BATTERY STORAGE PLANTS

A battery storage plant (often called a battery energy storage system, or BESS) is a facility to connect a battery into the utility grid for the purpose of interchanging energy between the utility and the battery, and sometimes to support a specific load. Figure 1 shows the elements of a battery storage plant. It consists of the battery itself; a power converter that can convert between dc and ac, allowing power flow either way; switchgear, transformers, and filters to interface to the utility power; and a controller to command the power flow. The controller is responsive to the utility's need for power and to the state of charge of the battery. Power ratings of battery storage plants currently operating are from 500 kW to 20 MW. Larger units are being planned.

The important characteristics of the battery storage plant compared with other power sources in the utility system are as follows: (1) it may be able to respond very quickly, going from full rated power in the charging direction to the same level discharging in a few milliseconds; (2) it has very small no-load losses, typically 1%, so it can be kept continuously on line; (3) modern designs can provide symmetric current capability in all four quadrants, watts or VARs in either direction; (4) it can be built quickly and located where it is needed. This siting flexibility is a consequence of the very small environmental impact of a battery plant.

APPLICATIONS OF BATTERY STORAGE PLANTS

Functions and Energy Rating

In most cases, the function of the battery storage plant is to accept changes of load that the power generation on the system cannot supply or that the BESS can supply more economically. In some applications the BESS is configured to supply

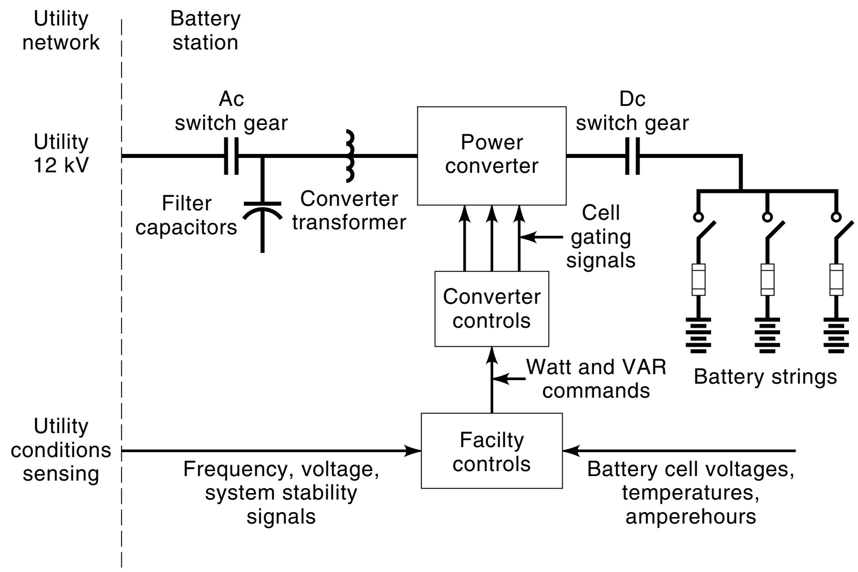

Figure 1. Elements of a battery storage plant.

a single critical load in case of a temporary outage of the local utility.

Most applications provide one or more of the following functions (1), each of which will be discussed briefly:

Load leveling
Peak shaving
Frequency control
Spinning reserve
Power system stabilization
Black start
Reactive power control
Voltage control
Facility deferral
Local load support (power quality)

The requirements for power and energy are highly variable depending on the application. The energy storage capability is defined as the product of the power level and the storage time, measured in watthours. This energy requirement determines the rating of the battery. The cost of the converter and switchgear is related to the power level, measured in watts or volt/amperes (VA).

Load Leveling. Load leveling usually involves storing power during periods of light loading on the system and delivering it during periods of heavy demand. During periods of low demand the battery is charged, usually at lower cost. During periods of high demand the battery station supplies power, reducing the load on less economical peak-generating facilities. For these applications the cycle is usually daily (diurnal), the storage time needed is in the range of 4 h, and the power level is large, up to 100 MW.

Peak Shaving. Peak shaving is similar to load leveling, but may be for the purpose of reducing peak demand rather than for economy of operation. The goal is to avoid the installation of capacity to supply the peaks of a highly variable load. Peak shaving installations are often owned by the electricity user, rather than the utility. The storage time and power rating may be much smaller, typically less than 1 h at a power in the range 0.5 MW to 2 MW.

Frequency Control. The frequency control application involves accepting transient changes in real power loading only long enough for the generating capacity to change its operating level as necessary to accommodate to the loading change. Ratings may be high (10 MW or greater), but the storage time needed may be very small (typically a few minutes).

Spinning Reserve. The term *spinning reserve* implies a generating capacity that is on line and underutilized, so it can be called into service quickly to meet transient needs. The spinning reserve application is the same as the frequency control application, except that the transient mismatch in load power and generated power is thought of as due to a sudden change in generating power; typically the tripping of an element of generation or transmission. The BESS performs much better than a physically spinning reserve due to its fast transient response and small no-load losses. The power handled by the battery station may be much larger than that involved in frequency control and it may be applied very suddenly. The storage time needed is that required to bring reserve generation on line, often less than 30 min, and ratings are 10 MW to 100 MW.

Power System Stabilization. In the power system stabilization application, the battery station is commanded to provide real and reactive power in the direction to damp oscillations, which may occur in the power flow between the generation and transmission elements of the system. These oscillations are most likely to occur when the load on the transmission system is heavy, but often below the thermal limitations of the line. By damping these oscillations, the BESS may allow the lines to be loaded more nearly to their thermal limits. The need for this damping also occurs on fault clearing. The storage time of the battery could be as little as 1 min if used only for this purpose; power levels needed can be up to 100 MW.

Black Start. In case of a total outage of the utility it is difficult to start most rotating generators due to the need for power to start up pumps, blowers, and other auxiliaries. Most BESS converters are capable of starting from the battery alone, so it is possible that the BESS can be used to initially energize the utility system after a total outage. A small (10 kVA or less) uninterruptible power supply (UPS) or station battery may be needed to power the signal electronics of the BESS and the facility control briefly at starting. The BESS can run without cooling for a few seconds until it can power its own blowers. The storage time needed is until other generation can be brought on line, typically less than 30 min, and the power rating of the available converter determines what loads can be connected.

Reactive Power Control. Reactive power control is often called VAR control, meaning control of voltamperes reactive (VARs). The VAR control capability of the battery station comes at no extra cost when the converter is of modern design. The converter is inherently able to deliver reactive power in either direction, leading or lagging, with a rating equal to its rating for real power. The battery is not involved in the provision of reactive power, and could be disconnected from the converter if this reactive power were the only function. The converter can carry out its real power functions and its reactive power functions simultaneously and independently, within its total current rating. The battery converter thus duplicates the function of a static reactive power controller (SRPC or statVAR) of the same rating.

Voltage Control. The reactive power control capabilities of the battery converter can be used for voltage control, load flow control, or power system stability purposes.

Facility Deferral. A utility in need of additional generation or transmission equipment may find itself unable to build this equipment due to difficulty with right-of-way acquisition, siting, environmental delays, and so on. In this case a battery storage plant can often provide a buffer to postpone the need for additional facility. All the functions of a BESS serve to reduce the need for additional generation or transmission capability. Battery plants can be planned and built relatively quickly (3 years or less), and have minimum environmental impact. They do not make noise or require fuel storage facilities. Their emissions and spill hazards are easy to contain. The materials of the batteries are fully recyclable. A battery energy plant can often be located at an existing substation using available land near the loads it serves, so it may require no new transmission lines to do its job. Some studies have shown transmission facility deferral as the most valuable application of BESS (2).

Local Load Support—Power Quality. If the BESS is connected into the utility network by a switch that isolates the BESS and a defined local load, then the BESS can power the local load during out-of-tolerance transients of the utility voltage. In this case the BESS can perform the function of a UPS in addition to its other functions. Power ratings that have been applied this way are up to 2.5 MW, with storage times from 10 s to 1 h. This application is described in more detail in the next section.

Situations Suited to Battery Storage Plants

Power Grids. Power systems in developed countries tend to be connected in grids. That is, all of the power companies over an area of up to 200,000 square miles, serving peak loads of more than 40,000 MW, are connected by transmission lines and by agreements to exchange power among utility companies. In such networks, the transient caused by a sudden change of operating conditions, such as the tripping of a large generator, can be absorbed by spreading it out among the large connected base. Thus, the loss of several hundred megawatts of generating power may be absorbed with a relatively small transient change in grid frequency. Daily demand peaks are smoothed in grids extending over several time zones. In these interconnected utilities there may be a substantial need for the power system stabilization function of a battery storage station, but many of the other functions are not needed. The application of battery storage plants may be hard to justify economically in grid-connected utilities.

Power Islands. In a utility that is an island, that is not connected to a grid, the situation is reversed. In an island condition all the functions of a battery storage station are likely to be needed. This occurs in geographic islands such as Puerto Rico or Hawaii, in political islands such as West Berlin in the 1950s through 1980s, and in remote areas such as Alaska, where the closest other utility is too far away to connect with economically. Almost any utility may become *islanded* for a period of time when a transient disturbance trips the connections within a grid.

In the power island condition, any sudden change in real power must be delivered by the inertia of the local rotating generation until the operating level of the generation can adjust to the change. This means that the frequency will be changed. In an island situation without battery storage, when a large generator or transmission line trips out of service, the only way to prevent an unacceptable frequency change may be to dump load. Those utilities that are permanent islands are good applications for battery storage plants.

Alternatives to Battery Storage

Combustion Turbines. Combustion turbine generators, which are similar to large aircraft jet engines, are relatively economic to build and operate as peaking generators. If they are not already running at the time of need they can be brought on line in 15 min or less. The availability of combustion turbines reduces the need for battery storage stations for load-leveling applications having storage times substantially longer than 15 min. They do not relieve the shorter time needs for battery storage, partly because they are not economical to leave running as spinning reserve. The fuel necessary to operate a combustion turbine at no load is approximately 30% of that required at full load. They cannot approach the speed of response of a BESS, so applications requiring fast changes of load (power system stability, frequency regulation, etc.) are better served by BESS than combustion turbines.

Superconducting Magnetic Energy Storage. A potentially competitive energy storage implementation is by storing the energy in a large air-cored inductor. This system is called superconducting magnetic energy storage (SMES). The inductor is refrigerated to cryogenic temperatures so that the conductors become superconducting and thus have no losses. The power is coupled into the inductor by a solid-state converter, somewhat similar to the battery converter. The efficiency as a storage element can be greater than a battery storage plant. The rapid response is the same. There are disadvantages to SMES. The refrigeration is expensive. The reactive power capability of the SMES converter does not come free as it does in the battery storage converter. The technology is not fully proven. Currently, pilot installations of SMES have been installed or are in operation, but the practical application of SMES may have to await the commercial availability of high-temperature superconducting materials.

Long-term Storage Technologies. Large amounts of energy may be stored by pumped hydroelectric storage or by compressed air energy storage. Neither provides the fast response of a BESS. Pumped hydroelectric storage is in widespread use for daily and weekly load leveling. It is difficult to build new such facilities because of cost and siting difficulties. Compressed air energy storage uses existing underground caverns as reservoirs to store compressed air. The air is compressed and pumped into the cavern using electric energy during off-peak hours and the compressors are reversed as prime movers driven by the released air to generate power during times of peak demand. Some compressed air storage facilities have been operated for over a decade, and a 110 MW compressed air plant was built in Alabama in 1991. The siting requires an existing cavern or abandoned mine to be practical (see Fig. 2).

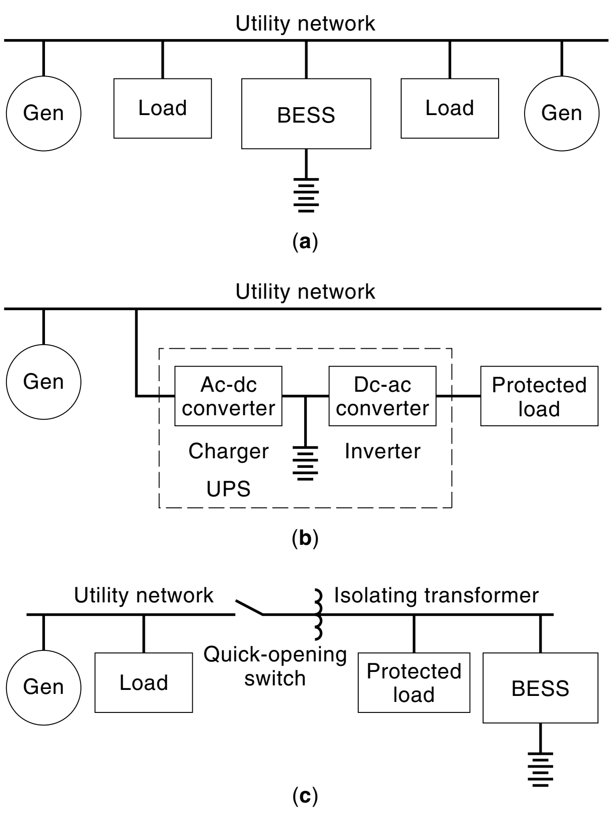

Figure 2. Comparison of BESS to UPS. (a) BESS in an utility system. (b) Uninterruptible power supply (UPS). (c) BESS configured for local load support (power quality).

Differences between a Battery Storage Plant and an Uninterruptible Power Supply

A UPS is often used to provide continuous high-quality power to a critical load such as a computer center. Its configuration is usually as shown in Fig. 2(b). It provides ride-through capability for power outages up to the energy limit of its battery, and it provides complete isolation from variations of utility voltage, frequency, or harmonics. It utilizes a battery and a power converter much like a BESS, although a UPS tends to be of lower kVA rating than a typical BESS application. Figure 2 shows the difference between the two systems. In the UPS there are two power converters, a battery charger, and an inverter. The inverter is a bilateral dc-to-ac converter, very similar to the converter of a BESS. The battery charger is an ac-to-dc converter which cannot return power to the utility. The protected load is normally isolated from the utility, being supplied through both converters. Both the converters normally run under load. The inverter supplies ac at the power level demanded by the load and the battery charger supplies dc to the inverter, while floating the battery. This implies continuous load losses in both converters, whereas the BESS serving as a UPS operates at no-load when utility power quality is adequate. There may be a bypass switch to supply the protected load directly from the utility in the case of failure in the UPS.

The BESS, as shown in Fig. 2(a), has one bilateral dc-to-ac converter that can charge the battery or supply power to the utility from the battery. The BESS is not necessarily associated with any specific load. It carries no current unless there is a specific need for real or reactive power. In the case of undesired variations of utility voltage or frequency, the BESS can provide real or reactive power up to the limits of its ratings to attempt to correct the utility power quality, but it does not buffer any load. The BESS is just one of the power sources on the network comprising the utility.

A BESS can be assigned to perform some of the functions of a UPS by partitioning the load. This function, providing local load support, is shown in Fig. 2(c). In this connection the BESS may be owned by the utility customer. The protected load and the BESS are connected to each other, and the combination is connected to the network through a quick-opening switch. In case of a transient of abnormal power on the utility, the switch opens, and the BESS maintains the power quality to the load until its battery is depleted or until the utility power returns to normal. The BESS does not provide the complete buffering of the load from power quality problems as the UPS does, because it does not have sufficient power to correct the power quality of the whole network while the load is attached to the network. It can provide some improvement in local power quality if an isolating impedance is provided between the local load and the utility. The transformer shown in Fig. 2(c) provides a buffering impedance to aid the BESS in attempting to maintain power quality at the load while the switch is closed.

The BESS used as a UPS can be controlled to absorb transient peak loads drawn by the protected load while it is connected to the utility (peak shaving). This may have significant economic advantage. Miller et al. (3) and Corey (4) describe installations providing the local load support function.

Description of a Battery Storage Plant

Battery storage plants are built in two configurations. In the large installations, the facility is usually in a special-purpose

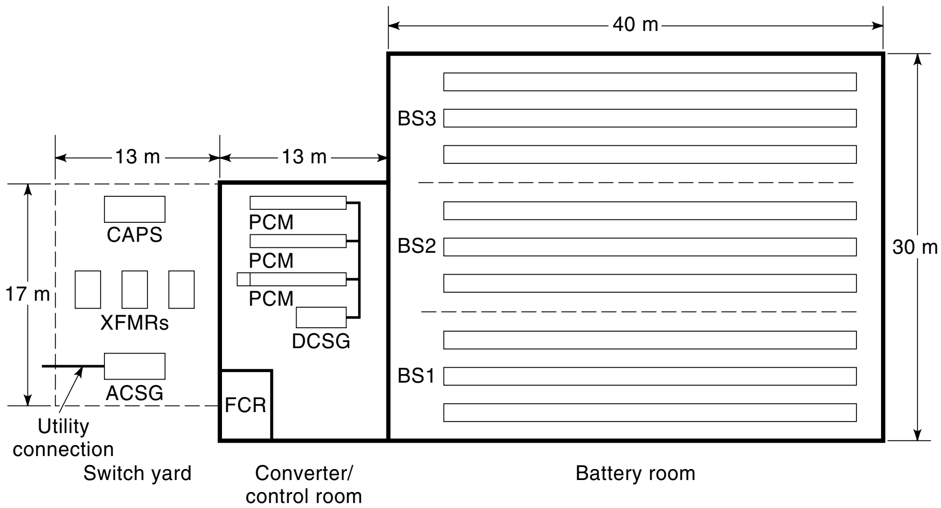

Figure 3. Equipment layout of a battery storage plant, 10 MW, 5 MWh. ACSG, ac switchgear; BS1–3, battery strings 1–3; CAPS, filter capacitors; DCSG, dc switchgear; FCR, facility control room; PCM, power conversion modules; XFMR, converter transformer.

building because of the size of the batteries and equipment. In installations with very small energy requirements (0.006 MWh) a modular approach is available that provides the entire system in a prepackaged outdoor module (4).

Figure 3 shows the layout of the equipment of a typical large BESS facility. This example is rated 10 MW with 30 min storage. This is not a specific existing site but is similar to one-half of the Puerto Rico BESS installation described in Refs. 5 and 8. The layout in Fig. 3 shows the same elements as the one-line diagram in Fig. 1.

The battery room is on the right. Its dimensions are 30 m × 40 m. The battery consists of three parallel strings of 1000 cells each. Each battery is rated 2083 A for 30 min to a final voltage of 1.68 V per cell (1680 V for the string). For the set of three strings, the total minimum rating is 6249 A dc, 1680 V dc, 10.5 MW. Batteries are lead-acid technology. Each battery cell is 33 cm wide × 36 cm deep × 56 cm high and weighs 209 kg. The cells are mounted in racks, two cells high. A disconnect and fuses are at the end of each string. There are facilities for supplying water and compressed air to the batteries and for monitoring the voltage of each group of four cells. The battery room is ventilated by forced air but is not heated or cooled in temperate climates.

The dc power is bussed to the converter hall and through dc switchgear to the converter. The converter consists of three identical power cabinets and a small central control cabinet. Each converter cabinet is 7.9 m long × 1.2 m deep × 2.4 m high. The converter cabinets are cooled by forced air. The output of each cabinet is approximately 1600 V rms, 3.3 MVA, 60 Hz. The waveform of each cabinet's ac output is a three-phase square wave with one or more notches or periods of zero voltage on the wave. The outputs of the three cabinets are each phase shifted by 20 electrical degrees from the next. These outputs are combined in three transformers, with the line-side windings in series, in such a way as to generate a three-phase output with harmonics canceled up to the 17th harmonic. The losses of the converter and transformers are less than 1% of rated power at no load and less than 3% at full load.

The transformers and switch gear are located in the switch yard, 13 m × 17 m. The voltage at the high-voltage side of the transformers is 12 kV. It is connected to the utility at this voltage through a circuit breaker. There are capacitors rated 1.4 MVAR located in the switch yard for harmonic filtering of the transformer output.

There is a control room in the converter hall where the facility is monitored and controlled. The voltages of the battery's individual four cell modules are monitored as well as electrical parameters in the converter and those of the utility. Auxiliary functions, such as temperature and blower status, are also monitored. The central control issues commands to the converters for magnitude and direction of real and reactive power and sequencing information, for example, to stop or standby.

Example Locations of Battery Storage Plants

Table 1 gives the location and a few facts regarding some specific battery storage plant applications. The references cited in the first column (3) to (9) give more information on certain applications.

BATTERY CONSIDERATIONS

Selection of a Battery Technology

At present, lead-acid batteries are the technology of choice. There are a wide variety of alternative technologies that have been and continue to be developed. At the time of this writing, the primary development is the zinc/bromine battery, which uses a pumped electrolyte system. Other battery technologies are being developed, driven by electric automobile requirements. These may be applicable to BESS purposes when fully developed. However, no technology has become commercially available that competes economically with the lead-acid battery.

The type of lead-acid batteries used for BESS are usually referred to as stationary batteries. The applications for stationary batteries are those in which the battery is under continuous light charging and is given a deep discharge only infrequently. This is typical of batteries used for telephone systems, emergency lighting, UPS, and station batteries in utility plants. In contrast batteries used in traction are seldom charged during a utilization cycle and are usually dis-

Table 1. Description of Several Battery Storage Plants

Owner/Location (Reference)	Power Rating	Energy Rating	Converter Technology	Battery Technology	Battery Voltage	Application
BEWAG, AG, Berlin, Germany (6)	8.5/17 MW	4.5 MWh	Line-commutated	Flooded	1180 V	Frequency control
Kansai Electric Power Co., Osaka, Japan (7)	1.0 MW	4.0 MWh	Self-commutated	Flooded	1052 V	Test plant
Southern California Edison, Chino, CA (8)	10 MW	40 MWh	Self-commutated	Flooded	2064 V	Load-leveling, PS stabilization
Crescent Electric Coop., Statesville, NC	0.5 MW	0.6 MWh	Self-commutated	Flooded	648 V	Peak shaving
Puerto Rico Electric Auth., San Juan, PR (5)	20 MW	10 MWh	Self-commutated	Flooded	2000 V	Spinning resv., freq. control
GNB Technologies, Vernon, CA (3)	2.5/5.0 MW	2.5 MWh	Self-commutated	VRLA	756 V	Local load sup., peak shaving
Metlakatla Power & Light, Metlakatla, Alaska (9)	0.8/1.2 MW	1.27 MWh	Self-commutated	VRLA	756 V	Peak shaving, freq. control
Oglethorpe Power Corp., Homerville, GA (4)	1.0 MW	5.6 kWh	Self-commutated	Flooded	576 V	Local-load support

charged deeply every day and recharged every night. The technology of stationary batteries has been under development for decades. Calcium-lead alloy is preferred to antimony-lead because the former has a much lower self-discharge rate under stand-by conditions. Because of this, the calcium-lead batteries require a smaller float charge current, and thus have a longer life under float charge operation. The diurnal load-leveling applications for BESS call for a deep-discharge, high cycle life battery which may differ from the traditional stationary battery application.

These calcium-lead batteries are available in two configurations; the flooded cell and the valve regulated lead-acid cell (VRLA). The flooded cell is usually vented. It has excess electrolyte and consumes water in normal operation. The VRLA cell is sealed (with an overpressure vent) and uses a gelled electrolyte or a glass separator impregnated with electrolyte (10). The VRLA cell requires no watering maintenance, it releases less gas to the environment, and there is little risk of massive leakage or spill of the electrolyte. It is more sensitive to nonuniform temperature throughout the rack, and has been known to enter a thermal runaway state. The life of the VRLA cell is shorter than that of the flooded cell, when both are maintained properly. Life values quoted are generally in the range of 10 to 15 years for flooded cells and 5 to 8 years for VRLA (10). Life estimates for batteries used in utility energy storage applications vary widely with application details. The life is particularly sensitive to the number and depth of discharge cycles and the ambient temperature.

The vented flooded cell requires both periodic watering (every 1 to 3 months) and periodic electrolyte stirring. The effort involved in watering is reduced by providing a system of watering tubes to each battery. Electrolyte stirring is necessary to prevent stratification of the electrolyte, which reduces cell performance. The stirring is accomplished by bubbling air through the electrolyte. The bubbling is active intermittently during each day to minimize evaporation of the water. The flooded cells are built in transparent containers that allow the inspection of the individual cells for early warning of the various end-of-life mechanisms. The VRLA batteries cannot be similarly inspected, so electrical tests are recommended periodically on VRLA cells to identify incipient failures. The flooded cells require a sill around the floor of the battery room to contain a large acid spill should one occur.

A decision between these technologies will depend on the specific application. As of this writing, the very large installations are better suited to the flooded cells, because they are available in larger ratings on a per cell basis. Thus there are fewer cells, fewer connections, and a more economic installation. Larger VRLA cells are in the process of becoming available. The factors affecting the decision between these two technologies are likely to change as development proceeds on both technologies.

Numbers of Cells in Series and in Parallel

In most BESS applications the number of cells needed to meet the energy requirements exceeds the number desirable in series. The resulting voltage would be too high. Thus, the cells are configured with cells in parallel and in series. The individual cells are not connected directly in parallel because a cell that fails in the shorted mode may be destroyed by the fault current fed to it by any cells directly in parallel. For this and other reasons, the cells are combined into strings one cell wide and as long as necessary to provide the desired voltage level. Each string is provided with a disconnect at each terminal of the string and with overcurrent protection to clear any fault in the wiring or the other battery strings (11). Each string can be disconnected separately for maintenance while the rest of the BESS continues to function.

The desirable voltage for most large banks is the maximum voltage that can be accommodated (12) in order to reduce the currents at all points. In the example 10 MW installation, the nominal voltage that could be accommodated was 2000 V dc. The resultant current per string was over 2000 A, and the converter input current was over 6000 A. These current levels require massive conductors and switchgear and great attention to maintaining low resistance at all connections.

The voltage selection is limited not by the battery but by the other components in the system. The power semiconductors are not voltage limiting at the present time. The devices needed are generally available with peak ratings up to 6000 V. This would be adequate for a dc voltage of approximately 3500 V maximum without series operation of semiconductors. Large induction motor drives (which are very similar to BESS converters) normally operate with dc levels of 6000 V dc or higher with power semiconductors in series.

The limiting parameter is often the dc switchgear and its accessories. A large variety of high power switchgear are not available for dc voltages higher than 3000 V maximum. Other practical considerations (battery racks, battery sensors, etc.) also put limits at around 3000 V dc. The voltage selected for recent large installations has been 2000 V nominal (1000 cells). This may result in a maximum voltage in the range of 2800 V dc at the highest charging mode. The 2000 V level was selected for the Chino and Puerto Rico battery storage facilities as shown in Table 1.

For smaller systems, the battery voltage choice may be made to utilize existing converters designed for induction motor drives in the 1000 hp range, or smaller. This results in a battery of 375 cells or 750 V dc or less. Applications of converters of this type have been described (3,4,9).

Selection of an Energy Rating

The application requirements determine the storage time needed for a particular BESS. Many of the applications could be served by a storage time less than 30 min, but with present battery technology times much less than 30 min are not practical. The internal impedance of the battery drops the voltage below practical values when the discharge time is below the 30 min rate. The characteristics of the cells used in the Puerto Rico BESS are given in Table 2. This table provides the following data: When the fully charged battery is discharged in a given time to a given final voltage, what is the maximum value of current which can be drawn? This battery is defined as discharged when the voltage reaches 1.68 V per cell. The data in this table show that the higher currents associated with shorter discharge times drop the battery voltage below acceptable levels well before the electrochemical energy in the battery has been fully recovered.

It would appear that development of batteries with lower internal impedance would allow the use of a much smaller battery for applications such as frequency control, which require only short storage times. Although some progress has been made in this direction, the concept is limited because battery life is enhanced by keeping the discharge cycle depth small with respect to full discharge capability.

Table 2. Discharge Characteristics of the Cells Used in the Puerto Rico BESS

Discharge Time, Hours	Average Amperes	Capacity, Amperehours	Percent of 5 h Capacity
5.0 h	453 A	2265 Ah	100%
3.0 h	696 A	2088 Ah	92%
1.0 h	1680 A	1680 Ah	74%
0.5 h	2560 A	1280 Ah	56%

Source. From Torres et al. (5).

Battery Efficiency

The round trip efficiency (one charge and discharge cycle) of the various batteries is generally between 78% and 85% depending on battery characteristics and rate of charge and discharge. The efficiency may be important for load-leveling diurnal storage stations. If the primary goal is to utilize low-cost off-peak power to supply peak loads, the economic advantage may be lost if the battery efficiency is low. But in most of the other applications battery efficiency is not a controlling parameter. The BESS is under heavy load for so little of the total operating time that small improvements in efficiency have negligible impact on lifecycle costs. The no-load losses of the battery and converter may be much more important to minimum operating costs. These losses may be less than 1% of the BESS rating.

Battery Monitoring

In most applications automated monitoring of cell voltages and temperatures is a requirement. With thousands of cells in a site, manual monitoring would be prohibitive and dangerous. In the process of charging and discharging the battery strings, some cells have slightly better coulombic efficiency than the others. This results in an overcharge on some cells and an undercharge on others. If this process is allowed to continue indefinitely, some cells can be reversed and may be damaged. This unbalance can be detected by monitoring cell voltage and cell temperature. The voltage is typically monitored in sets of four to six cells, or as many as can be combined without masking the deterioration of one cell in the set. The unbalance can often be corrected by an equalizing charge, bringing the charging voltage well above 2.3 V per cell for several hours to refresh the charge on those cells that are not being fully charged by the float voltage. In some cases, the cell must be replaced.

SELECTING AND RATING THE CONVERTER

Choice of Power Semiconductors

Power semiconductors suited to converters for battery energy storage converters fall into the following classes:

Thyristors (SCRs). Latching devices that are turned on by a pulse to the gate terminal and can be turned off only by reversing the anode current.

Gate Turn-off Thyristors (GTOs). Latching devices that are turned on and off by pulses applied to the gate terminal. Included in the category of GTOs is the integrated gate controlled thyristor, or IGCT.

Transistors. Nonlatching devices that are turned on and maintained on by a bias applied to the control terminal. The type of transistor now being applied to BESS converters is called an insulated gate bipolar transistor (IGBT).

All three device types are suited to converters for battery stations, but only the second and third types (GTOs and IGBTs), which can be turned off at the gate, allow the building of converters with independent four-quadrant current capability.

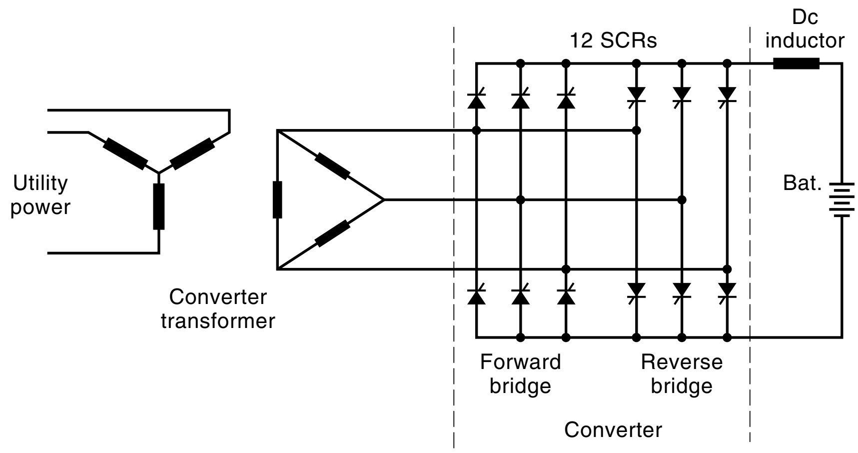

Figure 4. BESS power circuit with a six-pulse line-commutated converter.

The first two types (SCRs and GTOs) are available with peak voltage and current ratings in the range of 6000 V and 6000 A. They can be used without series connection on battery voltages up to approximately 3500 V dc maximum. This is well above the currently used battery voltages of 2800 V dc maximum. The IGBTs are available at the present time up to 3300 V peak, but higher voltages are likely to be available in the near future. At the 3300 V rating, IGBTs could be used in smaller applications without series connection. They would have to be used two effectively in series to provide sufficient voltage margin on the highest battery voltages currently used. Any of these would be a practical design.

Converter Topology Options

Line-Commutated Converter. The power converter can be built as a line-commutated converter or as a self-commutated converter. The line-commutated design is the historic approach. It is suited to SCRs and has been the less expensive approach. Figure 4 shows the circuit diagram of a line-commutated converter. In this converter, each SCR is turned on by a pulse synchronized to the line and delayed a controlled time from the earliest it could have begun conduction. Each SCR is turned off by the next phase of the line voltage, applied by the gating of the next cell. This type of converter was used in the BEWAG application as listed in Table 1 and by Dominik et al. (6). The converter in its basic form consists of two six-cell SCR converters connected in inverse parallel, described as a dual converter in the article on AC-DC POWER CONVERTERS (RECTIFIERS). The characteristics of a line-commutated converter will be discussed here only briefly because they are covered fully in the other article.

The line-commutated converter cannot operate without an energized line, so it cannot black start or provide local load support. It has a basic characteristic that causes the power factor (pf) presented to the ac system to be that of a lagging load. The maximum power factor is determined by the ratio of the dc voltage at the present time to the maximum dc voltage it could make in the charging direction.

$$\text{pf} = \frac{\text{present battery voltage}}{\text{maximum charging voltage that could be made at the present ac line level}}$$

Thus, if the present conditions of the ac line voltage and transformer ratio would allow a battery voltage of 2800 V with the converter gated full-on, and if the battery voltage is now 2300 V, then the power factor is:

$$\text{line pf} = 2300\ \text{V}/2800\ \text{V} = 0.821$$

For a charging load or discharging load of 10 MW, the converter line VA would be given by

$$\text{line VA} = 10\ \text{MW}/0.821 = 12.18\ \text{MVA}$$

The lagging MVAR would be

$$\text{lagging MVAR} = 12.18\ \text{MVA} \times \sin(\arccos \text{pf}) = 6.95\ \text{MVAR}$$

Thus, to get the full 10 MW in either direction, a lagging reactive load of nearly 7 MVAR would have to be tolerated. This fixed relationship between real and reactive power substantially reduces the benefits obtained from the battery storage plant. A BESS attempting to control frequency by variation of real power would also depress ac system voltage due to the reactive power that accompanied the real power. Similarly, for a converter applied as a power system stabilizer, the variation of instantaneous real power needed to damp the oscillation would be accompanied by a variation in instantaneous reactive power, which might aggravate the oscillation.

The power factor can be improved in the line-commutated configuration by using sequential control. This involves substantially increasing the complexity of the converter, using multiple converters in series, independently controlled (see THYRISTOR TYPES). It may be less expensive to use a self-commutated converter, which has no power factor problems.

Self-Commutated Converter (Voltage Source Converter). The voltage source converter (also called voltage source inverter) is the configuration of choice for new BESS applications. It is described in detail in the article on DC-AC POWER CONVERTERS. In its simplest three-phase form it has a power circuit as shown in Fig. 5. The power semiconductors (represented by switches in Fig. 5) must be able to be turned both on and off by gate control. They completely fulfill the function of switches, except that in general they are not suited to carrying reverse current. This is the reason the diode is in paral-

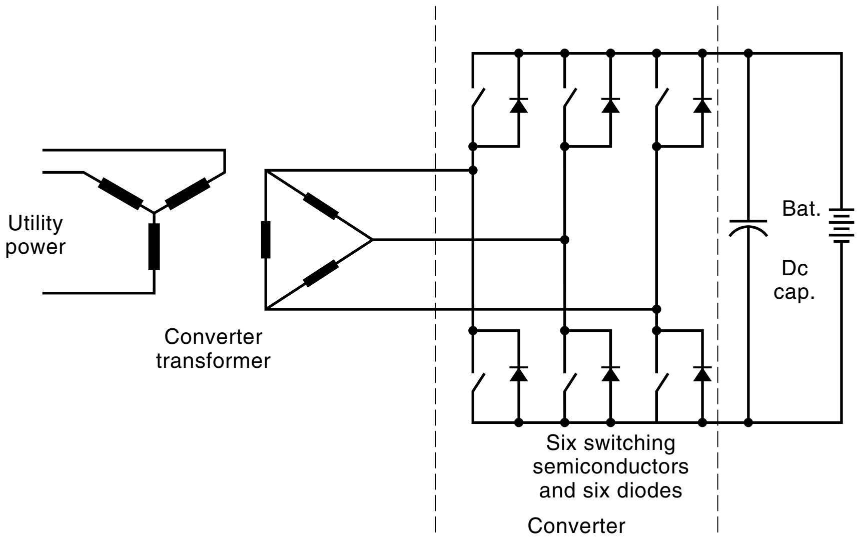

Figure 5. BESS power circuit with a six-pulse self-commutated voltage source converter.

lel with each switch in Fig. 5. This diode may be built into the semiconductor or connected externally. With the diode, the closed switch carries current in either direction, providing a closed connection from the battery terminal to the ac output terminal, hence the name *voltage source.* The voltage source inverter can be built at the present time using GTOs or IGBTs.

The voltage source inverter can be controlled to deliver real power or reactive power simultaneously and independently. It is more flexible in all respects than the line-commutated converter.

Harmonic Currents. Either converter type produces harmonic currents on the line and on the battery. The harmonic currents on the ac line and battery can be reduced substantially by using a converter of high pulse number (as will be explained later). At the battery side, battery life is compromised by ripple current. The voltage source inverter needs a capacitor across its battery terminals for several reasons, and this capacitor absorbs much of the ripple current. The line-commutated converter may need an inductor in series with the battery to reduce battery ripple current. This inductor serves little other purpose, so it is a cost penalty to the line-commutated converter.

Either converter type produces harmonic currents in the ac lines. The harmonic current of the line-commutated converter is defined by the pulse number and voltage control range. For the voltage source inverter, the harmonic voltage (rather than current) is defined by pulse number and chopping mode. These harmonic voltages are imposed across the leakage inductance of the converter transformer (L_0 in Fig. 6) to become harmonic currents in the utility. The level of harmonic current injected by a 12-pulse converter may be similar for the line-commutated and self-commutated converters. The self-commutated voltage source converter provides several design options to reduce its harmonics. With either converter option, harmonic filters are often needed. Considerations involved in selecting a filter are discussed later in this article.

Although the line-commutated converter may be less expensive to build, it has so much less versatility compared with the self-commutated voltage source converter that almost all applications consider only the voltage source converter. For the rest of this article only the self-commutated voltage source inverter is discussed.

Specifying the Voltage Source Converter

Converter Equivalent Circuit. The line-commutated converter is often visualized as constructing a dc voltage waveform from the ac line voltages by selecting appropriate portions of the wave from each phase to form a dc voltage approximately equal to the battery voltage and with as little ripple as possible. By raising or lowering the dc voltage thus generated, the power flow is controlled to or from the battery. The voltage source converter, in contrast, is visualized as taking the battery voltage as input, and forming a three-phase ac voltage which is more or less sinusoidal and approximately equal in amplitude and phase to the three phases of the ac line voltage. The power flow is controlled as it would be if the voltage source converter were a conventional rotating generator: the real and reactive power interchange with the line is controlled by controlling the amplitude and phase of the con-

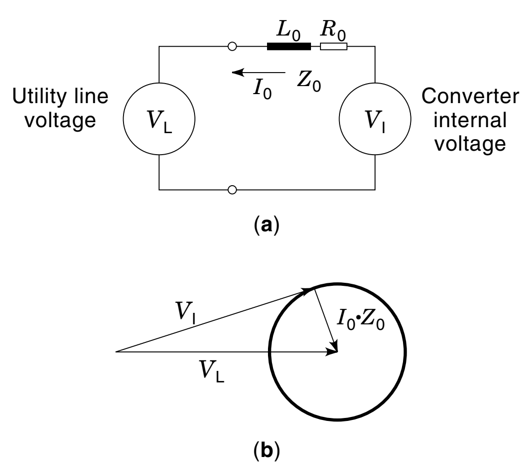

Figure 6. Equivalent circuit of a BESS with a voltage source converter. (a) Equivalent circuit of the utility and converter and transformer. (b).Vector relationships defining converter current.

verter's internal voltage (back EMF) to be slightly different from those of the line voltages.

Figure 6(a) shows the single-phase equivalent circuit of the voltage source converter with its output transformer. It can be considered as a balanced three-phase voltage behind the impedance of the transformer and converter. The impedance of the battery can be neglected in converter application discussions because its effect can be minimized by a feed-forward feature in the controls. The impedance of the battery and its feeders can be important, however, to the stability of the controls. The impedance of the converter is primarily resistive, and should be less than 1%. The impedance of the transformer is primarily reactive and is large with respect to the sum of all resistances. Thus the net impedance (Z_O) of the converter and transformer is thought of as reactive. The value of the transformer reactance is established by the converter system designer based on a variety of factors and is high compared with a general-purpose transformer. It is generally higher than 10%. This level is selected to reduce harmonic currents and currents due to line voltage imbalance.

Converter Control Concept. The control of the converter when connected to the utility that causes it to provide the commanded real and reactive power is based on the difference in phase and magnitude of the converter's internal voltage and the utility line voltage. The current is determined by the vector difference between the internal and utility voltages divided by the equivalent output impedance [shown in Fig. 6(b)]. The value of the converter current is given by the vector expression:

$$I_O = (V_I - V_L)/Z_O$$

Because the effective impedance of the converter and transformer is primarily reactive, the real power is controlled principally by controlling the phase of the converter internal voltage V_I, and the reactive power is controlled principally by controlling the magnitude of V_I. To provide fully independent control of watts and VARs, the control must, in fact, operate on both amplitude and phase in each case, correctly proportioned. One control method used in a BESS is similar to *vector control* as described in the article on INDUCTION MOTOR DRIVES. The concept is to set the converter's internally generated phase voltages approximately equal to the line voltages in amplitude and phase, and to implement current control functions which cause small shifts in the amplitude and phase of the converter internal voltages to cause the desired currents. If the converter output impedances (resistive and reactive) are known and are correctly modeled in the control loops, then the control of real and reactive current can be *uncoupled,* that is, the two components of the current can be controlled independently, even for rapid changes.

For BESS converters that are operated disconnected from the network (in black start or local-load support), the converter becomes an independent power source, and its control must regulate voltage and frequency, as opposed to watts and VARs. A typical BESS will have both modes of control and a way of transitioning between them: the watt/VAR mode when connected to the network and the voltage/frequency mode for operation as an independent source.

Factors Determining Converter Rating. The cost and rating of the converter is made greater by the degree of variability in the application. If there were no variability in the application, then the converter and its transformer rating would be equal to the BESS rating. The actual converter rating is the nominal BESS rating increased by the following factors, all expressed in per unit on the BESS base:

$$\mathrm{KVA_I} = \frac{V_{D,\max}}{V_{D,\min}} \times \frac{V_{L,\max}}{V_{L,\min}} \times \left(1 + \frac{V_U}{Z_O}\right) \times (1 + [\text{rated VAR@}V_{D,\min}] \times X_O)$$

$$\frac{V_{D,\max}}{V_{D,\min}} = \frac{\text{maximum battery voltage}}{\text{minimum battery voltage}}$$

$$\frac{V_{L,\max}}{V_{L,\min}} = \frac{\text{maximum line voltage}}{\text{minimum line voltage}}$$

$$\frac{V_U}{Z_O} = \frac{\text{maximum line voltage unbalance}}{\text{impedance of the converter and transformer}}$$

where unbalance is specified as a difference from the average, not from the highest to the lowest phase

$\text{VAR @ } V_{D,\min} \times X_O$ = maximum VARs to be sourced at minimum battery voltage × the reactance of the converter and transformer

The combination of these factors in a typical application causes the converter design to be at least double the rating that would be required in the absence of these variables. The factor causing the greatest increase in needed rating is the range of battery voltage. Minimizing these variables will produce the least expensive converter.

VAR Specification. To avoid paying for unneeded converter and transformer rating, the BESS should be specified (where possible) to avoid cascading factors that increase rating. For example, the VAR capability specified can be reduced at the operating condition of simultaneous high ac line voltage with low battery voltage. Because VAR output is usually used to raise line voltage, full VAR capability is unlikely to be needed when line voltage is already high. A good rule is to specify real power performance and accept the reactive power capability that inherently results.

Line Voltage Unbalance. Most voltage source inverters present to the line a balanced three-phase voltage behind the impedance of the converter transformer. This is similar to the equivalent circuit of any ac generator, where the impedance of the transformer is similar to the negative sequence impedance of the generator. When the BESS is connected to the line, any unbalance in line voltage will draw an unbalanced current from the BESS calculated by V_U/Z_O, where V_U is in per unit voltage difference from the average phase voltage. This current may add directly to the BESS current depending on the phase angle of the BESS load and of the unbalance, so the BESS must have its continuous current rating increased by this parameter. This is not a truly wasted rating, because the effect of the BESS currents tends to correct line voltage imbalances.

Some converter designs can generate an unbalanced voltage to match the line imbalance. They can then deliver the correct line volt amperes for each phase independent of the voltage imbalance. This avoids the rating penalty from unbalanced voltages and may reduce the ripple current in the battery at the double line frequency due to the imbalance. The features that allow for adjustment of the imbalance in the converter tend to reduce the effective rating of the converter, so that there may be no effective rating gain by providing these features.

CONCEPTUAL DESIGN OF A VOLTAGE SOURCE CONVERTER FOR A BATTERY ENERGY STORAGE SYSTEM

Building Block Approach

Configuration. Figure 7 shows the circuit design of an 18-pulse BESS converter with its transformer connection. The semiconductors with their parallel diodes are shown as switches. The angular position of each of the transformer windings on the figure signifies the phasor position of the voltage on the winding. The process leading to that configuration is now outlined.

A voltage source converter can be envisioned as made up of half-bridge inverters (poles) consisting of two power semiconductor switches with their parallel diodes as shown in Fig. 8(a). The two switches are arranged to connect either the positive or negative battery voltage to the ac terminal, labeled A. By connecting them alternately at a line frequency (f_L) rate, a square wave ac voltage is generated as shown in Fig. 8(a). If three poles are connected as in Fig. 5 or Fig. 8(b) and are gated 120 electrical degrees apart, then the waves generated are as shown in Fig. 8(b): V_{AO}, V_{BO}, and V_{CO} form a three-phase square wave between line and battery neutral. The line-to-line voltages V_{AB} and V_{BC} are square waves with 60 degree periods of zero dwell. When the switches are operated only once per line cycle as shown, then the ac output voltage has an amplitude proportional to battery voltage and a waveform that is relatively high in undesired harmonics. (Note that the center-tap shown in the battery voltage in Figs. 8–10 is for ease of explanation and is almost never used in actual applications.)

The major elements of the design process of the converter are the detailed design of the poles and the selection of methods to connect and gate the poles to:

1. Control the ac voltage magnitude independent of battery voltage
2. Reduce the harmonic content of the ac waveform

The special consideration in battery storage converters is that the rating of the converter is often so large that it is not possible to achieve the rating with a single set of six semiconductor switches as shown in Fig. 5. The additional semiconductors could be connected in parallel or series in the configuration of Fig. 5, but that is usually not the optimum design. A better configuration utilizes the multiple semiconductors to

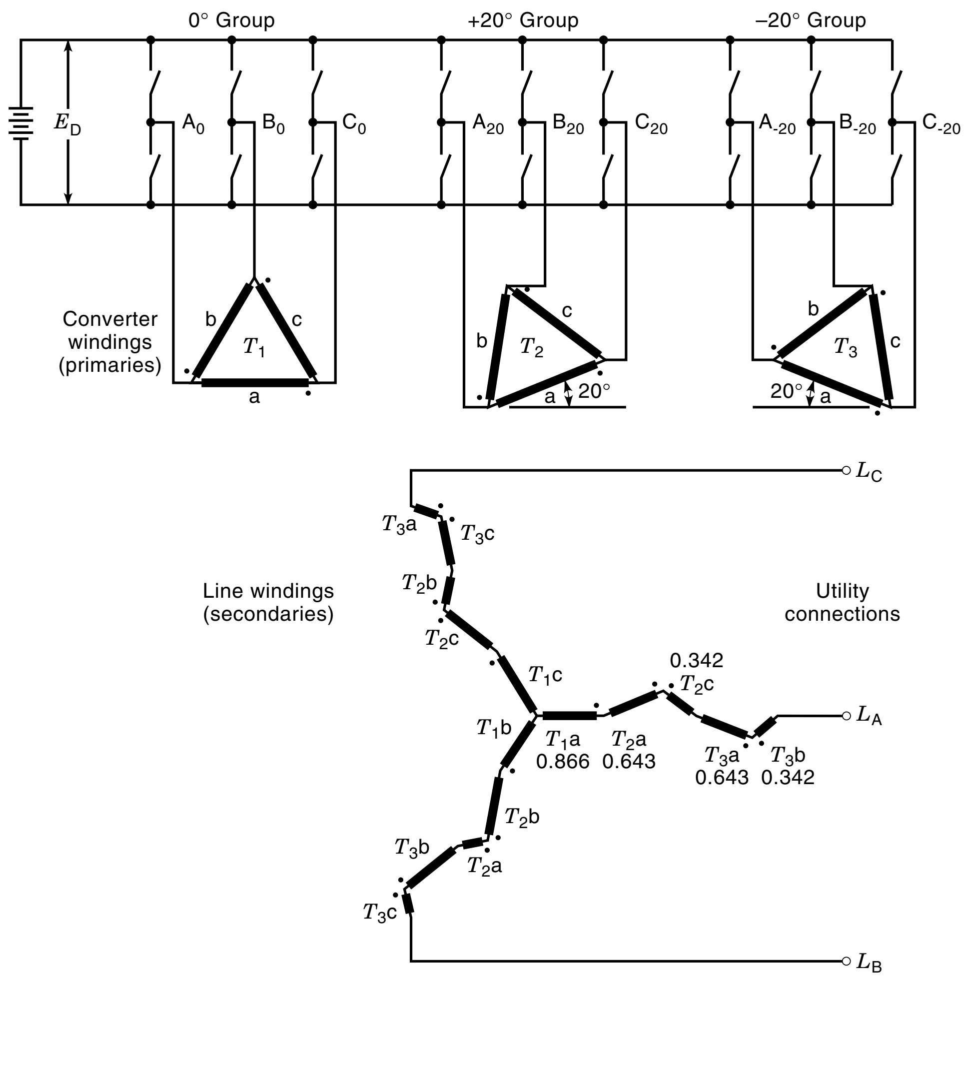

Figure 7. Circuit diagram of an 18 pulse voltage source converter and transformers.

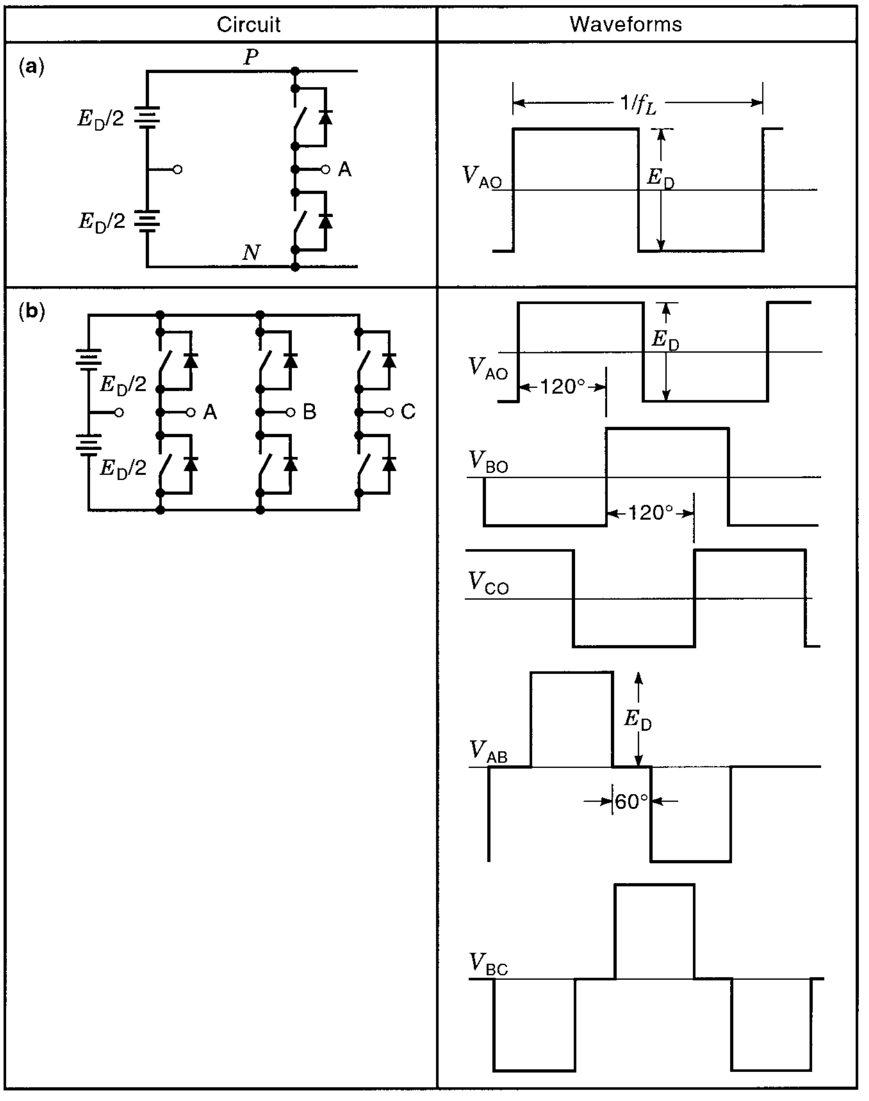

Figure 8. Waveforms in square wave operation. (a) A single pole, in square wave operation. (b) Three poles configured as a three phase voltage source converter. Waveforms shown: V_{AO}, V_{BO}, V_{CO} = line-to-neutral square wave voltages; V_{AB}, V_{BC} = two line-to-line six pulse voltages.

build multiple poles. The individual poles are gated to produce voltages at different phase positions and then are interconnected to accomplish the voltage control and harmonic reduction. The connections generally take the form of multiple poles connected in parallel across the battery voltage, with the outputs of poles connected effectively in series (using transformers) to form the ac output wave. The connections can be selected to fully and equally utilize all the poles, so that the converter rating is the sum of all the pole ratings. Thus, there is no hardware cost penalty in the converter for obtaining the harmonic reduction by multipole connections. A penalty is paid in the complexity of output transformers that combine the poles. Because the transformers are a major component of the hardware cost, the optimum design should consider the complexity of the transformer in selecting a gating and connection scheme.

Switching Frequency. To produce the square wave, each semiconductor is switched once per ac cycle (switching ON and OFF once per cycle). Many common means of voltage control or harmonic reduction involve switching the power semiconductors more than once per cycle. Example waveforms with more than one switching per cycle are shown in Fig. 9. Because each switching of the semiconductors produces switching loss, a higher switching frequency causes more heating of the semiconductors and reduces the operating efficiency and the converter rating. This puts a premium on maintaining a low switching frequency. The ratio of switching losses to conduction losses varies with the type of semiconductor chosen. As semiconductor devices are developed with very low switching losses (and requiring only small snubbers) then the advantages of low switching frequency are diminished. Power semiconductors currently in use for large battery converters are seldom switched above a 1 kHz rate, and efficiency will be maximized by switching them at a line frequency rate (50 or 60 Hz).

Types of Basic Elements

The H Bridge. Figure 9(a)shows a commonly used way to gain voltage control without multiple switchings per cycle. The minimum building block of the converter is a set of two poles, called a *full bridge* or an *H bridge.* The output is taken between the ac terminals of the two poles (between terminals

A and A′). Each pole of the H bridge is driven with a square wave at line frequency. For maximum output, the two poles are driven exactly out of phase (180° apart). Note that the output voltage magnitude $V_{AA'}$ is double that of a single pole. So, for the same current rating in the semiconductors, the VA rating of the H bridge (four switches) is double that of the pole (two switches): no rating has been lost by this connection. For voltage control, the phase of the gating of the two poles is shifted away from 180° by an angle β. The fundamental component of output voltage will be reduced from the maximum available by $\cos(\beta/2)$.

The transformer winding that accepts the output of the H bridge is connected across the two output terminals (A and A′) Thus, connecting a transformer to three H bridges to make a three-phase voltage requires an *open delta* primary winding with all six terminals brought out. By providing a transformer of this type, the H bridge becomes one of the more common building blocks for multipulse converters. It maximizes efficiency (because of the fundamental frequency switching), and it minimizes high-frequency harmonics (has no harmonics due to chopping). Full designs using the H bridge have been described (8,13).

Notched Square Wave. Figure 9(b, c) shows two forms of notched square wave. Both have a switching frequency three times greater than the fundamental. The notch in Fig. 9(b) is in the center of the wave. By varying the width of the notch, the fundamental component can be varied. The control range for the angle labeled γ is 0° to 60°. When the notch width reaches 60° the output wave has become 100% third harmonic and zero fundamental. The third harmonic vanishes in the line-to-line voltage, so the output is zero. This connection produces a mechanism for regulating the fundamental output but increases the higher-frequency harmonics substantially when compared with the H bridge. A large converter built of these elements has been described (14).

Figure 9(c) shows a similar way of generating a voltage-regulated wave in a single converter pole. The waveform may be obtained by extending the center notch in Fig. 9(b) beyond 60°. When the center notch labeled γ passes 60°, the phase of

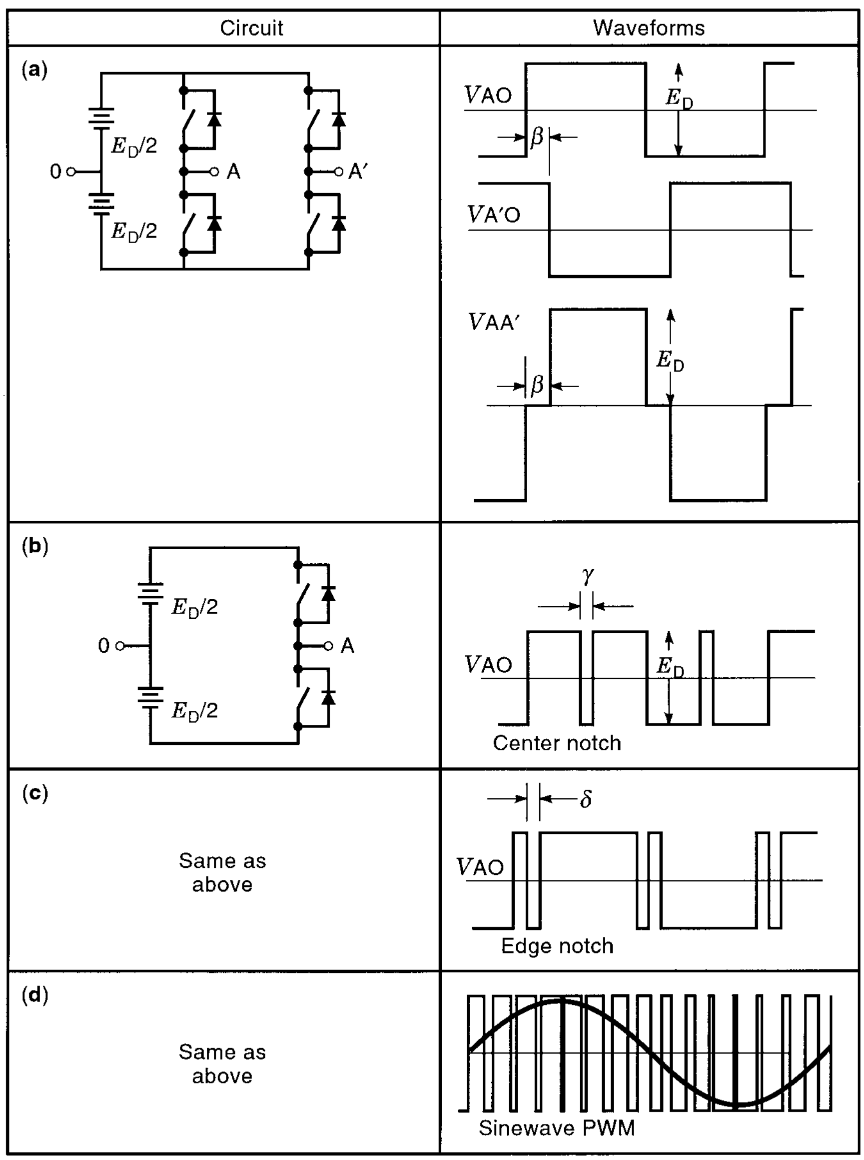

Figure 9. Methods of voltage magnitude control. (a) H bridge (one switching per cycle). (b) Center notch square wave (3 switchings per cycle). (c) Edge notch square wave (3 switchings per cycle). (d) Pulse width modulation (PWM) (15 switchings per cycle).

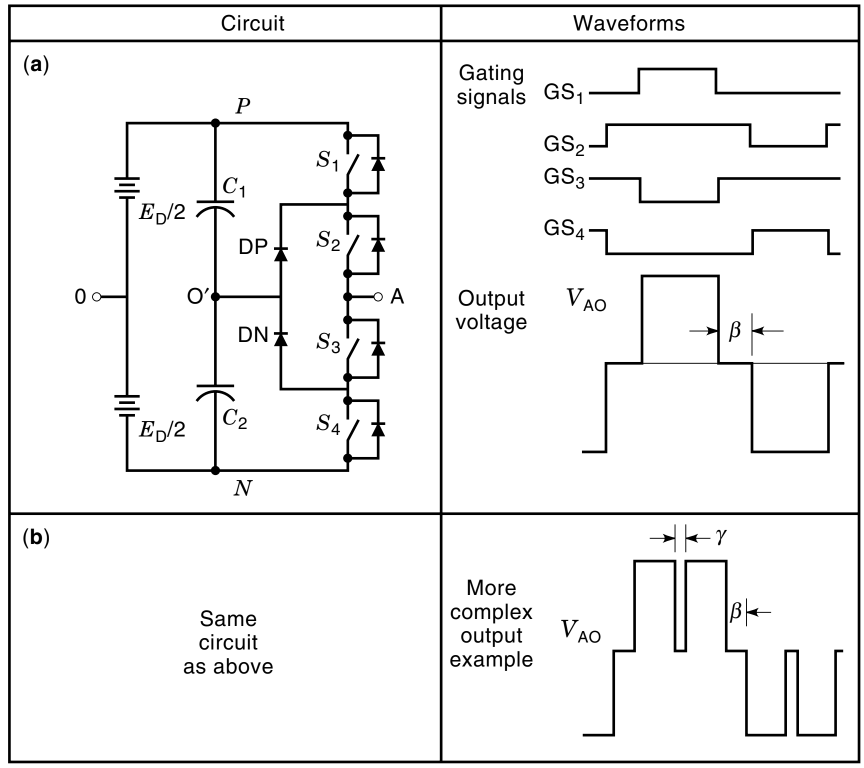

Figure 10. Three-level pole (neutral point clamped, NPC). (a) Circuit and simple waveform for control of voltage magnitude. Gating signals are shown for each semiconductor. One switching per semiconductor per cycle. (b) A more complex waveform with control of voltage magnitude and elimination of fifth harmonic. Two switchings per semiconductor per cycle.

the fundamental reverses, and the amplitude grows from zero to the square wave value as the center notch approaches 180°. If the waveform is characterized by the angle labeled δ as in Fig. 9(c), then the control range is 0° to 60°. The high-frequency harmonics are generally smaller than those of the center notch approach. The application of converters built of these elements have been described but the details were not given (3,9).

Pulse Width Modulation. The two waveforms in Fig. 9(b, c) could be described as *pulse width modulation* (PWM), but the term PWM is generally used for sine-programmed pulse width modulation as shown in Fig. 9(d). The pole voltage is chopped not once per cycle, but many times, with the area of each pulse equal to the average value of the desired sine wave at that point in the wave. This approach is the most common for voltage source converters whose ratings do not exceed that which can be built of only three poles. It allows the voltage regulation and harmonic improvement to be accomplished simultaneously and accomplishes harmonic reduction without complex output transformers. It can have the capability to control current on a per-phase basis, reducing the impact of unbalanced line voltages on the converter currents and reducing battery ripple currents at twice line frequency.

The chopping frequency shown in the PWM example waveform of Fig. 9(d) is 15 times the fundamental. For a 60 Hz fundamental, this would be switching each semiconductor at a 900 Hz rate, at the upper limit of the tolerable range for the larger semiconductors. Acceptable harmonic reduction can be obtained at lower rates, 9× for sine-wave programming and 7× for harmonic elimination modes (15).

Sine-wave PWM has not been commonly used for battery storage converters for several reasons:

1. It has a high switching frequency, hence lower efficiency.
2. It has a high magnitude of harmonics due to chopping frequency. Chopping harmonics tend to be in the frequency range most likely to excite accidental harmonic resonances in the utility network.
3. It cannot get to full output without voiding its harmonic improvement. The maximum output is approximately 90% of square-wave voltage, depending on the details of the modulating strategy.
4. If the rating requires more than three poles, the harmonics can be removed more effectively by the interconnection of the multiple poles.

As further development in semiconductor power components produces devices with very low switching losses, then PWM may be used more commonly to implement a battery converter.

Multilevel Poles. By adding to the complexity of the poles, it is possible to obtain output levels at each pole other than the positive and negative battery potential. Figure 10 shows a pole with two semiconductors in series in each position and two extra diodes. The two extra diodes, DP and DN, are returned to the center point of a pair of capacitors across the battery. The voltage at the capacitor centertap will be maintained essentially equal to that at the battery centertap. The voltage at the output point A can be tied to the positive bus P by gating switches S_1 and S_2, or to the negative bus N by gating switches S_3 and S_4, or to the centertap point O' by closing switches S_2 and S_3. In all cases, the closed switches and diodes provide a path for currents in either direction. Figure 10(a, b) shows examples of the waveforms that can be generated by a single pole of this construction. This connection is called a *three-level* pole or a *neutral point clamped* (NPC) pole.

The waveform of Fig. 10(a) duplicates the waveform of the H bridge, using only one pole and one switch per cycle for each semiconductor. The waveform of Fig. 10(b) accomplishes voltage control and elimination of one harmonic with only two switches per cycle. If the converter is built of three level poles, it can be controlled to have waveforms similar to a converter of twice as many poles. Thus, it can provide improved harmonic performance using a simple three-phase transformer (15,16).

The three-level pole is most advantageous when the semiconductors used do not have adequate voltage rating to be used without two in series. The two switches apparently in series in Fig. 10 (i.e., S_1 and S_2) are each exposed to exactly one half of the dc voltage, with no special provision required to ensure this voltage sharing.

The centertap of the capacitors could be tied to the centertap of the battery. This is not practical and is not necessary. The voltage at the capacitor centertap will theoretically remain centered as the converter operates (there is no net power drawn there). In practice it may be necessary to provide a feedback to trim the gating of the switches to maintain the voltage balance on the capacitor centertap. It is possible to build multilevel poles with more than three levels by extending the concept of a three-level pole.

Pulse Number. The pulse number of a converter configuration gated once per cycle is the number of times that there is a change in output level on the waveform presented to the ac line during one full fundamental cycle. All three output waves must be considered, because at some of the times, the change is effective on only two of the three output phases. In Fig. 8(b) consider the waveforms of V_{AB} and V_{BC}; there are six times when one or more phases have a step in level. This is a *six-pulse* waveform. Figure 11 shows 6, 12, and 18 pulse waveforms. The steps are uniformly spaced in time, and the height of each step is proportional to the cosine of the angle at which the step occurs. Thus a step at zero degrees (at the zero crossing of the wave) has a maximum height and a step at 90 degrees (at the peak) has a height of zero. This accounts for the steps that appear to be missing. The pulse number is generally equal to the number of independently gated semiconductor switches. The higher pulse numbers allow the best approximation of a sine wave, hence the lowest harmonic content. The term multipulse generally refers to more than six pulses.

Characteristic Harmonics. Harmonics are discussed on the assumption that the voltage waveform at each converter pole is a square wave. The pole waveform is often other than a square wave. In these cases the patterns and relationships discussed still apply, but the amplitude of the harmonics that are present will be different. The fundamentals apply as long as the waveforms at all poles are identical. Table 3 summarizes the relationships.

The harmonics of any symmetrical wave at the pole are at frequencies of all odd multiples of the fundamental. For a square wave, the amplitude of each harmonic is equal to $1/n$ of the fundamental amplitude (where n is the harmonic number). This is shown in Column 3 of Table 3.

In a three-phase converter made up of identical poles, the harmonics have a phase rotation as shown in Column 2 of Table 3. The triplen harmonics (whose frequencies are equal to the fundamental times 3, 6, 9, 12, . . ., etc.) are always zero sequence. Zero sequence voltage implies that the harmonics are the same in all three phases as though they were injected between the neutral of the transformer and the centertap of the battery. When a three-phase converter is connected to a transformer winding having only three terminals, as in Fig. 5 or Fig. 7, there can be no zero sequence components (hence no triplen harmonics) imposed on the transformer. If there are more than three terminals on a transformer primary, as in the case with three H bridges, zero sequence can be imposed on the primary and thus on the core flux, but the triplen harmonics still cannot appear on any connection of line side windings, which has only three terminals.

The most common line-side connections have only three connections. Thus, Table 3, Column 4 shows the harmonics for the three-phase connection to have all odd harmonics, with triplens eliminated. This results in harmonic pairs centered on each of the 6th harmonics (6, 12, 18, etc.) of the fundamental. This is the harmonic pattern of a 6 pulse wave.

When there is more than one group of three poles, as in Fig. 7, and they are gated and connected correctly, the connections described as 12 pulse, 18 pulse, and so on, can be formed. Each set of three additional poles raises the pulse number by six and eliminates one of the pairs of harmonics as shown in Columns 4–6 of Table 3. When a harmonic is eliminated, all multiples of that harmonic are eliminated. For example, when the 5th harmonic is eliminated, the 15th, 25th, 35th, etc., are also eliminated.

Gating Patterns. The proper gating patterns for any number of pulses is to gate the first three-pole group as a three-

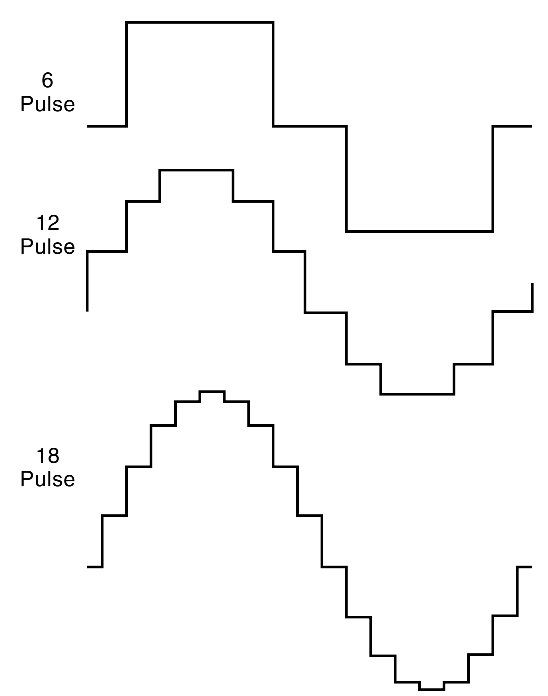

Figure 11. Stepped waves, 6 pulse, 12 pulse, and 18 pulse; composed of square waves.

Table 3. Harmonic Amplitudes of the Output Waveform Composed of Square Waves

Harmonic Number, n	Column 2: Phase rotation of harmonic, three phase	Column 3: Harmonics of a single phase square wave (only odd)	Column 4: Harmonics of a 3 phase, 6 pulse, 3 terminal connection (no zero sequence)	Column 5: Harmonics of a 12 pulse connection	Column 6: Harmonics of an 18 pulse connection
1	Forward	1.000	1.000	1.000	1.000
2	Reverse				
3	Zero	0.330			
4	Forward				
5	Reverse	0.200	0.200		
6	Zero				
7	Forward	0.143	0.143		
8	Reverse				
9	Zero	0.111			
10	Forward				
11	Reverse	0.091	0.091	0.091	
12	Zero				
13	Forward	0.077	0.077	0.077	
14	Reverse				
15	Zero	0.067			
16	Forward				
17	Reverse	0.059	0.059	0.059	0.059
18	Zero				
19	Forward	0.053	0.053	0.053	0.053

phase converter, and to gate each additional group similarly but shifted by a phase angle of 60° divided by the number of three-phase groups. Thus for 12 pulse the two groups are gated at 0° and 30°, for 18 pulse the three groups are gated at 0°, 20°, and 40°, and so on. Figure 12 shows an 18 pulse wave and the component waveforms from which it is composed. Notation is consistent with Fig. 7. The waveforms of Fig. 12 are based on square waves at the converter poles. They show no means of adjusting voltage magnitude. Figure 13 shows a similar set of waveforms in which the voltage of the individual poles is modulated by edge notches as in Fig. 9(b). It is evident that the lowest harmonics present, the 17th and 19th, have been increased by the notched modulation.

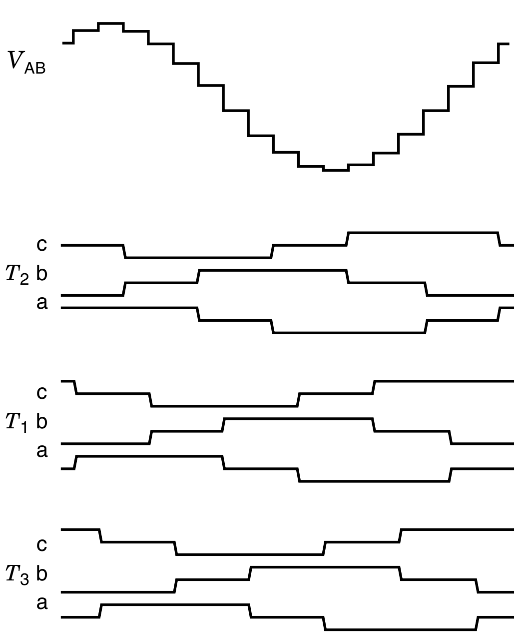

Figure 12. Waveforms of an 18 pulse voltage source converter. Waveforms for the circuit of Fig. 7 when gated for square waves at the poles. V_{AB} = 18 pulse stepped wave at the line-side transformer terminals; T_2 a, b, c, etc. = voltages at the 9 delta windings on the converter side.

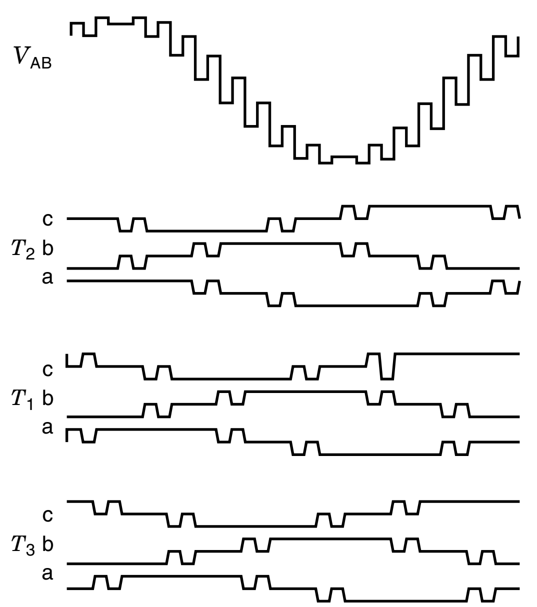

Figure 13. Waveforms of an 18 pulse voltage source converter with notched square waves, showing increase in chopping frequency harmonics on the line output. Waveforms for the circuit of Fig. 7 with edge-notched square waves at the poles. V_{AB} = 18 pulse stepped wave at the line-side transformer terminals; T_2 a, b, c, etc. = voltages at the 9 delta windings on the converter side.

Transformer Connections

Converter Side Connections (Primaries). For a converter configuration having only one three-phase group and three ac terminals on the converter, the transformer can be a simple three-phase transformer. The details of transformer design have to take into account the converter application, such as harmonics or fault currents, but the configuration is a simple three-phase transformer.

If the three-phase converter consists of three H bridges (12 semiconductor switches), the transformer winding connected to the converter must have three isolated windings (six terminals). This allows the H bridges to impose triplen harmonics (zero sequence voltage components) on the transformer. This requires of the transformer (1) a path for zero sequence flux, (2) a winding connection on the line side which tolerates the zero sequence flux, and (3) nothing connected to the neutral on the line side windings (8). The path for zero sequence flux in a three-phase transformer is formed by a *fourth leg* on a three-phase core, with no windings on the fourth leg. Alternatively, the transformer can be made of individual single-phase transformers. No closed delta windings may be used on the line side if there is zero sequence flux on the converter side.

Line-Side Transformer Connections (Secondaries). Figure 7 shows an example of the interconnection of secondary windings to implement a multipulse converter secondary. The definition of a correct winding configuration for a multipulse connection is as follows: In general there is one three-phase transformer for each three-phase converter group, and the line-side windings connect the outputs of the several three-phase converter groups in series to produce the line voltage. Each phase on the line side should be built using windings from all of the three-phase groups in series. Within a line-side phase, the contribution from each three-phase converter group should be zigzagged to get in-phase with the line-to-neutral voltage of that phase and each three-phase group should contribute an equal share of the line side voltage. Once a winding is made that meets the above requirements, it may be simplified to meet the requirements in only the line-to-line voltages if the neutral is not to be used. This simplification can involve wye-delta conversions unless the converter side windings had triplen harmonics imposed.

As a check of a finished winding configuration, when the poles are driven square wave the resulting stepped wave at the line-to-line terminals on the line side of the transformer must have the amplitude of each (uniformly spaced) step proportional to the cosine of the angular position of the step on the wave.

Figure 7 shows an example of such a connection for an 18 pulse converter without triplen harmonics on the primaries. The numbers beside each line side winding are proportional to the turns that must be on each winding to meet the design requirements. Examples of connections for 12 and 18 pulse converters with zero sequence voltages on the primary have been given elsewhere (13,8).

The apparent *neutral* of the line-side windings is usable unless either (1) the transformer winding was simplified by combining windings or (2) the primary voltages had triplen harmonics. If a harmonic-free neutral is required in a design that does not provide one, it is often economical to provide a small zigzag neutral-forming transformer rather than modify the design of the converter transformer.

Harmonic Filters

The harmonic voltages remaining in the converter stepped wave are impressed across the reactance of the output transformer and become harmonic currents injected into the utility network. The magnitudes of the harmonic voltages caused on the utility by these harmonic currents are related to the ratio of the MVA rating of the BESS divided by the available fault MVA at the point in the system at which the BESS is connected. This makes it advantageous to connect large BESS converters at a high-voltage (low-impedance) point in the network. The harmonic voltage levels allowed will be specified by the utility or by an industry standard such as IEEE Standard 519 (17).

Some applications require no harmonic filters. These are the larger installations with 12 pulse or 18 pulse design and no chopping harmonics. They can meet industry standards for harmonic voltage at the point at which they are connected to the utility network, partly because they have low harmonic voltages and partly because they are connected at a point of high available fault MVA.

Most applications require filters. They are connected across the line side of the converter transformer, and take the form of a capacitor or a combination of capacitors and tuned *LC* branches. The VAR rating of capacitors used varies with the installation, but is generally between 10% and 35% of the BESS rating. Larger filters are sometimes used to enhance the capability of the BESS to deliver leading MVARs. The filter design is straightforward, based on the harmonic voltage spectrum of the converter and the impedance of the converter transformer and the network. But if there are other capacitors in the utility network located near the BESS point of connection, additional resonant poles may develop between the capacitance of the converter filter, the network series reactance, and the other capacitors. These other capacitors are often power factor correction capacitors associated with other loads. These capacitors might be switched in and out as needed or installed or removed later. These changes of capacitance cause the unwanted poles to change frequency, so that they may coincide with the higher order harmonics generated by the BESS converter. A harmonic analysis is recommended for all sites to avoid unexpected harmonic problems.

Future Converter Design Trends

The most recent designs for BESS converters combine some harmonic elimination by transformer connection and some by notching the waves. Multilevel and PWM techniques, which further reduce transformer costs, are becoming more practical due to new developments in power semiconductor devices. It is likely that new designs in battery converters will continue to move in these directions.

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BATTERY VOLTAGE BOOSTER. See SYNCHRONOUS CONVERTER TO BOOST BATTERY VOLTAGE.