POWER QUALITY

Society is becoming more and more reliant on machines, devices, and processes that are sensitive to the quality of the electrical power they use. At the same time, the generation and distribution system for electrical power is becoming more and more complex and vulnerable to internal and external perturbations that disrupt the quality of power available to the end user. For these reasons, there is a large market developing for high-quality power, and several technologies that can provide such power have been or are being developed. In this article, we discuss some of these power quality issues and provide some insight into one of the technologies proposed to provide high-quality power. The first part of the article focuses on power quality issues and how microSMES (Superconducting Magnetic Energy Storage) technology is inserted into the power flow stream. The second part is devoted to a discussion of the fine points of microSMES technology from a design and performance point of view.

POWER QUALITY

The term *power quality* encompasses a broad range of technical issues that concern everyone, from the casual computer user to the equipment manufacturer, the industrial plant manager, and the utility transmission engineer. The technical issues associated with power quality at all these levels are complex, and they are often disguised behind misconceptions, vague definitions, and misapplied solutions. The lack of a consistent vocabulary, difficulty in fully characterizing power quality at the ultimate point of use, and confusion over the applicability of available solutions often encourages an adversarial relationship between the user, the equipment manufacturer, and the utility provider.

The technical community as well as the general public is increasingly concerned about power quality factors for a number of interrelated reasons. Some of the issues behind this growing apprehension include:

- Increasing levels of automation and flexibility have caused a proliferation of microprocessor-based controls and power electronic systems that are more sensitive to power quality variations than older electromechanical devices.
- Utility operating procedures designed to minimize sustained interruptions have increased the frequency of short-duration interruptions through wider use of line reclosers and instantaneous breaker operations.
- A growing emphasis on energy conservation has encouraged greater use of high-efficiency adjustable-speed motor drives and nonlinear power supplies that generate high levels of harmonics and heating of neutral conductors.
- The increasing sophistication of industrial processes and their reliance on expensive raw materials have greatly

multiplied the cost of recovering from disruptions caused by poor power quality.

These factors combine to place a tremendous economic burden on industry, particularly in high-tech operations such as semiconductor wafer fabrication. Estimates of this economic impact on US industry alone range from $13.3 billion to $25.6 billion per year (1).

Power Quality Standards

The definition of power quality terms and standard methods for measuring and characterizing electromagnetic phenomena have received considerable attention in recent years from numerous standards bodies. The principal bodies involved in establishing international power quality standards are the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC). Other North American standards organizations involved with power quality issues include the American National Standards Institute (ANSI), National Electrical Manufacturers Association (NEMA), Underwriters Laboratory (UL), Canadian Standards Association (CSA), and Semiconductor Equipment and Materials International (SEMI). European organizations involved in similar activities include the European Union Standards Organization (CENELEC) and the International Conference on Large High Voltage Electric Systems (CIGRE).

The electromagnetic disturbances defined in the standards and recommended practices produced by these organizations can be classified in several ways, depending on the perspective of the defining body. Table 1 is an example of a particularly comprehensive classification system that not only defines a generally accepted term for each type of disturbance but also gives typical values for spectral content, duration, and magnitude where appropriate (2).

Power Quality Data

The most frequently referenced method of representing power quality data and equipment compatibility information is the CBEMA curve, originally developed by the Computer Business Equipment Manufacturers Association. This organization, now known as the Information Technology Industry Council (ITIC), approved a revised version of the CBEMA curve in 1996. The revised curve, shown in Fig. 1, specifies an envelope of acceptable power quality defined in terms of volt-

Table 1. Classification of Power Quality Disturbances

Categories	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	<50 ns	
1.1.2 Microsecond	1 μs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1 ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 μs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μs	0–4 pu
2.0 Short-duration variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5–30 cycles	<0.1 pu
2.1.2 Sag (dip)		0.5–30 cycles	0.1–0.9 pu
2.1.3 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles–3 s	<0.1 pu
2.2.2 Sag (dip)		30 cycles–3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	<0.1 pu
2.3.2 Sag (dip)		3 s–1 min	0.1–0.9 pu
2.3.3 Swell		3 s–1 min	1.1–1.2 pu
3.0 Long-duration variations			
3.1 Interruption, sustained		>1 min	0.0 pu
3.2 Undervoltages		>1 min	0.8–0.9 pu
3.3 Overvoltages		>1 min	1.1–1.2 pu
4.0 Voltage unbalance		Steady state	0.5–2%
5.0 Waveform distortion			
5.1 dc offset		Steady state	0–0.1%
5.2 Harmonics	0–100th harmonic	Steady state	0–20%
5.3 Interharmonics	0–6 kHz	Steady state	0–2%
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0–1%
6.0 Voltage Fluctuations	<25 Hz	Intermittent	0.1–7%
7.0 Power frequency variations		<10 s	

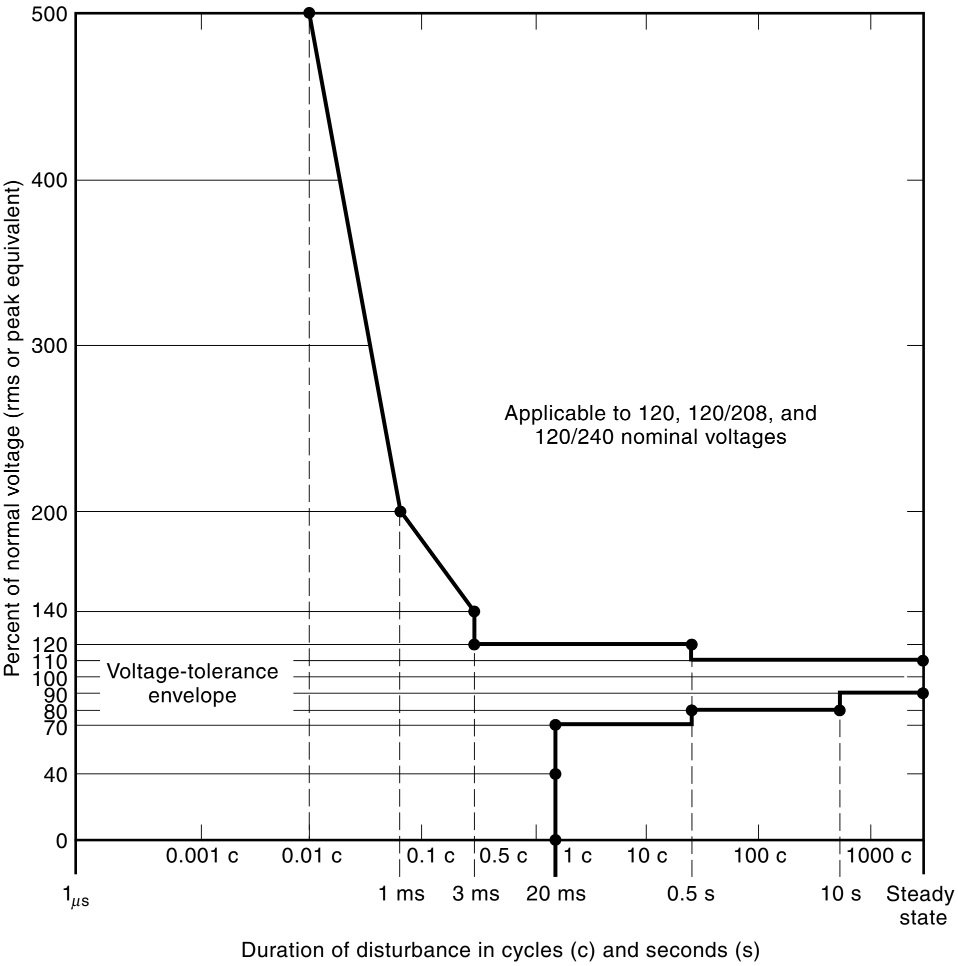

Figure 1. Revised voltage tolerance envelope developed by CBEMA to characterize compatibility at the users's load in terms of the minimum voltage magnitude and duration of the disturbance. This de facto standard was intended to provide a benchmark for measuring the ride-through capability of sensitive electronic equipment against the quality of the available electric supply.

age magnitude and duration. The curve assumes that equipment will ride through disturbances falling within the envelope without any malfunctions. It is assumed that disturbances that fall below the envelope may cause the load equipment to drop out because of a lack of energy, whereas disturbances that fall above the envelope may lead to overvoltage trips, insulation breakdown, and other problems. Unfortunately, the actual voltage tolerance of electronic equipment varies quite widely and rarely approximates the CBEMA curve. Nevertheless, the CBEMA curve has become a de facto reference for evaluating the quality of the electrical supply and the tolerance of sensitive equipment to voltage disturbances.

Figure 2 shows a plot of voltage sag data collected from 15 semiconductor manufacturing sites overlaid on the lower portion of the CBEMA envelope. The disturbance data are a subset of the data collected as part of the EPRI Distribution Power Quality (DPQ) study (3). The DPQ study collected data on a representative sample of utility distribution feeders, with monitors placed on 100 different feeders at 24 geographically dispersed utilities over a period of approximately 2 years. The data shown in Fig. 2 was restricted to data acquired at semiconductor plants to characterize the electrical environment faced by large industrial customers served by dedicated substations. These sites generally have fewer disturbances than the average substation serving a mix of com-

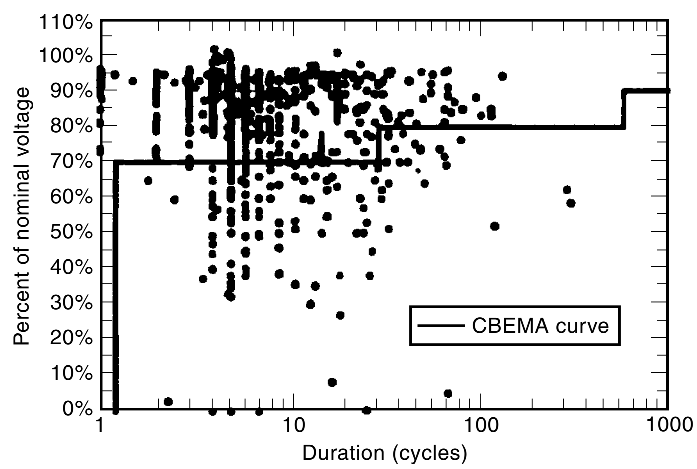

Figure 2. Scatterplot of EPRI DPQ study data overlayed on the relevant portion of the revised CBEMA curve. The 1076 disturbance events were acquired at 15 semiconductor manufacturing plants over a period of approximately 2 years. The number of disturbances that fell on or below the CBEMA curve was 166, giving an average of 5.4 events per year per site outside the voltage tolerance envelope.

mercial and residential loads. Even so, the semiconductor plants experienced 1076 disturbances, with 166 of the events lying below the CBEMA curve. This resulted in an average of 5.4 sags and interruptions per year at each site that fell outside the CBEMA voltage tolerance envelope.

The DPQ disturbance data is shown in contour format in Fig. 3 to display the frequency of occurrence for sags and interruptions as a function of their magnitude and duration values (4). This visualization method clearly indicates that the vast majority of the disturbances are relatively small amplitude sags of short duration. Statistical analysis of the DPQ data reveals:

- The average interruption rate was 0.5 per month per site;
- The average sag rate was 4 per month per site (10% < V ≦ 90%);
- The ratio of voltage sags to interruptions was approximately 10 : 1;
- Most voltage sags had a duration of less than 167 ms (10 cycles at 60 Hz).

From this data, we can conclude that power conditioning equipment providing ride-through protection times of at least 1 s can protect sensitive industrial loads against the vast majority of the electrical disturbances they will encounter.

Superconducting Magnetic Energy Storage Configurations

The acronym SMES was coined in the 1970s at the University of Wisconsin. It stands for superconducting magnetic energy storage, a concept whereby energy is stored in the form of a magnetic field. The field is created by a superconducting magnet, which has virtually no electrical resistance when cooled to the boiling point of helium. The lack of electrical resistance means that there are no storage losses; so in principle SMES is a very efficient means of storing energy.

The basic energy storage element of a microSMES system can be connected to the utility and the protected load in a number of ways to maximize protection capabilities for different applications. The operating requirements for the magnet subsystem are fairly similar for these various configurations, whereas the power electronics interface is quite specific to the target application. Several potential application classes will be briefly discussed in the following sections.

Shunt-Connected System. A simplified block diagram of a shunt-connected microSMES application is shown in Fig. 4. This configuration can be used to protect virtually any type of sensitive ac load or industrial process. The load is initially fed from the utility source through the normally closed mechanical disconnect switches on either side of the solid-state isolation switch. When a voltage sag or interruption occurs on the utility source, the solid-state isolation switch is opened to isolate the load from the unreliable utility power. The microSMES unit instantly begins to discharge through the inverter so that the load is seamlessly transferred from the utility source to the energy storage system. If utility power is restored during the discharge, the microSMES unit is synchronized to the grid, and the solid-state isolation switch transfers the load back to the utility source. The microSMES unit is then recharged to full-energy storage capacity in preparation for additional protection cycles.

Series-Connected System. A series-connected microSMES unit is shown in the simplified block diagram of Fig. 5. In this application, the microSMES unit is configured to compensate for voltage sags by providing a voltage boost in series with the load. Because the microSMES unit does not support the full load as it does in the shunt-connected configuration, the same amount of energy storage can support a larger electrical load for an equivalent time or the same size load for a longer time. The load is normally fed from the utility source through the solid-state isolation switch bypassing the injection trans-

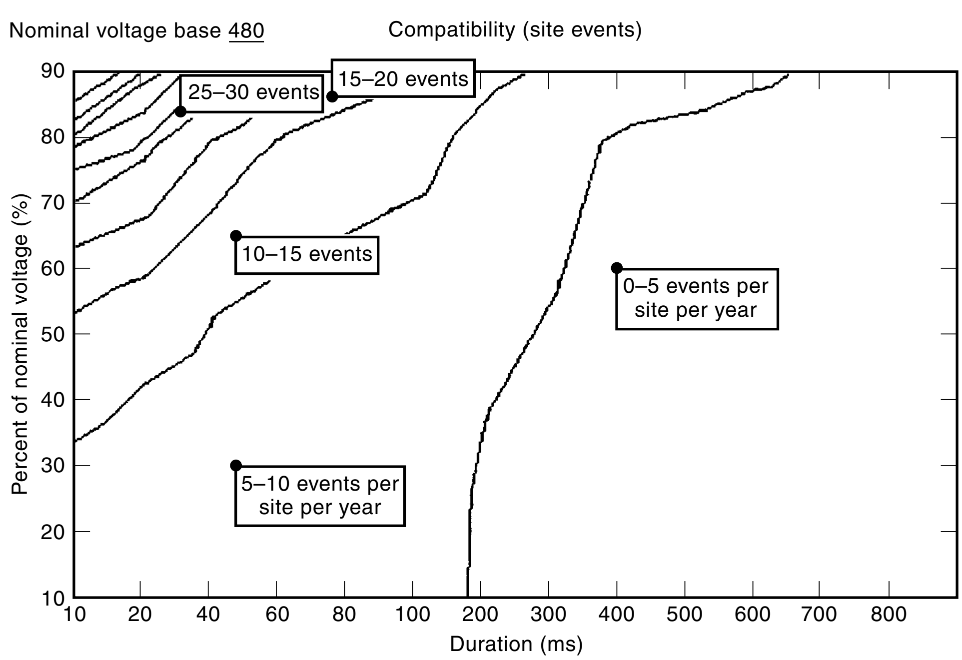

Figure 3. Contour plot of EPRI DPQ study data. The contour lines represent the average number of disturbance events per site that are more severe (having a lower voltage and longer duration) than the magnitude and duration values along the contour line. For example, there were 15 events per year with a magnitude less than 60% of nominal voltage and a duration longer than 20 ms.

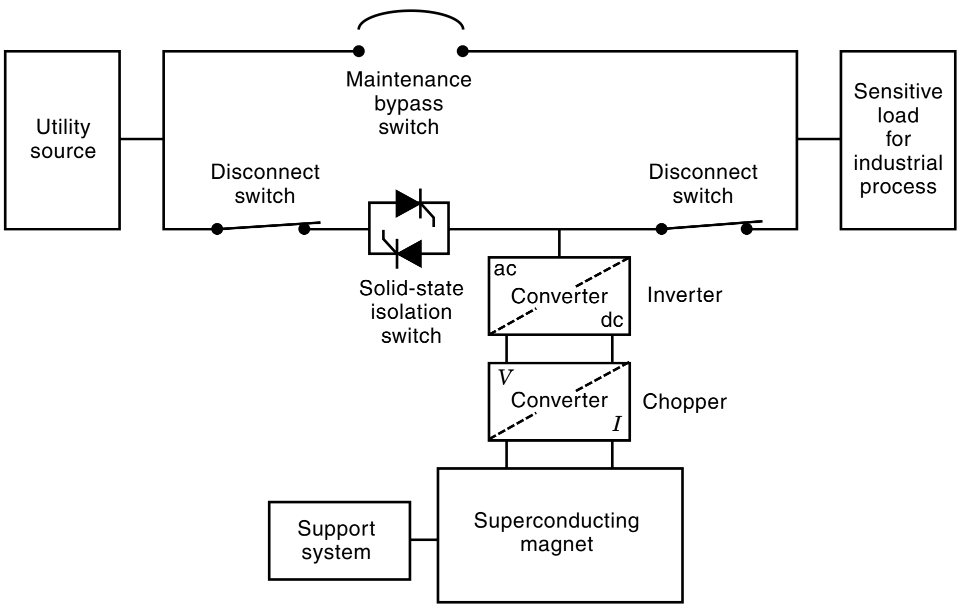

Figure 4. Simplified block diagram of a shunt-connected microSMES system. This configuration protects sensitive ac loads against dips and interruptions by disconnecting from the utility service during a disturbance and supplying the load with energy stored in the superconducting magnet.

former. When a voltage sag is detected, the solid-state switch opens, and the load current flows through the injection transformer. The inverter then injects just enough energy into the transformer to maintain the desired voltage level at the load. The isolation switch closes when nominal utility voltage is restored and the microSMES unit is recharged and placed in standby mode in preparation for the next event.

Motor Drive System. In adjustable speed motor drive applications, the microSMES unit supplies a dc voltage rather than the ac voltage supplied in shunt- and series-connected applications. As shown in the block diagram of Fig. 6, the dc voltage from the microSMES unit is fed into the dc link between the rectifier and inverter of the motor drive itself. This configuration eliminates the need for a separate inverter for

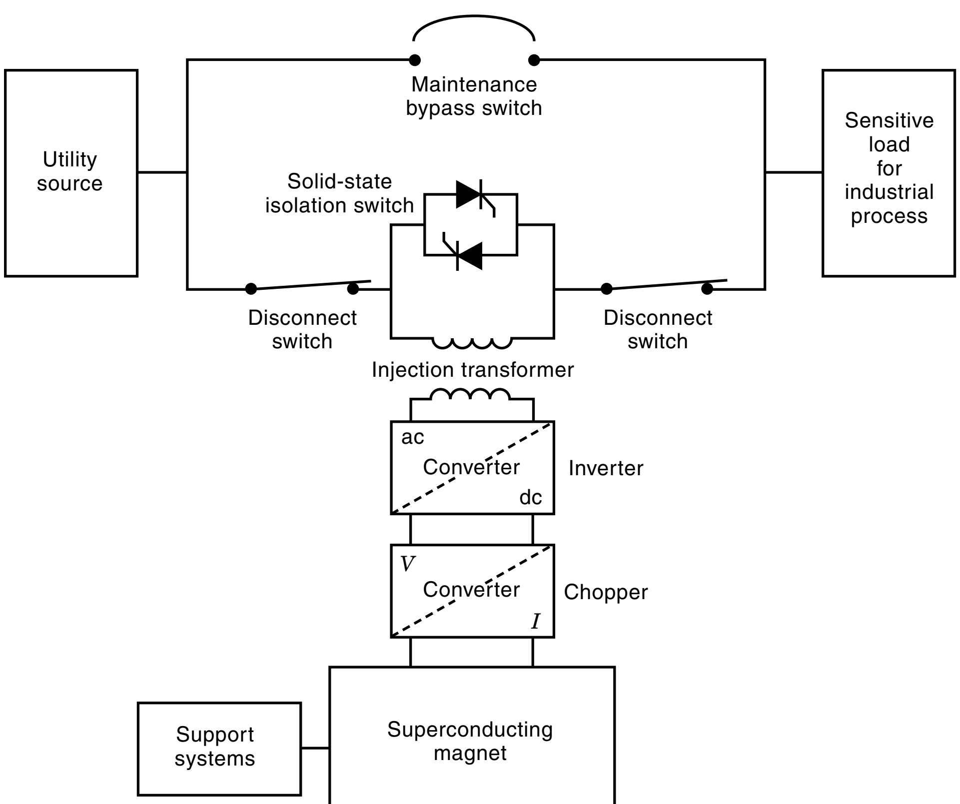

Figure 5. Simplified block diagram of a series-connected microSMES system. This configuration protects sensitive ac loads against voltage dips by boosting the voltage across the injection transformer to compensate for low voltages at the utility source.

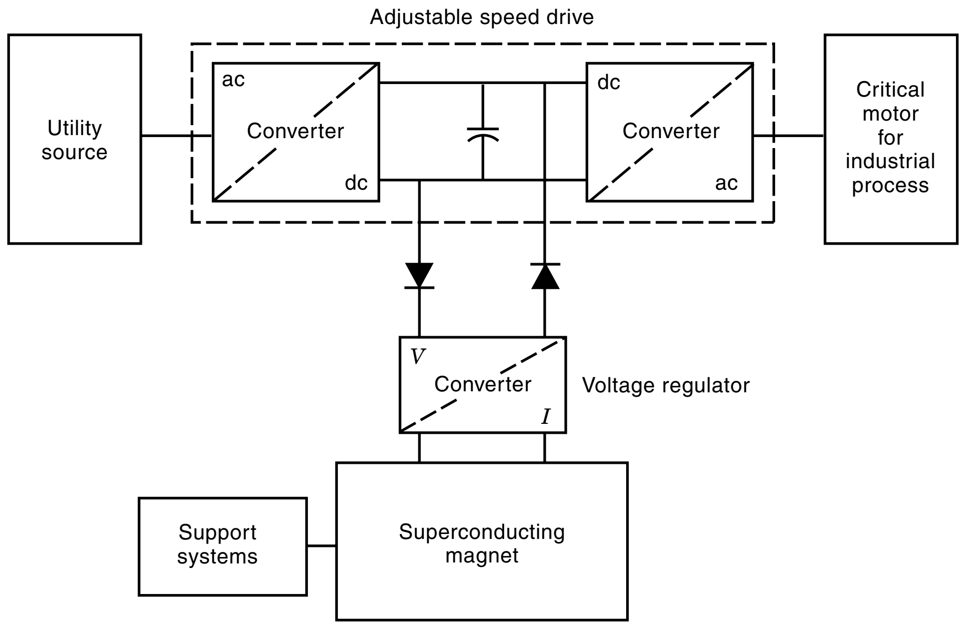

Figure 6. Simplified block diagram of a microSMES system protecting an adjustable speed motor drive. This configuration eliminates the inverter in the microSMES system because the stored energy in the magnet is supplied directly to the dc link of the motor drive.

the MicroSMES system. The voltage regulator in the microSMES system simply ensures that the dc link capacitor remains fully charged in the event of a loss of utility power feeding the rectifier.

Hybrid UPS System. A second configuration requiring dc output from the microSMES is shown in Fig. 7, where the microSMES unit is integrated with a conventional battery Uninterruptible Power Supply (UPS) system. The microSMES voltage regulator monitors the dc link of the UPS and supplies energy from the magnet whenever the link voltage drops because of a loss of power at the input rectifier. If the loss of input power persists, the batteries gradually begin to supply energy to the inverter as the stored energy in the microSMES is depleted. This configuration allows the microSMES unit to support the load completely during short disturbances and to slow down the rise time of the battery discharge for longer disturbances. This hybrid configuration can significantly enhance battery performance because battery lifetime is decreased by deep discharges with fast rise times.

MicroSMES

The remainder of this article concentrates on the system that provides the energy to ride through a power disturbance. In particular, energy stored in a magnetic field is discussed. Magnetic energy storage systems are described in general and compared with other forms of storage. Details of the design

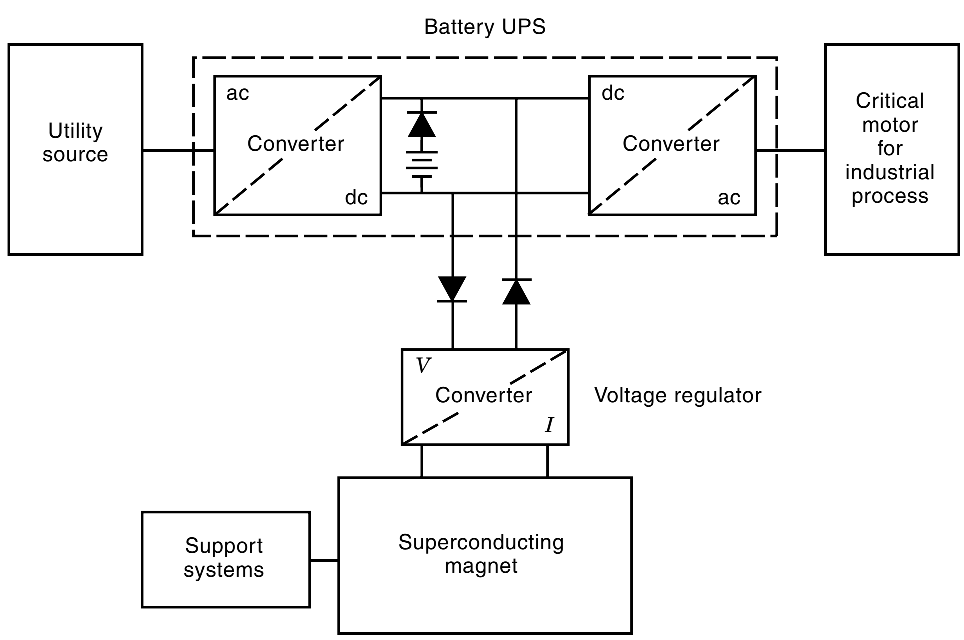

Figure 7. Simplified block diagram of a hybrid microSMES/battery UPS system. In this configuration, the superconducting magnet supplies energy to the load during short-duration disturbances, and the batteries must be discharged only during sustained outages. The fewer number of cycles and lower discharge depth required from the batteries significantly increases their lifetime.

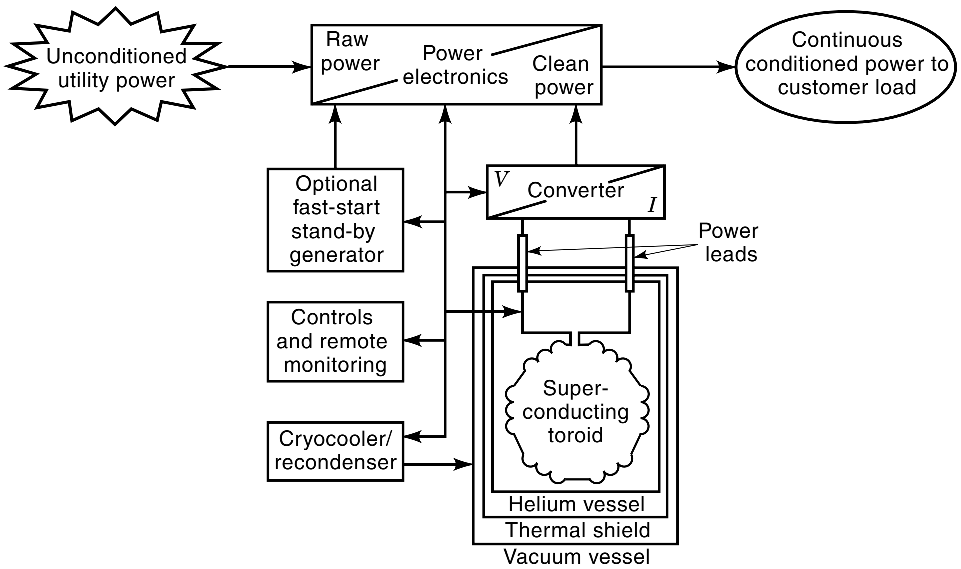

Figure 8. Block diagram of a microSMES storage system, showing major subsystems. Each subsystem is a major cost driver for SMES technology and must provide optimum performance.

are discussed, with the purpose of identifying the design drivers that affect the economy of such systems. Finally, a generalized algorithm to arrive at a design that minimizes the cost required to store a unit of energy is developed to further illuminate the design issues related to microSMES.

What is μSMES?

Designs for SMES systems have been proposed at several sizes and stored energy scales. Early SMES studies focused on very large systems, which stored thousands of megawatt-hours of energy and were designed to provide peaking power for large utility baseloads. SMES systems storing tenths of megawatt-hours have been proposed to provide stabilization of power distribution grids subject to transients that can disrupt the delivery of power over transmission lines. Some applications in the military and elsewhere require hundreds of megawatt-seconds of energy delivered at very high power that can be supplied by SMES systems. Finally, SMES systems storing on the order of 1 MW · s to 10 MW · s of energy are proposed to provide short-term high-quality power to equipment and processes sensitive to voltage sags and/or power outages. The latter set of systems as a group is referred to as microSMES, or μSMES.

A typical block diagram of a μSMES system is shown in Fig. 8. There is a power electronics subsystem that provides an interface between the energy storage system (the magnet) and the power source/load. Depending on the application, there might be an auxiliary stand-by power source included in the system to handle long power outages. Ancillary subsystems support the magnet. It operates at liquid helium temperature and requires refrigeration and insulating vacuum systems to maintain operating conditions. The heart of the system is a superconducting magnet. This is an electromagnet wound with superconducting wire. When the wire is operated at liquid helium temperature (4.5 K, or −450°F), it will carry an electric current with no resistance. Thus there are no resistive losses, and the storage of energy in the form of a magnetic field becomes possible.

The economics of μSMES are determined by these three major subsystems. Unlike battery storage, where all the cost is in the power electronics, or capacitors, where all the cost is in the energy storage system, μSMES costs are split between the power electronics and the storage, with nontrivial stand-by power needed to run the refrigeration system. Each of these subsystems must be optimized for maximum performance at minimum cost for μSMES to be successful in the marketplace.

Because the power electronics are somewhat common to all types of energy storage, the magnet system and refrigeration system must be optimized for SMES to be competitive with other technologies. For the magnet system, the maximum stored energy must be obtained using the minimum amount of material (superconducting wire). For the refrigeration system, minimizing the heat leaking into the cold space is the key to optimum performance. These issues will be discussed in greater detail later.

How Does μSMES Compare to Other Forms of Energy Storage?

Before describing a μSMES system in greater detail, some points about the technology should be made, with the purpose of driving out those applications where μSMES makes sense and where it doesn't make sense. A discussion of the desirable and undesirable qualities of SMES follows.

Positive Attributes. SMES technology has many virtues. It can provide power at an arbitrary level and do so virtually instantaneously. Furthermore, the life of the device is not limited by the power level or depth of discharge. A SMES system will provide power pulses throughout its design lifetime of up to 30 years with no degradation in performance.

The conversion from magnetic energy to electrical energy is very efficient. Because the magnetic field is created by an electric current circulating in a magnet, it is very straightforward to extract the energy. All that is needed is a voltage applied across the terminals of the magnet. The only loss is in the form of heat dissipated in the leads and electronic devices in the power electronics system (PCS), which is minimal.

A large fraction of the stored energy can be extracted from the system. The only limitation is that the voltage must be applied to maintain the delivered power. As will be discussed in further detail later, the voltage must rise as the current drops during a discharge. Eventually the voltage will rise to a level where it can break down the insulation on the coil. The discharge must be stopped just before this happens. With proper design, it is possible that this limit is not reached until only a few percent of the original stored energy remains.

The storage system itself requires no maintenance. The only moving parts are in the refrigerator. Maintenance is required on the refrigeration system, but it is possible that it can be performed while the remainder of the system is operating. Thus SMES has the potential to have no down time for maintenance.

SMES is generally environmentally benign (see the discussion of fringe magnetic fields). It does not employ hazardous or toxic materials. There are no components requiring recycling or disposal during or at the end of its life.

Finally, the state of charge of the system is easily determined. A simple current or magnetic field measurement is all that is needed to ascertain that the system is charged and ready to deliver power.

Negative Attributes. SMES has some undesirable characteristics as well. Some are real, and some are falsely perceived by the market, but nonetheless have prevented SMES from being an overwhelming success to date.

First, SMES is an expensive technology. The superconducting wire used in the magnets is expensive to begin with. The cost of the labor and materials to fabricate the structure of the magnet, the helium containment vessel, the cryostat, and the supporting refrigeration system is and will always be an order of magnitude greater than the cost of batteries storing the same amount of energy.

The technology is esoteric and is perceived to be risky. Superconducting magnets are esoteric for several reasons. Because they operate at such cold temperatures, vacuum insulating technology and helium refrigeration technology are a necessary part of the design. Furthermore, it takes a trivial amount of energy to destroy the superconductive properties of the wire (e.g., the frictional heat generated if two adjacent wires rub together through the distance of 4/100ths of a *mil,* or the heat generated by the creation of microcracks in an epoxy-impregnated coil when it is energized). If the superconductive property is lost, systems must be in place to protect the wire from overheating and burning out from the excessive resistive heat that is generated. In addition, there can be very high internal voltages in a superconducting magnet that has gone resistive, which can potentially arc through the electrical insulation around the wire and render the magnet useless at worst, or have much reduced capacity at best. These problems are usually encountered when a magnet is first energized, but rarely afterwards. A magnet might require several attempts before it can be fully ramped to its design current and field, but once it has been operated at design conditions, the risk of an unwanted quench virtually vanishes. The risk inherent in the technology is to the producer because if a magnet is not properly designed and fabricated, it becomes apparent only after it has been built. Then it must be scrapped. The risk to an end user is negligible once a magnet has been operated at design conditions. Over the years, the potential problems have come to be understood, and although they cannot be eliminated, they can be mitigated by paying close attention to proper design practice and quality control during fabrication. Indeed, superconducting magnets have reached a mature state of reliability for commercial applications: refer to magnetic resonance imaging (MRI) systems routinely operating in hospitals throughout the world.

It is possible that a SMES system will have fairly large fringe fields (i.e., the magnetic field will extend well beyond the physical limits of the magnet system). This can lead to siting problems or restrictions that can add to the cost. An alternative is to use toroidal magnet systems, where the field is confined totally within the bore of the toroid. This essentially eliminates the fringe field, with the penalty of requiring more superconducting wire to produce the same amount of energy as a solenoid.

The maintenance required for the refrigeration system can be expensive. Depending on the size of the refrigerator required, maintenance can vary from requiring a simple seal replacement to rebuilding a compressor periodically. The cost of this maintenance must be factored into the life cycle cost of the installed system. Typical practice is to provide redundant components such as compressors, with an associated penalty of additional capital cost.

Finally, μSMES suffers from a penalty imposed by the Second Law of Thermodynamics. In order to operate at temperatures close to absolute zero, large amounts of power are required to operate the refrigerator. Typical helium refrigerators require from 500 W to 5000 W of compressor power to remove a single watt of heat load from a helium bath. Thus there are large parasitic power requirements to operate a system. In addition, the current that circulates through the magnet must also circulate through the power electonics system, creating waste heat that must be removed. This waste heat becomes an air conditioning load that represents additional parasitic power.

Because μSMES will always be more expensive than batteries, it should be considered only for applications where batteries cannot compete: power levels higher than 2 MW or so and situations requiring many repetitive discharge cycles lasting on the order of two or three seconds or less. These conditions exploit the positive attributes of μSMES to best advantage.

What Does the Storage System Look Like?

The storage subsystem of a μSMES unit consists of a magnet and a cryogenic system. The magnet is a superconducting coil or array of coils. The cryogenic system includes a cryostat that insulates the cold helium vessel from the ambient surroundings, and a helium liquefier.

The magnet may be a single coil or an array of coils. It may be wound in a solenoid configuration or in a toroid. The advantage of a solenoid is that it produces more stored energy per unit conductor than a toroid does, and it is much simpler to fabricate. The advantage of a toroid is that the magnetic field is confined almost completely within the bore of the torus.

It is not within the scope of this article to discuss the art of designing and fabricating superconducting magnets. However, insofar as they relate to the technology of μSMES, the main components of a magnet will be discussed. A superconducting magnet consists of a conductor, wound on some structure, with the conductor isolated from adjacent turns and the supporting structure by some insulation system.

The conductor represents the major materials cost of a μSMES system. It will be either a single monolithic wire, or a cable of smaller wires. At currents up to 2000 A to 3000 A, a single wire will do the job and is easier to fabricate and wind. At higher currents (higher powers), a cable is the preferred approach. The primary reason is that, as the size of wire increases, the ac losses during discharge become significant. These losses are reduced in a cable because of the resistance created at the many contact points between individual wires.

The structure must support the winding against the Lorentz loads created when a conductor is placed in a magnetic field. In a simple solenoid, the structure is trivial because the net force on the coil is zero (excepting its own weight). The forces act to expand the coil radially outward and compress the coil axially. The winding itself is the structure. In solenoidal arrays, or toroids, there are significant forces that act on the individual coils, which must be reacted with structure. The nature of the forces depend on the geometry and arrangement of the coil array. For a toroid, a centering force acts to compress the toroid into as small a diameter as possible.

The insulation system is key to the economic viability of μSMES because it determines the maximum allowable voltage at which the coil can be discharged. The voltage level determines how much of the stored energy can actually be delivered at a given power level, and the higher the voltage, the lower the current can be, which reduces the refrigeration load. The largest voltages appear across the terminals of the coil, and also from coil to ground. The insulation in these areas must be designed to withstand high voltage stresses for many cycles. The voltages between layers of the coil, and between turns, are generally much less because the terminal voltage gets divided essentially evenly over each layer and turn.

The cryogenic system maintains the operating environment for the superconducting coil, which is at the normal boiling point of liquid helium, or approximately 4.5 K. The components are the helium refrigerator and the cryostat. A key part of the cryostat that affects the economics of μSMES are the leads that connect the cold magnet to the warm power conditioning system.

The complexity, size, and cost of the refrigerator depends on the size of the heat load to the refrigerated space. Larger heat loads, on the order of tens of watts, require a refrigerator based on the Collins cycle. These are commercially available and consist of a compressor and a cold box. The compressor produces a high-pressure stream of gas, which is passed through the cold box. Inside the cold box are counterflow heat exchangers, which cool the high pressure gas with cold, low-pressure gas returning from the cold space. At several temperature stages, part of the gas stream is diverted through an expansion engine to produce additional cold cooling gas. Only a portion of the gas that is compressed actually is used to refrigerate the magnet. One of the problems with helium refrigerators is that any other contaminants in the gas stream condense out on the heat exchanger surfaces. This includes the oil that must be used to lubricate the compressor. One of the reasons helium refrigerators are so expensive and hard to maintain is that the gas cleaning systems require periodic cleaning.

At smaller heat loads, newer cryocooler technology is preferred. These are small refrigerators based on the Gifford McMahon cycle, which employs a regenerator heat exchanger to cool the high-pressure gas stream. These devices are also subject to degradation resulting from fouled heat transfer surfaces, but they have the advantage of not requiring cold expansion engines that can wear out, and the regenerator tends to be self-cleaning to some degree. Cryocoolers still require periodic maintenance, but the system can be designed to accommodate a changeout of the cold head without having to shut down the magnet. The disadvantage of cryocoolers is that they are not as efficient as the Collins machines, which is why they are not used for large heat loads.

The cryostat provides a vacuum enclosure for the helium vessel and supports the vessel with low conductivity supports. A thermal shield is placed between the vacuum vessel and helium vessel to intercept heat radiated from the warm surface. The thermal shield is cooled either with liquid nitrogen or by conduction to a cryocooler. Multilayer insulation is used to further reduce the heat leak. As long as the vacuum is maintained at a pressure of 10^{-2} Pa or lower, the heat leak into the helium vessel can be made very low, with proper design practice.

The current leads to the coil will always be the largest single source of heat into the magnet. The connections, or power leads, cannot be made from materials with low thermal conductivity because they would then have a high electrical resistance. More electrical resistance means more resistive heating, which then ends up in the cold magnet system. The fundamental tradeoff for power leads is the balancing of the heat conducted down the lead against the heat generated by resistance within the lead. Whatever one does to make one component smaller increases the other by roughly the same amount. All is not lost, however; there are three things that can be done to minimize the heat input.

- The first is simply to reduce the current the leads have to carry. The required refrigeration power is directly proportional to the amount of current in the leads. A good magnet design, then, will use the least amount of current possible. The drawbacks are threefold. First, less current in the conductor means more turns of conductor are required to provide the same stored energy. Depending on how the conductor is priced, this can mean additional capital cost for the magnet system. (Note that the total volume of conductor stays about the same, so if the cost of conductor is dominated by bulk material cost, the cost is about the same regardless of current; if the conductor cost is primarily the result of processing, longer lengths of smaller wire will cost more.) The other two drawbacks are risk related. More turns of conductor make it harder to protect the magnet from overheating in the event of a quench. Also, as the current is decreased, it requires more voltage across the coil terminals to extract the same amount of power. As the voltage increases, so does the risk of damaging the coil insulation as a result of voltage breakdown.
- The second way to reduce the heat leak is to employ a high-temperature superconductor for a portion of the leads. The ceramic materials are an exception to the general rule that thermal conductivity goes up as electrical

resistivity goes down. Although still a developing technology, high-temperature superconductor (HTS) leads have been built and have demonstrated a fourfold reduction in heat leak over conventional leads. They are complex and lack design maturity at the present time but offer a promising path to reduced heat leak.

- The final way to reduce the heat load caused by the power leads is to short the coil leads with what is called a persistent switch. This is a length of superconducting wire stabilized with copper–nickel alloy instead of pure copper, so it is more resistive when normal. The switch is opened by driving it normal. Allowing it to cool to helium temperature makes it superconducting. When superconducting, the current circulates entirely within the helium vessel. The leads only carry current during a current pulse when the energy is extracted from the μSMES device. As a consequence, the leads can be rated for transient operation only, resulting in a much smaller cross-section and a reduced heat leak.

What Drives the Design?

The design of a μSMES storage system is fundamentally driven by the need to minimize the cost necessary to provide a specified amount of power for a specified span of time. The cost includes the cost of materials (primarily superconductor), the cost of labor to manufacture the magnet system, and the life-cycle operating cost of the system (the cost of electricity to run the refrigerator dominates). In this section, the design issues and tradeoffs are discussed, and a generic algorithm for producing an optimized design is outlined.

The ultimate design drivers for a μSMES device are the power P it is required to deliver and the time duration t_p the power is needed. It is then basic to SMES that the energy stored in the magnet system be at least equal to the product of the required power and the time duration. Other considerations force the total stored energy to exceed this amount.

There are constraints to the design as well. The fact that the voltage must rise as energy is extracted from the magnet has been mentioned. The maximum allowable voltage is one constraint on how much energy can be extracted.

Another constraint to the efficiency of the design is the fact that heat is produced in the windings when the coil is discharged. This is the result of what are commonly referred to as ac losses. They arise when a magnetic field changes with time in a conducting medium. If the ac losses heat the conductor to the point that superconductivity is lost, some of the stored energy is lost to heat dissipated in the windings and cannot be extracted as electrical power.

Another constraint is the stress level in the coil pack. The factors that make a coil efficient in terms of cost are the current density in the conductor, the field that the coil produces, and the size of the coil. Making any of these three larger to improve cost efficiency also increases the stress level in the conductor. Thus there is an upper limit to the economics resulting from the strength of the materials.

The behavior of superconducting material in a magnetic field also places a limit on the performance of μSMES. There is a limit to the amount of current a conductor can carry at any given field. This is called the critical current. The critical current density in the niobium–titanium superconducting alloy is limited to about 3×10^9 A/m^2 at 5 T and drops to zero at about 9.5 T.

Finally, although one would like to make the current in the magnet as large as possible so that the discharge voltage is small, the heat leak associated with the current leads gets larger as the current increases. The economics of refrigeration places an upper limit on the value of current.

What Are the Design Tradeoffs?

The constraints on the design lead to tradeoffs between various cost and risk elements. Quantification of these tradeoffs is the first step toward an algorithm that can be used to produce an optimized design. The ultimate goal of a μSMES design is to provide the necessary power for the necessary time at minimum cost. The cost will include materials, fabrication labor, and life cycle support and maintenance costs. The primary material cost will be cost of the superconductor. The main labor cost will be to wind the coils and assemble the structure and vessels. The largest life cycle cost will be the cost of electricity to run the helium refrigerator and cooling for the power electronics.

Excess Storage (Cost) vs. Current. There is a tradeoff between the cost of excess storage in the coil and the cost of refrigeration to remove the heat load resulting from the current leads. The system cost can be represented in a simple fashion by the expression

$$C = a \cdot U_o + b \cdot I_o \tag{1}$$

The coefficient a represents the material and labor cost per unit megajoule of stored energy to build the unit, and b represents the cost of electricity to refrigerate the heat load due to the current leads.

As energy is extracted from the magnet, the voltage must always rise to maintain constant power as the current in the magnet drops. At some point before all the energy is extracted, the voltage reaches the maximum allowable value V_m, and the discharge must stop. If P is the power extracted from the unit, V is the terminal voltage, and I is the current in the coil, then

$$P = IV \tag{2}$$

The energy U stored in the magnet at any time is

$$U = \frac{1}{2} LI^2 \tag{3}$$

where L is the inductance.

During a discharge, the energy stored in the magnet is reduced from the original amount U_o by the product of power and time Pt. Thus

$$U = U_o + Pt \tag{4}$$

Note that for a discharge, the sign of P is negative (a negative voltage must be applied to the coil to extract energy). If t_f is the duration the power is needed, then the ratio of the energy extracted to the energy initially stored in the SMES unit can be expressed as

$$-\frac{Pt_f}{U_o} = 1 - \left[\frac{P}{V_m I_o}\right]^2 \tag{5}$$

Equation (5) was developed by noting that at any time the ratio of U to U_o is equal to the square of the ratio of I to I_o and that at the end of the discharge, when the current is a minimum, the voltage is at its maximum value (in a negative sense). Note that, for a given allowable maximum voltage, power level, and time duration, as the initial current increases, the required initial stored energy decreases. Depending on the relative values of the cost coefficients a and b, there will be a minimum in the total cost that should be sought.

Excess Storage vs. Power (ac Losses). The discharge can also be limited by ac losses. If the losses cause the magnet to quench before the end of the discharge time t_f, the energy remaining in the magnet is lost to heat deposited in the windings. The factors that determine this limit can be determined as follows.

The ac loss heating $\dot{Q}$ is proportional to the square of the field decay rate $\dot{B}$. For the purposes of this article, this can be written as

$$\dot{Q} = a\dot{B}^2 \tag{6}$$

Now, the field is proportional to the current. If B_p is the operating field at the operating current I_o, then it can be shown that the total heat Q that is deposited in the conductor during a discharge is equal to

$$Q = a\int_0^{t_f} \dot{B}^2\,dt = a\frac{B_p^2}{4}\frac{P}{U_o}\ln\left[\frac{U_o}{U_o + Pt_f}\right] \tag{7}$$

At some value of Q, the magnet will quench. This equation defines the parameters that can reduce Q. Operating at a lower field will reduce Q but will mean the magnet will be larger (stored energy is proportional to the square of the field integrated over all space). A larger magnet in turn will most likely mean higher costs. Increasing the stored energy also reduces Q with more cost. The tradeoff here is to determine the minimum size and stored energy which allows a total energy Pt_f to be extracted before the magnet quenches (if it does at all).

How Is the Design Optimized?. Given all these issues related to cost and performance, how does one go about finding the optimum design for a μSMES unit? The ideal approach would be to set down the end requirements P and t_f, derive the required initial stored energy U_o, apply all the constraints, and end with the geometry of the coil defined. Unfortunately, the relationships between field, current density, inductance, and coil geometry do not lend themselves to closed form solutions, which can be manipulated to provide such an approach. Instead, an iterative process must be followed, whereby a trial geometry is selected first and then the resulting μSMES system is checked to see that it satisfies all requirements and constraints. If not, the process is iterated until it does. Then cost is determined as a function of the geometry, and the geometry is varied again until a minimum cost is attained. It is worthwhile to outline in a little more detail the steps involved because it helps to illuminate a little better the design issues that affect the cost performance of μSMES.

This algorithm finds the minimum wire cost per unit stored energy for a μSMES device. The variables that are free to adjust are the descriptors of the coil geometry: the length, the coil pack thickness, and the radius of the coil. It is common to use the nomenclature shown in Fig. 9, where a_i is the inner radius of the coil pack, α is the ratio of outer to inner radius, and β is the ratio of coil pack length to diameter. The optimized design will satisfy the constraints that

- the hoop stress in the conductor will be equal to or less than some allowable value σ_w,
- the absolute value of voltage at the end of a discharge of duration t_f and power level P will be equal to or less than an allowable value V_m,
- the critical current density in the superconductor will be equal to or less than the critical current density J_c at the point where the field is highest in the coil pack, and
- the coil will not quench as a result of ac losses before the energy extraction is complete.

The first step is to pick trial values for α and β. (It is assumed that a solenoid design is being pursued. In the case of a toroid, there will be some relationship between the "length" of the coil and the major radius of the torus. Therefore, the major radius becomes a free parameter instead of β.)

The next step is to determine the resulting magnetic field, with an assumed value of $J_o\,a_i$. It doesn't matter what the value is at this stage, just something convenient. One of the reasons for computing the field is to compute the stress level in the conductor subsequently. Exactly what detail is needed for the field distribution is a function of the detail needed for the stress calculation. In every case, however, the field at a particular point can be expressed as

$$B = \mu_o J_o a_i F(\alpha,\ \beta) \tag{8}$$

The value of F depends on where it is evaluated, but the point is that B anywhere is proportional to the overall coil pack current density J_o and the coil radius a_i.

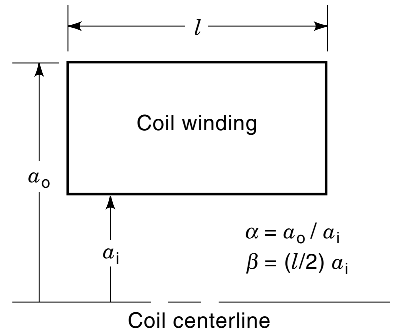

Figure 9. Identification of nomenclature used to describe magnet geometry.

The stress is proportional to the product of radius, field, and current density. It can always be written as

$$\sigma = \mu_o (J_o a_i)^2 S(\alpha, \beta) \quad (9)$$

The function S will depend on the level of complexity in the stress analysis. For thin solenoids with an approximately linear field profile through the winding, Wilson provides a closed form expression (5). Given a stress allowable σ_w, the product of current density and radius is then determined:

$$J_o a_i = \sqrt{\frac{\mu_o \sigma_w}{S(\alpha, \beta)}} \quad (10)$$

Now the field at any point is known. In particular, the peak field in the coil pack is now determined, using Eq. (8).

The next step is to find the value of current density that minimizes the amount of superconductor needed. This value is the critical current density of the superconductor at the peak field. In any coil winding, there is space needed for material other than superconductor, and prudent design calls for some temperature margin for the conductor. If ϕ is the ratio of nonsuperconductor to superconductor in the wire, λ is the fraction of the coil pack actually occupied by wire, and ΔT_m is the temperature margin of the superconductor, then

$$J_o = \frac{\lambda}{1+\phi} J_c(B_p, T_o + \Delta T_m) \quad (11)$$

Once J_o is known, a_i is known.

Given a complete description of the geometry and the current density, the stored energy can be found. Usually the value of (L/n^2) is determined, either from tables, or from a computer code. In general, it will be proportional to a_i and a function of the shape of the coil; thus,

$$(L/n^2) = a_i G(\alpha, \beta) \quad (12)$$

Once (L/n^2) is known, the stored energy is found from

$$U = \frac{1}{2}\frac{L}{n^2}(J_o A)^2 = \frac{1}{2} a_i G(\alpha, \beta)[J_o 2a_i^2(\alpha - 1)\beta]^2 \quad (13)$$

Note that U is proportional to the fifth power of the coil radius.

At this point, it must be determined whether (a) the energy stored is sufficient to provide the required power for the required time and (b) the ac losses limit the energy extraction or not. If not, a new trial geometry must be selected and the process begun again. If both requirements are met, the algorithm proceeds. The next step is to determine the current, from Eq. (5). Then the cost of wire is determined. Usually, conductor can be estimated at some fixed rate per kiloamp meter. Thus it is straightforward to scale cost data from a single point.

Once the cost as a function of stored energy is established, it is straighforward, at least in principle, to apply some optimization routine to the algorithm to find the optimum geometry that minimizes cost. The advantage of this algorithm is that, to the extent possible, it automatically finds the conditions of maximum stress and current density for a given field to minimize the amount of conductor needed. The current is set to the minimum value allowed by the voltage limit and the available stored energy (for a given configuration) to minimize the heat load.

SUMMARY

We have seen how the economics of μSMES are affected by the power conditioning system, the storage system, and the parasitic power required to maintain operating conditions. There are certain power quality application that benefit most from the advantages of μSMES. These are high-power situations with many repetitive cycles lasting a few seconds or less. The primary design driver for the magnet system is producing the maximum amount of stored energy for minimum cost, subject to constraints that available materials impose. A systematic algorithm to produce a cost-optimized design was developed. It maximizes the efficiency of the superconductor, while satisfying the constraints of stress, ac loss heating, maximum voltage, and allowable current density in the superconductor.

As the market for high-quality power develops and the relative benefits of μSMES as an option become better understood, it is expected that magnetic energy storage will make a major impact on the economics of power quality sensitive processes.

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POWER QUALITY. See POWER SYSTEM HARMONIC CONTROL.
POWER, REACTIVE. See REACTIVE POWER.
POWER SEMICONDUCTOR CIRCUITS. See POWER DEVICES.
POWER SEMICONDUCTOR DEVICES. See POWER DEVICES.
POWER SEMICONDUCTOR SWITCHES. See POWER DEVICES.
POWER SPECTRAL DENSITY. See SPECTRAL ANALYSIS.
POWER SPLITTERS. See POWER DIVIDERS.
POWER STATION DESIGN, NUCLEAR. See NUCLEAR POWER STATION DESIGN.