POWER QUALITY (UNIT-II)

VOLTAGE SAG:

A *voltage sag* is a short-duration (typically 0.5 to 30 cycles) reduction in rms voltage caused by faults on the power system and the starting of large loads, such as motors. Momentary interruptions (typically no more than 2 to 5 s) cause a complete loss of voltage and are a common result of the actions taken by utilities to clear transient faults on their systems. Sustained interruptions of longer than 1 min are generally due to permanent faults.

SOURCES OF SAGS AND INTERRUPTIONS:

Voltage sags and interruptions are generally caused by faults (short circuits) on the utility system. Consider a customer that is supplied from the feeder supplied by circuit breaker 1 on the diagram shown in fig.1. If there is a fault on the same feeder, the customer will experience a voltage sag during the fault followed by an interruption when the breaker opens to clear the fault. If the fault is temporary in nature, a reclosing operation on the breaker should be successful and the interruption will only be temporary. It will usually require about 5 or 6 cycles for the breaker to operate, during which time a voltage sag occurs. The breaker will remain open for typically a minimum of 12 cycles up to 5 s depending on utility reclosing practices. Sensitive equipment will almost surely trip during this interruption.

A much more common event would be a fault on one of the other feeders from the substation, i.e., a fault on a parallel feeder, or a fault somewhere on the transmission system (see the fault locations shown in Fig.1).In either of these cases, the customer will experience a voltage sag during the period that the fault is actually on the system. As soon as breakers open to clear the fault, normal voltage will be restored at the customer. Note that to clear the fault shown on the transmission system, both breakers A and B must operate. Transmission breakers will typically clear a fault in 5 or 6 cycles. In this case there are two lines supplying the distribution substation and only one has a fault. Therefore, customers supplied from the substation should expect to see only a sag and not an interruption. The distribution fault on feeder 4 may be cleared either by the lateral fuse or the breaker, depending on the utility's fuse saving practice.

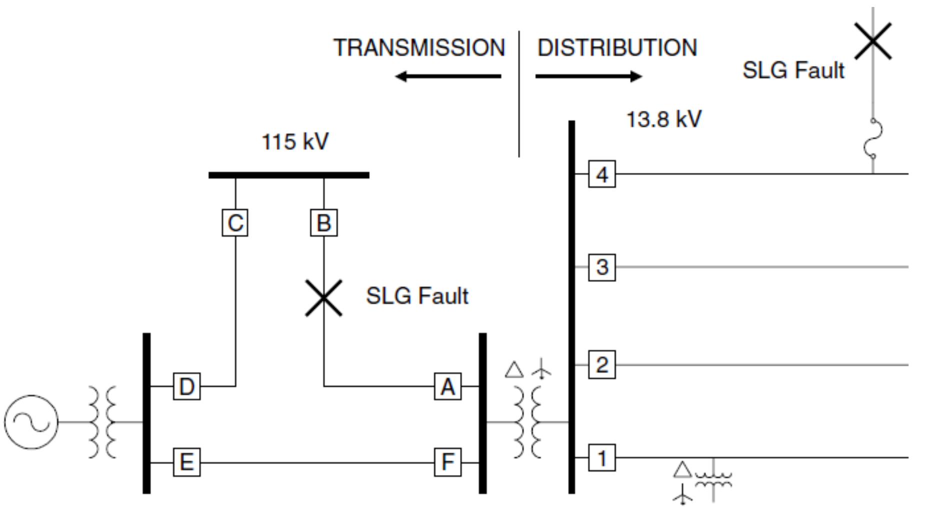

Fig.1 Fault location on the utility power station

Any of these fault locations can cause equipment to misoperate in customer facilities. The relative importance of faults on the transmission system and the distribution system will depend on the specific characteristics of the systems (underground versus overhead distribution, lightning flash densities, overhead exposure, etc.) and the sensitivity of the equipment to voltage sags.

SOURCES OF VOLTAGE SAG AND INTTURUPTION:

Motors have the undesirable effect of drawing several times their full load current while starting. This large current will, by flowing through system impedances, cause a voltage sag which may dim lights, cause contactors to drop out, and disrupt sensitive equipment. The situation is made worse by an extremely poor starting displacement factor—usually in the range of 15 to 30 percent.

The time required for the motor to accelerate to rated speed increases with the magnitude of the sag, and excessive sag may prevent the motor from starting successfully. Motor starting sags can persist for many seconds, as illustrated in Fig.2.

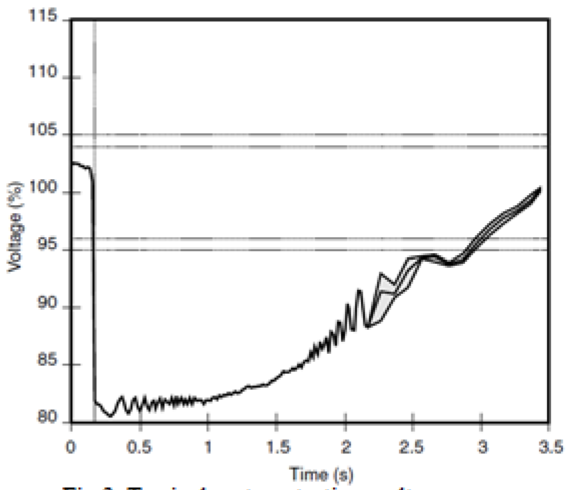

Fig.2. Typical motor-starting voltage sag

ESTIMATING VOLTAGE SAG PERFORMANCE

It is important to understand the expected voltage sag performance of the supply system so that facilities can be designed and equipment specifications developed to assure the optimum operation of production facilities. The following is a general procedure for working with industrial customers to assure compatibility between the supply system characteristics and the facility operation:

1. Determine the number and characteristics of voltage sags that result from transmission system faults.
2. Determine the number and characteristics of voltage sags that result from distribution system faults (for facilities that are supplied from distribution systems).
3. Determine the equipment sensitivity to voltage sags. This will determine the actual performance of the production process based on voltage sag performance calculated in steps 1 and 2.
4. Evaluate the economics of different solutions that could improve the performance, either on the supply system (fewer voltage sags) or within the customer facility (better immunity).

FUNDAMENTAL PRINCIPLES OF PROTECTION

Several things can be done by the utility, end user, and equipment manufacturer to reduce the number and severity of voltage sags and to reduce the sensitivity of equipment to voltage sags. This essentially means keeping problem equipment out of the plant, or at least identifying ahead of time power conditioning requirements. Several ideas, outlined here, could easily be incorporated into any company's equipment procurement specifications to help alleviate problems associated with voltage sags:

1. Equipment manufacturers should have voltage sag ride-through capability curves (similar to the ones shown previously) available to their customers so that an initial evaluation of the equipment can be performed. Customers should begin to demand that these types of curves be made available so that they can properly evaluate equipment.
2. The company procuring new equipment should establish a procedure that rates the importance of the equipment. If the equipment is critical in nature, the company must make sure that adequate ride-through capability is included when the equipment is purchased. If the equipment is not important or does not cause major disruptions in manufacturing or jeopardize plant and personnel safety, voltage sag protection may not be justified.
3. Equipment should at least be able to ride through voltage sags with a minimum voltage of 70 percent (ITI curve). The relative probability of experiencing voltage sag to 70 percent or less of nominal is much less than experiencing a sag to 90 percent or less of nominal.

SOLUTIONS AT THE END-USER LEVEL

Solutions to improve the reliability and performance of a process or facility can be applied at many different levels. The different technologies available should be evaluated based on the specific requirements of the process to determine the optimum solution for improving the overall voltage sag performance.

The solutions can be discussed at the following different levels of application:

1. *Protection for small loads [e.g., less than 5 kilovoltamperes (kVA)]*. This usually involves protection for equipment controls or small, individual machines. Many times, these are single-phase loads that need to be protected.
2. *Protection for individual equipment or groups of equipment up to about 300 kVA.* This usually represents applying power conditioning technologies within the facility for protection of critical equipment that can be grouped together conveniently. Since usually not all the loads in a facility need protection, this can be a very economical method of dealing with the critical loads, especially if the need for protection of these loads is addressed at the facility design stage.
3. *Protection for large groups of loads or whole facilities at the low-voltage level.* Sometimes such a large portion of the facility is critical or needs protection that it is reasonable to consider protecting large groups of loads at a convenient location (usually the service entrance). New technologies are available for consideration when large groups of loads need protection.
4. *Protection at the medium-voltage level or on the supply system.* If the whole facility needs protection or improved power quality, solutions at the medium-voltage level can be considered. The size ranges in these categories are quite arbitrary, and many of the technologies can be applied over a wider range of sizes. The following sections describe the major technologies available and the levels where they can be applied.

MOTOR-STARTING METHODS

Energizing the motor in a single step (*full-voltage starting*) provides low cost and allows the most rapid acceleration. It is the preferred method unless the resulting voltage sag or mechanical stress is excessive.

Autotransformer starters have two autotransformers connected in open delta. Taps provide a motor voltage of 80, 65, or 50 percent of system voltage during start-up. Line current and starting torque vary with the square of the voltage applied to the motor, so the 50 percent tap will deliver only 25 percent of the full-voltage starting current and torque. The lowest tap which will supply the required starting torque is selected.

Resistance and reactance starters initially insert an impedance in series with the motor. After a time delay, this impedance is shorted out. Starting resistors may be shorted out over several steps; starting reactors are shorted out in a single step. Line current and starting torque vary directly with the voltage applied to the motor, so for a given starting voltage, these starters draw more current from the line than with autotransformer starters, but provide higher starting torque. Reactors are typically provided with 50, 45, and 37.5 percent taps.

Part-winding starters are attractive for use with dual-rated motors (220/440 V or 230/460 V). The stator of a dual-rated motor consists of two windings connected in parallel at the lower voltage rating, or in series at the higher voltage rating. When operated with a part-winding starter at the lower voltage rating, only one winding is energized initially, limiting starting current and starting torque to 50 percent of the values seen when both windings are energized simultaneously.

Delta-wye starters connect the stator in wye for starting and then, after a time delay, reconnect the windings in delta. The wye connection reduces the starting voltage to 57 percent of the system line-line voltage; starting current and starting torque are reduced to 33 percent of their values for full-voltage start.

Q.1. Discuss the term "Area of Vulnerability".

ANS. The concept of an *area of vulnerability* has been developed to help evaluate the likelihood of sensitive equipment being subjected to voltage lower than its *minimum voltage sag ride-through capability.*

The latter term is defined as the minimum voltage magnitude a piece of equipment can withstand or tolerate without misoperation or failure. This is also known as the equipment voltage sag immunity or susceptibility limit.

An area of vulnerability is determined by the total circuit miles of exposure to faults that can cause voltage magnitudes at an end-user facility to drop below the equipment minimum voltage sag ride-through capability. Figure shows an example of an area of vulnerability diagram for motor contactor and adjustable-speed-drive loads at an end-user facility served from the distribution system. The loads will be subject to faults on both the transmission system and the distribution system. The actual number of voltage sags that a facility can expect is determined by combining the area of vulnerability with the expected fault performance for this portion of the power system. The expected fault performance is usually determined from historical data.

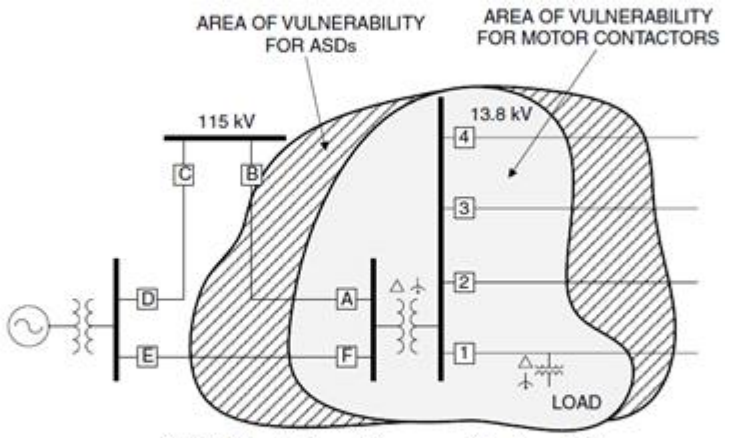

Fig.3. Illustration of an area of vulnerability

Q. With a typical ferro-resonant circuit diagram discuss, how a ferro-resonant transformers hands voltage sag conditions?

ANS: Ferroresonant transformers, also called constant-voltage transformers (CVTs), can handle most voltage sag conditions. (Fig.4.) CVTs are especially attractive for constant, low-power loads. Variable loads, especially with high inrush currents, present more of a problem for CVTs because of the tuned circuit on the output. Ferroresonant transformers are basically 1:1 transformers which are excited high on their saturation curves, thereby providing an output voltage which is not significantly affected by input voltage variations. A typical ferroresonant transformer schematic circuit diagram is shown in figure.

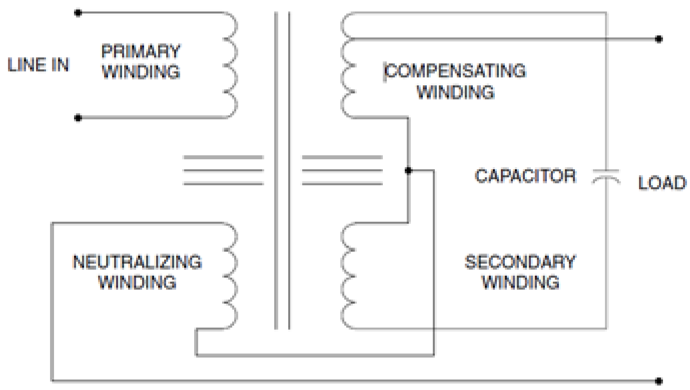

Fig.4. Schematic of ferroresonant constant-voltage transformer

Q. What are magnetic synthesizers? Explain its working with suitable block diagram.

ANS. Magnetic synthesizers use a similar operating principle to CVTs except they are three-phase devices and take advantage of the three-phase magnetics to provide improved voltage sag support and regulation for three-phase loads. They are applicable over a size range from about 15 to 200 kVA and are typically

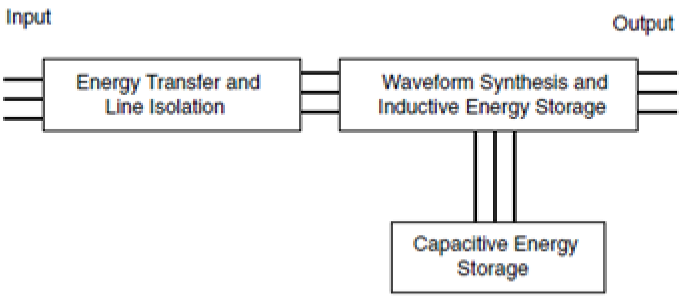

Fig.5. Block diagram of magnetic synthesizer

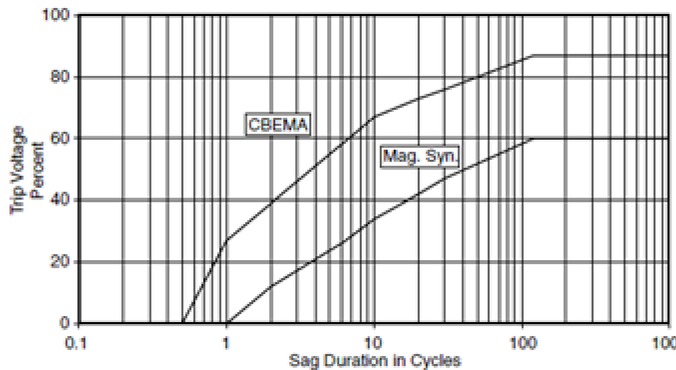

Fig.6. Magnetic synthesizer voltage sag ride-through capability

applied for process loads of larger computer systems where voltage sags or steady-state voltage variations are important issues. A block diagram of the process is shown in Fig.5.

Working: Energy transfer and line isolation are accomplished through the use of nonlinear chokes. This eliminates problems such as line noise. The ac output waveforms are built by combining distinct voltage pulses from saturated transformers. The waveform energy is stored in the saturated transformers and capacitors as current and voltage. This energy storage enables the output of a clean waveform with little harmonic distortion. Finally, three-phase power is supplied through a zigzag transformer.

Figure 6 shows a magnetic synthesizer's voltage sag ride-through capability as compared to the CBEMA curve, as specified by one manufacturer.

Q. Write a short note on: (a) On-line UPS; (b) Off-line (Standby) UPS; (c) Hybrid UPS; (d) Motor-generator sets (e) Superconducting Magnetic Energy Storage (SMES) Devices.

ANS. (a) On-line UPS: Figure-7 shows a typical configuration of an on-line UPS. In this design, the load is always fed through the UPS. The incoming ac power is rectified into dc power, which charges a bank of batteries. This dc power is then inverted back into ac power, to feed the load. If the incoming ac power fails, the inverter is fed from the batteries and continues to supply the load. In addition to providing ride-through for power outages, an on-line UPS provides very high isolation of the critical load from all power line disturbances. However, the on-line operation increases the losses and may be unnecessary for protection of many loads.

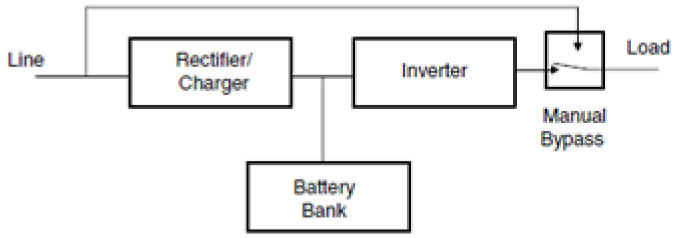

Fig.7. On-line UPS

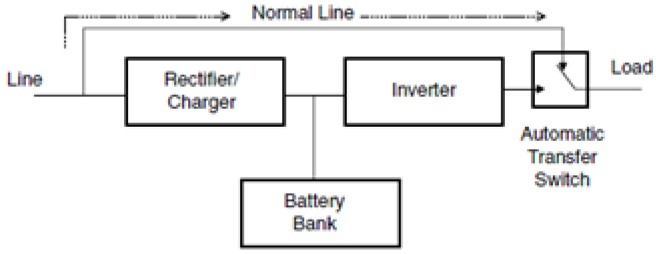

Fig.8. Standby UPS

(b) Standby UPS: A standby power supply (Fig.8) is sometimes termed *off-line UPS* since the normal line power is used to power the equipment until a disturbance is detected and a switch transfers the load to the battery backed inverter. The transfer time from the normal source to the battery-backed inverter is important. The CBEMA curve shows that 8 ms is the lower limit on interruption through for power-conscious manufacturers. Therefore a transfer time of 4 ms would ensure continuity of operation for the critical load. A standby power supply does not typically provide any transient protection or voltage regulation as does an on-line UPS. This is the most common configuration for commodity UPS units available at retail stores for protection of small computer loads. UPS specifications include kilovoltampere capacity, dynamic and static voltage regulation, harmonic distortion of the input current and output voltage, surge protection, and noise attenuation. The specifications should indicate, or the supplier should furnish, the test conditions under which the specifications are valid.

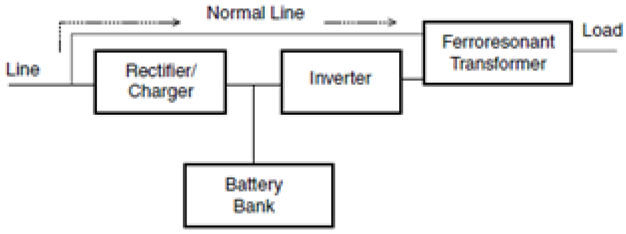

Fig.9 Hybrid UPS

(c) Hybrid UPS: Similar in design to the standby UPS, the hybrid UPS (Fig. 9) utilizes a voltage regulator on the UPS output to provide regulation to the load and momentary ride-through when the transfer from normal to UPS supplies is made.

(d) Motor-Generator Set: Motor-generator (M-G) sets come in a wide variety of sizes and configurations. This is a mature technology that is still useful for isolating critical loads from sags and interruptions on the power system. The concept is very simple, as illustrated in Fig.10. A motor powered by the line drives a generator that powers the load. Flywheels on the same shaft provide greater inertia to increase ride-through time. When the line suffers a disturbance, the inertia of the machines and the flywheels maintains the power supply for several seconds. This arrangement may also be used to separate sensitive loads from other classes of disturbances such as harmonic distortion and switching transients. While simple in concept, M-G sets have disadvantages for some types of loads:

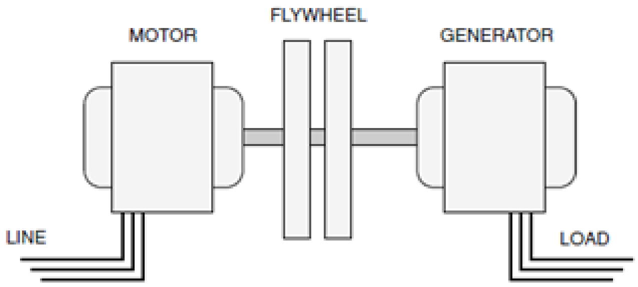

Fig.10. Block diagram of typical M-G set with flywheel

1. There are losses associated with the machines, although they are not necessarily larger than those in other technologies described here.
2. Noise and maintenance may be issues with some installations.
3. The frequency and voltage drop during interruptions as the machine slows. This may not work well with some loads.

Another type of M-G set uses a special synchronous generator called a written-pole motor that can produce a constant 60-Hz frequency as the machine slows. It is able to supply a constant output by continually changing the polarity of the rotor's field poles. Thus, each revolution can have a different number of poles than the last one. Constant output is maintained as long as the rotor is spinning at speeds between 3150 and 3600 revolutions per minute (rpm). Flywheel inertia allows the generator rotor to keep rotating at speeds above 3150 rpm once power shuts off. The rotor weight typically generates enough inertia to keep it spinning fast enough to produce 60 Hz for 15 s under full load. Another means of compensating for the frequency and voltage drop while energy is being extracted is to rectify the output of the generator and feed it back into an inverter. This allows more energy to be extracted, but also introduces losses and cost.

(e) Superconducting Magnetic Energy Storage (SMES) Devices: An SMES device can be used to alleviate voltage sags and brief interruptions. The energy storage in an SMES-based system is provided by the electric energy stored in the current flowing in a superconducting magnet. Since the coil is lossless, the energy can be released almost instantaneously. Through voltage regulator and inverter banks, this energy can be injected into the protected electrical system in less than 1 cycle to compensate for the missing voltage during a voltage sag event.

The SMES-based system has several advantages over battery-based UPS systems:

1. SMES-based systems have a much smaller footprint than batteries for the same energy storage and power delivery capability.13
2. The stored energy can be delivered to the protected system more quickly.
3. The SMES system has virtually unlimited discharge and charge duty cycles.

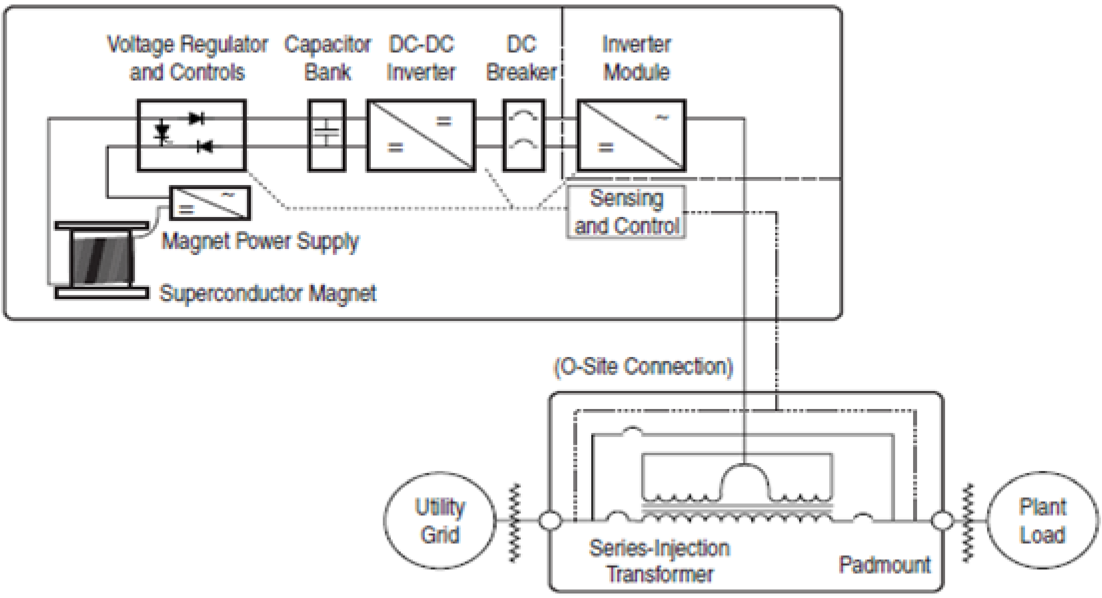

Fig.11. Power quality-voltage regulator (PQ-VR) block diagram

4. The discharge and recharge cycles can be performed thousands of times without any degradation to the superconducting magnet.
5. The recharge cycle is typically less than 90 s from full discharge.

Figure-11 shows the functional block diagram of a common system.

It consists of a superconducting magnet, voltage regulators, capacitor banks, a dc-to-dc converter, dc breakers, inverter modules, sensing and control equipment, and a series-injection transformer.

The superconducting magnet is constructed of a niobium titanium (NbTi) conductor and is cooled to approximately 4.2 kelvin (K) by liquid helium.

The cryogenic refrigeration system is based on a two-stage recondenser.

The magnet electrical leads use high-temperature superconductor (HTS) connections to the voltage regulator and controls.

The magnet might typically store about 3 megajoules (MJ).

The voltage regulator keeps the dc voltage at its nominal value and also provides protection control to the SMES.

The inverter subsystem module consists of six single-phase inverter bridges.

The switching scheme for the inverter is based on the pulse-width modulation (PWM) approach where the carrier signal is a sine-triangle with a frequency of 4 kHz.

A typical SMES system can protect loads of up to 8 MVA for voltage sags as low as 0.25 pu.

It can provide up to 10 s of voltage sag ride through depending on load size.