angles provide two degrees of freedom of control for the system, so two parameters can be regulated. In particular, SMES could be used for simultaneous control of P and V – regulation of the real power and the bus voltage. Just such a scheme was devised and tested with computer simulations.

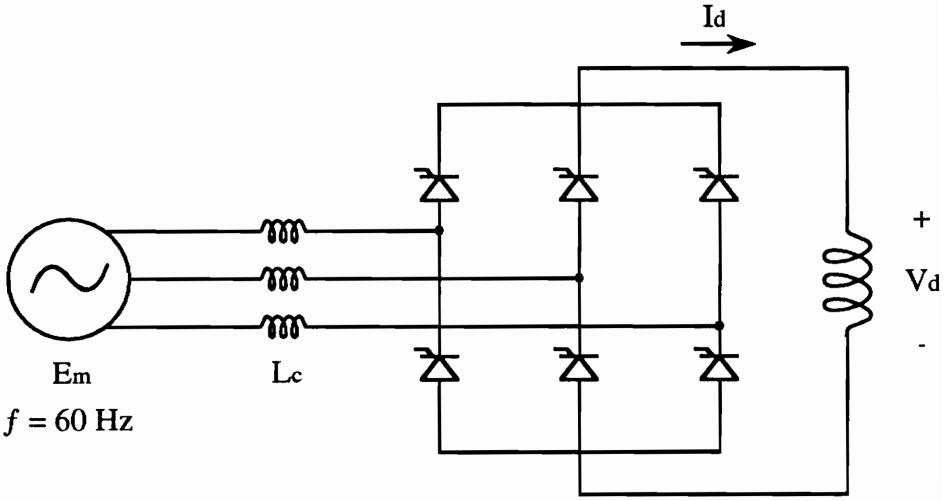
3.4.1 Computer Simulations

The model SMES system described in the previous section was modified to incorporate unequal α's for the two 6-pulse bridges. The control strategy was also adapted to respond to changes in AC bus voltage. The block diagram of the control system is shown in Figure 3-6. The bus voltage (V_{bus}), already measured for calculating P_{bus}, is now compared to a reference voltage ($V_{reference}$). The difference generated becomes an error signal (V_{error}) used to adjust the firing angles. The mode signal determines which parameter(s) to regulate, and therefore, which error signal(s) to use for feedback. To adjust real power the sum of the α's is changed; to adjust voltage the difference between the α's is changed. For these tests, the mode was set to regulate real power and voltage.

Simulations were conducted to examine the system's ability to compensate for sudden significant deviations in grid voltage. Both sudden overvoltage and undervoltage events of 10% were investigated. In Figures 3-8 through 3-11 that follow, the response of the overall SMES system is shown. Figure 3-8 shows a sudden overvoltage of 0.1 PU while the SMES coil is charging. Figure 3-9 shows a scenario of an undervoltage of 0.1 PU with the SMES is charging. Figures 3-10 and 3-11 represent over- and under- voltage conditions, respectively, while the SMES is discharging. In all four cases, after very brief deviations, P is maintained as it should be, and V is quickly returned to its target value. The α's and Q are also included to show how they are affected. These tests confirm that the scheme devised can regulate voltage within a limited range.

3.4.2 Limitations

As with P/Q control or any other unequal α control scheme, this technique is only possible over a limited operating range. Furthermore, it should be clear from the plots of reactive power that this P/V mode is not compatible with maintaining a steady Q mode at the same time. Any change in the firing angles to compensate for voltage will have an effect on the reactive power flow. With only two independent control variables (the two α's) only two independent system parameters can be regulated (P and Q, or P and V), not three (P, Q, and V). This obvious restriction to its potential use should not be considered a critical shortcoming. Instead, it should be recognized that P/V control is actually an extension to P/Q control that could be used under extreme conditions, and that is available without modifications to the system. The only adjustment necessary to provide this additional usefulness is the inclusion of the measured AC bus voltage in the feedback loop.



$$V_d = \frac{3\sqrt{3}}{\pi} E_m (\cos\alpha) - 6fL_cI_d$$

Figure 3-1. 6-Pulse AC/DC Converter Configured for SMES

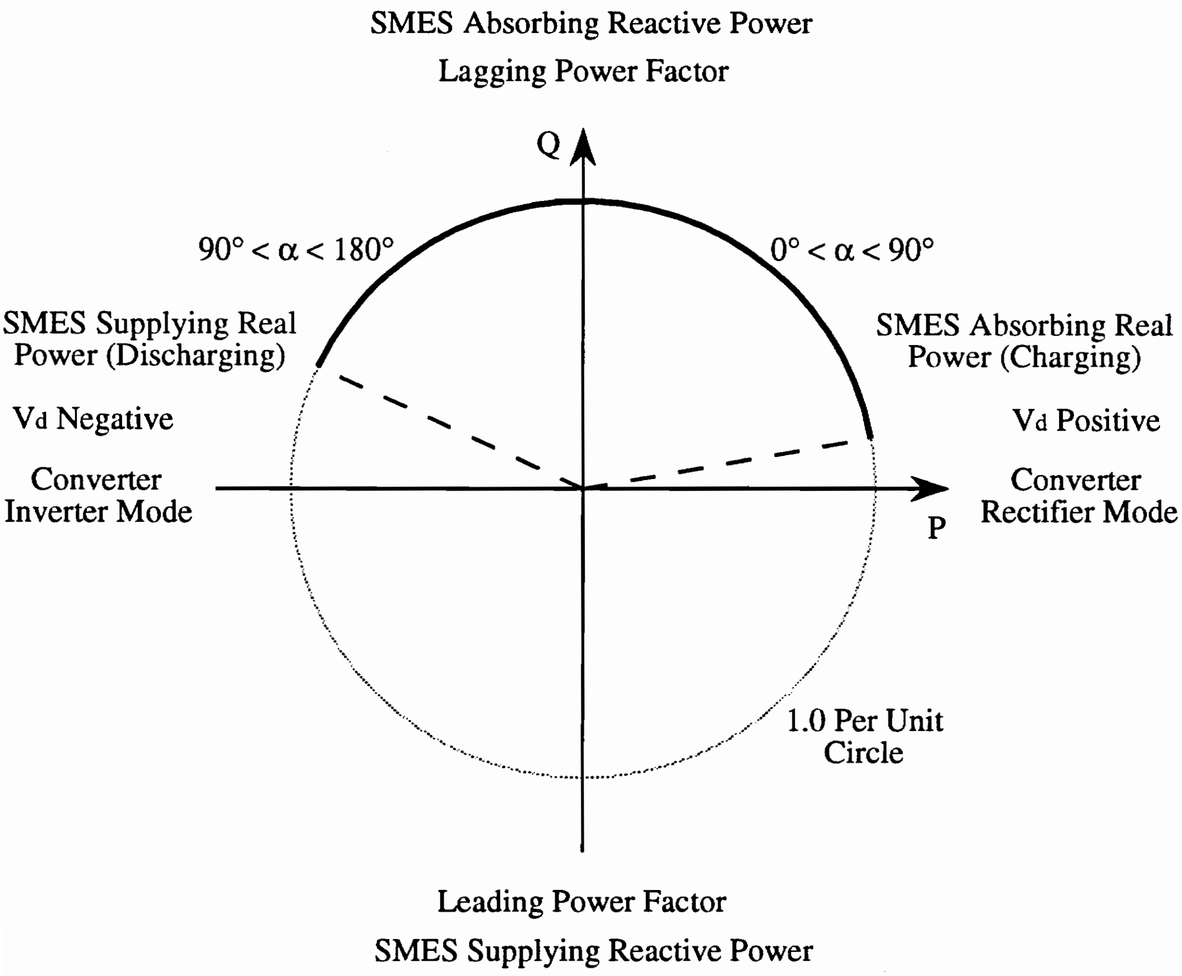


Figure 3-2. Operating Range in the Complex Power Plane for 6-Pulse Bridge

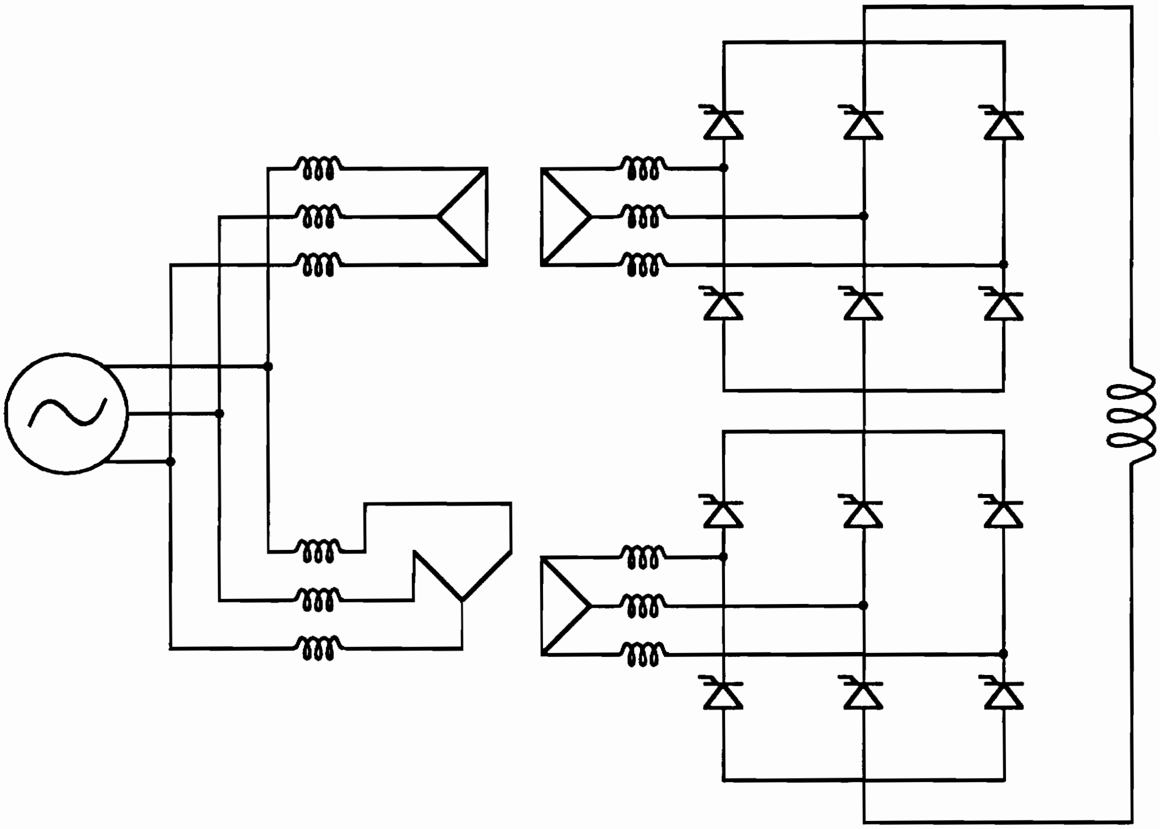


Figure 3-3. 12-Pulse AC/DC Converter Configured for SMES

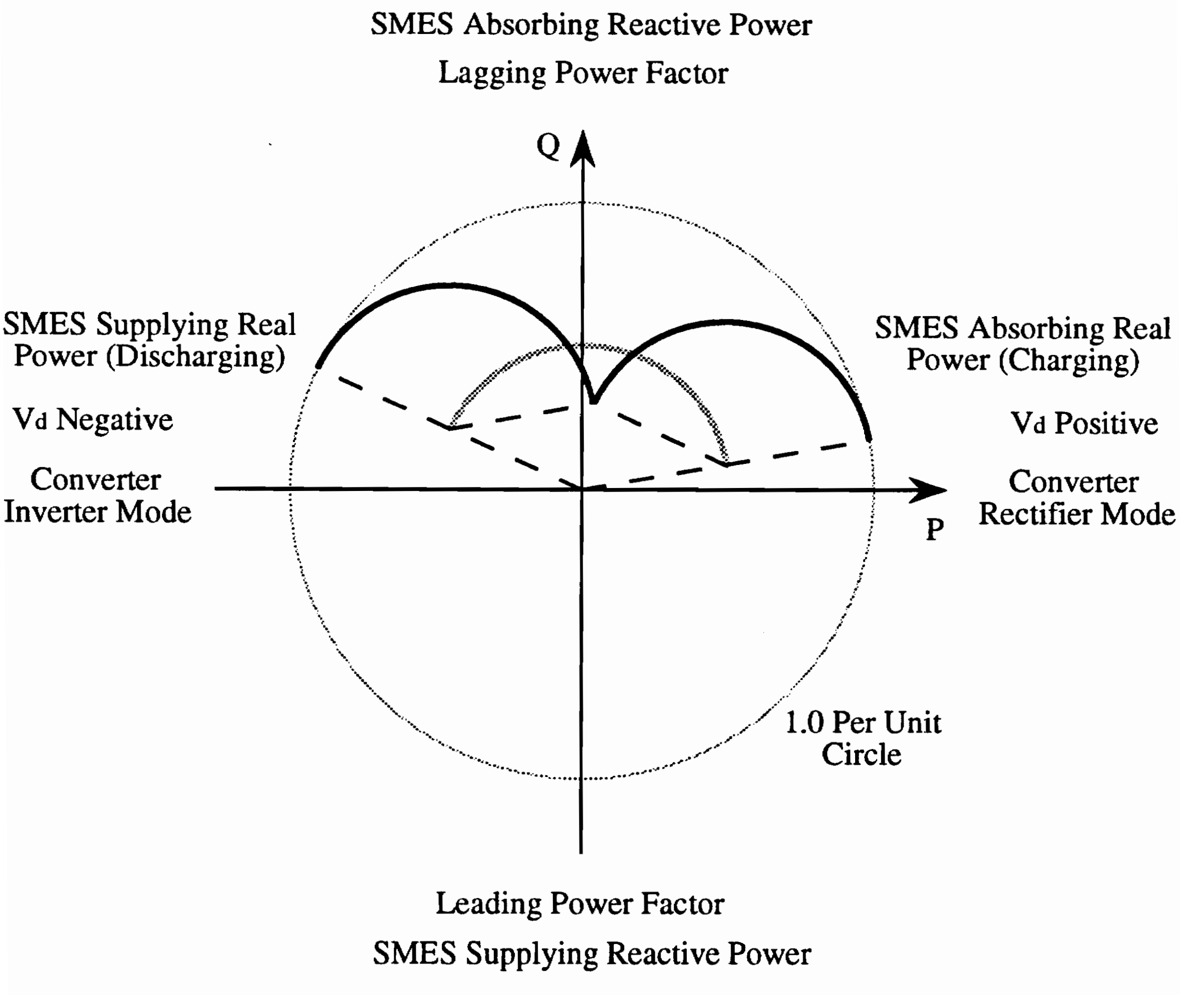


Figure 3-4a. Operating Range in the Complex Power Plane for 12-Pulse Bridge with Independent Firing Angles – One Bridge Held at Firing Angle Limits

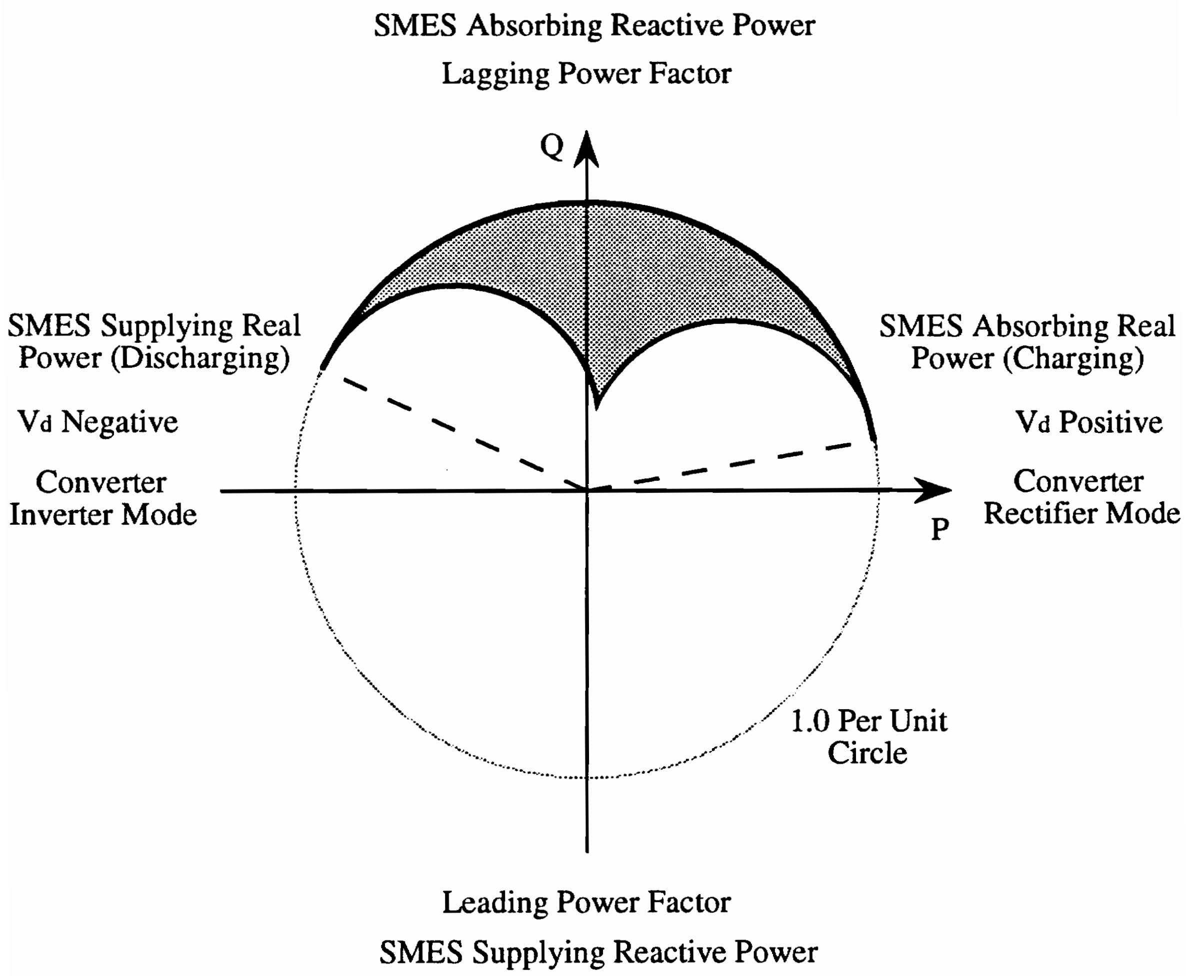


Figure 3-4b. Operating Range in the Complex Power Plane for 12-Pulse Bridge with Independent Firing Angles – For a Single Current

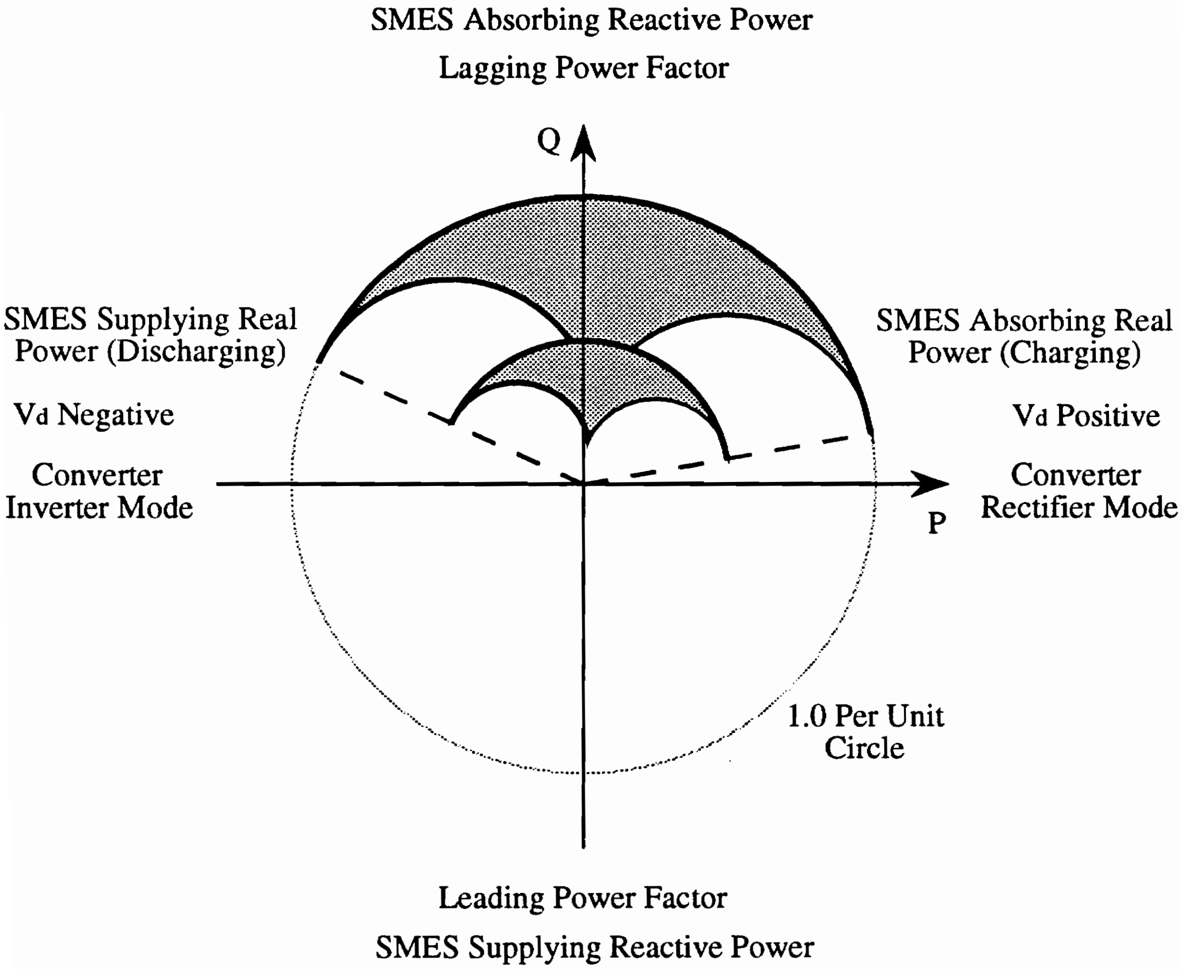


Figure 3-4c. Operating Range in the Complex Power Plane for 12-Pulse Bridge with Independent Firing Angles – For Two Values of Current

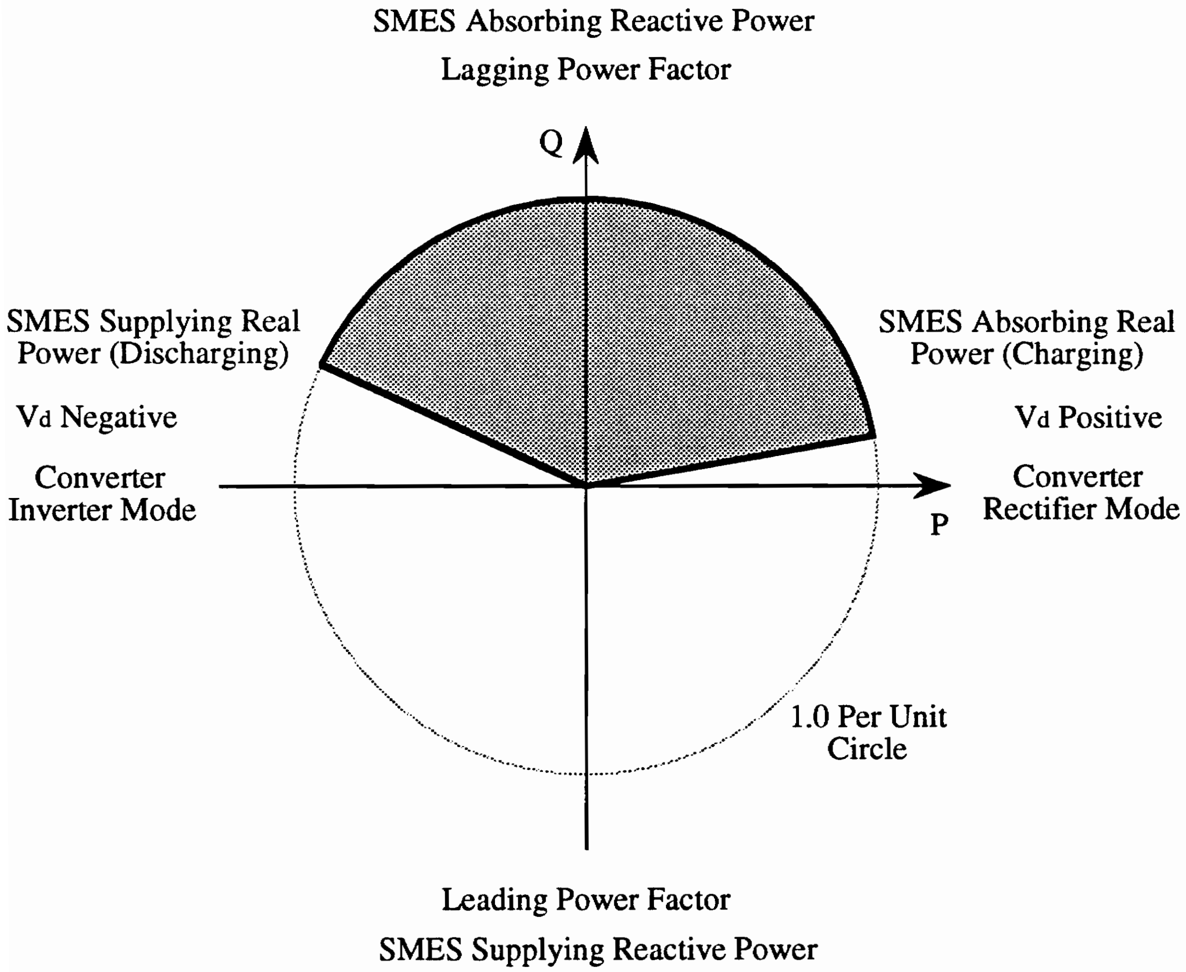


Figure 3-4d. Operating Range in the Complex Power Plane for 12-Pulse Bridge with Independent Firing Angles – For All Values of Current

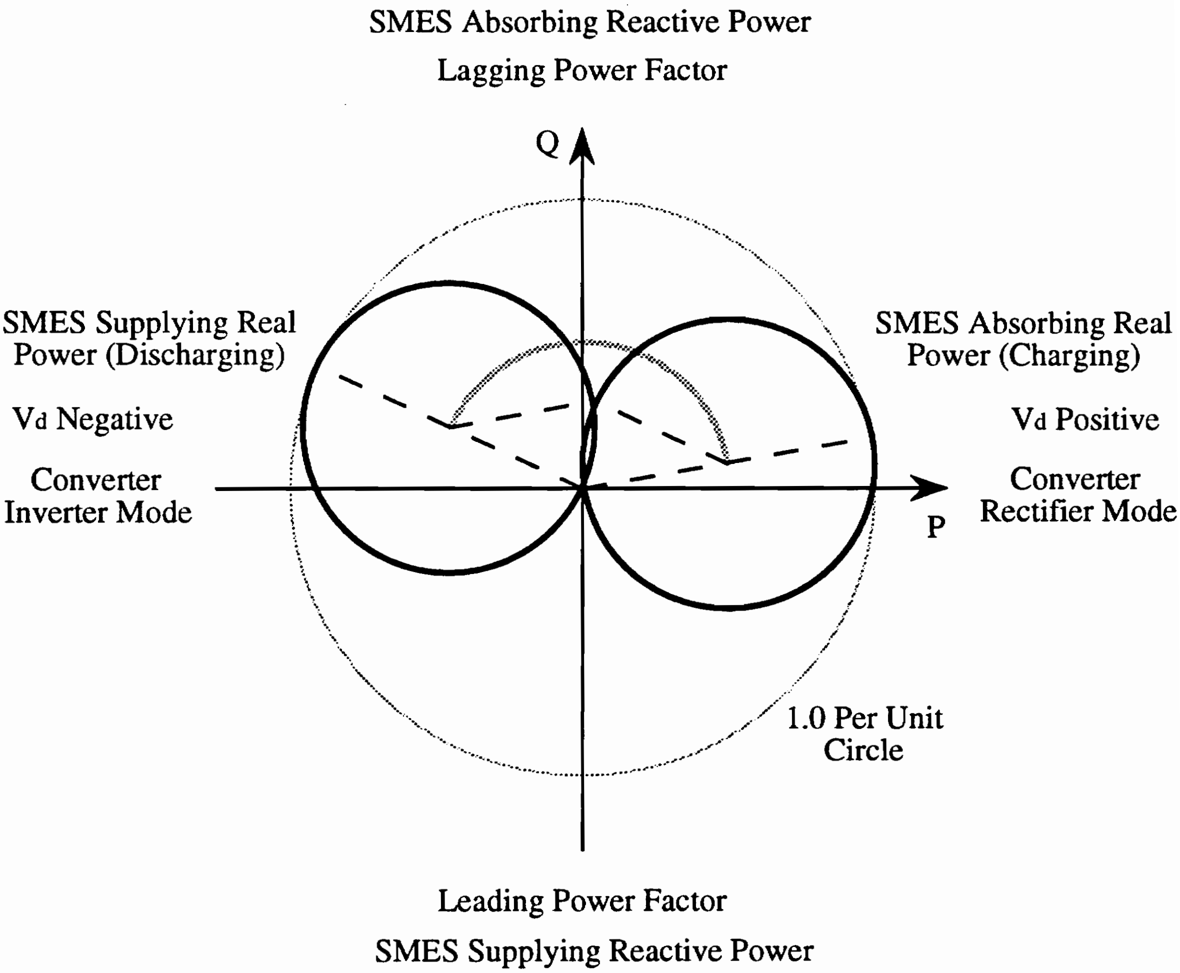


Figure 3-5a. Operating Range in the Complex Power Plane for 12-Pulse Bridge Employing Artificial Commutation in One 6-Pulse Bridge – Naturally Commutated Bridge Held at Firing Angle Limits

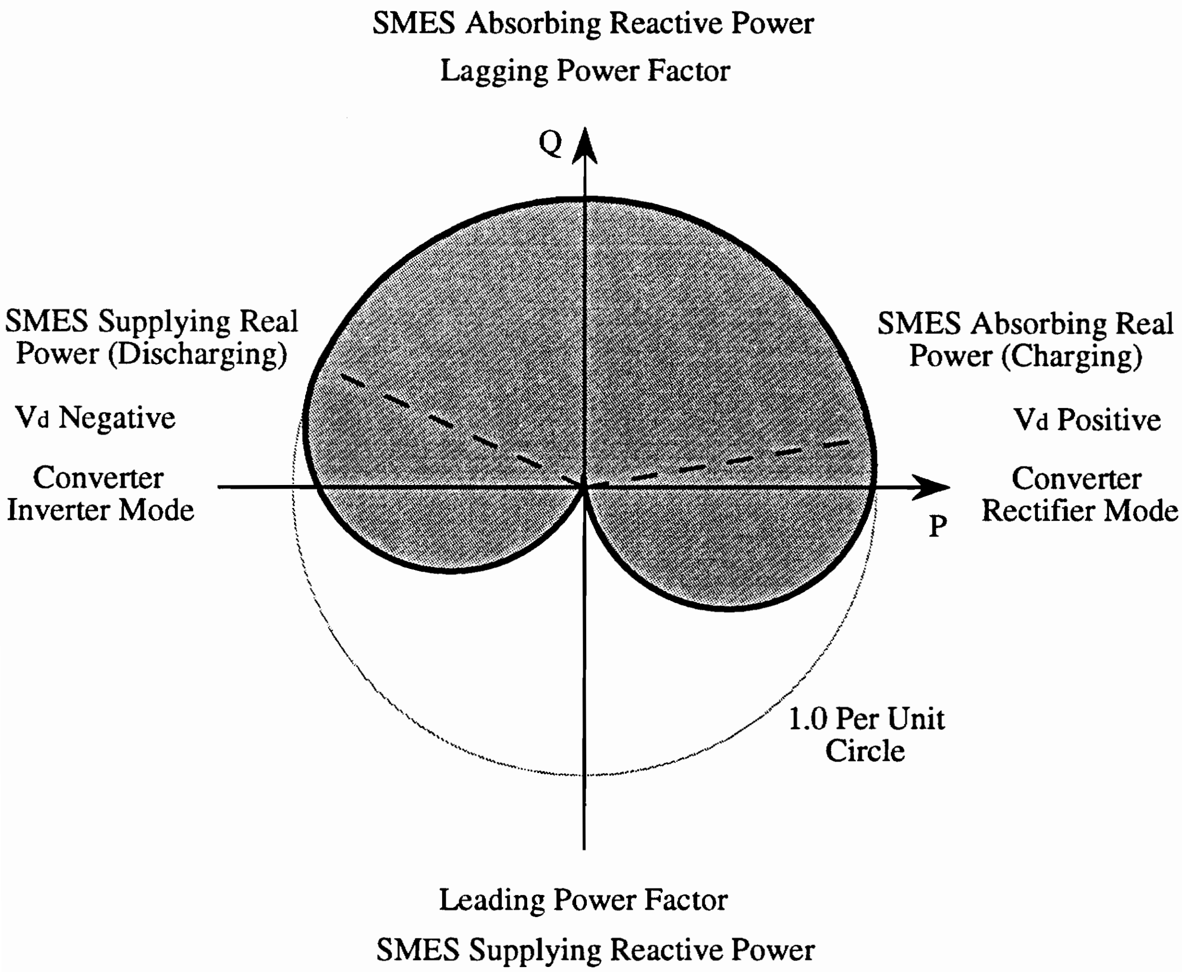
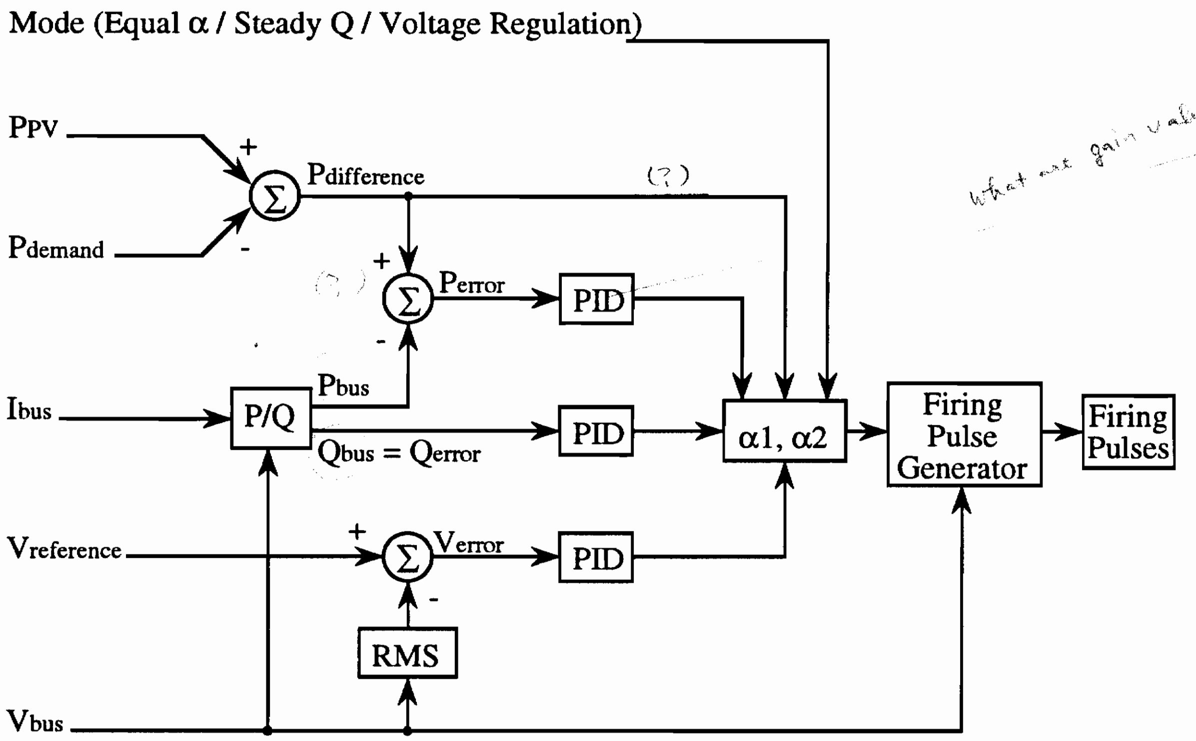


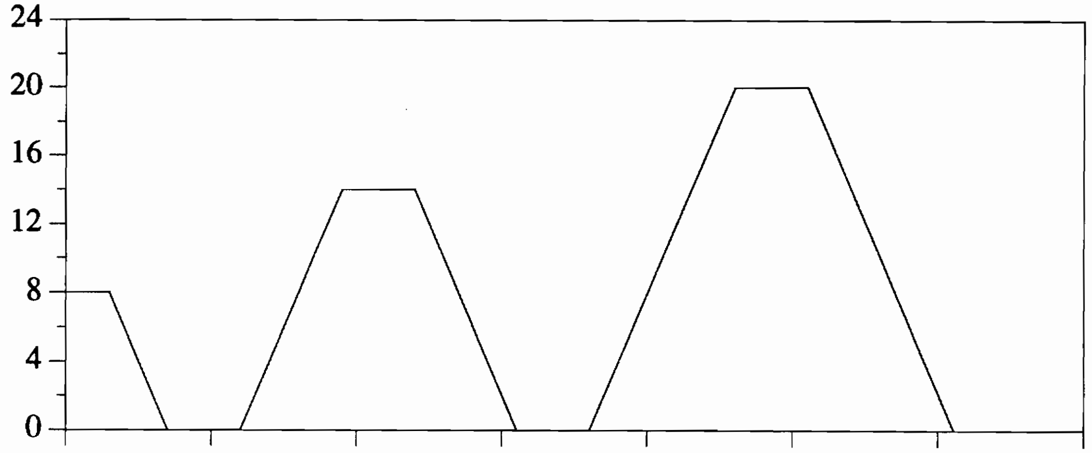
Figure 3-5b. Operating Range in the Complex Power Plane for 12-Pulse Bridge Employing Artificial Commutation in One 6-Pulse Bridge



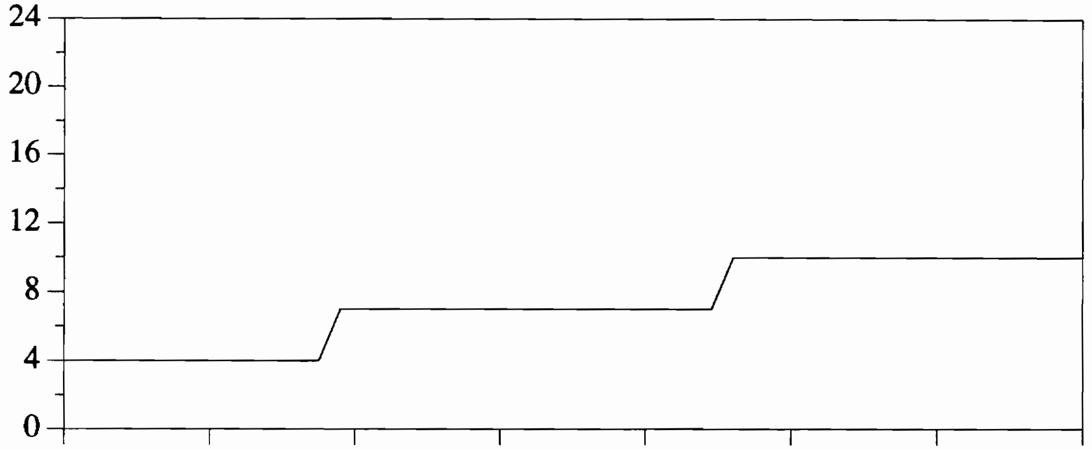
What are gain values ?

Does it change only α's to control P, Q and V ?

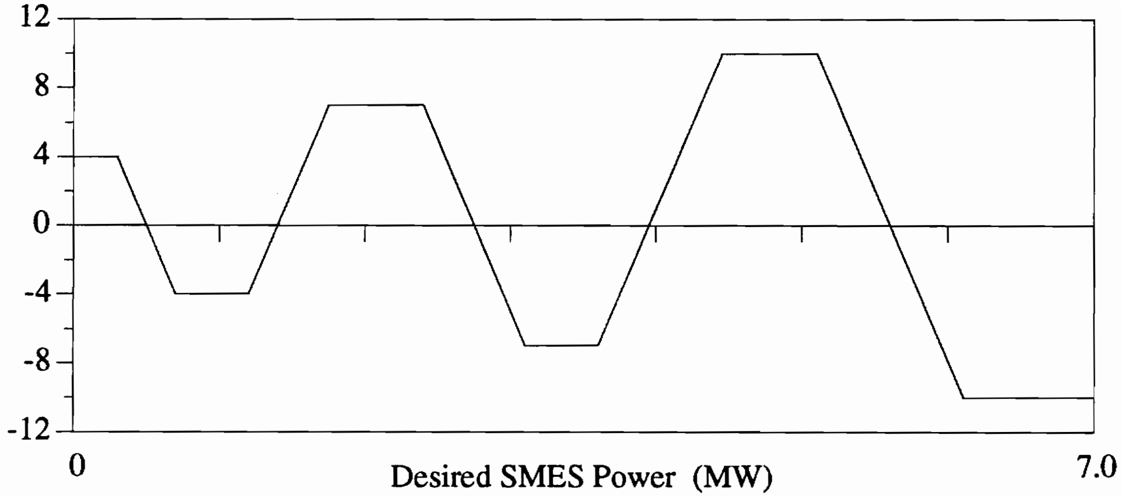
Figure 3-6. Block Diagram of Control Scheme for AC/DC Converter



PV Power Output (MW)

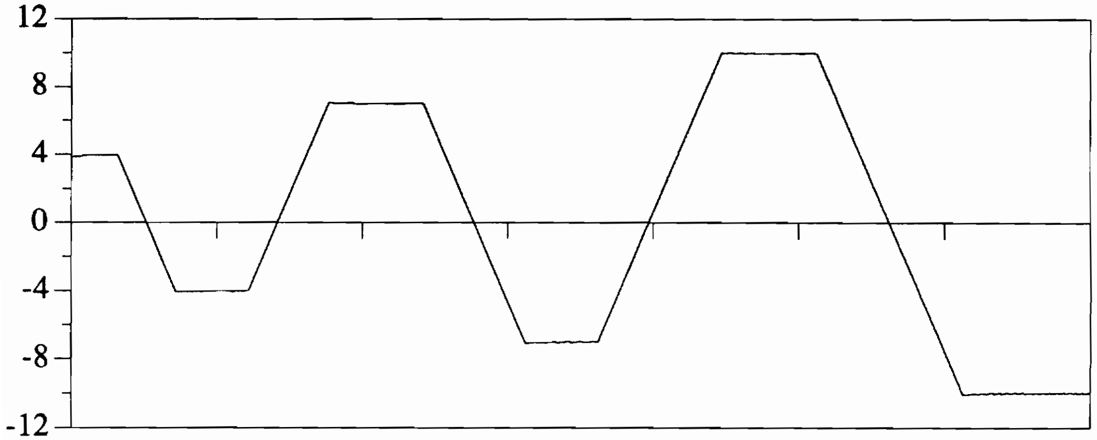


Combined Power Demand of System (MW)

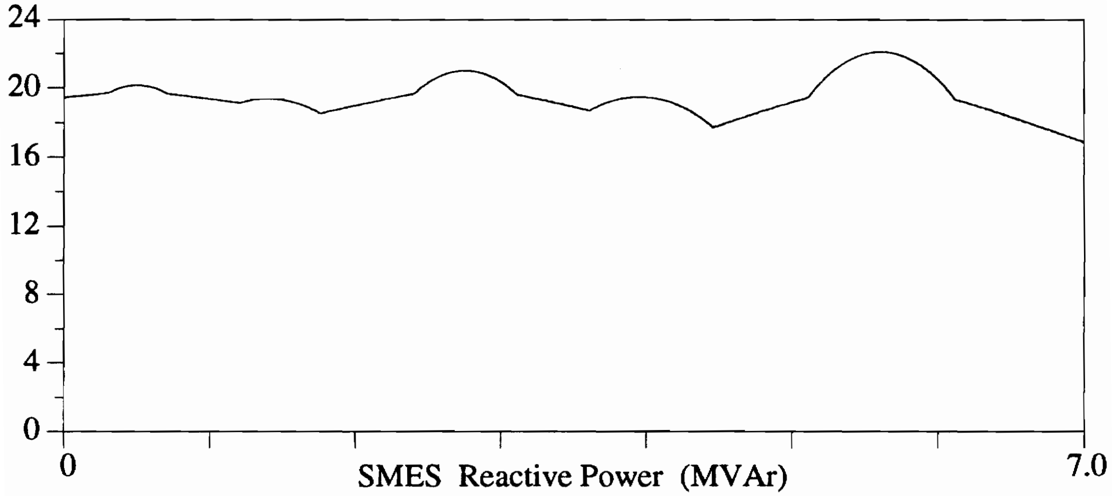


Desired SMES Power (MW)

Figure 3-7a. SMES Response to PV Power Fluctuations (7.0 s)

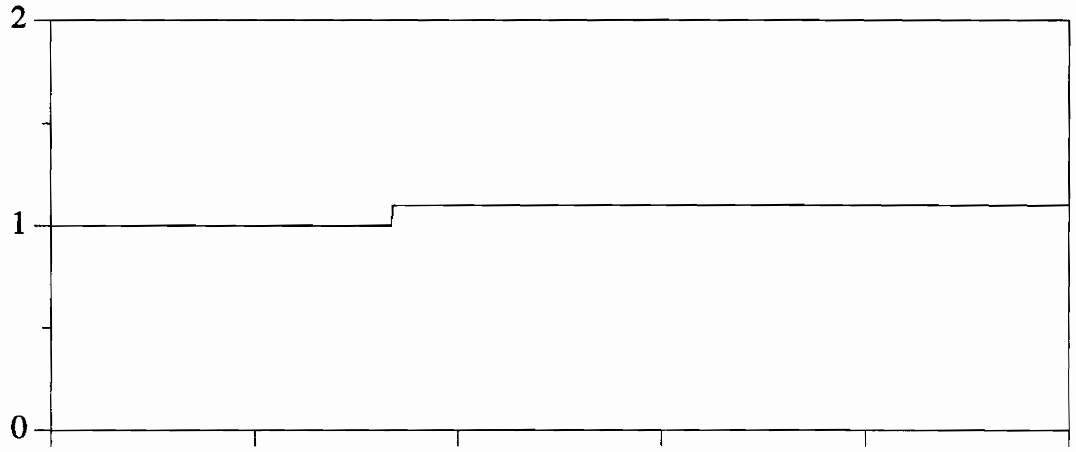


SMES Power (MW)

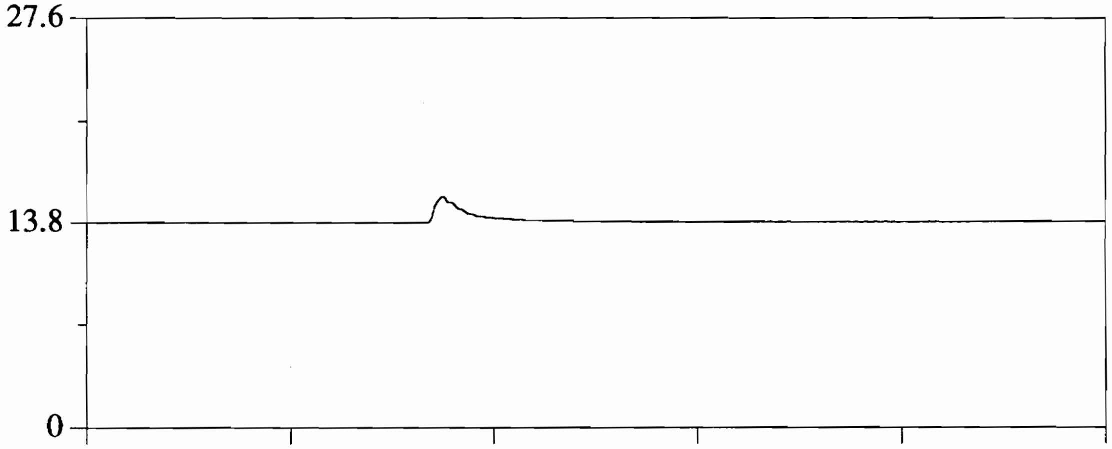


SMES Reactive Power (MVAr)

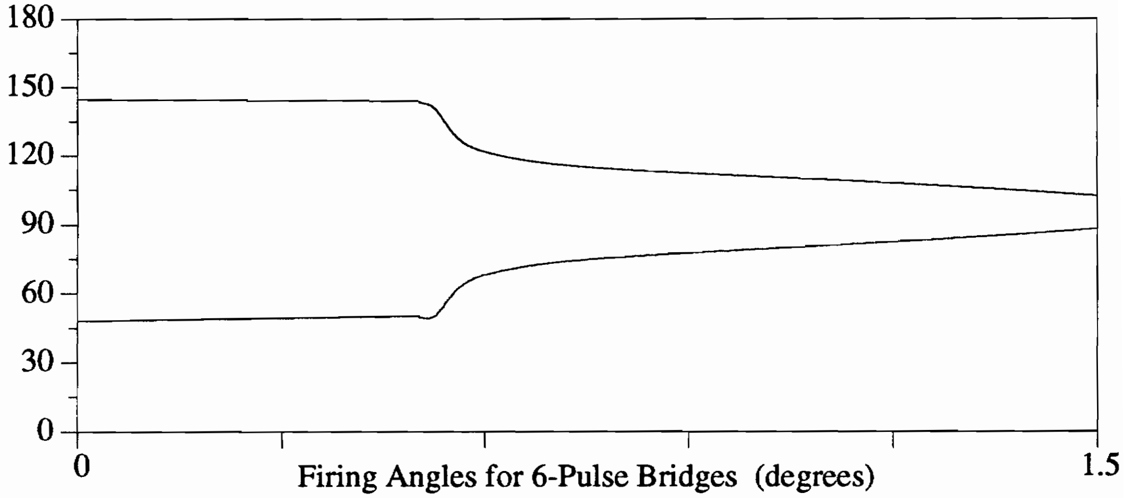
Figure 3-7b. SMES Response to PV Power Fluctuations (7.0 s)



Grid Voltage (PU)

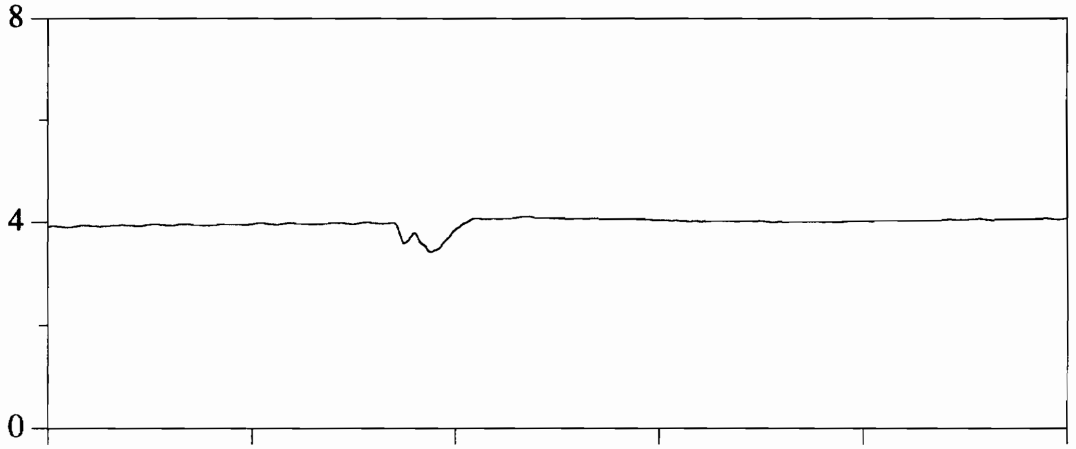


Bus Voltage (kV)

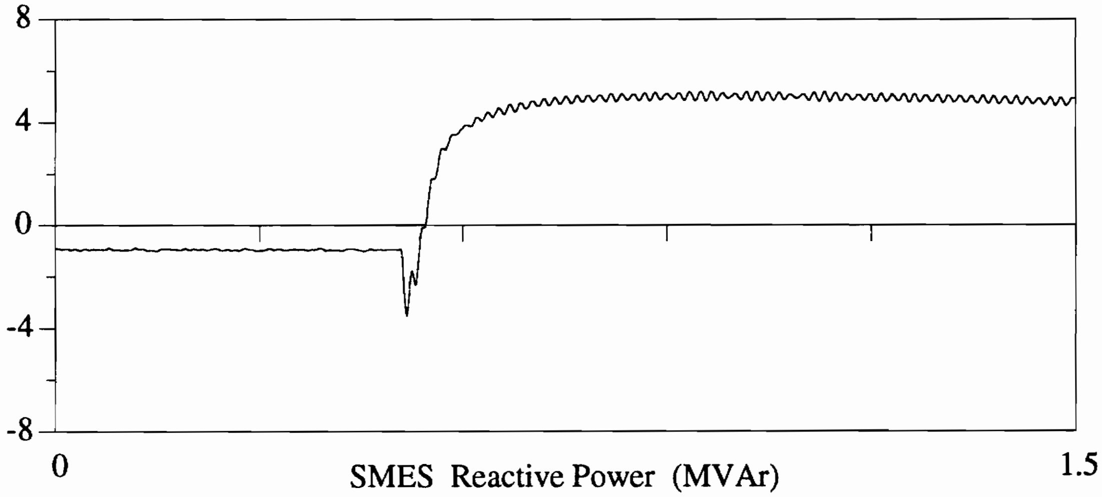


Firing Angles for 6-Pulse Bridges (degrees)

Figure 3-8a. System Response to Overvoltage of 0.1 PU – SMES Charging (1.5 s)

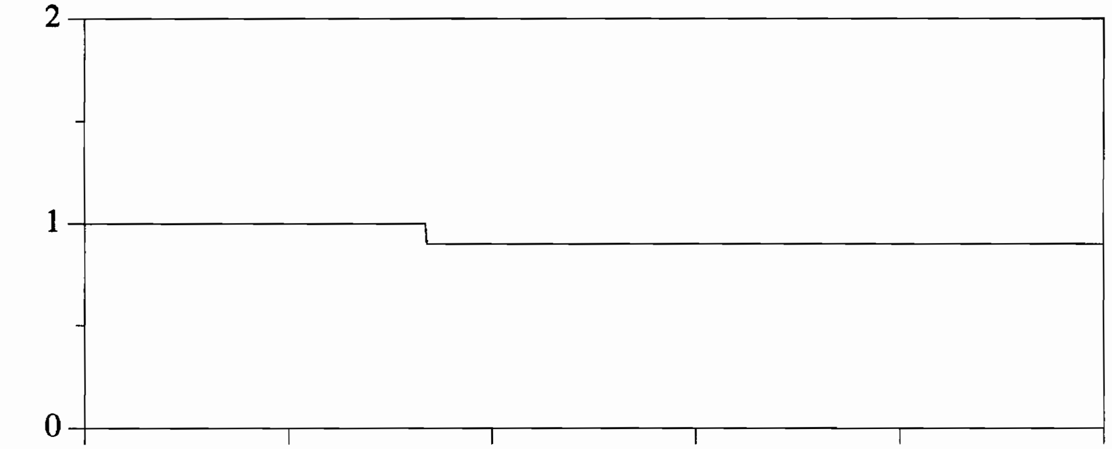


SMES Power (MW)

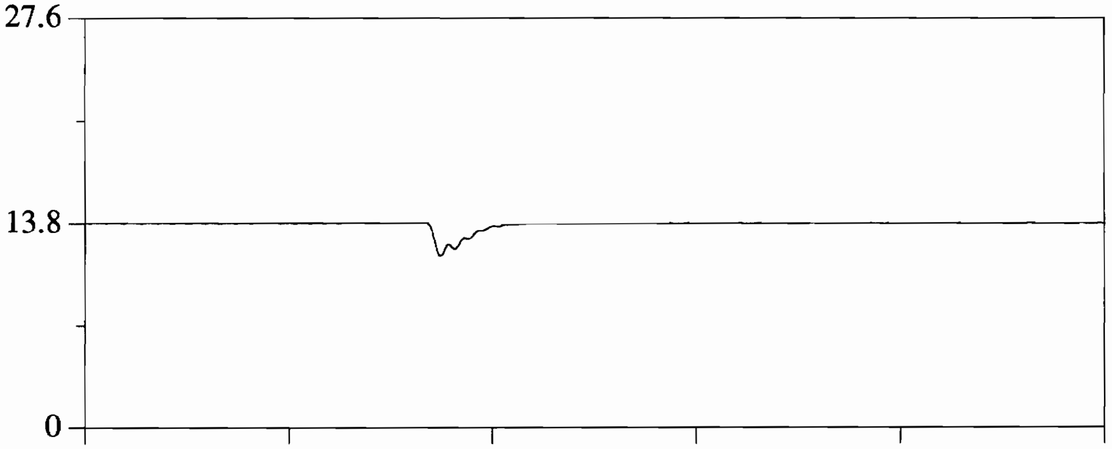


SMES Reactive Power (MVAr)

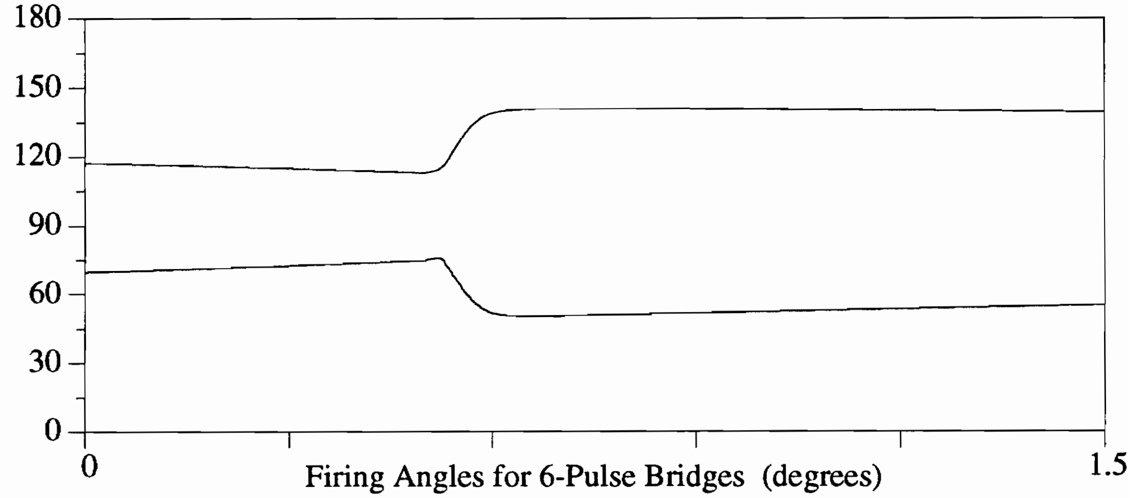
Figure 3-8b. System Response to Overvoltage of 0.1 PU – SMES Charging (1.5 s)



Grid Voltage (PU)

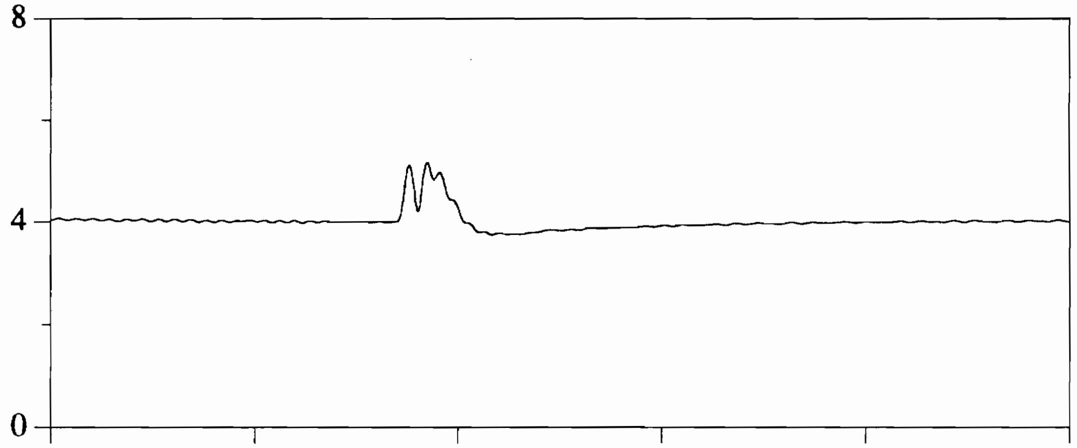


Bus Voltage (kV)

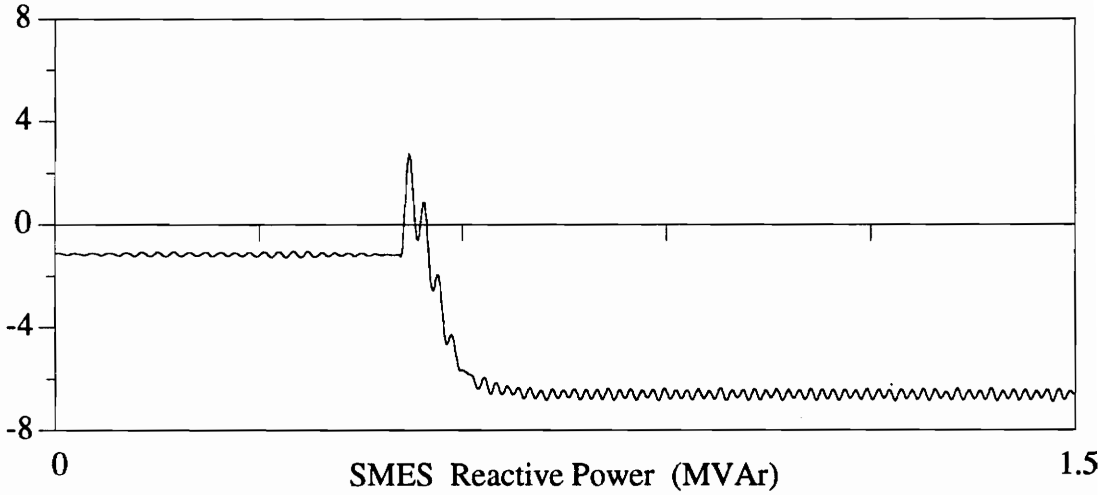


Firing Angles for 6-Pulse Bridges (degrees)

Figure 3-9a. System Response to Undervoltage of 0.1 PU – SMES Charging (1.5 s)



SMES Power (MW)



SMES Reactive Power (MVAr)

Figure 3-9b. System Response to Undervoltage of 0.1 PU – SMES Charging (1.5 s)

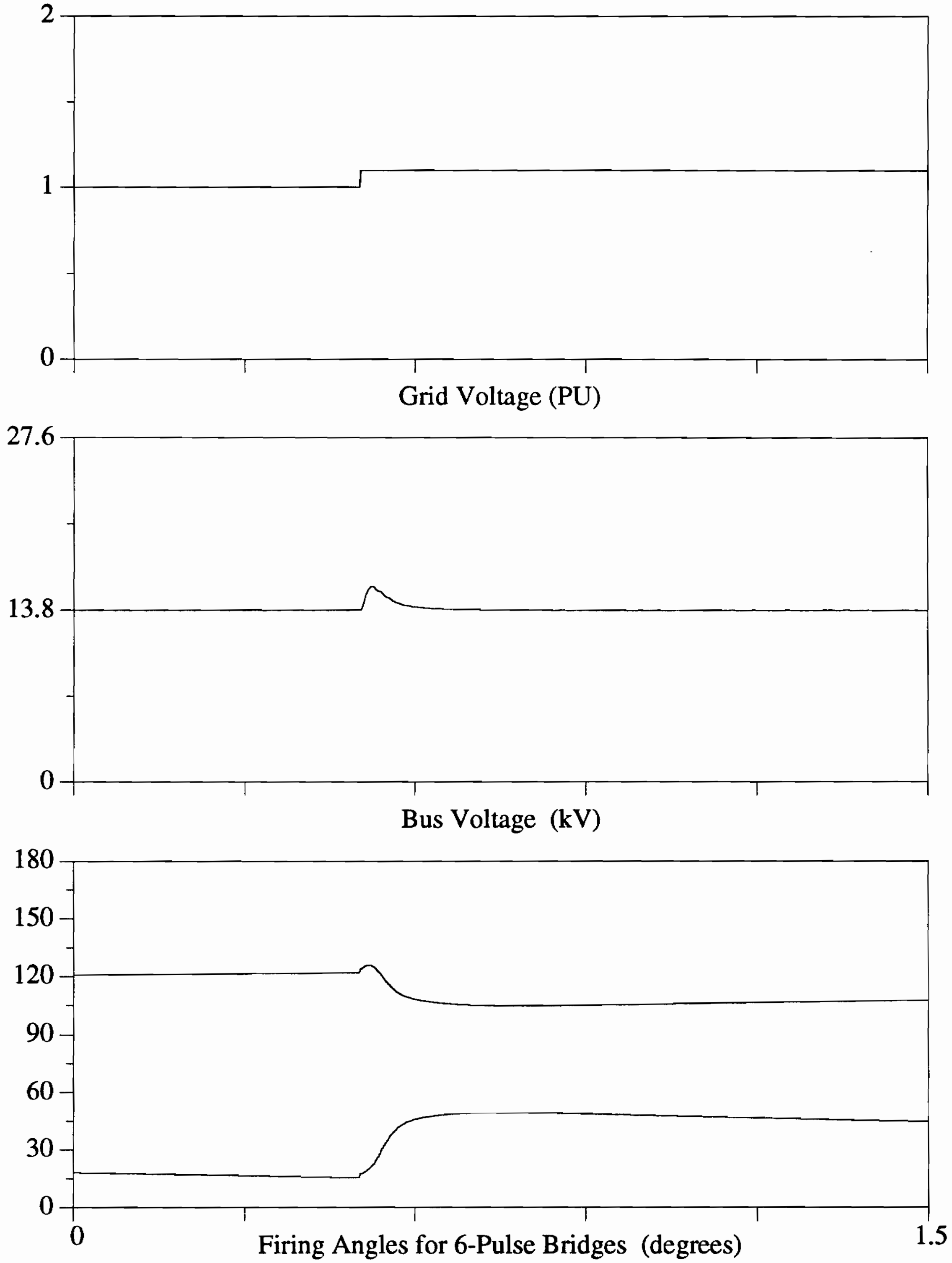
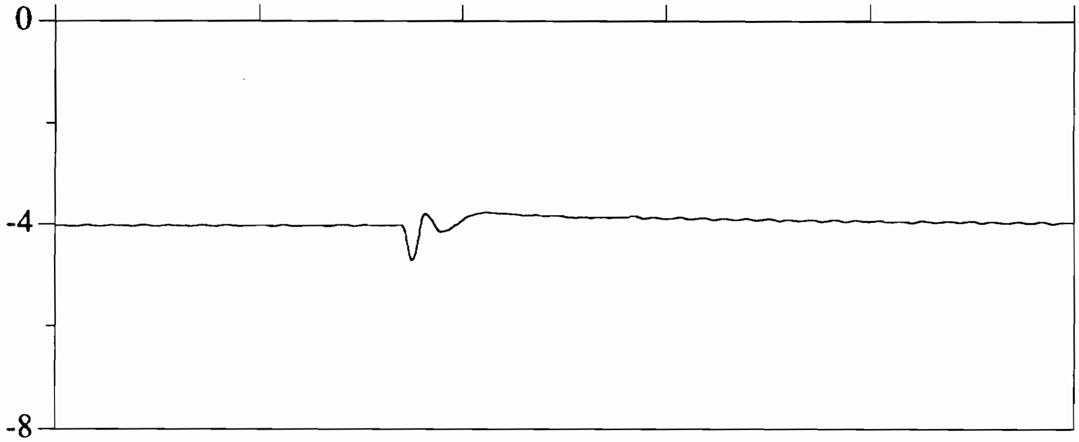
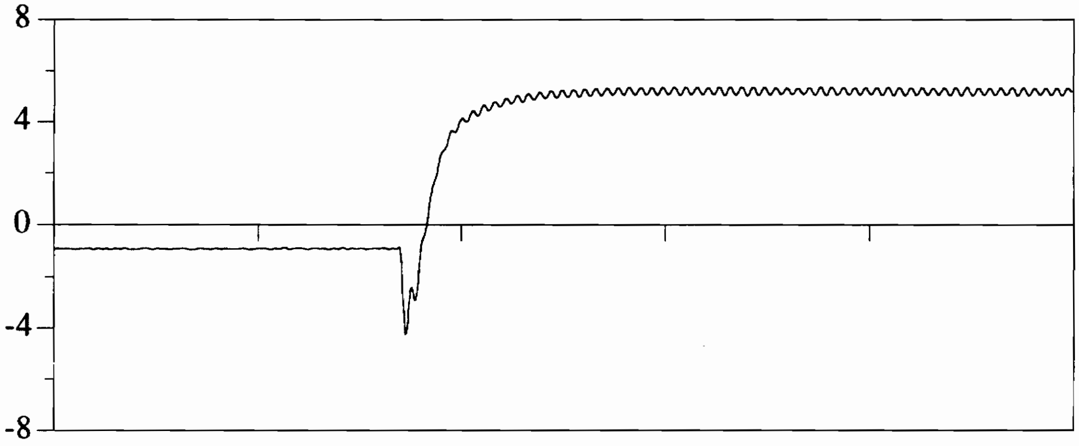


Figure 3-10a. System Response to Overvoltage of 0.1 PU – SMES Discharging (1.5 s)



SMES Power (MW)



SMES Reactive Power (MVAr)

Figure 3-10b. System Response to Overvoltage of 0.1 PU – SMES Discharging (1.5 s)

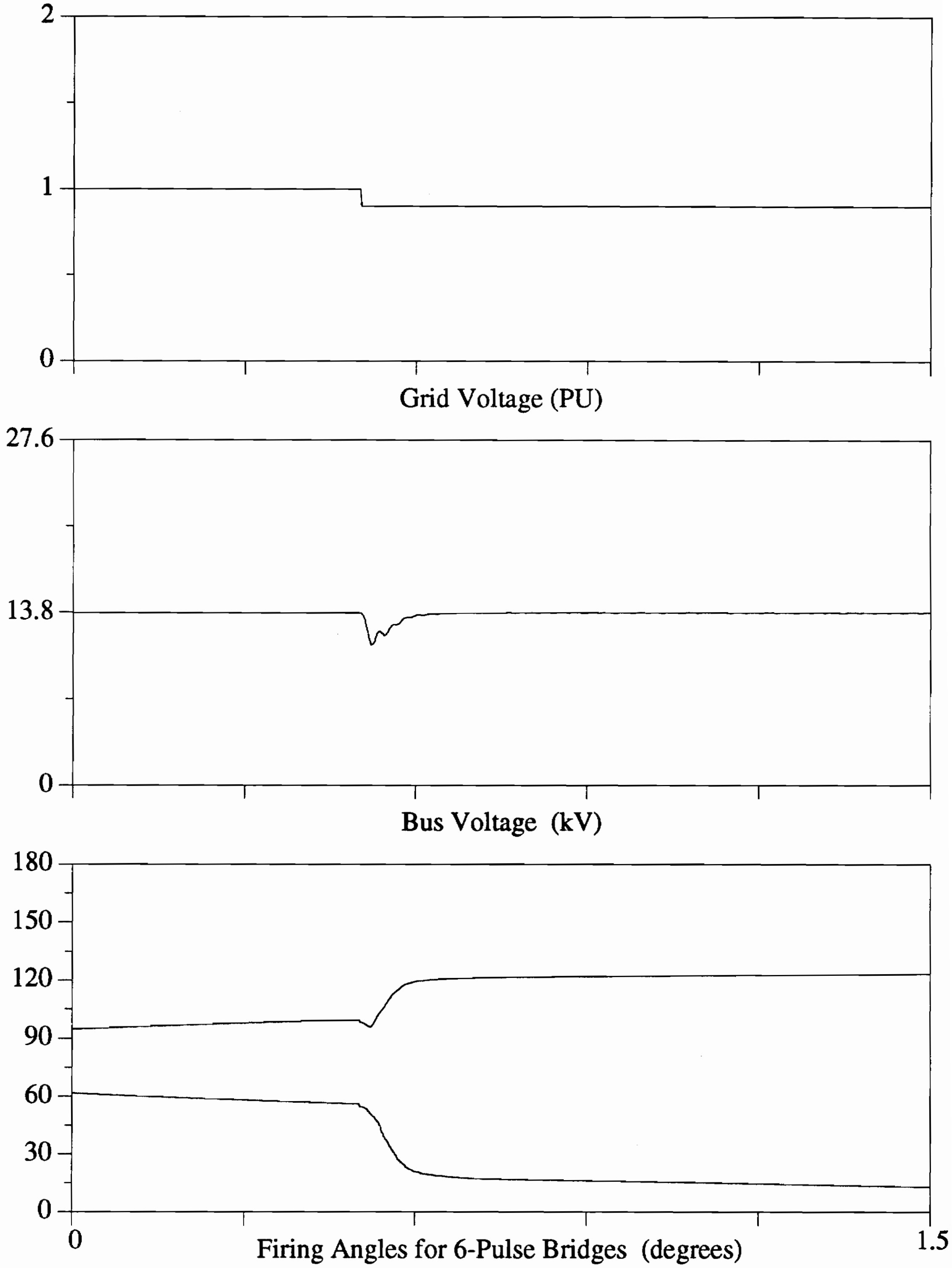
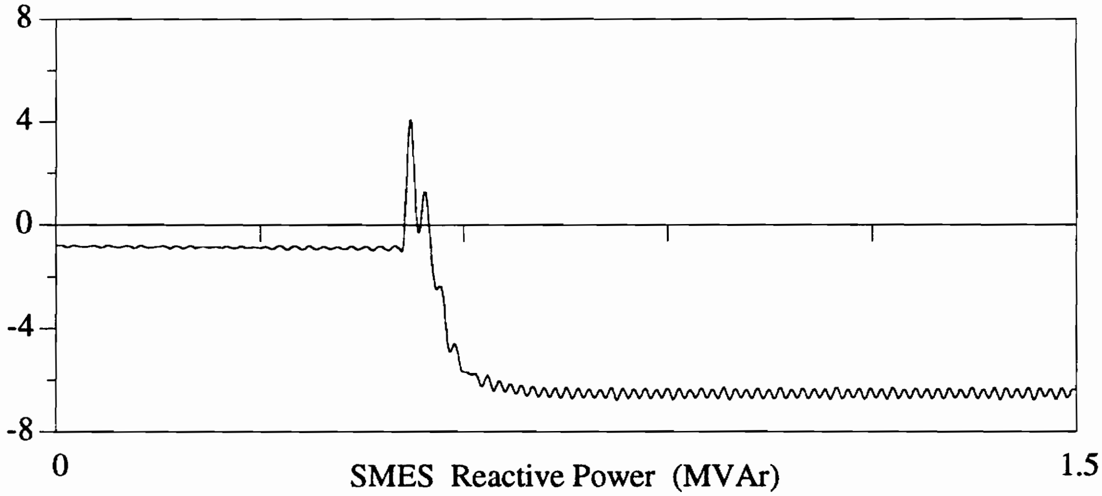


Figure 3-11a. System Response to Undervoltage of 0.1 PU – SMES Discharging (1.5 s)

SMES Power (MW)



SMES Reactive Power (MVAr)

Figure 3-11b. System Response to Undervoltage of 0.1 PU – SMES Discharging (1.5 s)

CHAPTER 4

DC/DC INTERFACE

This chapter discusses the control and operation of DC/DC power processing systems as they relate to SMES applications. In particular, it presents a new power conversion arrangement for connecting a SMES system to a DC environment. The converter topology takes advantage of the DC nature of SMES and PVs. This scheme uses two DC/DC converters to control the charging and discharging of the SMES while maintaining the optimum loading on the DC source. Included are the selection of circuit, development of control and operation schemes, simulation results, interpretation of the results, and potential applications.

4.1 Background

Connection of a SMES system to the AC grid, as discussed in Chapter 3, necessitates that the interface be through AC/DC converter bridges, so research for utility load leveling has concentrated on that type of converter. At the same time, DC/DC work for SMES has most often focused on pulsed energy transfer between SMES coils or on all-superconducting rectifiers and fluxpumps. The schemes for transferring energy between SMES coils are usually for very fast pulsed operation (e.g., megawatts for milliseconds), whereas those using superconducting rectifiers and fluxpumps are typically for slower energy transfer (e.g., watts for minutes or hours) due to the nature of their superconductive switches. However, there could be promise for a DC/DC interface which connects a SMES system with DC systems that have a broader range of energy transfer rates falling somewhere between these two extremes. Photovoltaic arrays (PVs), wind powered generators, magneto-hydrodynamic systems, batteries, or any other scalable DC source or load could potentially make use of such a scheme.

4.2 Advantages of DC/DC Connection

Because of their inherent DC, intermittent, and modular nature, PV arrays are an attractive candidate for a DC/DC interface with a SMES system. The usefulness of SMES and PV technology can each be enhanced by the combination of the two. The benefit to a utility of a combined SMES/PV system is greater than the sum of the benefits from each system used separately. Furthermore, a DC/DC connection between the SMES and PV systems offers advantages over an AC/DC arrangement.

4.2.1 One Step Conversion

For terrestrial applications, the SMES/PV connection could be made through the 3-phase AC utility grid with each of the systems having its own AC/DC converter. However, because of the DC nature of both SMES and PVs, no intermediate conversion to

60 Hz AC is needed. By eliminating an unnecessary intermediate conversion step with less than 100% efficiency, the number of switching components, converter cost, and conversion losses could all be correspondingly reduced.

Connection to the AC grid could then be made through a single AC/DC converter at the SMES/PV interface. Furthermore, joint siting could reduce long distance transmission losses and reduce the total amount of land allocated to the combined system. Large scale PV arrays require a correspondingly large land area, and SMES needs large land area to be restricted because of its high magnetic field, so placing a PV array above an underground SMES coil could better utilize available land.

For space applications or other stand-alone arrangements, no 60 Hz AC connection even exists; satellites have no intermediate AC distribution system. It should be noted, though, that the proposed NASA space station might employ a 20 kHz AC distribution system between its DC solar power source and DC storage system.

4.2.2 Voltage and Current Ratings

The DC/DC conversion can also be performed at the voltage and current levels that minimize component stress and cost. PV arrays are sources that lend themselves well to series and parallel connections, as well as modular converter configurations. AC systems and AC/DC converters, in contrast, are restricted by transmission losses and operational constraints to be at certain levels of voltage and current, which do not necessarily match the characteristics of SMES. As noted before, the AC utility grid is high voltage/low current, whereas SMES is low voltage/high current.

4.2.3 Reactive Power Requirements

DC/DC converters do not draw reactive power from an external system. Their AC/DC counterparts, on the other hand, draw reactive power whether in rectifying or (?) inverting mode. Therefore, regardless of the quantity of power supplied by the PV array, and regardless of the magnitude or direction of energy transfer with the SMES system, both AC/DC converters would require a supply of reactive power from the AC system.

4.2.4 Higher Switching Frequency

Operating the DC/DC converters at a nominal frequency of 5-10 kHz reduces the size, weight, and cost of components in comparison with corresponding 60 Hz AC/DC converters. This higher switching frequency allows faster dynamic response and wider control loop bandwidth. It also reduces the magnitude of circuit harmonics, and causes harmonics to begin at a higher frequency. Switching frequencies higher than 10 kHz are certainly possible depending on the switching elements utilized.

4.3 Requirements for SMES/PV DC/DC Converter

With such apparent advantages available from a DC/DC converter, a search was conducted for a topology that would be appropriate for a SMES/PV application. The DC/DC converter chosen for the new scheme must fulfill several specifications particular to PVs and especially SMES.

4.3.1 Bidirectional Power Flow

Bidirectional power flow is necessary for charging and discharging the SMES coil, preferably without component or converter duplication. Basic DC/DC converters make use of semiconductor switches that are unidirectional in current and voltage: diodes, transistors, or thyristors. Each of them operates in only one quadrant of the V-I power plane, which is sufficient for many potential applications. PVs, for example, never reverse power flow, so the PV converter can stay unidirectional in both voltage and current. When bidirectional power flow is needed for other applications, a solution frequently employed is reversing the current flow through anti-parallel duplication of the switches. However, SMES is unidirectional in current; any reversal of current would require first reducing the current (and energy stored) to zero then increasing the current in the opposite direction. The only alternative for SMES is reversing the voltage polarity across the inductor.

4.3.2 Wide Range of Voltage Gain

A broad range of conversion ratio is needed for PVs and for SMES, preferably including both step-up and step-down operation. The voltage and power available from PVs vary with the incident level of solar radiation, so a wide sweep in gain is needed to maintain the PVs at their maximum power point. The SMES system also requires a large range in conversion ratio because it must be able to respond to the supply/demand of the external system which certainly is not steady.

4.3.3 Continuous Current at SMES and PV Ends

SMES, like any inductive energy storage, is inherently continuous; if the current is pulsating and goes to zero for a portion of each switching cycle, so does the energy stored. Therefore, any converter that charges the SMES coil must have non-pulsating output current. When the coil is discharging and acting as a source, the converter it supplies must have non-pulsating input current.

For the application to PVs, the converter needs non-pulsating current at its input to stay at the maximum power point. Otherwise, when the input current goes to zero during each cycle, the power transferred goes to zero also.

If a single converter lies between the PV and SMES systems, it must have non-pulsating input current to extract power efficiently from the PVs and non-pulsating output current for the purely inductive load of the SMES. If separate DC/DC converters serve the

PV and SMES systems connected to a central DC bus, then the converters should probably have non-pulsating current at the bus. For the individual converters, their output current doesn't necessarily have to be non-pulsating for their own operation, but discontinuous current at the bus could adversely affect other converters or a load connected there.

4.3.4 Single Converter Topology

A generally advantageous feature for this particular application would be if the same converter could be used for PVs alone, SMES alone, or combined operation. Though this condition is not essential for the converter, it is a desirable one if a suitable converter could be found. Such a topology would make design simpler, and could reduce production costs if a large number of converters were produced for a modular arrangement or connections in series or parallel.

4.3.5 Technology Independent

Another attractive attribute for a candidate converter is switch technology independence – diodes, transistors, thyristors, and other semiconductor switches. If a converter topology is not dependent on a specific type of switch, then other switches could be substituted for various reasons – cost, circuit losses, reliability, or changes in scale. It should be noted that some designs do require turn off capability for some switches.

4.3.6 Other Considerations

One additional feature that might be useful under some circumstances would be DC isolation between the input and output. Finally, for all topologies that meet all of these technical requirements, simplicity, efficiency, and cost must also be considered.

4.4 Basic DC/DC Converters

The four most basic DC/DC converter topologies were examined and their characteristics compared to find an appropriate match for a combined SMES/PV system. Information about various DC/DC converters is available from a myriad of sources [see H-1 through H-68], and only the most fundamental properties of the converters are pertinent to the discussion, so substantial detail will not be included here. Instead, the focus is primarily on the characteristics of voltage gain and pulsating current.

The converter topologies considered were buck, boost, buck-boost, and boost-buck, named for their respective voltage gain capabilities. Each one has its own unique combination of various features, as summarized in Figure 4-1. As implied by their names, the buck converter has only voltage step-down capability; the boost converter can only step-up voltage; and both the buck-boost and boost-buck converters can step-up or step-down voltage. (The boost-buck converter is often referred to as the Cuk converter in the literature, and it will be called that throughout the rest of this text.)

Buck and buck-boost converters have pulsating input current while boost and Cuk converters do not. Similarly, boost and buck-boost types have pulsating output current while the buck and Cuk types do not. Output current is typically smoothed out to a certain extent by a capacitor in parallel with the load. The simple converters (buck and boost) have output voltage polarity the same as the input; the compound converters (buck-boost and Cuk) exhibit an output voltage polarity reversal.

4.5 Selection of Cuk Converter

From these four primary options, the Cuk converter showed the greatest initial promise, and it was pursued for the remainder of the effort. A basic Cuk converter implementation is shown in Figure 4-2 along with several modified versions. The Cuk converter is not necessarily the perfect choice for SMES/PV operations, even if finding an ideal converter were possible. However, it does exhibit the fundamental features considered essential for a SMES/PV system, and its performance in later simulations was certainly adequate for demonstrating the validity of the concept.

4.5.1 Meets Minimum Requirements

The Cuk converter meets the specifications outlined above, and does it with a relatively simple design. It provides voltage step-up and step-down for a wide range of voltage gain, and smooth input and output current. In fact, it is the only topology of the four with non-pulsating current at both the input and the output. A cascade connection of a boost converter with a buck converter could meet the input and output requirements, but the Cuk converter has fewer components and a simpler design for the same performance.

4.5.2 Attractive Features

The Cuk converter provides the desired performance while retaining a simple design, a low component count, and low component stresses. The component values can be designed for an arbitrary ripple and frequency; there is even a modified configuration that can achieve zero ripple [H-24]. The ability of integrated magnetics to eliminate the input and output current ripple could improve system performance by helping to maintain the PVs at the maximum power point and reducing AC losses in the superconductor. The improvement in performance may or may not be worth the corresponding increase in cost and complexity.

A possible extension to the Cuk converter mentioned in the literature is the addition of a transformer in the circuit to provide DC isolation [H-8]. Such a configuration is also shown in Figure 4-2. Like the zero-ripple option, the performance enhancement must be weighed against the additional cost and complexity.

4.5.3 Switch Modification

Though its basic form allows operation in only one quadrant of the power plane, a minor modification permits bidirectional power flow. Normally the switch component on the output side of the converter is a diode with no ability to be controlled [H-19]. However, if the diode is replaced by a controllable switch identical to the one on the input side (e.g., a transistor or gate-turn-off thyristor), the converter becomes symmetrical from input to output. Because of the symmetry of this modified Cuk converter, operation in the reverse direction is identical to forward operation. The switching element substituted for the diode acts as the input-side switch when power flow is reversed, and no additional components are necessary.

The modified Cuk converter still provides for unidirectional current flow in the switches but allows a reversal of voltage polarity when input and output are interchanged. Since unidirectional current flow is an inherent feature of inductive energy storage, this voltage polarity inversion permits two-quadrant power flow. Therefore, the bidirectional charging and discharging requirements of the SMES system are met without anti-parallel duplication of the converter or its components.

4.5.4 Similarity to Flying Capacitor Converter

With the output switch modification mentioned earlier, the Cuk converter is effectively a single flying capacitor converter (or Karlsruhe converter) with the inductive source replaced by a voltage source in series with an inductor [L-1, L-2, L-15]; see Figure 4-2. The modified Cuk converter is operated at a higher frequency and with a nominal ripple on the capacitor instead of completely discharging it during each switching cycle.

Since the modified Cuk converter and the single flying capacitor converter are essentially identical topologies, the converter used in this effort could be referenced by either name. The choice to use the Cuk label was based on three reasons. First, during the course of this work, the circuit design in question was arrived at by means of the Cuk converter; the similarity with the flying capacitor converter was noticed later. Second, though the circuits are the same, their operational characteristics, as defined by their respective innovators, are substantially different; the operational modes used for this study more closely resemble those associated with the Cuk converter. Third, the extensions and modifications derived from the primary circuits are significantly different as well; the ones considered more likely to have an impact on this type of system are those developed from the Cuk converter. For example, the dual flying capacitor, a derivative of the single flying capacitor design, offers some advantages over the single version in voltage harmonics and current ripple, but it is still operated in a bang-bang manner where the capacitor is completely discharged during each cycle [L-13]. In contrast, DC isolation and zero-ripple options available for the Cuk converter show some promise for a SMES/PV system.

The single flying capacitor work discussed in the literature was certainly not ignored, however. It is particularly important to note that this basic circuit design had already been examined and tested to a limited extent for use with SMES [L-1, L-2]. The success of that work provided confidence for attempting the modifications mentioned here.

4.5.5 Voltage Polarity Reversal

As mentioned earlier, the bidirectional charging and discharging requirements of the SMES system are met without anti-parallel duplication of the converter or its components because the Cuk converter exhibits a voltage polarity reversal appropriate for an inductive load. However, if the source/load at the other end of the converter is not similarly inductive in nature (e.g., PVs or a constant voltage bus), the voltage polarity will be wrong when the SMES coil is discharging. A double-throw double-pole switch between the unidirectional voltage terminal and the converter is all that is necessary to maintain proper output voltage polarity. This switch does not need to have turn-off capability, nor does it need to be especially fast; it will only be thrown when the SMES system transitions between charging and discharging modes, at which time the current through the switch will already be at zero.

4.6 Cascade Connection of Two DC/DC Converters

The discussion above detailed the requirements for converters connected to individual SMES and PV systems. When a combined SMES/PV system is designed, additional constraints must be considered – in particular, what is the nature of the load, and what circuit parameter(s) will be regulated. The simplest circuit option would be if the SMES itself is the load for the PV array. In that case, the converter would always be in the SMES charging mode and would maintain the PV at its maximum power point. However, at some point, the SMES is fully charged and must be discharged; such a circuit has no value if it doesn't supply a load.

A more practical option would be if the combined SMES/PV system supplied an effective resistive load; the form of the load, even if it is actually another converter, is not crucial at this point. The PV array supplies power to the load when there is sunlight; the SMES coil absorbs the excess energy available from the PVs and supplies it to the load when the PV supply is insufficient. To operate this circuit, the desired parameters for regulation would be providing the load with steady power (i.e., steady voltage for a resistive load) and maintaining the PVs at their maximum power point. These conditions suggest the solution of a cascade connection of two converters. A single converter does not provide a steady voltage output to drive the load and only allows one degree of freedom of control where two parameters are desired.

4.6.1 Two Control Parameters

With a cascade connection of two converters, each one can regulate a single circuit parameter with feedback control of its duty ratio. Used independently, the most likely parameters for the converters to regulate are the output voltage from the PV converter and the output power from the SMES converter. Operation of the two converters can be combined to maintain a constant voltage at the common bus where they intersect and adjust the power flow between them.

When the PV converter regulates its output voltage, it cannot simultaneously control the loading of the PV source. To keep the PVs operating at the maximum power point requires an additional control variable provided by the SMES converter. If the bus voltage is held constant by the PV converter, the SMES converter regulates the voltage across the SMES coil. Since the inductor current is essentially constant over a switching cycle, the voltage determines the power absorbed or delivered by the inductor. With negligible converter losses, this in turn is the power transferred at the bus. The duty ratio of the SMES converter could then be manipulated to maintain the PVs at their maximum power point. At the same time, the SMES automatically stores any excess PV power available or delivers any needed load power that is lacking.

4.6.2 Operational Modes

The control of the complete system has four operating modes determined by the relative values of the PV power available and the load power demanded. The entire system is shown in Figure 4-3, including the double-pole double-throw switch between the common bus and the SMES converter. The switch is implemented in this model as two pairs of switches labeled "C" for charging and "D" for discharging.

4.6.2.1 Mode 1: PV Power Greater Than Load Power

The first mode is when the PV array supplies enough power to handle the load at the bus and charge the SMES coil. In that case, the charging switches are on, and the discharging switches are off. The second switch of the SMES converter is given a constant gating signal to operate as a diode, and the first switch is turned on and off each switching cycle in the same manner as the first switch in the PV converter. The power available for charging the SMES system is the power provided by the PVs less the power demanded by the load.

Any one of a number of algorithms could be used for determining the conditions necessary for maintaining the PV cells at their maximum power point. A typical current-voltage (I-V) characteristic curve for a PV cell, shown in Figure 4-4 along with a standard PV cell model [N-2, N-18, N-24], reveals that an effective resistive load maximizes output power. An equivalent effective resistance is presented to the PVs because the feedback control loop for both of the DC/DC converters is based on the DC transformer characteristic of the converter – it reflects the impedance of the load to the input side. Furthermore, if the source is not a PV array, the same control scheme could be used to maintain any loading on the input.

4.6.2.2 Mode 2: PV Power Equals Load Power

The second mode is when the PVs supply just enough power for the load at the DC bus. In that case, the SMES converter is turned off (with both the charging and discharging switches off) and the inductor current circulates only in a steady loop – holding its state of charge. The PVs are maintained at the maximum power point automatically because such an operating point is unique. If the PVs deviate from the maximum power point, the circuit immediately transitions to either the first or third mode.

The second mode is really an intermediate step between the first and third modes. If the charging and discharging switches between the bus and the SMES converter were considered ideal, the second mode would not even be necessary for that transition. When the PV power is increasing or decreasing through that single value where it exactly equals the load, the circuit may remain in mode two less than one switching period. In normal operation it is very unlikely that the PV power would stay exactly equal to the load with no deviation for any significant length of time.

Under other circumstances mode two has an additional use. If the SMES system needs to be disconnected for any reason (e.g., maintenance), regardless of whether or not it is carrying a current, the PV converter can continue to supply power to the load at the bus. However, in this situation, it can only maintain either the bus voltage or the maximum power drawn from the PVs; it cannot simultaneously regulate both parameters because they are interdependent. If possible the PV converter would maintain the constant voltage at the bus even while the PV power supplied declines. Since the maximum power point and the power demand intersect at only one point, when the maximum PV power available drops below the the power demanded, the PV converter will no longer be able to sustain the output bus voltage.

In some SMES circuits, a holding (persistent) mode is achieved by use of an additional external switch or a superconducting switch. In this circuit, the SMES holding mode is handled entirely by the DC/DC converter. The ability to go into and out of a special hold configuration with little loss is crucial for applications where the source cannot provide a steady voltage for constantly converting schemes like the 6-pulse bridge. This is the case for PVs, wind energy, and systems where the charged SMES must be disconnected from the network for faults, maintenance, or transport.

4.6.2.3 Mode 3: PV Power Less Than Load Power

In mode three the PV power is not sufficient to meet the demand at the DC bus, so the SMES supplies the difference. The discharging switches are on, and the charging switches are off. Opposite of mode one, the first switch of the SMES converter is given a constant gating signal to operate as a diode, and the second switch is turned on and off each switching cycle.

4.6.2.4 Mode 4: PV Power Equals Zero

In the fourth mode, the PV supplies no power at all, and the SMES meets the entire load demand at the DC bus. For this mode, like mode three, the discharging switches are on, and the charging switches are off. The duty ratio for the SMES converter regulates the DC bus voltage. At the same time, the PV converter is turned off. This mode could also be entered if the PV array needed to be disconnected for maintenance.

4.7 Computer Simulations

The control parameters are not independent from one another so adjusting one will have an effect on the other. Therefore, a seemingly more logical feedback control than mentioned earlier would have the PV converter maintain the array at the maximum power point and the SMES converter regulate the bus voltage. A control block diagram for this arrangement is shown in Figure 4-5. The approximate duty ratio for the PV converter is calculated from the ideal equivalent resistance (R_{ideal}) of the array and the constant bus voltage ($V_{reference}$). The difference between the ideal resistance and the actual measured one (R_{equiv}) produces an error signal (R_{error}) that adjusts the duty ratio calculation through a proportional-integral-derivative feedback loop. For the SMES converter, the duty ratio is calculated from the SMES coil current (I_{SMES}) and the difference ($P_{difference}$) between the PV power (P_{PV}) and the load power (P_{load}). The deviation of the actual bus voltage (V_{bus}) from its expected value ($V_{reference}$) generates an error signal

(V_{error}) that is fed back to the SMES converter duty ratio calculation. The state of the charging/discharging (C/D) switches is determined by the direction of SMES power flow (sign of the $P_{difference}$ signal).

To test the validity of the design of this proposed combined SMES/PV system, and to demonstrate the effectiveness of its control scheme, a model was developed and computer simulations were run using EMTP. The circuit used was the one shown in Figure 4-3 where a PV array is connected to a SMES system through two DC/DC converters in cascade; there is a resistive load at the constant voltage bus; there is no AC connection. These computer simulations display the combination SMES/PV system in its charging, discharging, and standby modes of operation. They also show the transitions among these modes and the combined operation of the SMES/PV system under normal operating conditions as well as extreme circumstances.

Among other reasons for choosing to demonstrate a combined SMES/PV system was to show that the configuration of two independent DC/DC converters in cascade provided the ability to control two completely different parameters of the system – in this case the maximum power transfer from the PVs and the DC bus voltage.

4.7.1 Charging, Discharging, and Standby Modes

The first three simulations show the SMES system compensating for PV fluctuations. In Figure 4-6, the PV power increases from 500 W to 1000 W. In this figure, and in the figures that follow, the ideal maximum power that can be extracted from the PV array is plotted on the same axis as the actual PV power so that a comparison can be made. Obviously, the idealized value that assumes no losses will always be the larger of the two. Figure 4-7 shows a decrease in PV power from 1000 W to 500 W. In Figure 4-8, PV power decreases from 500 W to 0 W, and the SMES supplies power to the load by itself. In all three cases, the results show that the maximum power from the PVs is tracked very closely, and the bus voltage is steady.

4.7.2 Transitions Between Modes

When the PV power decreases to a point such that it exactly matches the load requirement, the SMES goes into a holding mode, and the PV array supplies power to the load by itself. That transition is shown in Figure 4-9. Once again the maximum power from the PVs is tracked well, and the bus voltage is steady.

The transition from SMES charging to discharging in response to a decrease in PV power is shown in Figure 4-10. The PV power is tracked very well, but this time the bus voltage shows a slight temporary drop from its reference value. The deviation is caused by the reversal of the polarity of the capacitor in the SMES converter; the SMES current recharges the capacitor in the opposite direction before it returns to regulating the bus voltage. A larger capacitor at the bus could reduce the depth and duration of the bus voltage drop if needed.

The transition from SMES discharging to charging in response to an increase in PV power is shown in Figure 4-11. The drop in bus voltage is more severe in this case because the PV array and the bus capacitor must supply the energy to reverse the polarity of the SMES converter capacitor instead of the SMES coil. The tracking of the maximum PV power is also affected because the equivalent load line resistance changes when the bus voltage changes. As in the previous case, a larger capacitor at the bus could diminish the severity of the voltage drop.

4.7.3 Response to Transients

The last three simulations show the SMES/PV system responding to more drastic changes in PV power. Figure 4-12 shows a sudden drop in PV power to zero while the SMES coil is discharging. It continues in that mode and adjusts the amount of power delivered to the load. There is ringing in the bus voltage as the feedback control settles, but the duration is very short.

In Figure 4-13, the same sudden drop in PV power is shown for a case where the SMES coil is initially charging. It must change operational mode and begin supplying power to the load. The bus voltage drop is most severe in this scenario because, unlike the SMES transition from charging to discharging shown earlier, the PV array is not there to support the bus voltage while the SMES current recharges the SMES converter capacitor.

Even in such a circumstance, the drop is short-lived and the SMES system completely recovers from the sudden removal of all PV power.

The last simulation, shown in Figure 4-14, is the response to sudden changes in the load. An additional load resistance is added, then removed. The ringing in the bus voltage is not very large nor very long because both the PV array and the SMES system are able to respond to the sudden change.

By testing the circuit in all of its operational modes and under sharp transitions, the results of these simulations demonstrate that this DC/DC converter configuration can handle PV fluctuations and respond to even more drastic situations. The combined control of the two DC/DC converters can simultaneously maintain a constant voltage at the load and keep the PV array at its maximum power point.

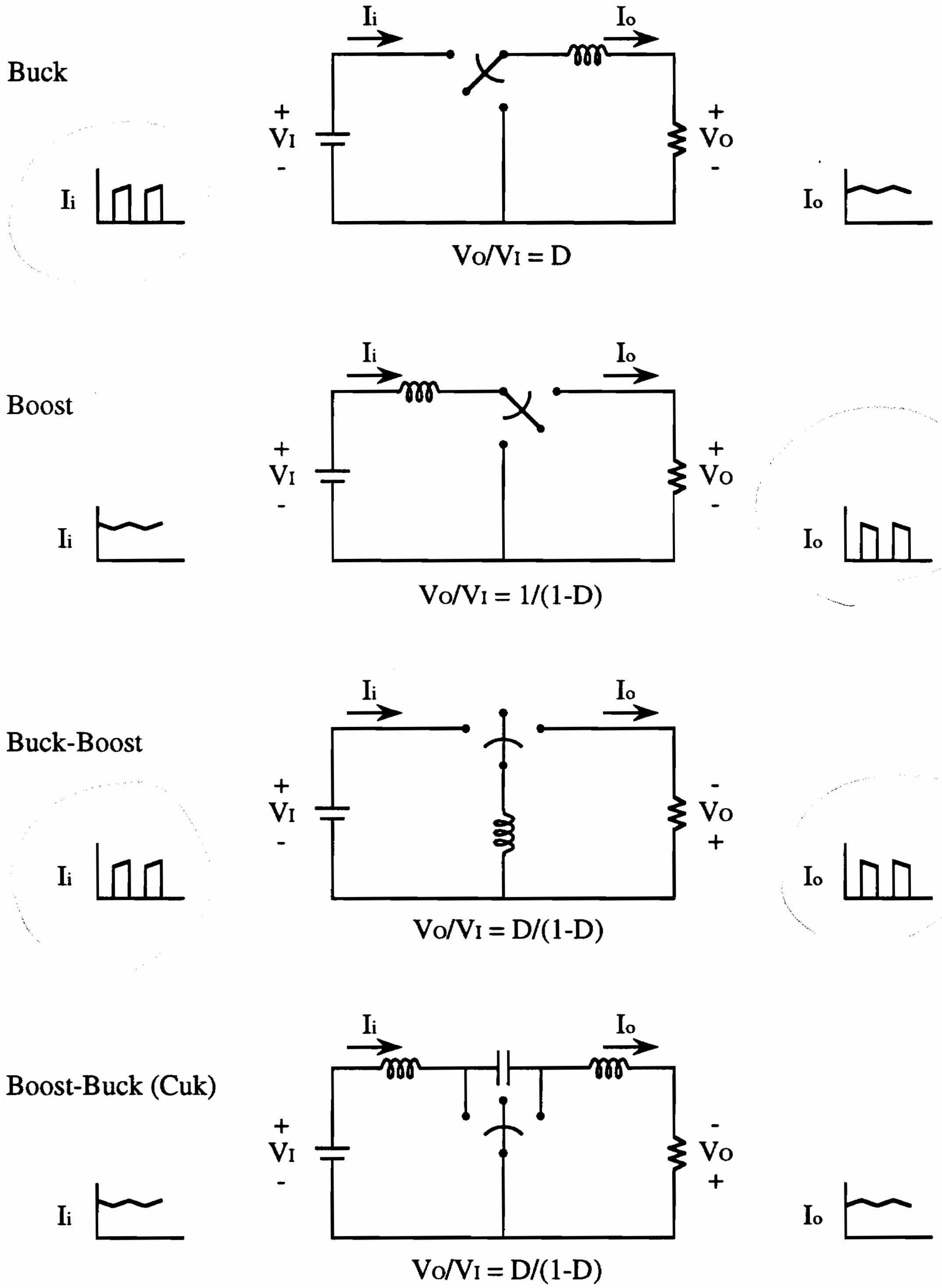
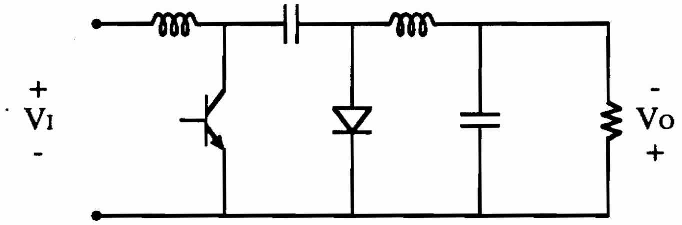
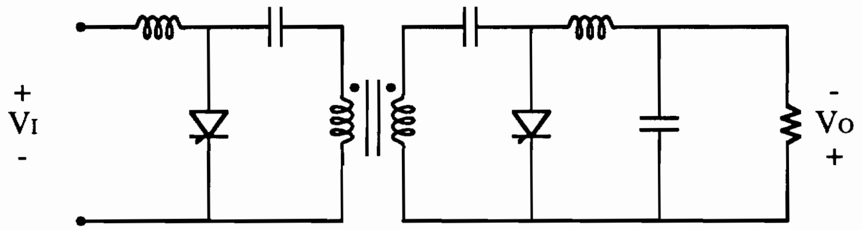


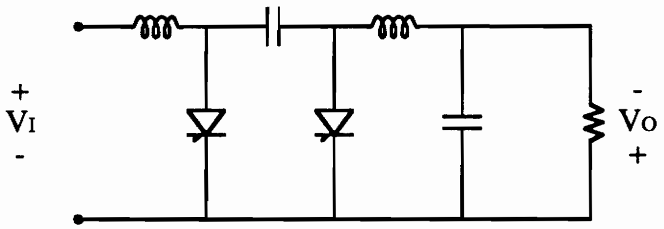
Figure 4-1. Primary Features of the Four Basic DC/DC Converter Topologies



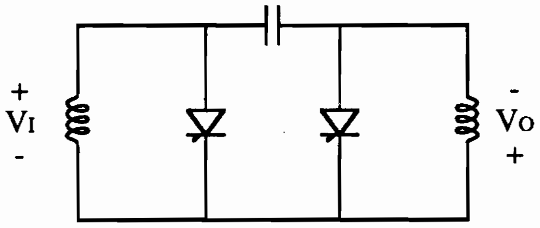
Basic Cuk Converter



DC-isolated Cuk Converter



Bidirectional Cuk Converter



Flying Capacitor Converter

Figure 4-2. Practical Cuk Converters and Flying Capacitor Converter

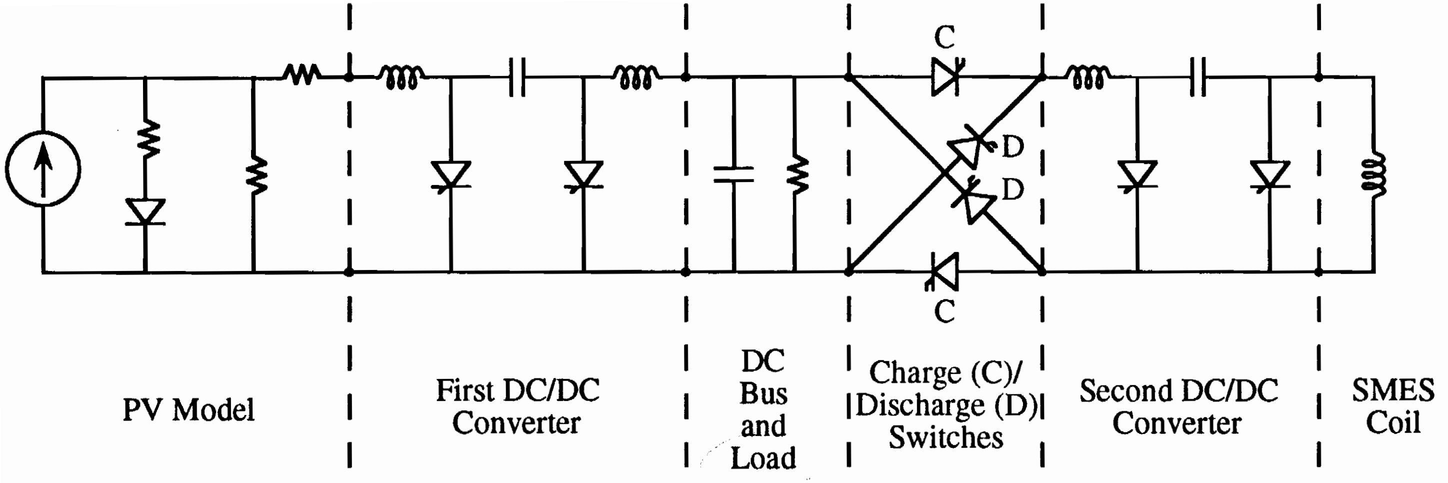
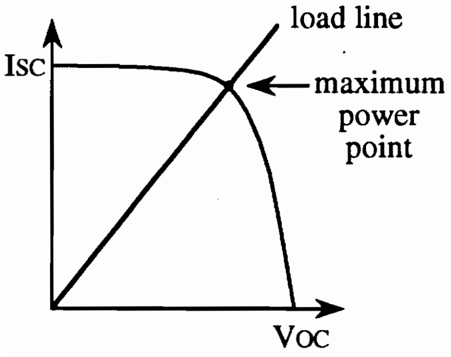


Figure 4-3. Complete SMES/PV System Connected by Two DC/DC Converters



Typical parameters for PV cell
(2 cm x 2 cm)

Isc = 0.14 A

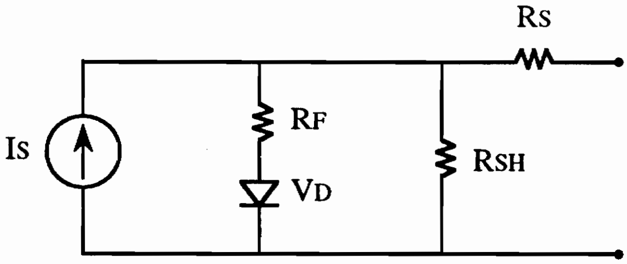
Voc = 0.56 V

Rs = 0.5 Ω

RSH = 200 Ω

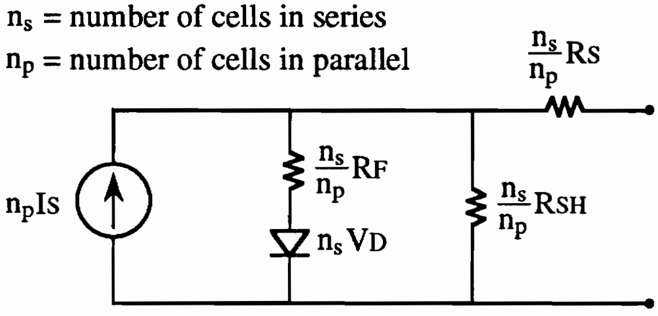
RF = 1 Ω

Typical I-V Curve and Parameters for PV Cells



Basic PV Model

n_s = number of cells in series
n_p = number of cells in parallel



Model of PV Cells Combined in Series and Parallel

Figure 4-4. PV Cell I-V Curve and Practical Models

How do we know Rideal everytime solar intensities change ?
(Rideal changes depending on solar intensity
and temperature)

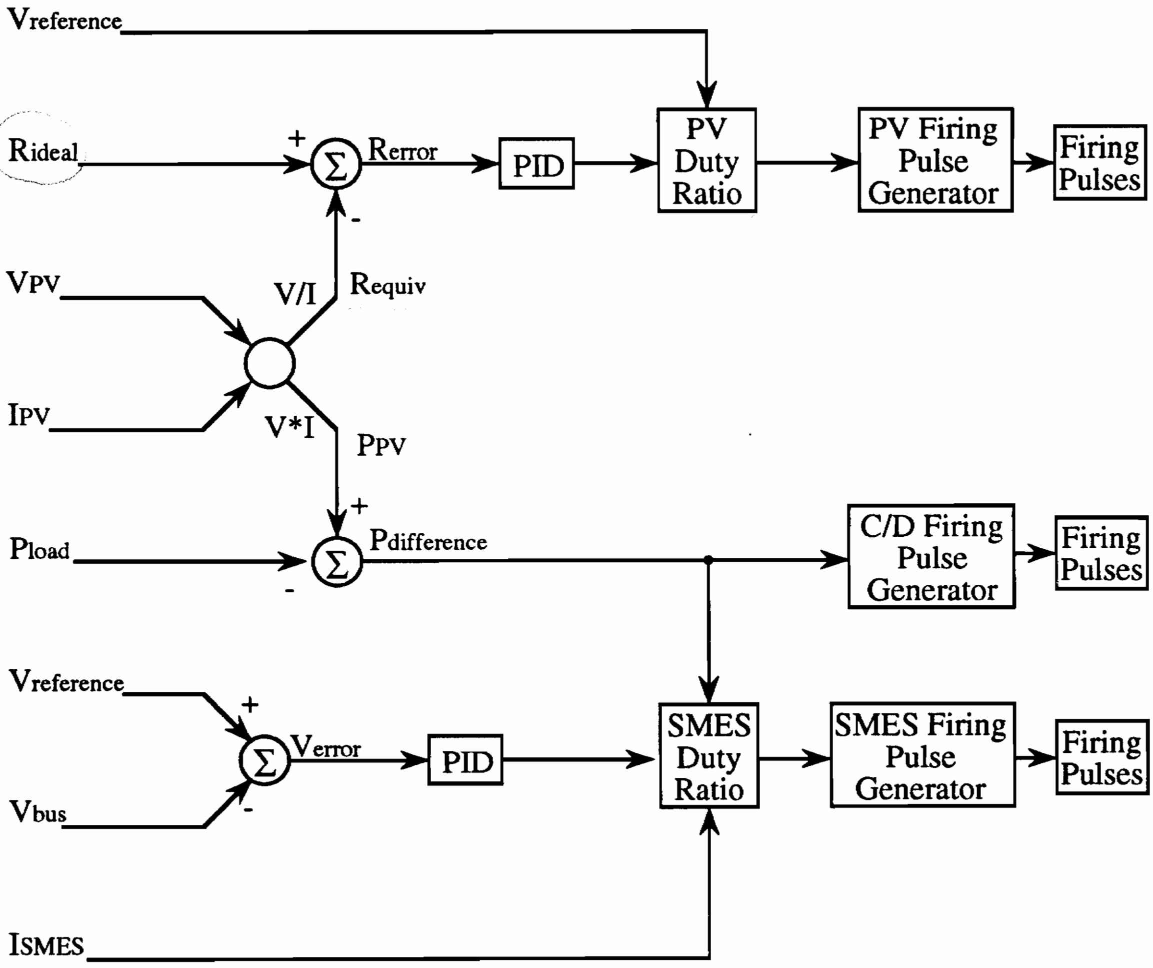


Figure 4-5. Control Block Diagram for Cascade of SMES and PV DC/DC Converters

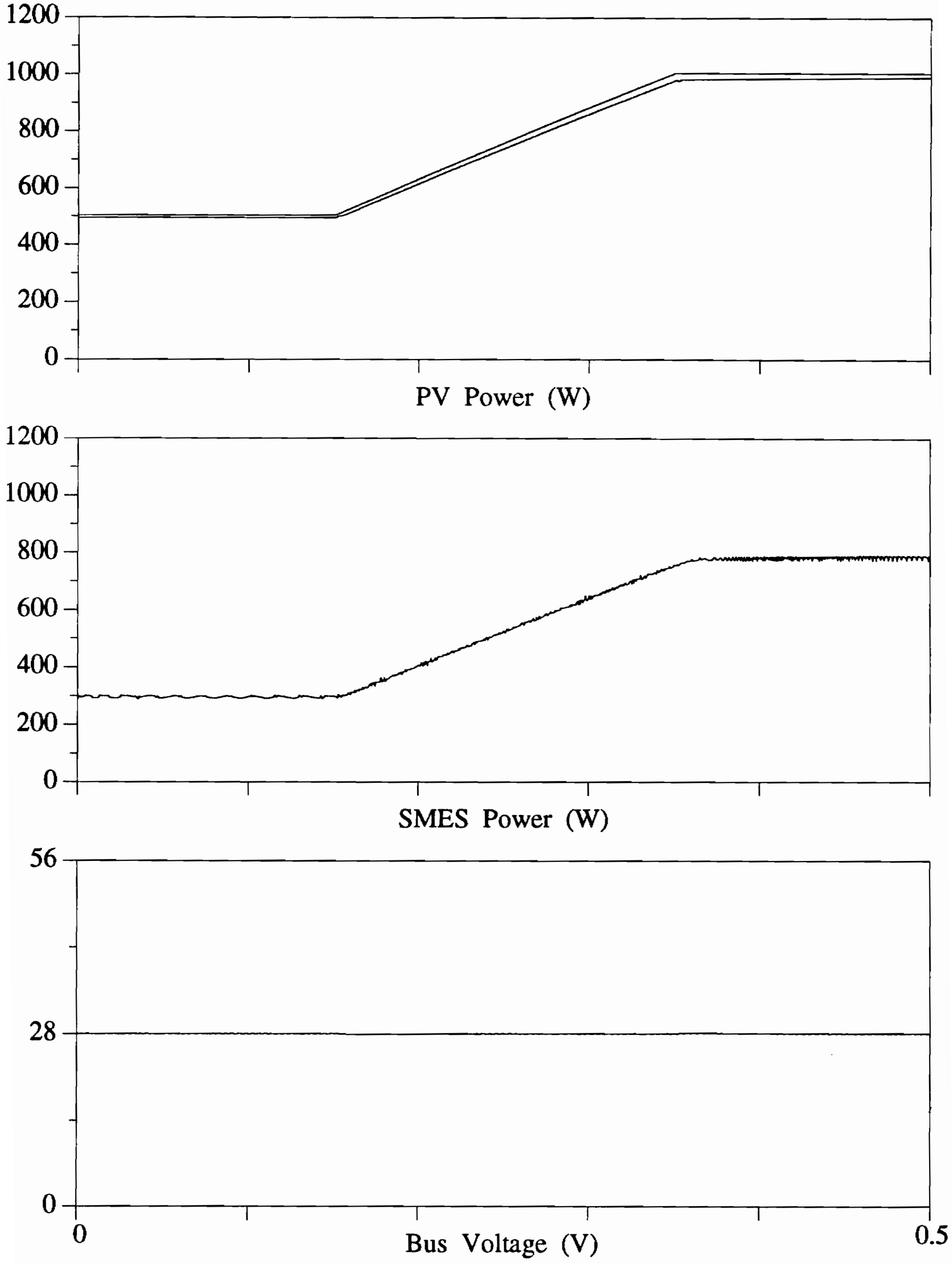


Figure 4-6. System Response to Increase in PV Power (0.5 s)

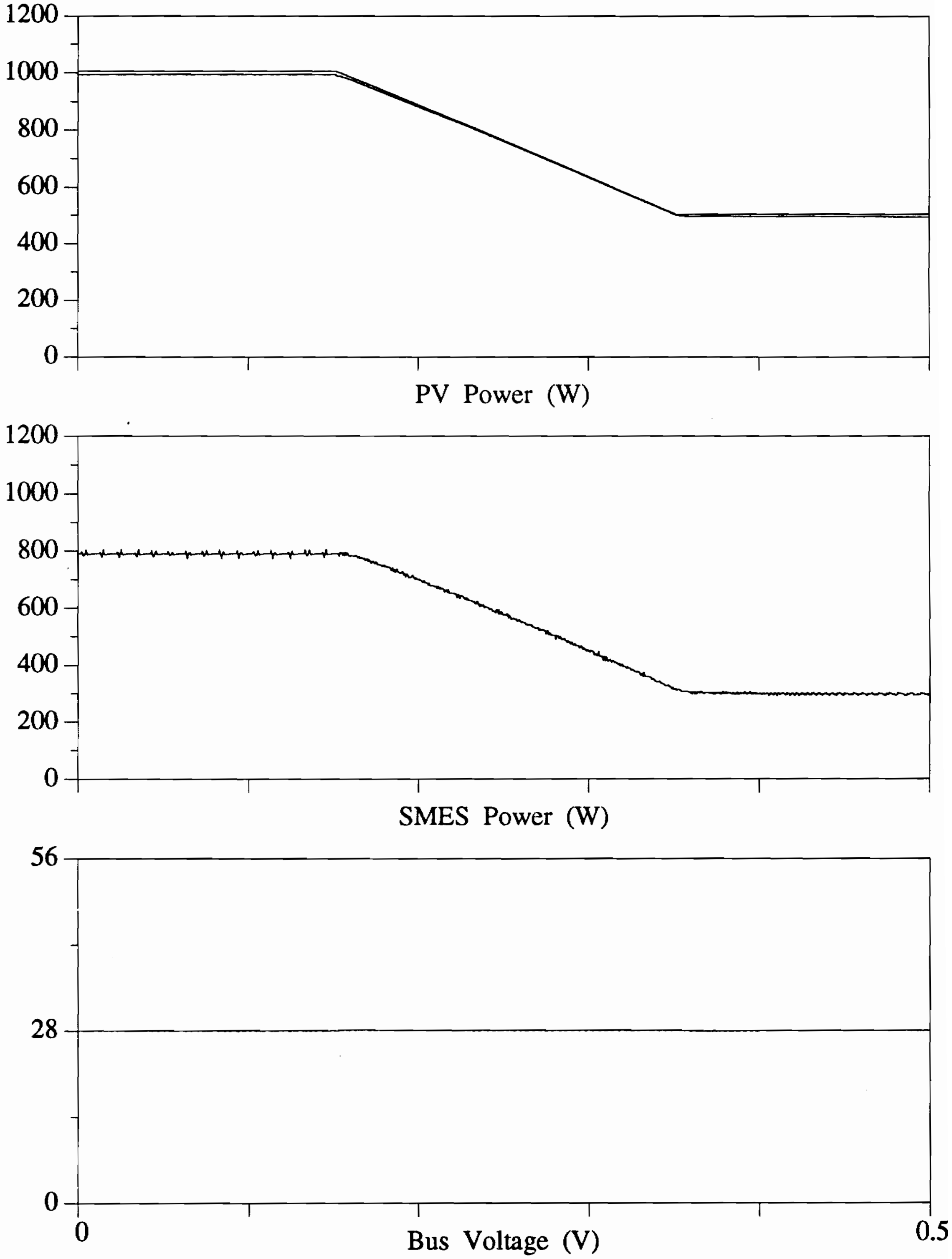


Figure 4-7. System Response to Decrease in PV Power (0.5 s)

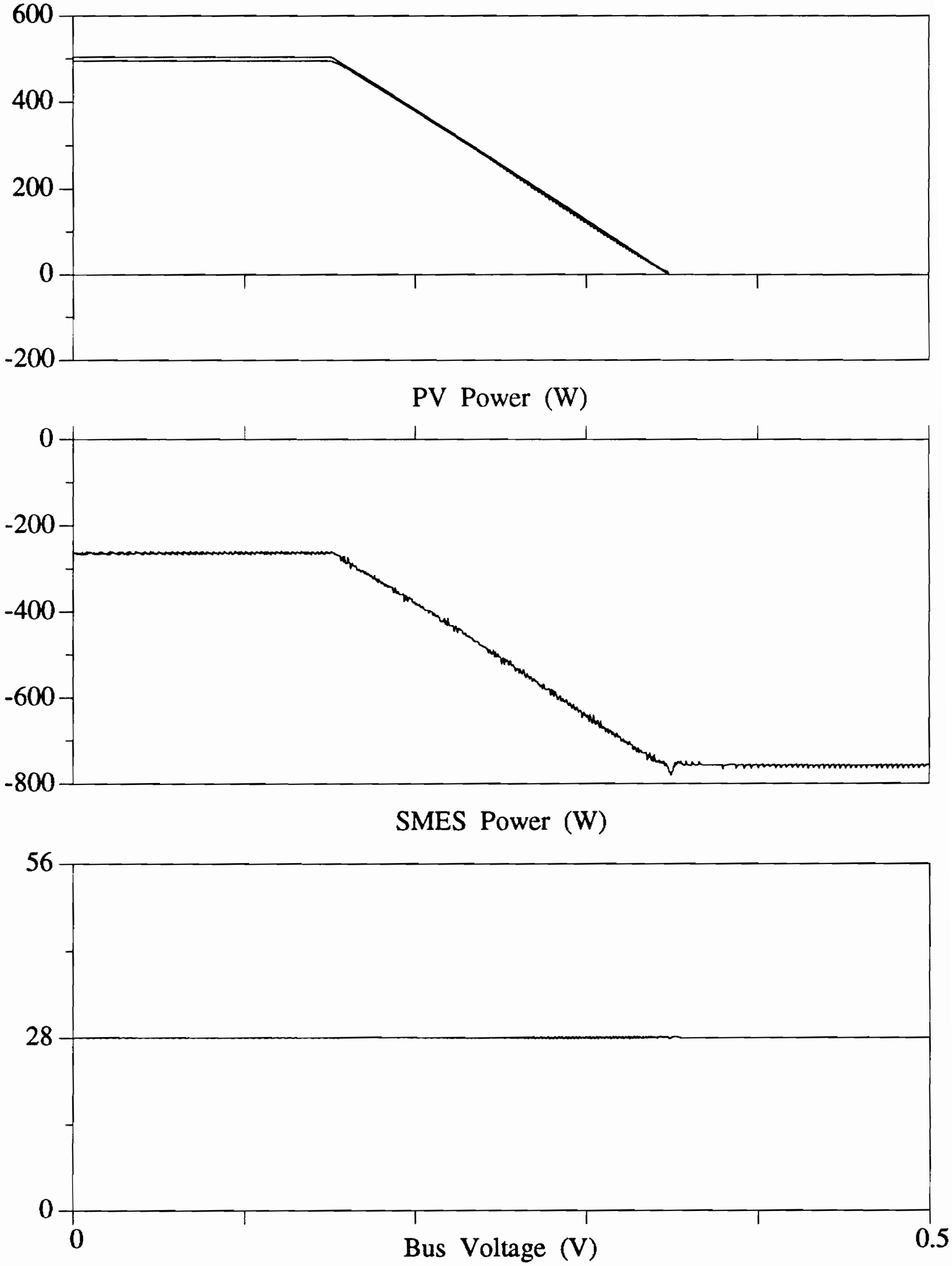


Figure 4-8. System Response to Decrease in PV Power to Zero (0.5 s)

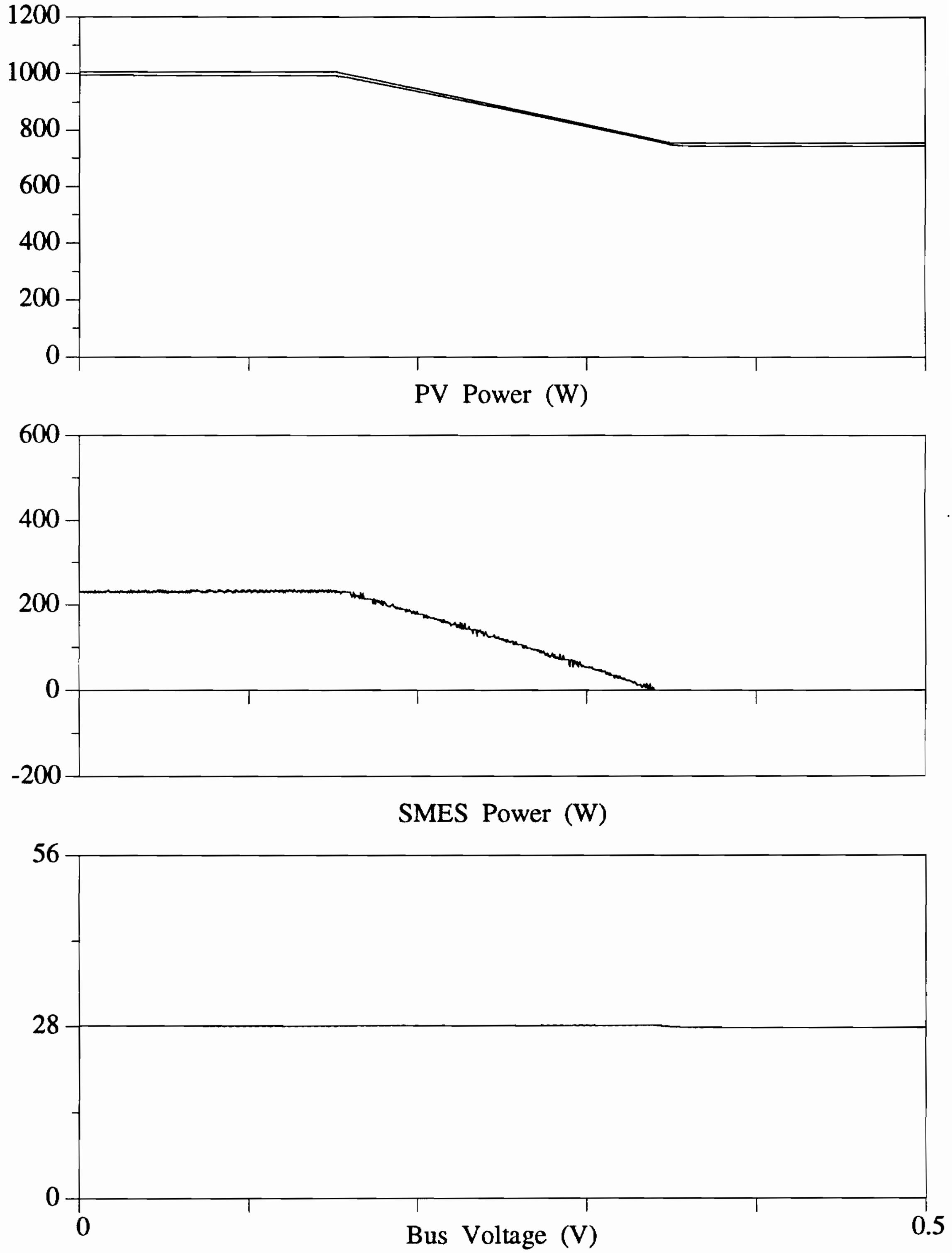


Figure 4-9. System Transition to SMES Holding Mode (0.5 s)

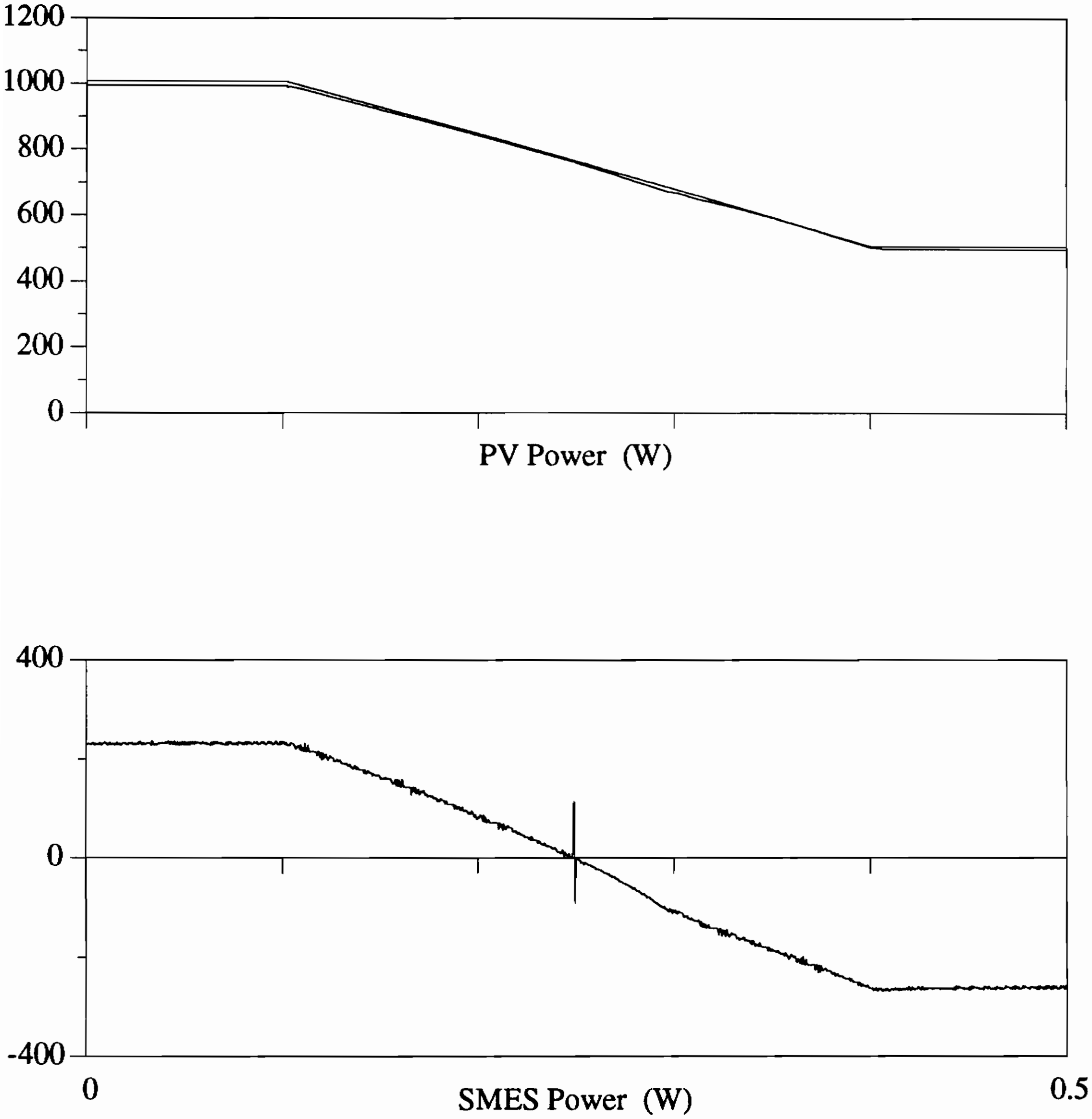


Figure 4-10a. System Response to Decrease in PV Power;
SMES Transitions from Charging to Discharging (0.5 s)

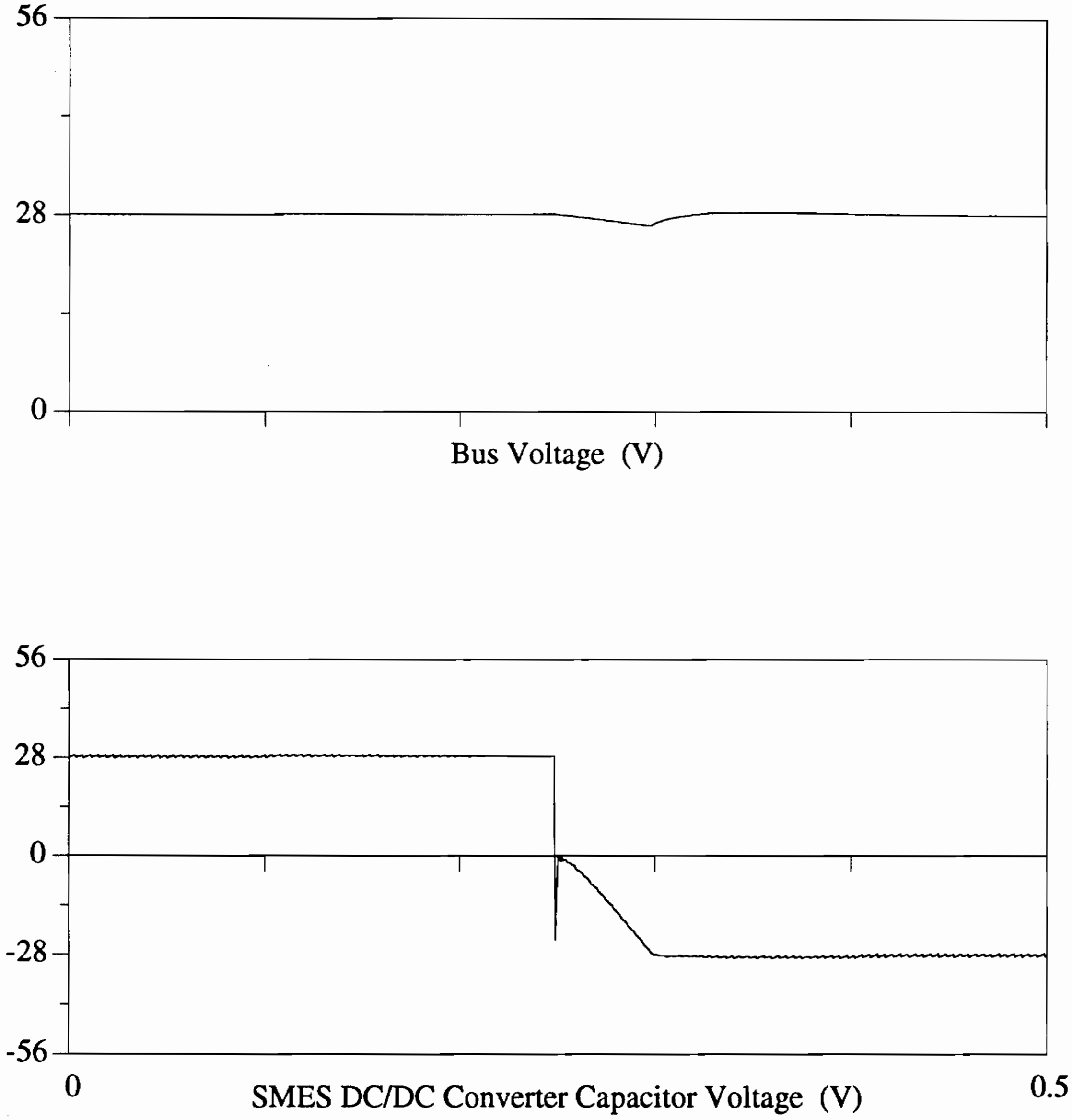


Figure 4-10b. System Response to Decrease in PV Power;
SMES Transitions from Charging to Discharging (0.5 s)

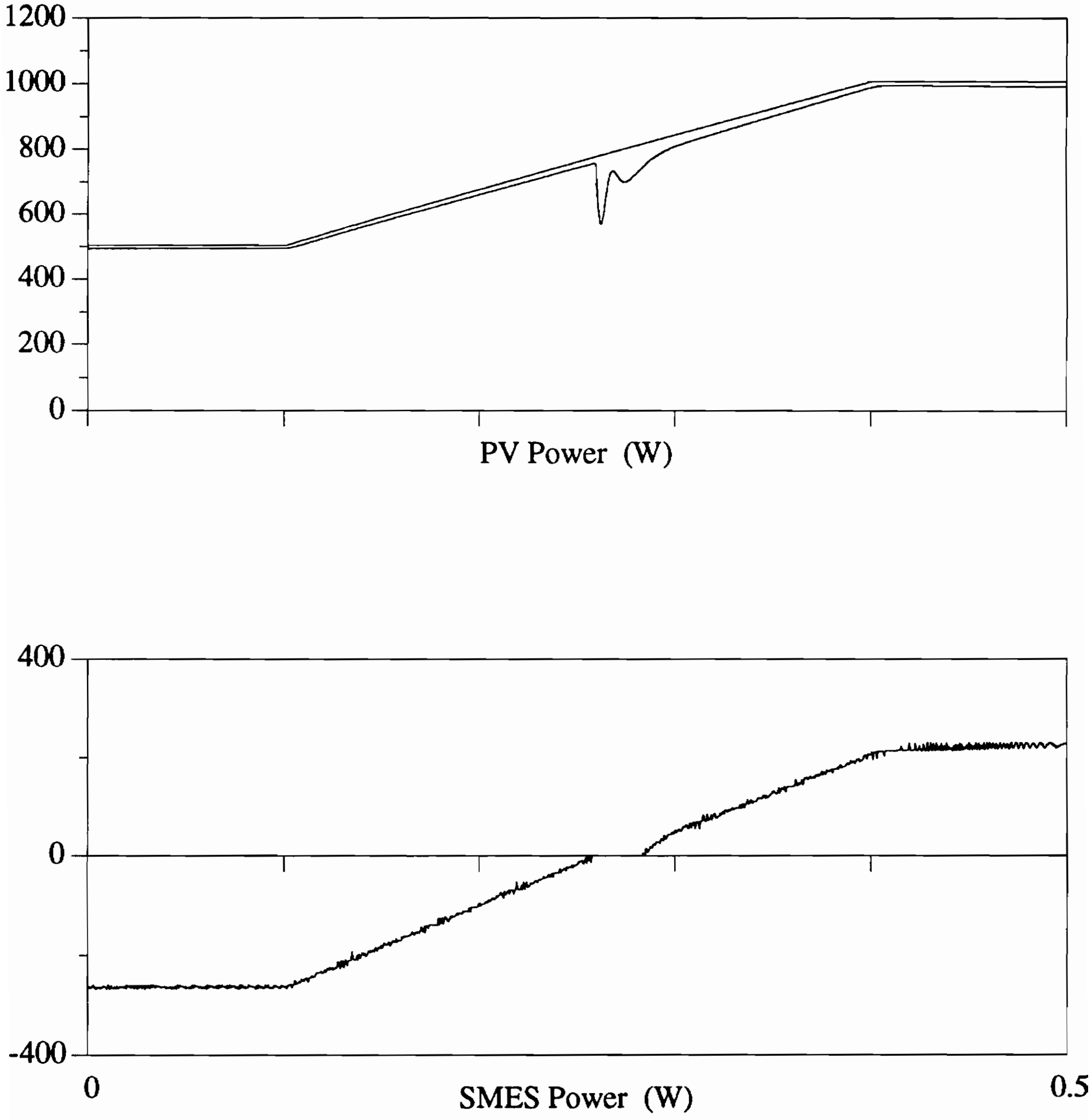
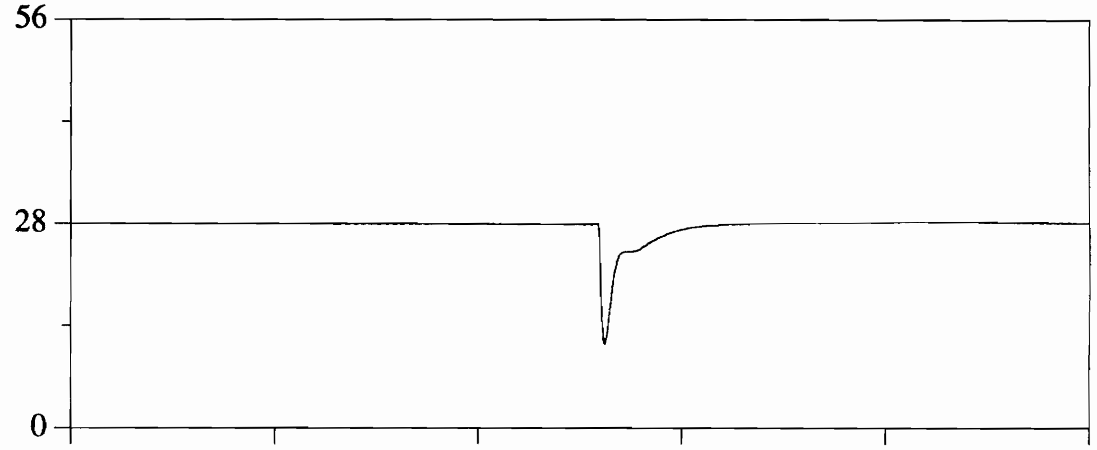
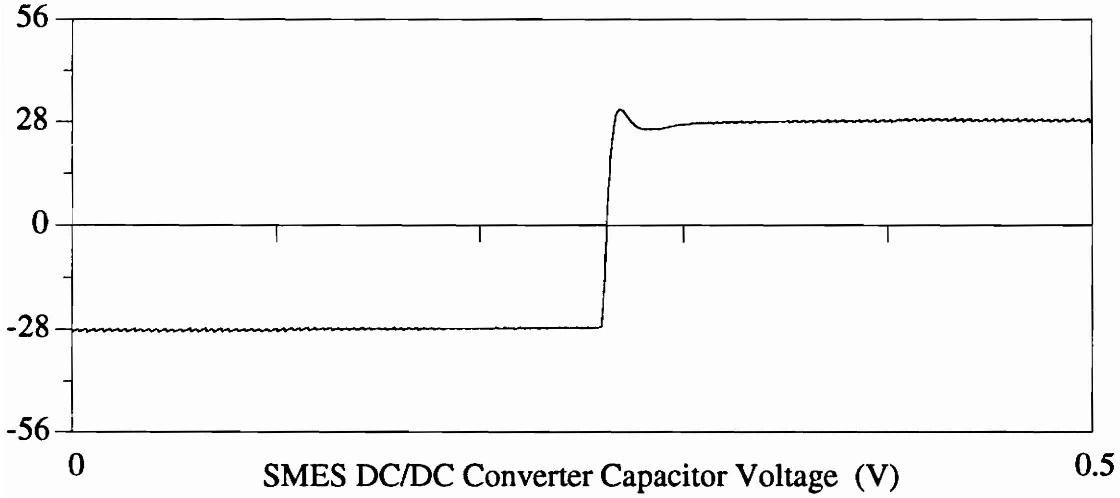


Figure 4-11a. System Response to Increase in PV Power;
SMES Transitions from Discharging to Charging (0.5 s)

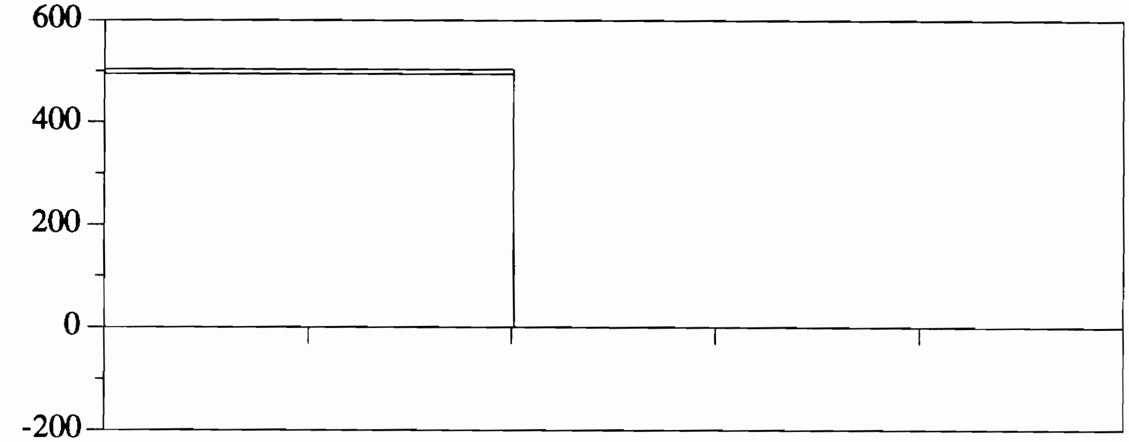


Bus Voltage (V)

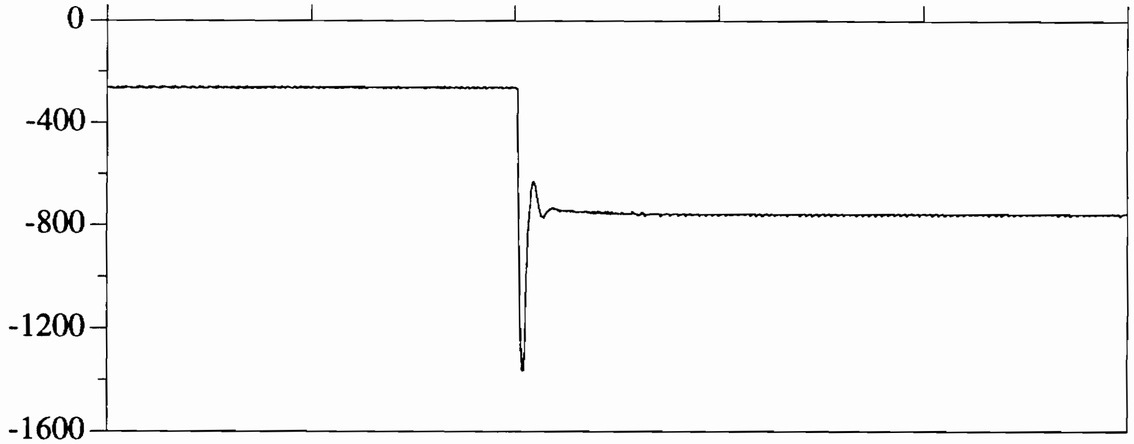


SMES DC/DC Converter Capacitor Voltage (V)

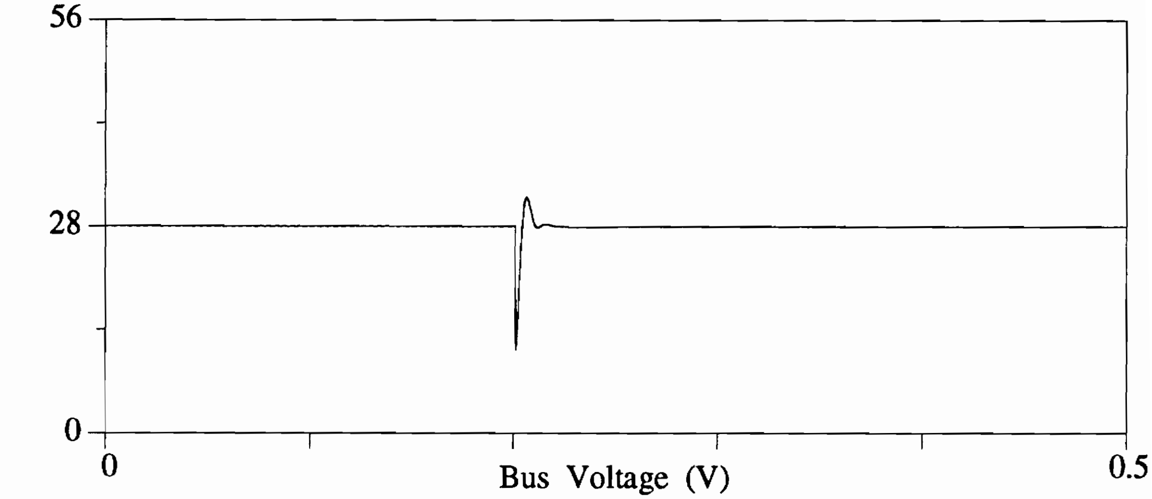
Figure 4-11b. System Response to Increase in PV Power;
SMES Transitions from Discharging to Charging (0.5 s)



PV Power (W)



SMES Power (W)



Bus Voltage (V)

Figure 4-12. System Response to Sudden Drop in PV Power (0.5 s)

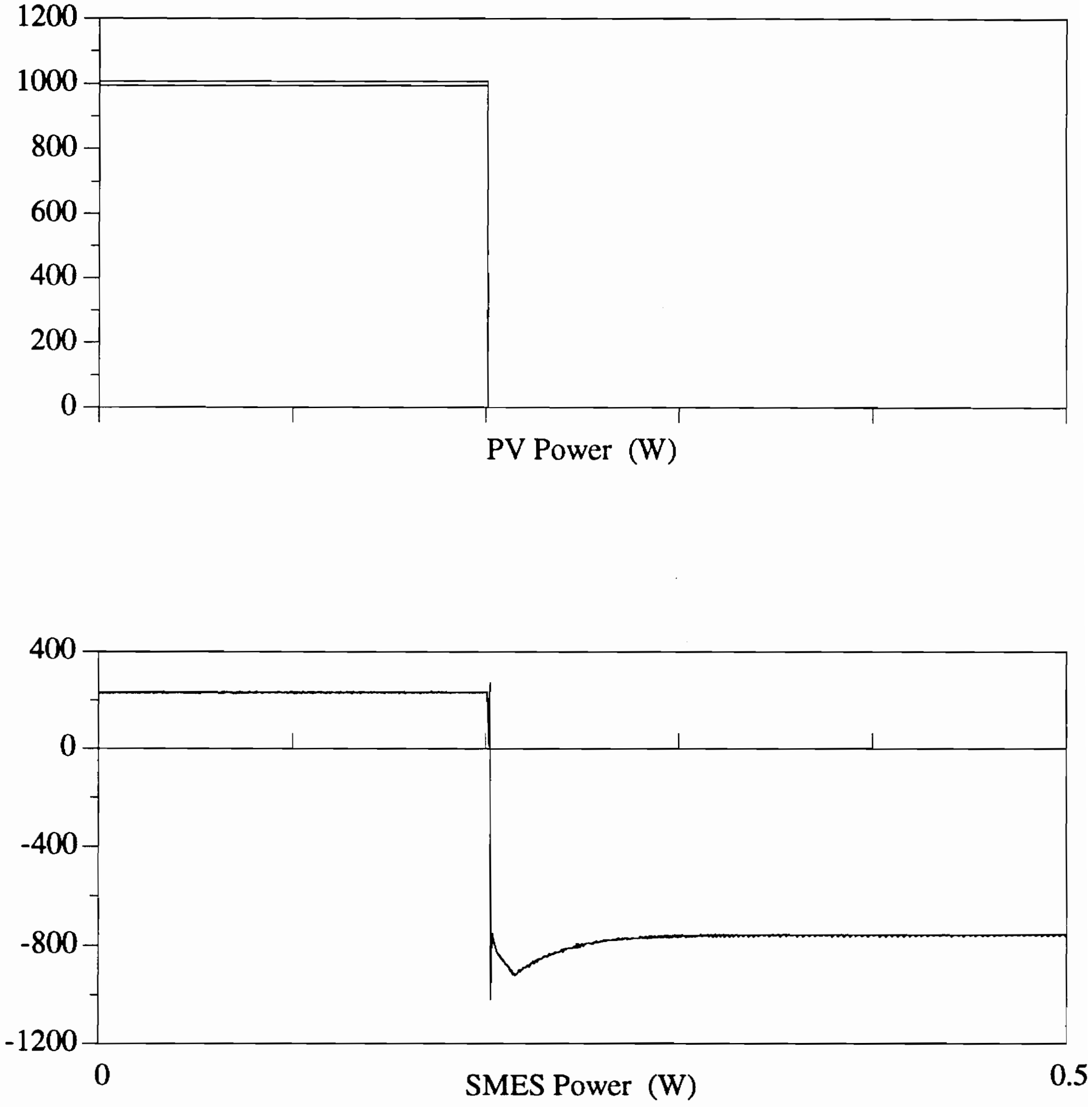
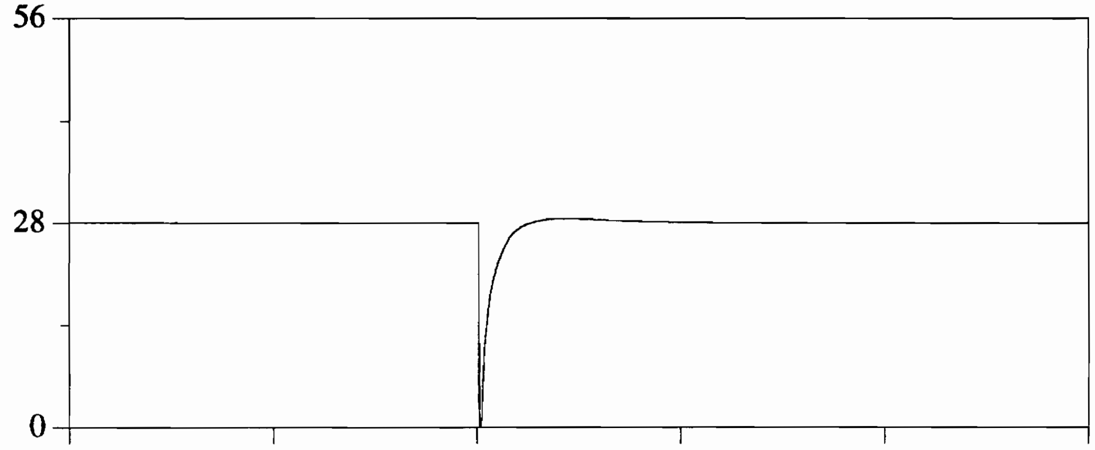
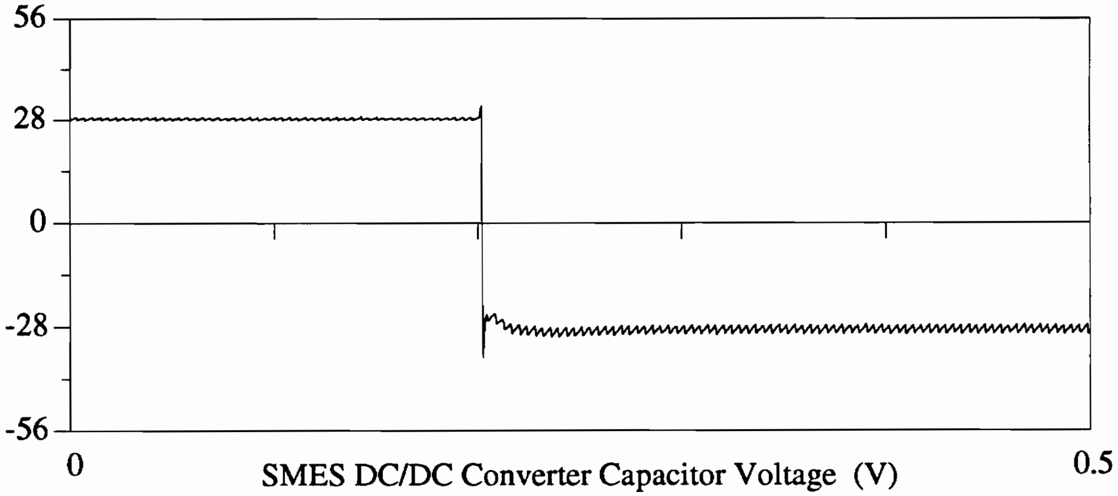


Figure 4-13a. System Response to Sudden Drop in PV Power;
SMES Transitions from Charging to Discharging (0.5 s)

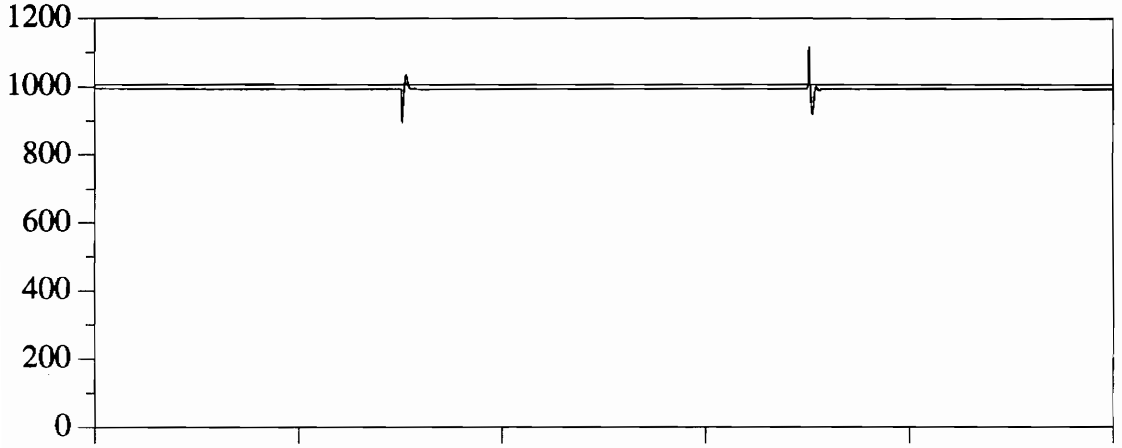


Bus Voltage (V)

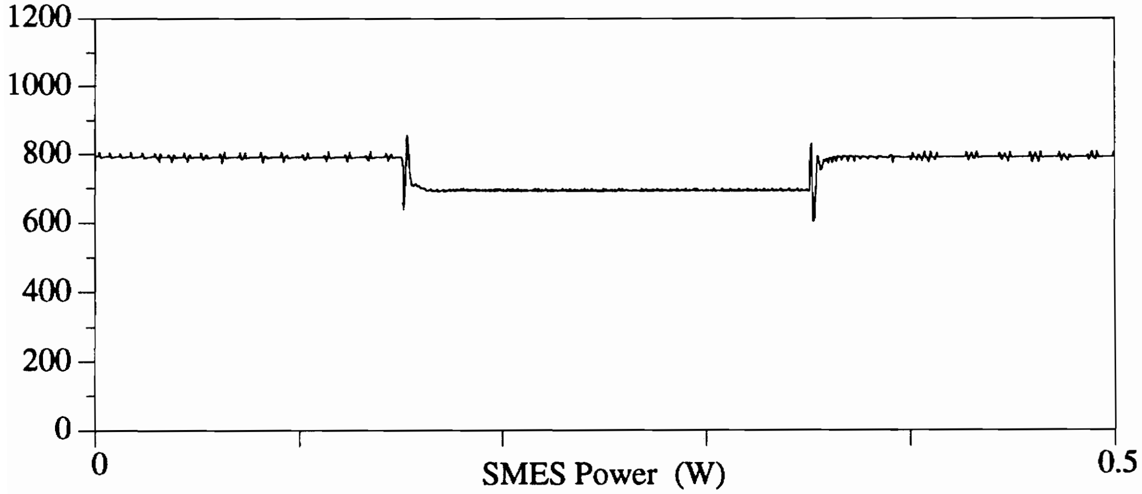


SMES DC/DC Converter Capacitor Voltage (V)

Figure 4-13b. System Response to Sudden Drop in PV Power; SMES Transitions from Charging to Discharging (0.5 s)

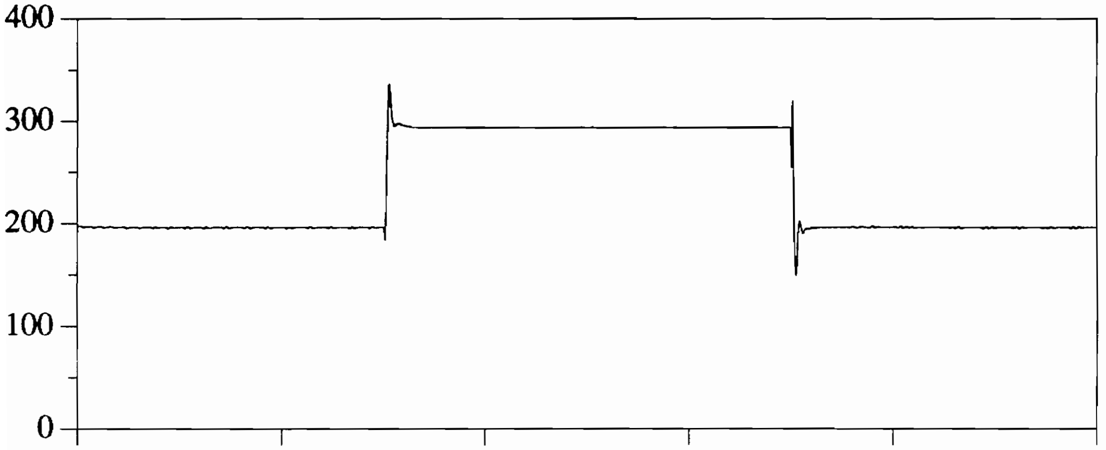


PV Power (W)

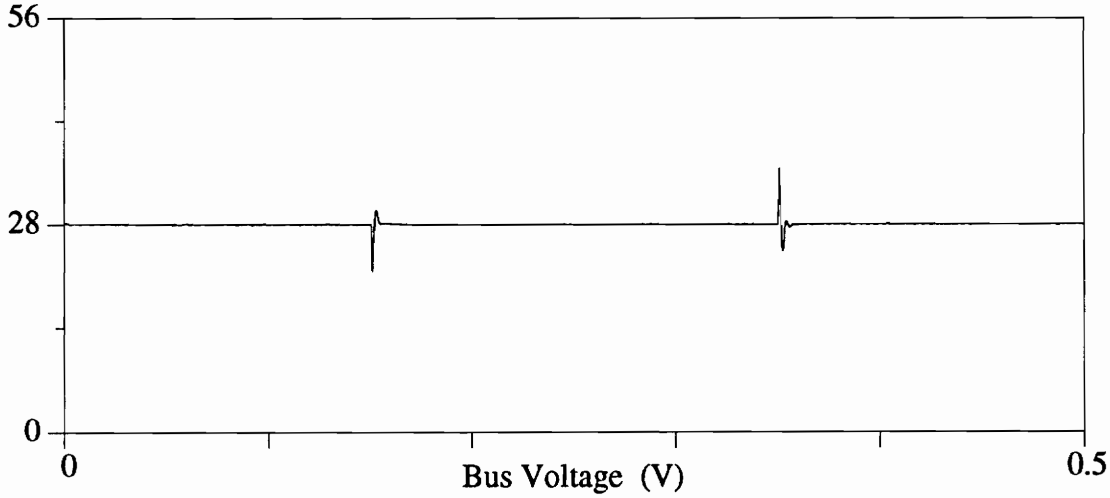


SMES Power (W)

Figure 4-14a. System Response to Sudden Changes in Load (0.5 s)



Load Power (W)



Bus Voltage (V)

Figure 4-14b. System Response to Sudden Changes in Load (0.5 s)

CHAPTER 5

CASCADE OF AC/DC AND DC/DC CONVERTERS

The previous two chapters dealt with the application of AC/DC and DC/DC converters, respectively, to SMES. This chapter presents a configuration that combines the two types of converters in an attempt to take advantage of the best features of each.

5.1 Practical Considerations for Large Scale SMES

The earlier discussions of AC/DC and DC/DC converters for SMES included mention of appropriate applications. In both cases, there were limitations that would likely prevent them from being used for very large scale operations in the form presented. The AC/DC simultaneous P/V control scheme would require a tremendous supply of reactive power for a utility scale system, and the DC/DC combined SMES/PV system would still need an additional converter to be connected to the AC grid. For suitable applications, however, each of these systems had distinct benefits. A similar match between a converter topology and utility scale SMES would need to consider a number of seemingly conflicting characteristics.

5.1.1 Power Rating vs. Energy Storage Capacity

A utility scale SMES system intended for diurnal load leveling would need to have a substantial energy storage capacity to have a useful impact on the operation of the utility. Its power conditioning system, in contrast, would not need a correspondingly large capacity. A power rating sufficient for completely charging or discharging the SMES system over a period of several hours or even days could be adequate.

In comparison, the BPA system was not designed for load leveling. It could handle a reasonable power exchange, but could not carry enough current for large energy values. When fully charged, it could only discharge at its rated power for a few seconds before completely dissipating all of its stored energy.

5.1.2 Factors for High Voltage/Low Current on AC Side

5.1.2.1 AC Transmission

Utility scale AC power generation and transmission is carried out at high voltage and low current. Various transformer stages allow electrical consumers to tap power from the grid at different voltage levels, but something as large as a utility scale SMES system would need to be connected at a terminal capable of handling high power, which would necessarily be at a high voltage. High power transmission lines are typically at several thousand amps and hundreds of thousands of volts.

5.1.2.2 Lower Losses

For a given power value, higher voltage corresponds to lower current, and therefore, lower I^2R losses in the conductor. Lower current means lower resistive losses in transmission lines, transformers, switches, joints in the superconducting wiring, and the transitional area between cryogenic and ambient temperatures. Lower current also decreases the loss associated with forward voltage drop across the switches.

5.1.2.3 Switch Technology

The state of semiconductor switch technology is more appropriate for high voltage and low current. Thyristors, for example, can be rated at 5 to 6 kV; a single thyristor would be capable of handling the 4 kV envisioned for large scale SMES. However, for current ratings, thyristors are generally capable of carrying no more than 3000 to 3500 A [R-4]; more than fifty would be needed in parallel for the 200 kA planned for utility size SMES [B-13].

Typically, for higher voltage operation, individual switches are placed in series. For higher current, individual switches are not usually operated in parallel; instead, entire AC/DC bridges are combined in parallel, providing more ability to control the distribution of current than with individual switches in parallel. Even with parallel bridges, the switches must be overrated in case the current is not evenly distributed among the bridges, and an interphase reactor is needed to connect them [E-17, E-19].

5.1.2.4 Commutation Overlap

A lower current reduces the commutation overlap in AC/DC converters. The total reactance in line with each phase of the converter prevents the instantaneous switching of the current to the next phase. Greater current corresponds to a longer commutation time. The consequences are a slower response to changes in the firing angle, a narrower range of firing angles attainable, and the consumption of more reactive power.

5.1.2.5 Control Options

The standard 12-pulse bridge consists of two 6-pulse bridges connected in series on the DC side. Connecting the 6-pulse bridges in parallel requires an interphase reactor and necessitates that the individual firing angles remain the same. Any control scheme utilizing unequal α's (e.g., simultaneous P/Q or P/V) requires that the individual bridges be in series. Of course, unequal α's means that 12-pulse operation is lost. If 12-pulse operation is to be retained, then the two distinct α's must be used to fire entire 12-pulse bridges; in other words, two complete 12-pulse bridges would need to be connected in series with each other on the DC side.

5.1.3 Factors for Low Voltage/High Current on SMES Side

For a given coil inductance, the energy stored increases proportionally with the current squared ($E=1/2\ LI^2$). A higher inductance only raises the energy stored linearly and requires more windings in the coil for a given geometry.

A lower operating voltage means a lower voltage differential between the SMES system and its surroundings, which creates less risk of potentially disastrous high-voltage arcs.

Anticipated large scale SMES systems would most likely be rated at several thousand volts and hundreds of thousands of amps to attain the multiple megawatt power ratings desired.

5.1.4 Ideal Configuration

To meet all of the criteria mentioned, an ideal arrangement would be to operate two complete 12-pulse bridges connected in series on the DC side at high voltage and low current yet still have the SMES coil be at low voltage and high current. Unfortunately, these conflicting requirements could only be achieved by a physically non-realizable DC transformer situated between the DC terminals of the AC/DC converter and the SMES coil.

The alternative is to compromise among these criteria. AC transformers lower the grid voltage to the AC side of the AC/DC converters. Many identical 12-pulse bridges are then operated in parallel with overrated switches to handle extra current if one bridge doesn't conduct its share. The bridges are connected through interphase reactors to the SMES coil.

Such a compromise, however, is not absolutely necessary. Though a DC transformer does not exist, modern switchmode DC/DC converters can emulate the operational characteristics of a DC transformer. The converter's range of duty ratio, possibly augmented by an isolation transformer, permits a significant effective turns ratio for this virtual DC transformer between the AC/DC converter and the SMES coil.

5.2 Cascade Connection of AC/DC and DC/DC Converters

In all AC/DC converter control schemes (even those that utilize unequal α control or artificial commutation), the α's can be varied to change power, reactive power, and voltage, but they cannot quickly change the direct current on the DC side. They are constrained by that inductive current to stay within certain regions of the complex power plane. However, the cascade connection of a DC/DC converter with the AC/DC one permits the current at the AC/DC converter to be varied by changing the gain of the DC/DC converter – equivalent to varying the effective turns ratio of an imaginary DC transformer. This proposed solution meets the basic requirements set forth for an ideal topology.

5.2.1 Reactive Power Requirements

The cascade connection has the ability to reduce substantially the reactive power requirements by allowing the AC/DC converter to operate at either minimum or maximum α where its reactive power demand is the lowest. Varying the duty ratio of the DC/DC converter provides the additional degree of freedom of control necessary to maintain the proper flow of power.

The prospect of maintaining AC/DC bridges at their minimum or maximum α makes possible still more options. The hybrid converter described in Chapter 2 combines two 6-pulse bridges in series on the DC side – one a naturally commutated converter (NCC), and the other an artificially commutated converter (ACC). With the cascade converter topology allowing a higher voltage at the DC end of the AC/DC bridges, several 12-pulse bridges could be placed in series on the DC side. Therefore, the ACC portion of the hybrid could be less than one half, and true 12-pulse operation could be retained. For example, a single 12-pulse ACC could be configured in series with two, or even three, 12-pulse NCCs and still be able to maintain the combined converter at zero reactive power over virtually its full range of real power.

5.2.2 Voltage and Current Ratings

AC/DC bridges operating at higher voltage and lower current means that: there is less current to be commutated between phases, I^2R losses are reduced, and the loss from thyristor forward voltage drop is a smaller fraction of the rated power.

For large power applications the converters will not need for the transformers to have as large a turns ratio from the high voltage transmission lines. Put another way, the SMES system could be connected to the AC grid at a higher voltage/lower current substation.

5.2.3 Switch and Component Utilization

The cascade connection, as shown in Figure 5-1, adds just one switch to the standard AC/DC bridge topology that uses a free-wheeling thyristor. Plus, only two switches need gate turn off capability. For a given semiconductor switch, the DC/DC converter makes more use of its full rating because the switches are, on average, conducting half the time, whereas the AC/DC converter switches conduct only one third of the time.

The combined converter reduces individual switch stresses for the AC/DC converter because those switches no longer have to carry full rated current. For the DC/DC converter, there are operational modes or other topologies (including resonant or quasiresonant options) where the switches could possibly be turned off at zero current or zero voltage to reduce their stresses as well.

Inclusion of the capacitor in the DC/DC converter can be traded off by a reduction in the need for capacitors at the AC bus used for reactive power compensation. In a similar manner, adding an isolation transformer in the DC/DC converter could allow the removal of an AC transformer stage at the grid.

5.2.4 Higher Switching Frequency

An AC/DC converter for SMES switches at a rate of 60 Hz because that is the frequency of the utility grid to which it is connected. A DC/DC converter, however, is not constrained in the same manner. It can, and most certainly would, have a much higher switching frequency. A nominal frequency of 5 to 10 kHz has been suggested as a practical initial value.

There are several ramifications of a higher converter switching frequency. The components of the DC/DC converter are smaller. The harmonics at the SMES coil are reduced in magnitude and start at a higher frequency. The harmonics at the AC/DC converter can also potentially be reduced by special pulse width modulation of the DC/DC converter. Higher switching frequency permits a quicker dynamic response and provides a mechanism for balancing the current among parallel DC/DC converters.

5.2.5 Additional Features

In addition to meeting the criteria previously specified for an optimal configuration of a SMES system for utility load leveling, the cascade connection of AC/DC and DC/DC converters has other advantages.

The DC/DC converter provides isolation between the SMES coil and the AC/DC converter. Since the DC/DC converter can handle a circulation mode by itself, the AC/DC converter doesn't always have to be carrying current. This feature is particularly important because under normal operation, the AC/DC converter draws the most reactive power from the grid when it is circulating the SMES current with no real power exchange.

If a number of complete cascade converters were placed in parallel, the individual AC/DC converters would not actually be in parallel on the DC side. Instead, they would be disjoint – each one connected separately to a DC/DC converter; the DC/DC converters, in turn, would connect to the SMES coil. Since the AC/DC bridges would not be in parallel, no interphase reactors would be necessary. Furthermore, DC/DC converters, because of their higher switching frequency, can more easily balance current flow among themselves. Still another option would be to connect separate cascade converters to different segments of a segmented coil. The proposed Wisconsin plan calls for a segmented coil, and their researchers have been studying the effect of slightly different α's when 8 AC/DC bridges are operated in parallel and connected with interphase reactors [B-13].

5.3 Computer Simulations

The simulations of the cascade connection of an AC/DC converter with a DC/DC converter demonstrate the basic operation of the configuration. The scenario used in Chapter 3 to demonstrate the ability of SMES to handle PV fluctuations was repeated with the same AC/DC circuit augmented by a DC/DC converter. Charging and discharging modes, as well as the transitions between them, can be seen in Figure 5-2. As in the previous case, the SMES can respond quickly enough to smooth the PV power. The spikes in real power at the zero crossings are the result of the DC/DC converter capacitor being discharged and recharged to the opposite polarity. Of greatest significance is the reactive power; compare the magnitude and fluctuations with the simulation of the plain AC/DC bridge configuration shown in Figure 3-7. The arrangement that includes a DC/DC converter consumes a substantially smaller quantity of reactive power. Two additional simulations were conducted to demonstrate the difference in reactive power more clearly. The plain AC/DC converter configuration and the cascade one were both run through a scenario that simply swept the real power over its full range from the maximum of 12 MW to the minimum of -12 MW. Then the reactive power for each run was plotted on the same axis versus the real power. Those results are shown in Figure 5-3.

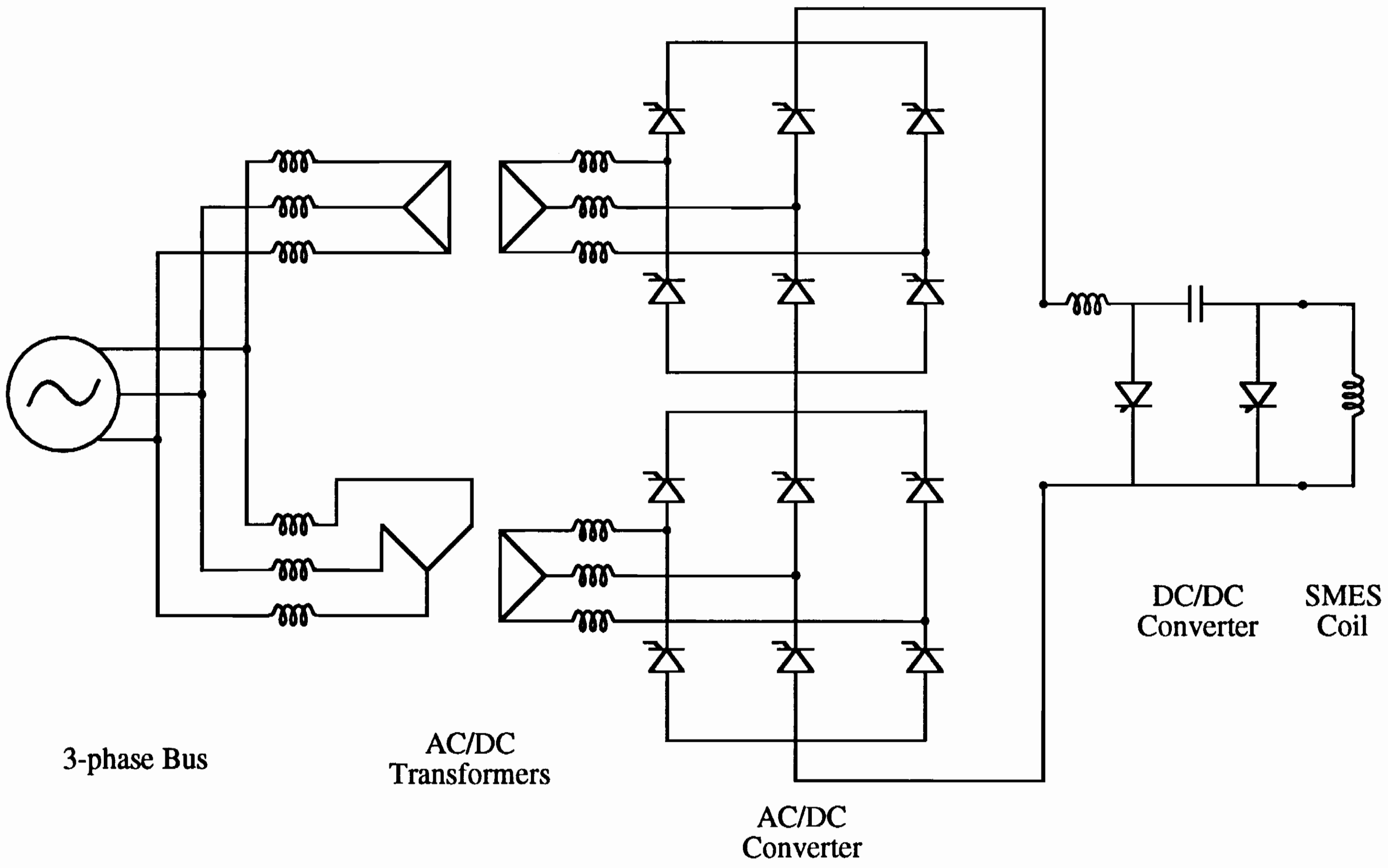
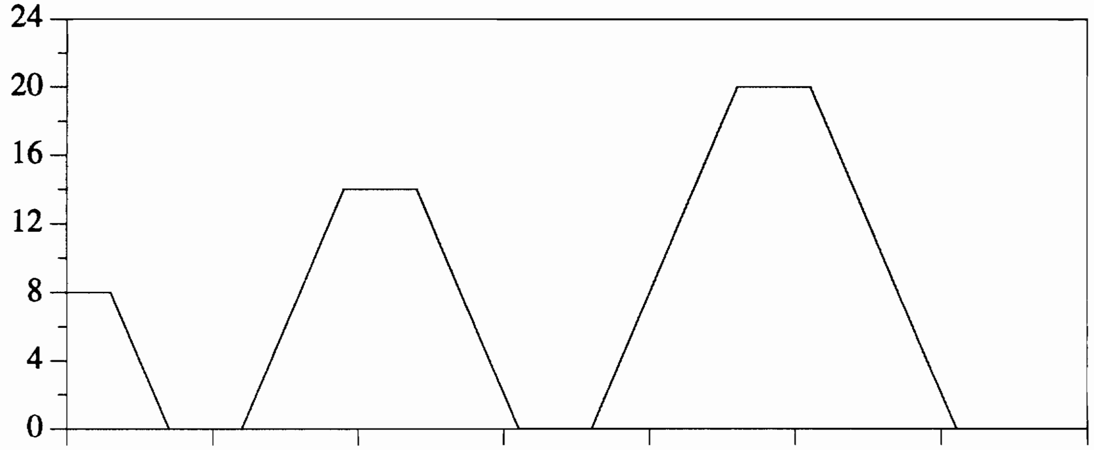
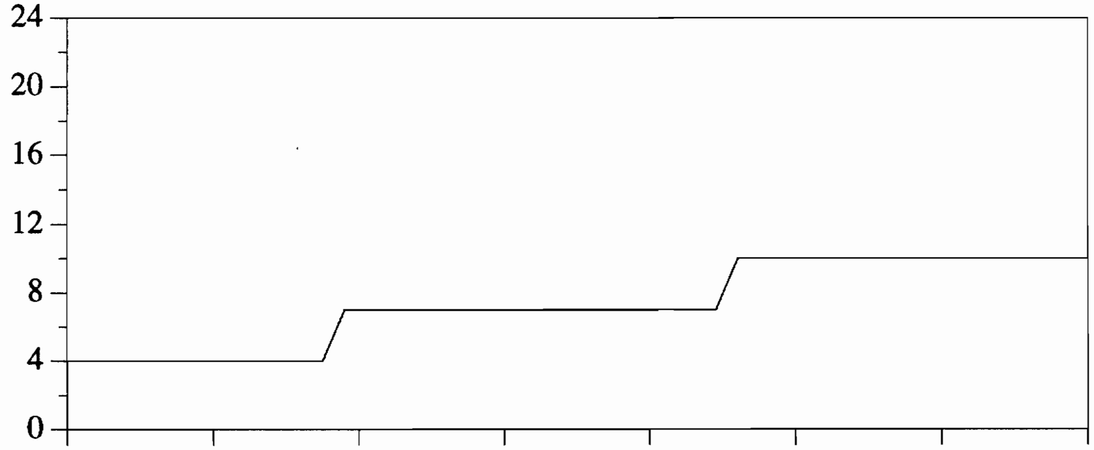


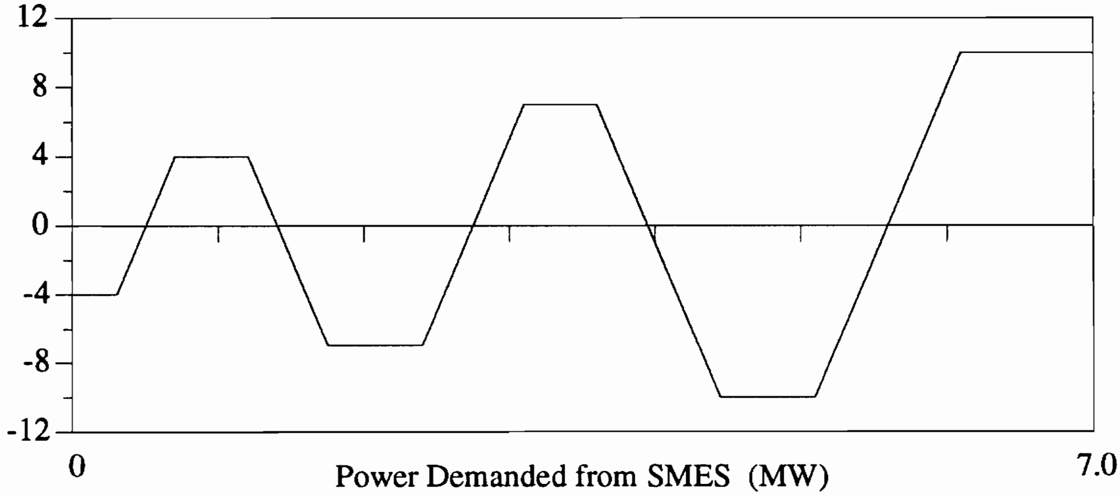
Figure 5-1. Cascade Connection of AC/DC Converter and DC/DC Converter Configured for SMES



PV Power Output (MW)

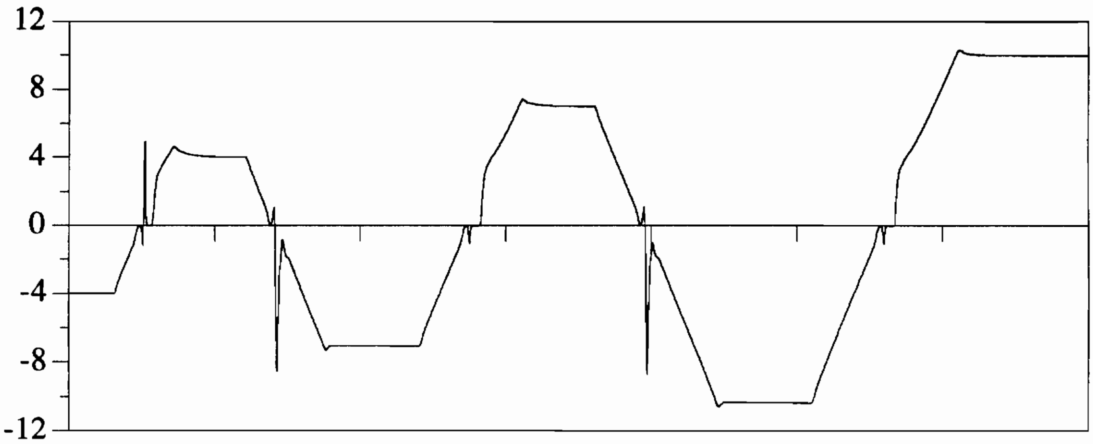


Combined Power Demand of System (MW)

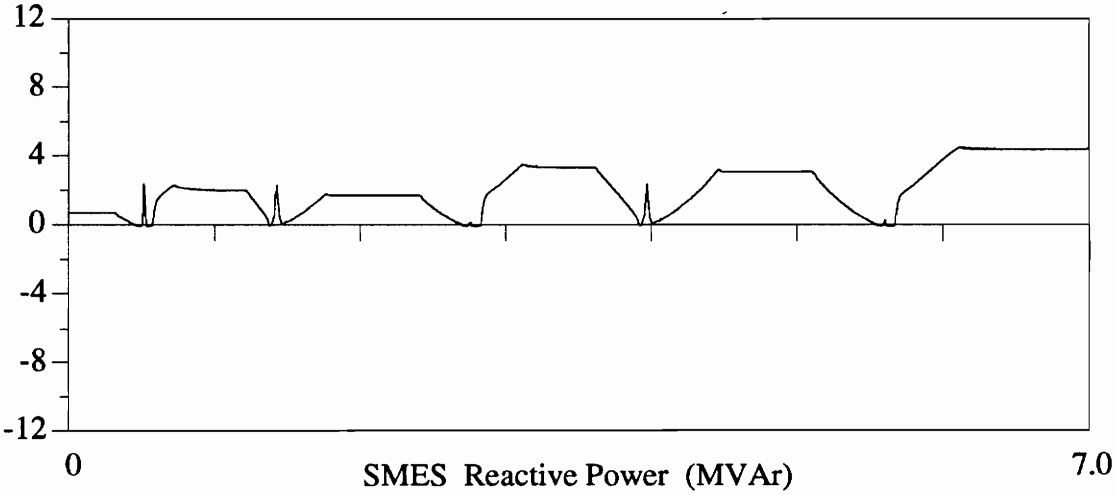


Power Demanded from SMES (MW)

Figure 5-2a. SMES Response to PV Power Fluctuations (7.0 s)



SMES Power (MW)



SMES Reactive Power (MVAr)

Figure 5-2b. SMES Response to PV Power Fluctuations (7.0 s)

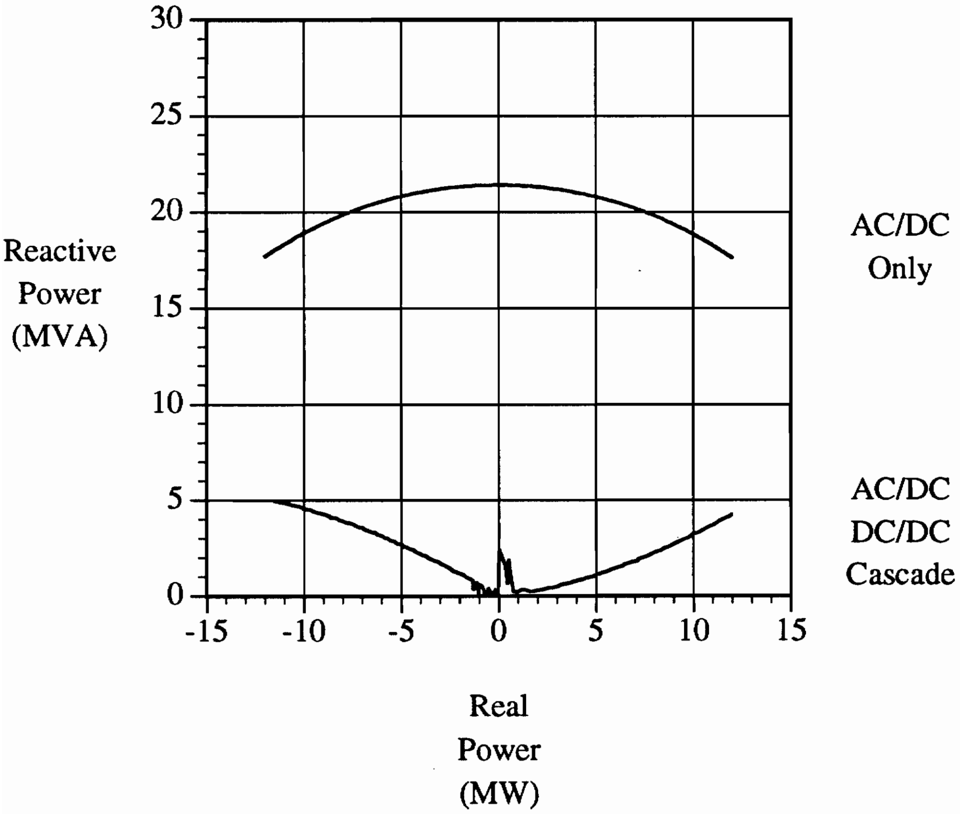


Figure 5-3. Reactive Power Versus Real Power for AC/DC Configuration and Cascade AC/DC - DC/DC Configuration

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

This chapter very briefly summarizes the major results of this study, discusses their significance and potential applications, and outlines suggestions for future work.

6.1 Conclusions

A number of concepts related to SMES have been demonstrated by the work reported in this thesis.

- SMES systems and standard AC/DC converters offer performance fast enough to compensate for PV fluctuations due to changes in weather conditions. The combination of large scale SMES and PV systems could be substantially more attractive than either one individually. The presence of a SMES system to smooth PV fluctuations could allow a significant penetration of the utility grid by large scale PV arrays.
- The standard AC/DC bridge arrangement used with SMES for simultaneous P/Q control can be operated under a modified control scheme to regulate P and V. With no hardware modifications to the circuit, the SMES system can provide another useful mode of operation.

- DC/DC converters can also respond with sufficient speed to handle variations in PV power. SMES applications that interface with another DC environment, such as PVs, do not need the additional step of conversion to AC. An all-DC conversion circuit can take advantage of all the benefits of DC/DC converters over AC/DC converters, including reduced size and cost of components and faster dynamic response.

- A modification to the Cuk converter permits bidirectional power flow suitable for SMES. Charging, discharging, and holding modes are handled without duplication of switches or pulsating current.

- Two DC/DC converters in cascade can effectively maintain a PV array at its maximum power point and use a SMES system to regulate a common bus voltage. Remote or space applications could use the SMES/PV combination for a reliable source because the SMES could compensate for PV fluctuations.

- A cascade connection of an AC/DC converter and a DC/DC converter can reduce substantially the reactive power requirements of an AC/DC converter alone. This combination has the potential to make large scale SMES systems more attractive by improving their operational characteristics.

With the possible exception of space applications, the potential impact of high temperature superconductors is probably not that significant for the foreseeable future, unless superconductors with substantially higher critical temperature (T_c), higher current carrying density (J_c), or higher magnetic flux density (H_c) are discovered.

SMES systems show the most promise for applications that already require a large land area, involve a DC power supply, involve an intermittent power supply and/or an intermittent load, or are remotely located. Therefore, a large scale PV power station in a geographic region with strong sunlight, yet removed from a densely populated area, seems to be the ideal location for a first large scale SMES. From here the most important step to be taken next is to build the first utility scale prototype to prove the viability of the concept. The first version of any new system is always the most difficult and expensive because designs, hardware, and methods of construction are still being refined.

6.2 Areas for Further Research

Several topics briefly mentioned in the text deserve additional attention.

- The operational performance of multiple DC/DC converters or cascade converters in parallel (as discussed in Chapter 5) needs to be verified for handling the extremely large currents expected for SMES.
- The effects of very strong magnetic fields on photovoltaic cells need to be investigated if PVs are to be placed above large SMES solenoids.

- Since the feedback control functions used here were deliberately simple, perhaps better performance could be achieved through the use of more elaborate control schemes.

- The development of lightweight superconductors and lightweight containment vessels for space applications should be pursued.

- Once a prototype utility scale SMES is built, its control scheme should be tested for handling its potential multiple purposes – simultaneously providing diurnal load leveling, PV compensation, reactive power regulation, voltage support, system stability, and subsynchronous resonance damping.

6.3 Related Areas of Development

In addition to the areas suggested for further research, there are fields peripherally related to SMES where developments could make SMES more attractive.

- Advances in magneto-hydrodynamic (MHD) systems could be beneficial to SMES. Both technologies employ superconducting magnets so a SMES/MHD combination could possibly share cryogenic support facilities. Because they are also both inherently DC, they could benefit from a DC/DC converter configuration similar to that devised for SMES and PVs.

- Improved photovoltaic cell efficiencies or reduced fabrication costs could make large scale PV installations more attractive. As PV penetration of the utility grid increases, there could be more demand for a compensation mechanism such as SMES.

- Any substantial improvement in the area of artificial commutation could be advantageous for SMES because of the potential for reducing the reactive power demands of the system.

- The development of higher power (and especially higher current) semiconductor switches could significantly reduce the initial costs and operational difficulties of a large scale SMES. There would be less need for parallel combinations of switches and bridges to carry the current.

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