CHAPTER 3
Voltage Sags Mitigation

3.1 Introduction

The way to classify the equipment providing ride-through for electric loads is by considering the use of some kind of energy storage device. In the following sections, several solutions providing ride-through for electric loads are discussed.

3.2 Solutions using energy storage devices

3.2.1 Battery Back-up Systems

Batteries operate similarly to adding capacitive energy storage with a much higher ratio on an energy per volume basis than standard capacitors [20]. In the ride-through for electric loads application, battery back-up systems can be used to retrofit ride-through for electric loads as add-on modules on the ride-through for electric loads link. The operation of battery back-up systems is limited due to the electrochemical way to store energy into the cells. One of the limitations is the cycle life, which is the number of charge/discharge cycles possible for a given cell. Another limitation is the depth of discharge, which is the fraction of stored energy that can be taken out. Furthermore, the battery back-up systems must be monitored to maintain the ambient temperature within acceptable limits and the proper charging current. The footprint for batteries is large, and high disposal costs must be considered because the waste is hazardous. This technology has an approximate cost of $100-200 per kW[20].

3.2.2 Advanced Batteries

Recent developments in lead acid battery technologies include the thin metal foil (TMF) battery, which holds promise for ride-through for electric loads applications. This type of battery is capable of delivering flat voltage profiles at very high discharges rates, hence achieving very high power densities [21]. Other types of batteries are available with better characteristics but are much more expensive. Advanced battery back-up systems use low cost readily available active materials and employ simple electrochemical reactions, which should lead to excellent durability [22].

3.2.3 Large Capacitor

Capacitors have also been shown to provide ride-through for electric loads capability during voltage sags and short-term power interruptions but for only small loads. Several companies had been considering combining large capacitor banks with ASDs to provide ride-through to critical continuous processes. In ASD applications, the filter capacitors must provide the power to the AC motor during the power line failure. The addition of large capacitors, to increase the storage of energy often used to provide ride-through for electric loads capability, is a brute force method with some drawbacks. The cost of enclosures, fuses, a pre-charge circuit, and bus bars are additional. The addition of large capacitors as an energy storage technology has an approximate cost of $600 per kW [20]. The amount of energy stored *(E)* in capacitors with a capacitance defined as *C* and voltage across the capacitor, *V,* is defined as,

$$E = \frac{1}{2} C V^2 \qquad (3.1)$$

As the voltage decreases when the energy is extracted from the capacitor, only 75% of the total amount of energy stored is available. Special power electronic converters are needed to extract most of the energy stored in capacitors.

3.2.4 Supercapacitors

Supercapacitor or ultracapacitor(double-layer capacitor) technology combines the principle of the electrochemaial double layer. This energy storage technology has proprietary bipolar electrodes characterized by extremely high surface area, excellent conductivity, and a superior chemical and physical stability [23]. Two important characteristics in energy storage devices are the energy density, which defines how much energy can be stored in a given volume, and power density, which determines how fast the energy can be put into or taken out of that volume. These two important parameters have been demonstrated and independently verified on supercapacitor technology. Energy and power densities are reported in order of magnitude greater than known capacitors [23], [24]. The performance capabilities of new engineering advancements are expected to bridge the traditional gap between batteries and capacitors. Therefore, supercapacitor technology is becoming increasingly functional for both specific energy storage and pulse power. This technology has an approximate cost of $300-400 per kW[20].

3.2.5 Uninterruptible Power Supplies (UPS)

One of the main energy storage technologies to mitigate voltage sags and interruptions is the so-called uninterruptible power supply (UPS). The typical configuration of a UPS consists of a diode rectifier and inverter stages. An energy storage device is connected to the DC bus of the UPS. Batteries are the most typical energy storage units used in currently commercially available UPS equipment. New energy storage technologies might become more suitable than batteries. Fig. 3.1 shows a typical configuration for a UPS system. The UPS operates as follows: the load is connected directly to the utility supply by the transfer switch as long as the voltage from the utility supply is within an acceptable range, during this time the inverter is in stand-by mode. During a disturbance, the transfer switch will transfer the load to an alternate supply composed by the inverter and battery bank. The output voltage of the inverter is filtered prior to being applied to the load. The battery bank is assumed to be always charged to ensure a reliable operation of the system. The rectifier takes care of the charging for the batter bank. One advantage of this system is the high efficiency achieved by the use of the inverter only during the ride-through mode. Another approach called “double conversion” keeps the load connected permanently to the inverter. In this case, the load will not be affected by any disturbance coming from the utility grid. In case of voltage sag or power interruption, the battery bank will provide the power required keeping the load undisturbed. The double conversion is completed by and AC/DC converter placed between the utility grid and the inverter: this converter also takes care of the battery charging process. A disadvantage of this method is the double conversion performed in the main power path yielding in a reduced efficiency.

In addition, permanent and expensive maintenance is required by the battery bank is order to achieve peak performance. Furthermore, environmental issues associated with batteries are motivating the exploration of new sources to store energy such as supercapacitors[25].

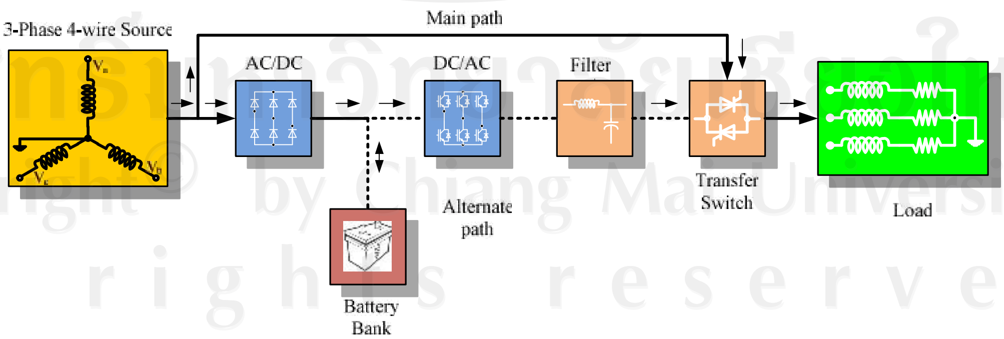

Figure 3.1 Battery based UPS system

3.2.6 Rotary based Uninterruptible Power Supplies (UPS)

This solution is essentially the same approach as the previous one: the main difference is in the nature of the energy storage device. In this case, the energy is stored as mechanical energy in a high-speed flywheel. The flywheel is spinning at speeds above 300 rmp [26], [27], [28]. The amount of energy that can be stored in this system depends on the high speed and the inertia of the flywheel. This mechanical energy is transformed into electric energy by a generator coupled to the flywheel. A promising approach combines the motor-generator flywheel system in on rotary set [36] reducing the size of the entire system. Fig. 3.2 shows typical UPS using a flywheel as the energy backup system.

Opposite to batteries, flywheels do not require an exhaustive maintenance. In addition, the weight and footprint required by flywheel is considerable less. Moreover, flywheels can be interconnected to battery banks to preserve batteries life and add redundancy. However, flywheels are required to provide protection due to hazard potential of high speeds of the rotors.

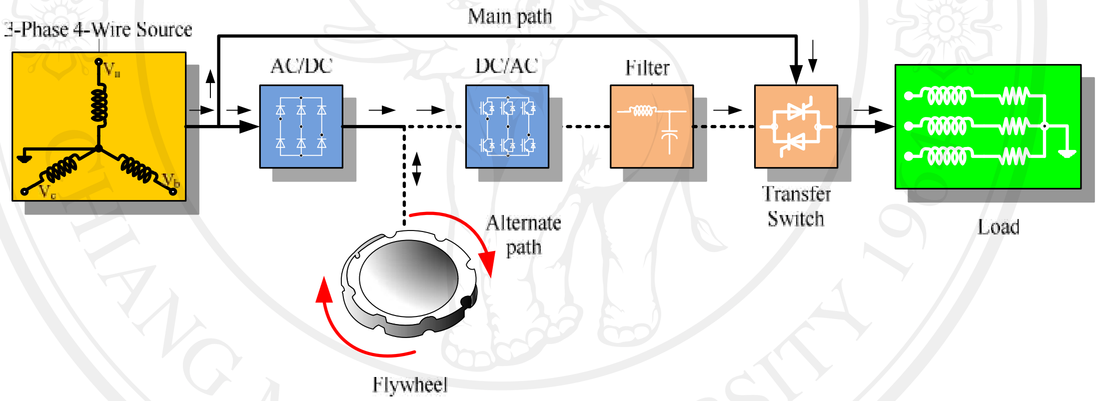

Figure 3.2 Typical UPS with flywheel

3.2.7 Superconducting magnetic energy storage systems (SMES)

This technology is similar to batteries, capacitors and flywheels, which store energy and supplies it when need it. In this case, a set of power electronic converters process the energy stored in a superconducting magnet that is capable of releasing megawatts power to rebuild the voltage coming from then utility supply [29], [30], [31]. Fig. 3.3 shows a typical connection of SMES where a series transformer is used as interface between the SMES system and the main power system.

The amount of energy stored in the magnetic field is given by the following expression:

$$E = \frac{1}{2} L i^2 \tag{3.2}$$

where L represents the superconducting inductor carrying a current i.

Good handle of high power bursts and highly repetitive charge and discharge cycles are some of the advantages of this technology. However, a sophisticated cooling system is required to maintain cryogenic temperatures yielding in high cost and safety concerns.

Recently, this technology has been implement as a mobile solution with the development of SMES on trailers [32], avoiding the construction of special facilities at customer site.

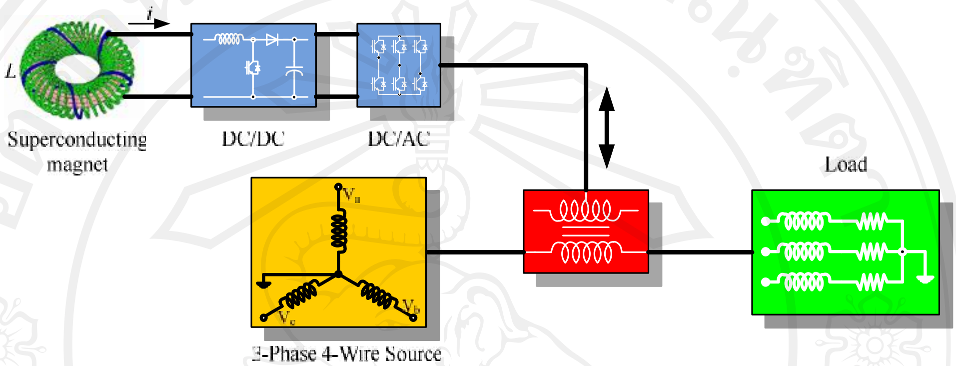

Figure 3.3 Typical superconducting magnetic energy storage system.

3.2.8 Fuel cells

The fuel cell is an emerging technology drawing a lot of attention due to salient characteristics such as [25]:

- Fuel cell are environmentally friendly
- They are efficient and reliable
- Minimum maintenance is required since it has no considerable moving parts
- No fossil fuel is required since hydrogen is the primary fuel source.

However, fuel cells are unable to respond to sudden load changes, therefore they need to be interfaced with batteries. In addition, because of their high cost, it is recommended to operate the fuel cell system permanently connected to the utility grid to maximize its use. Fig. 3.4 shows a typical configuration of a fuel cell and its connection to the electric grid.

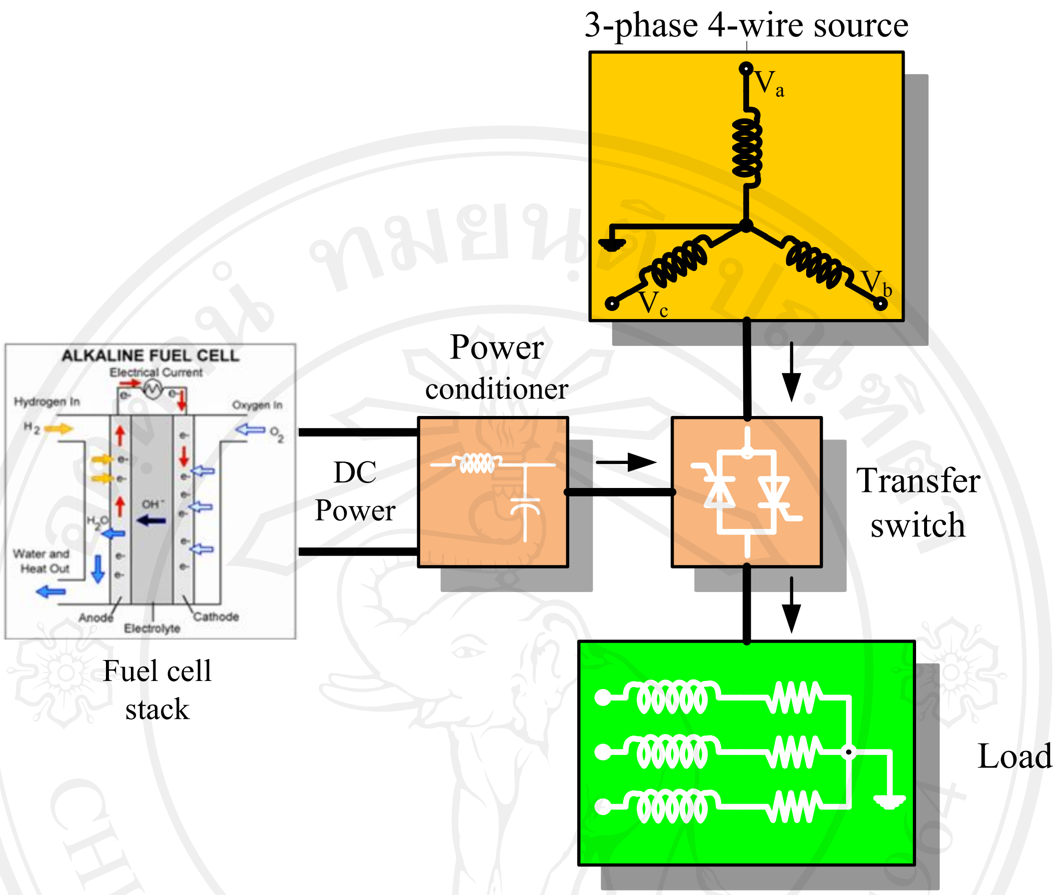

Figure 3.4 Typical fuel cell system used as energy storage device.

One way to operate the system of Fig. 3.4 is that during normal conditions the utility supply and the fuel cell both provide the power absorbed by the load. Then, during a disturbance, the utility supply is isolated and the fuel cell provides the necessary power to keep the load undisturbed. When the disturbance is over, the power from the utility grid is restored to the load. It can be noticed that the fuel cell is permanently providing power to the load. A fuel processor is needed for a fuel other than hydrogen.

3.2.9 Dynamic Voltage Restorer (DVR)

The DVR employs a power converter to generate a voltage that is added to the input voltage to compensate voltage variations. The DVR is considered part of the family of custom power devices. It is a multi-purpose device capable to restore voltage sags and swells, regulate voltages and compensate for harmonic line voltages. Fig. 3.5 shows the concept of DVR.

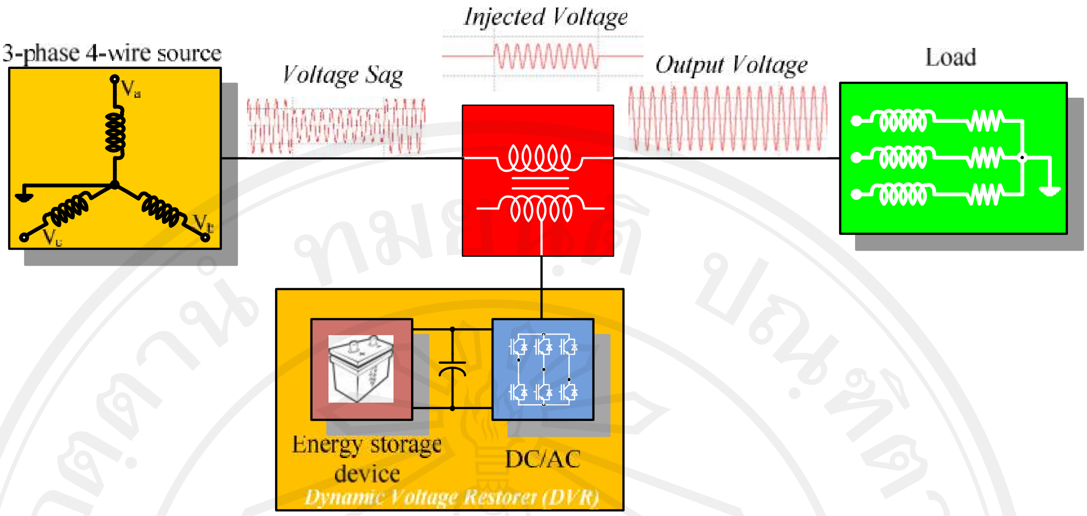

Figure 3.5 Typical dynamic voltage restorer.

The DVR will inject a voltage of compensating amplitude, phase and harmonic content of the line as required by the actual conditions of the utility voltage [33]. A transformer connected in series with the load is injecting voltage to compensate voltage sags and voltage swell.

The capacity of the energy storage device determines the duration of the correction. Electrolytic capacitors are commonly used as DC storage devices. To enhance the load support capability batteries, flywheels or SMES can be connected in parallel with the existing capacitors [34].

3.3 Solution without using energy storage devices

There are some systems capable to provide ride-through without using energy storage devices In this section, a brief discussion of such systems is presented highlighting the salient features of each approach.

3.3.1 Power line conditioners

There are several approaches on this kind of equipment. Most of power line conditioners can be considered as dynamic voltage compensators because they are compensation for the missing voltage from the utility grid. However, they do not require a series transformer as the DVR does, yielding in a smaller footprint. Next, one approach is discussed to illustrate the operation principle of the power line conditioners.

The power line conditioner called dynamic sag corrector (Dysc) [35], [36] is a system capable to provide protection against deep voltage sags and protection against momentary loss of power. As shown in Fig. 3.6, the approach includes a static by-pass switch, which keeps the load connected to the utility supply during normal conditions.

Hence, during a voltage sag, the static by-pass switch is opened and the system compensates boosting the input voltage via the power converter placed between the utility source and the load. It can be noticed that this approach does not need any special energy storage device because it is drawing power from the reduced voltage at utility side. Obviously, to provide ride-through for power interruptions this approach needs to incorporate some kind of energy storage device in the power conditioning stage. The approach presented in Fig. 3.6 can be modified conveniently to provide compensation in three-phase systems.

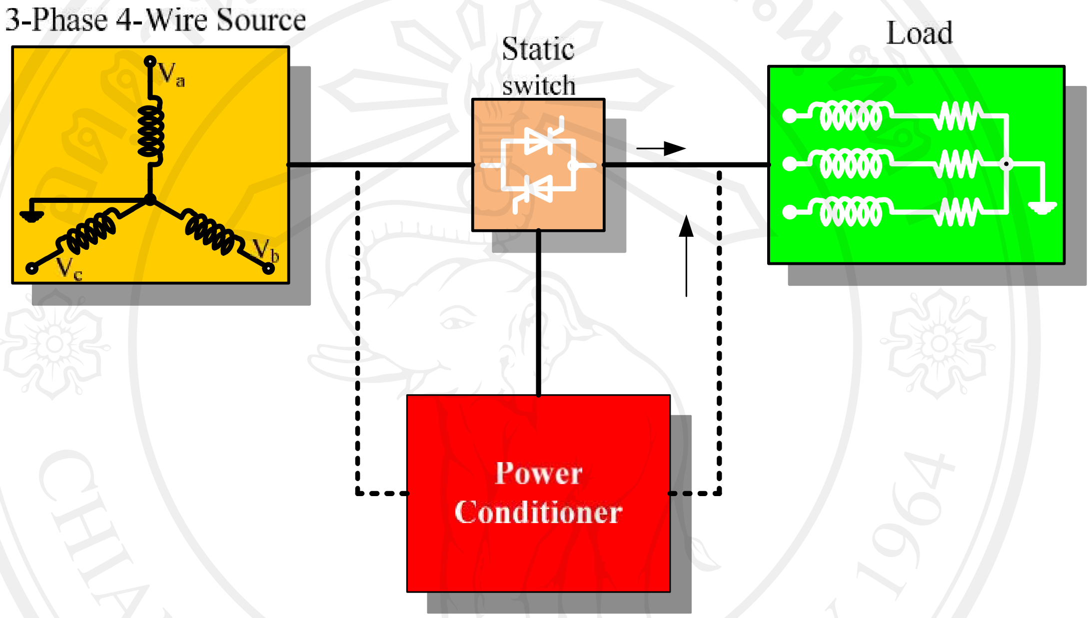

Figure 3.6 Dynamic sag corrector, Dysc.

3.3.2 Static Transfer Switch (STS)

Probably this is the simples approach to provide ride-through. As shown in Fig. 3.7 it consists of an arrangement of solid-state switches along with two independent power sources. One of these sources is denominated preferred power source and the other is named as alternate power source [36], [37].

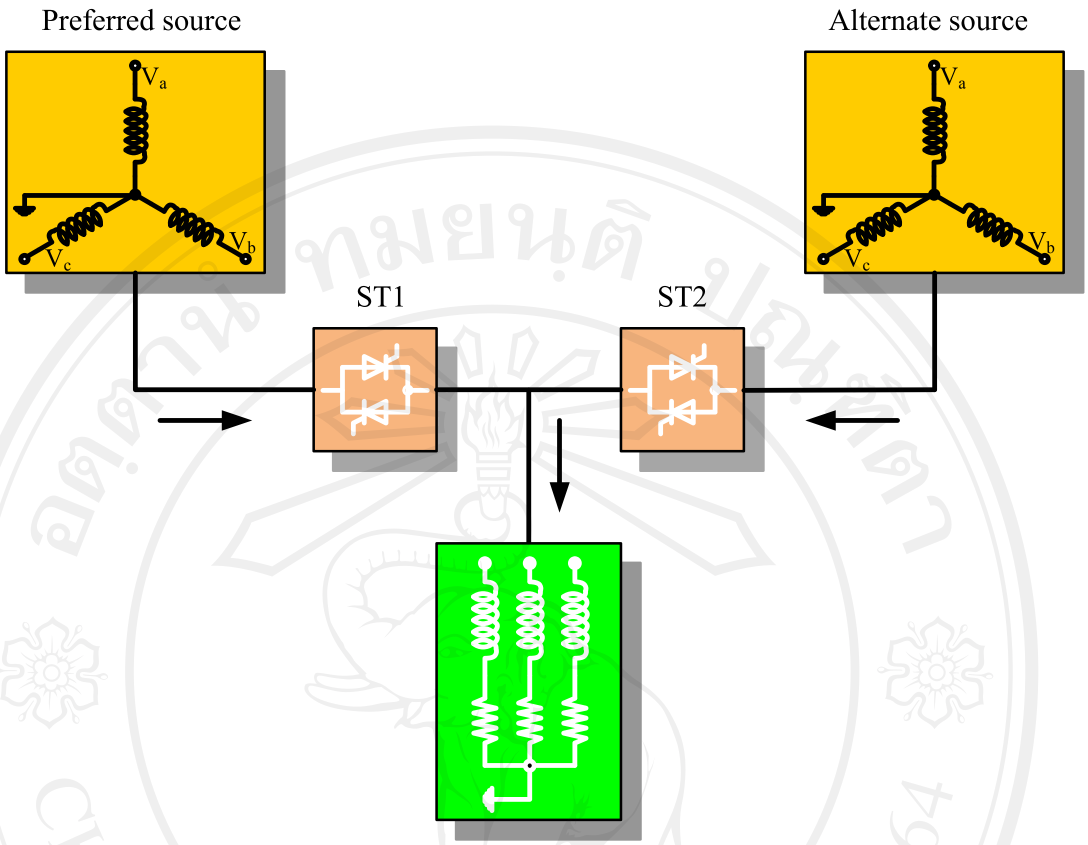

Figure 3.7 Typical static transfer switch system.

Normally, the load is connected to the preferred power source through the solid state switch ST1; it will remain connected to that source as long as the source is under normal conditions. Hence, when a disturbance occurs at the preferred source side, the load is transferred to the alternate source by proper switching of ST1 and ST2. When the preferred source is back to normal conditions, the load is transferred back from the alternate source to the preferred one. In some cases, a transformer can be placed right before the load allowing both sources to be of high voltage. To ensure proper operation, both sources must be independent. In addition to switches ST1 and ST2, mechanical switches are placed in parallel with each solid state switch for maintenance purposes and redundancy.

3.3.3 Transformer with tap changer

A conventional power distribution transformer can be retrofitted with additional windings or taps provide voltage regulation for input voltage variations below or above the nominal input value. Fig. 3.8 shows a transformer with additional windings and static switches to perform the change between taps.

Depending on the input voltage of the transformer is the activation of the proper static switch; for instance, during normal conditions switch SN is activated yielding nominal voltage to the load. In case of a voltage variation, the system will deactivate SN and activate switch SL to compensate for voltages variations such voltage sags.

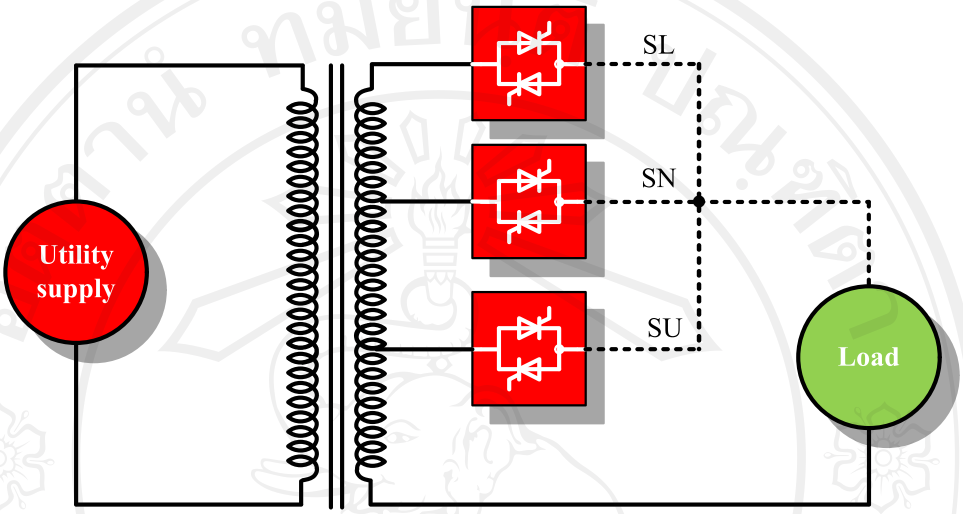

Figure 3.8 Transformer with electronic tap changer.

Similarly, switch SU will be activated to compensate for voltages swells. The amount of voltage compensating depends on the turn ratio of each winding, therefore to achieve quasi-continuous compensation several windings are needed yielding in high volume and high cost. One of the main concerns with this approach is the possibility of transients due to switching taps.

3.3.4 AC-AC converters

In general, these types of converters are intended to work as AC boost converters to provide compensation for voltage sags [38]. Similarly, an AC buck converter is required to compensate for voltage swells. However, a step-up transformer plus a buck converter may operate with input voltages greater than and less than the output voltages respectively. Therefore, the nominal input voltage has to be approximately 0.8 pu for the boost converter and about 1.2 pu for the buck converter respectively. A generic representation o this approach is shown in Fig. 3.9.

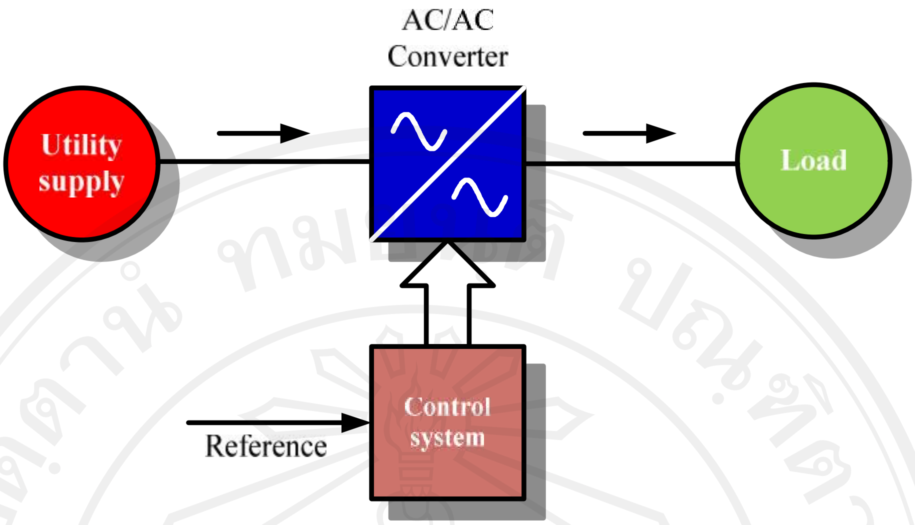

Figure 3.9 Typical AC-AC converter.

An arrangement of L and C devices is required to achieve the boost or buck configuration in the three-phase converter depicted in Fig. 3.8. In addition, since the input and output voltage are AC, bidirectional power electronic switches are needed to implement the switching devices. Consequently, the number of power electronic devices is high leading to high cost. One concern with this type of converters is the difficulty to control each phase independently.

3.4 Conclusions

Two comparative tables are shown next to summarize the characteristics of most of the systems described in previous sections. First, Table 3.1 presents the salient characteristics of the systems using energy storage devices.

Table 3.1 Solutions using energy storage devices.

Technology	Advantages	Disadvantages	Cost
Battery Back-up System	-This system can provide ride-through for deep sags and full outages. - They are easily obtained. - Their transfer time is almost instantaneous	-Additional hardware and space are required, although much less than standard capacitors. - In order to ensure peak performance, more, maintenance is required. - In ASD applications, the corrosion of the electrolyte may be hazardous.	$200/kW
Advance Batteries	-Suitable energy storage technology for smaller ASD loads - There is no transfer time from one power source to another to consider.	- It requires additional critical hardware. - Cost of this energy storage technology becomes prohibitive for large loads. - Pre-charging, recharging and discharging currents require special circuit configurations.	$300 - $400/kW
Large Capacitors	-Large capacitors can provide limited ride-through for minor power electric disturbances. - This technology is a simple and rugged approach.	-The cost is relatively higher. - It requires a large space, additional precharge circuits, and safety considerations.	$600/kW
Supercapacitors	-Longer lifetime than batteries. - ASD ride-through capability for deep voltage sags and STPIs. - A minimal maintenance is required.	-Additional charging circuit and space are required. - They are only available for voltage upto a few volts.	$300-400/kW
Uninterruptible Power Supplies (UPS)	-Simple operation and control. - UPS systems mitigate all voltage sags and short-term power interruptions.	-Normal operating loss due to rectifier and inverter conversions and the use of batteries. - Require maintenance. - Regular testing to ensure proper operation under disturbances.	

Table 3.1(con.) Solutions using energy storage devices

Technology	Advantages	Disadvantages	Cost
Rotary based Uninterruptible Power Supplies(UPS)	- high reliability and ride-through duration of 15s.	-Continuous maintenance is required for rotation components.	\$200-\$300 /kW
Superconducting magnetic energy storage system(SMES)	-SMES requires minimum maintenance, and they are reliable. - Repeated discharging and charging cycles do not affect the SMES performance or life.	-Additional hardware and space are required. - A sophisticated cooling system is required to maintain cryogenic temperatures. - SMES technology involves high costs and safety concerns.	\$600/kW
Fuel Cell	-Fuel cells are efficient and reliable. - Minimum maintenance is required with few mechanically moving parts.	-Fuel cells are unable to respond rapidly to load changes. - The installation involves additional hardware and high cost.	\$1500/kW
DVR	-Versatile	-It requires a transformer in series with the load.	\$500/kW

Table 3.2 Solutions without using energy storage devices.

Technology	Advantages	Disadvantages	Cost
Power line conditioner	- Good for voltage sag compensation	-Suitable for low and medium power	N/A
Static Transfer Switch (STS)	-Simples approach	-It needs dual feed utility supply.	$500/A
Transformer with tap changer	-Simple	- Recommended for small variations.	$500/kVA
AC-AC	-Continuous compensation	- Required many switches	Not commercially available

It is clear from the above discussion that almost all of the solutions are high in cost and are complex. Besides, the majority of solutions proposed to compensate voltage disturbances are concerned with voltage sags because voltage sags are more frequent than voltage swells. Furthermore, compensation of voltage swells is not possible to achieve with some approaches due to technical limitations or resulting high cost. The use of energy storage devices imposes a higher cost of some solutions; however, it brings the advantage of extended ride-though.

In addition, it can be noticed from the approaches discussed before that it is not possible to generalize a solution to provide ride-through because the number of factors involved in every case and the characteristics of each solution.