CHAPTER 1

INTRODUCTION

1.1 GENERAL

The wide spread use of non-linear power electronic devices and the occurrence of faults, pollute the relatively high quality power from the generating stations. The pollution in power is not only due to utilities but also due to the non-linear loads in the industries. So the power quality gets degraded due to the disturbances, occurring in the transmission as well as in the distribution sides. (Flexible AC Transmission System) FACTS devices are employed at the transmission side to overcome the power quality problems. The Custom Power System (CUPS) devices employed in the distribution side compensate for sags, swells, harmonic distortions interruptions etc, to improve the power quality. Moreover many industries based on communication, on-line service, information technology, precise manufacturing technique, advanced control and automation are using embedded systems like computers, micro controllers, microprocessors, and field programmable gate arrays. These embedded systems are very much sensitive to the supply voltage variations. Even a small change in the supply voltage will affect these sensitive loads such that the automated process will be disturbed heavily which will results in data and economic losses.

The severity of a power quality issue depends upon the type of utility. Certain issues may pose a serious problem for a given utility class, but
it may not be considered a big issue for another class. So it is practically quite difficult to rank the above issues according to their severity.

As the various issues originate both from utility and customer sides, the solution is also to be provided on both the sides. While the FACTS devices are controlled by the utility, the custom power devices are installed operated, maintained by the customers at their premises. Hence, line conditioners have been developed to perform the role of regulating, conditioning, isolating, purifying and distributing incoming power with adequate power quality standards. Many Custom Power System (CUPS) devices are commercially available in the market today such as, active power filters (APF), battery energy storage systems (BESS), distribution static synchronous compensators (DSTATCOM), distribution series capacitors (DSC), power factor controllers (PFC), surge arresters (SA), super conducting magnetic energy storage systems (SMES), static electronic tap changers (SETC), solid-state transfer switches (SSTS), solid-state circuit breakers (SSCB), static VAR compensators (SVC) and thyristor switched capacitors (TSC), the Dynamic Voltage Restorers (DVR) and Uninterruptible Power Supply (UPS) systems have been developed recently to compensate voltage harmonics, sags and swells for the entire duration of their occurrence, maintaining a clean regulated voltage at critical loads. While UPS can compensate for interruptions, it suffers with disadvantages like higher cost and higher losses compared to DVR since the UPS has to supply power to the load continuously irrespective of occurrence of voltage disturbances.

1.2 LITERATURE SURVEY

A detailed literature survey is presented in this thesis, point to the scope of research possibilities in the area of sag and swell mitigation in the power systems.
1.2.1 Methods and Devices for Power Quality Enhancement

Hingorani (1995) and Woodley et al (2000) illustrated that the pollution in power is not only due to utilities but also due to the non-linear loads in the industries. The power quality also gets degraded due to the disturbances, originating from both the transmission and the distribution side as explained by Elmofty & Youssef (2007). FACTS devices are employed in the transmission side as they allow for increased controllability and optimum loading of the lines without exceeding the thermal limits. Domijan et al (2005) highlighted the use of Custom Power System Devices (CUPS) in the distribution system for greater reliability and a better quality of power flow to the load centres by compensating power quality issues like voltage sags, surges, harmonic distortions, interruptions and flicker. Koval et al (1993) and Daehler et al (2003) highlighted that it is mandatory to maintain the power quality of the system in order to avoid process disturbances in the precision and automated industries, which employ many embedded systems and controllers, which are very sensitive to power supply disturbances.

Different Power Quality issues like voltage sags, swells, outages, under and overvoltage, harmonics, flicker, frequency deviations, spikes or surges, and electrical noise and are listed in the literature Kara et al (1998) and Bulent et al (2008). Therefore, different types of tools are required to analyse these phenomena and different compensating techniques are to be employed to mitigate their effects.

It is practically quite difficult to rank the various Power Quality issues according to their severity. A recent literature survey by Banaei et al (2006), Fitzer et al (2004), Vilathgamuwa et al (2002), Fitzer et al (2002) and Bollen (2001), reveals that as far as industrial and commercial customers are concerned, voltage sag is the most important, when compared to the other
power quality issues. This is due to the high risk attended with frequent operation of tripping devices.

IEEE Standard 1100-1992 in IEEE Emerald Book defines voltage sag as, “a rms reduction in the AC voltage, at the power frequency, for durations from a half-cycle to a few seconds”. If the voltage is reduced to zero, it is said to be an outage. The voltage sags are also caused due to the heavy starting currents of big motors, switching of large loads, putting on power transformers and equipment faults as explained by Bollen (2001).

Voltage swell is defined as, “a short duration increase in rms supply with an increase in voltage ranging from 1.1 p.u. to 1.8 p.u. of nominal supply”. Sanchez & Acha (2009) highlighted that the main reasons for voltage swells are switching large capacitors or the removal of large loads.

The reasons for interruption are listed by Bollen (1999) which may be due to the malfunction of protection equipment or lightning. In a system without protection, a fault will lead to a long interruption, necessitating manual intervention.

Most of the electronic equipment can operate at 80-85% of nominal voltage for several cycles. The operating characteristic of electronic equipment pointed up by Acar (2002) is shown in the Figure 1.1 and it is originally given by Information Technology Industry Council (ITIC).

It was suggested by Middlekauf & Collins (1998) that either the process equipment should be made less sensitive, allowing it to ride-through the disturbances or install a custom power device to suppress or counteract the disturbances.
In order to mitigate the voltage sag, swell and interruptions, many CUPS have been realized as listed in the previous section. Generally the CUPS can be classified as shunt and series compensators. So a survey is presented by comparing the DVR with all other shunt and series compensators. Chan et al (1999) compared three types of popular devices.

![Figure 1.1 The ITIC Curve](image)

**Figure 1.1** The ITIC Curve

![Diagram](image)

**Figure 1.2** (a) Double conversion UPS with energy storage (b) Series connected DVR with energy storage (c) Solid state transfer switch operation
• UPS: Uninterruptible Power Supply converts the AC to DC and stores the energy in the battery. Then the stored DC is again converted to AC and delivered to the utilities. It mitigates most of the power quality problems with a double conversion process. The topology is illustrated in Figure 1.2a.

• DVR: Dynamic Voltage Restorer is a series compensator; unlike UPS it mitigates power quality issues only when the supply fluctuates. The DVR topology is illustrated in Figure 1.2b.

• SSTs: Solid State Transfer Switch doesn’t need an energy storage device for mitigation. When a power quality issue occurs it changes from a faulted feeder to a healthy feeder. The topology is illustrated in Figure 1.2c. Some of the advantages and disadvantages with the three solutions are summarized in Table 1.2.

Table 1.1 Comparison of UPS, DVR and SSTs

<table>
<thead>
<tr>
<th>Device</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPS</td>
<td>Can Compensate for Interruptions</td>
<td>High Cost /kW  &lt;br&gt; High Losses</td>
</tr>
<tr>
<td>DVR</td>
<td>Low Losses, Injects only the missing part of the supply voltage, Cost Effective</td>
<td>Difficult to Protect  &lt;br&gt; Cannot compensate Interruptions</td>
</tr>
<tr>
<td>SSTs</td>
<td>Low Standby Losses, Low Cost, Can compensate Interruptions and Voltage Dips  &lt;br&gt; Higher benefit/cost ratio</td>
<td>Needs a second undisturbed feeder, which is difficult to maintain.  &lt;br&gt; Slow Response</td>
</tr>
</tbody>
</table>
Cost-comparison of the three solutions has been done by Chan et al (1999) with reference to the total annual cost, cost of solution per kVA, expected savings, annual operating cost, and benefit/cost ratio. The SSTS is considered to be the best if a secondary independent feeder is present; otherwise the DVR is considered to be the most cost effective solution.

Hingorani & Gyugyi (2000) and Wang et al (1998) explained the compensation of small voltage variation by reactive power injection through shunt controllers like Static Compensators (STATCOM), Static Condensers (STATCON) or Advanced Static VAR compensators (ASVC). As the supply impedance is usually low, the injected current has to be very high to increase the load voltage. So the reactive power injection is very difficult to achieve. Injection of active power by the shunt converter has a poor effect on the load voltage. In order to compensate voltage sag of 0.5 p.u, it has to inject approximately 5 p.u reactive current to stabilize the load voltage. This method requires much stored energy and a shunt converter of rating more than 5 p.u.

Campos et al (1996) shown that the series PWM compensators, static series regulators like the dynamic voltage restorers require only the minimum power for compensation when compared to shunt controllers. For example, to compensate a 0.5 p.u voltage sag the rating of a series compensator could be 0.5 p.u. The supply continues to be connected and no re-synchronization is necessary as it is the case with the shunt connected converter. So the series controller is recognized as a cost effective solution for voltage sag mitigation. Fujita & Akagi (1998) combined the shunt/series controllers which is the unified power quality conditioner (UPQC) with which the performance can be improved at the expense of higher costs.

Ibrahim (2007) compared the advantage and the disadvantages of the various mitigating devices and is shown in the Table 1.1.
Table 1.2 Comparison of mitigating devices

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor-generator set</td>
<td>• High efficiency</td>
<td>• Noise</td>
</tr>
<tr>
<td></td>
<td>• Large size</td>
<td>• Long duration ride-through</td>
</tr>
<tr>
<td></td>
<td>• Low initial costs</td>
<td>• Maintenance requirements</td>
</tr>
<tr>
<td>Electric tap changer</td>
<td>• High efficiency</td>
<td>• Time delay of at least one-half cycle</td>
</tr>
<tr>
<td></td>
<td>• Smooth</td>
<td></td>
</tr>
<tr>
<td>Uninterruptible power supply</td>
<td>• Low cost</td>
<td>• Limited power</td>
</tr>
<tr>
<td></td>
<td>• Simple operation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Simple control</td>
<td></td>
</tr>
<tr>
<td>Static transfer switch</td>
<td>• Effective method for interruption</td>
<td>• Attractive for installations that already have a</td>
</tr>
<tr>
<td></td>
<td>and voltage sags</td>
<td>mechanical transfer system</td>
</tr>
<tr>
<td></td>
<td>• Cheap</td>
<td></td>
</tr>
<tr>
<td>Series-connected voltage source converter e.g.,</td>
<td>• Very effective and attractive for</td>
<td>• Expensive</td>
</tr>
<tr>
<td>DVR</td>
<td>large industrial customers</td>
<td></td>
</tr>
<tr>
<td>Shunt-connected backup source</td>
<td>• Enables a certain voltage support</td>
<td>• Draws high reactive current</td>
</tr>
<tr>
<td></td>
<td>capability</td>
<td>• Low efficiency</td>
</tr>
</tbody>
</table>

It has been decided from the above brief pilot survey that the DVR is a much better device for mitigating voltage sag and swell, meriting further consideration. Hence an in-depth study of technical literature of Direct Voltage Restorers including the design aspects of various sub-systems and components and various configuration arrangements in Power Systems, control etc., has been conducted. Such an extended survey of DVR’s is presented in the following paragraphs.
1.2.2 Literature on DVR Basics

The DVR is a power electronic device, which basically injects a voltage of required magnitude, phase and frequency in series with the grid voltage to mitigate sag and swell. Arindam Ghosh & Gerard Ledwich (2001) presented the conventional DVR which receives the power from an energy storage device like a battery-bank or a super-capacitor of appropriate capacity as shown in the Figure 1.3. So it can supply both active and reactive power at its AC output terminal. It compensates the voltage sag or swell by injecting a set of three-phase AC voltages in phase with the distribution feeder voltages through an inverter and a series transformer. Real and reactive power exchange between the device and the distribution system is varied by controlling the amplitude and phase angle of the injected voltages.

Figure 1.3 Topology of a conventional DVR

Under normal power supply conditions, the DVR should be in off condition such that it should not inject any voltage through the series transformer. At the same time the power has to flow from grid to load. So the low voltage side of the series transformer is shorted either by a solid state bypass switch or by switching one of the inverter legs. The series transformer
will then act as a short circuited current transformer. Since no switching takes place, the power loss is only that of the series transformer. This loss should be kept a minimum as DVR will be in off condition in most of the time. The short circuit impedance of the injection transformer determines the voltage drop in the DVR under normal condition. So this impedance must be low. The short circuit impedance also affects the fault current through the VSI on secondary side caused by a short circuit at load side and. In case of fault or over current exceeding the rating of DVR on the load side, solid-state bypass switches or electromechanical by-pass switches must be provided as a measure to protect DVR from getting damaged.

When a disturbance occurs the DVR will be in the compensating mode and the switches will be modulated to generate the required compensating voltage. When the DVR is compensating, the required energy for compensation has to be supplied by an energy source. The rating of the energy source depends upon load MVA requirement, deepest sag to be compensated and the control strategy applied. When the switches are modulated, the compensating voltage is synthesized by the DVR along with the harmonics. The harmonic content is depending up on the modulation scheme and the switching frequency. Choi et al (2002) explained the design of filters to reduce the harmonics to an acceptable limit.

The factors determining the rating of a DVR are listed by Wunderlin et al (1998) as follows:

- Rating of the load,
- Range of voltage sags to be compensated,
- Duration of voltage sag to be compensated,
- Allowed voltage drop across DVR under steady-state.
1.2.3 **Survey of Energy Systems for DVRs**

In order to compensate large voltage reductions effectively, the DVR requires active power. The active power can be supplied by: (i) Energy storage units (ii) Auxiliary supply units (iii) Line connected shunt converter at the source side or at the load side. Accordingly, the DVR topologies are categorized into three main groups. Wang et al (2006) proposed a topology under first group, in which the required energy for compensation is taken from the dc capacitor or another energy storage element such as a lead-acid battery or even a superconducting magnet. The rating and duration of compensation are proportional to the size and capacity of the energy storage devices. Increasing the rating of the DVR increases the size of these devices and vice versa.

DVRs based on energy storage units suffer from limitations such as, large and costly energy storage units to compensate long duration sags, maintenance problems associated with the storage units and higher weight per kVA rating.

The second group of the topologies uses ac/dc/ac conversion as adopted in Nielsen & Blaabjerg (2005). In these topologies, the required dc voltage is provided through a transformer from the grid (source side or load side) via a rectifier. In both the groups of topologies, it is necessary to embed a large capacitor in the dc link in order to maintain the voltage across the converter. Meyer et al (2008) explained that the compensating time of this topology is proportional to the size and rating of the energy storage elements. The cost of this dc-link capacitor is high and results in limited applications of DVRs. So they cannot compensate sag or swell for an infinite time and this topology also suffers from the same disadvantages of the previous topology. Jimichi et al (2008) have attempted to reduce the rating of the energy storage elements. Though Sanchez et al (2009) have presented DVR based on
multilevel converters it is found that they too depend up on the energy storage devices.

Silva & Cardoso (2002) suggested a few methods to reduce the cost of the DVR, mostly by avoiding energy storage systems, series transformers and also by using converters with reduced number of semiconductor devices and gate-driver circuits.

Only a limited analysis has been done on the DVRs without energy storage devices. Prasai & Divan (2008) proposed a zero energy sag corrector without capacitors which can only compensate balanced and unbalanced voltage sags but it can’t compensate the voltage swells. Perez et al (2006) proposed a single phase DVR based on a matrix converter such that the compensation ranges for voltage sag and swell are restricted to 25% and 50%, respectively. A DVR using indirect matrix converter has been presented by Wang & Venkataramanan (2009) for balanced voltage sags compensation. This topology uses a flywheel energy storage element and the capability to compensate voltage swells has not been examined. As it is based on the energy-storage elements, it cannot compensate the voltage sags for a long time. Moreover, regulation and control of the flywheel speed is complicated. Another matrix converter-based DVR has been presented by Babaei & Kangarlu (2009). The two main problems of this topology are the high number of switches and very limited compensation range. Recently Ebrahim et al (2010) proposed a topology for a DVR based on a direct ac/ac converter, for which the compensation ranges for voltage sags and swells are restricted to 33% and 100%, respectively. A control method has also been proposed in which the switching pulses are generated through a tedious computation process.
1.2.4 Survey on Selection of Converters and Injection Transformers

In a DVR, the power required to compensate the voltage sag or swell is supplied from the energy storage devices or from the grid, to the series transformer through a pulse width modulated voltage source inverter (VSI) and a line filter. Further, the switching losses should be minimized since the DVR conducts the load current continuously and a fast response is needed to maintain the load voltage within power quality standard.

Nielsen (2001) suggested choosing the converter depending upon the switching frequency as it determines the following:

- Generation of switching harmonics
- Ripple current in the converter
- Power losses caused by the switching and conduction

Generally useful topologies are those where active power can be easily transferred to the DVR converter with a good dynamic response.

The compensating voltages are added into the distribution system through a boosting transformer connected in series with the distribution feeder. Choi et al (2000) enumerated the following factors for the selection of the series boosting transformer.

- The power rating proportional to the rating of the load
- The turns-ratio depends upon the range of voltage sag or swell to be compensated
- The short-circuit impedance of the transformer which determine online voltage drop across the transformer.
The current rating of the series transformer is determined by the rated capacity of the sensitive load as it is in series with DVR for protection.

Choi et al (2000) recommended that the filters should be placed on the inverter-side as the high-order harmonics from the converter are filtered and thus its effect on the injection transformer current rating can be ignored.

1.2.5 Survey on Topologies Based on Converter Connection

The DVR injects a voltage in series with the supply, in which the VSI may be either isolated using transformers or the VSI may be allowed to float at the potential of the supply lines. These two schemes are referred to as (a) transformer connected converter or (b) direct connected converter.

1.2.5.1 Transformer Connected Converter

Using a low frequency transformer the compensating voltage is injected to the feeder as shown in the Figure 1.4(a).

It has the following advantages:

- According to the compensating range the transformer ratio can be designed to achieve the best performance.

- The transformer ensures Basic Insulation Level (BIL) between the DVR and the line.

- The transformer itself is a line filter.

- A simple converter topology is sufficient to inject the voltages.
Some of the disadvantages with injection transformers are:

- increase losses
- Bulky with high cost, weight and volume.

Figure 1.4 Topology based on converter connection (a) Using Transformers for galvanic isolation of DC link (b) Using 3 separate transformer-less single phase DVRs

1.2.5.2 Direct Connected Converter

DVR based on transformer less converter is proposed by Choi et al (2002). The converter is connected directly with the grid without a series transformer as shown in the Figure 1.4(b). The advantages of directly connected DVR are:

- Increased Bandwidth
- Less weight and negligible losses
- compact fabrication
Some of the disadvantages are:

- No insulation between the DVR and the grid. So protection of the power electronics is more complicated.
- Complexity in design

1.2.6 Topologies Based on Energy Storage Devices

In this case, energy is kept stored even before the voltage dip occurs and a small scale converter is expected to charge the storage device. Two different control/hardware methods have been considered by Nielsen & Blaabjerg (2001):

- DVR operating with a constant DC-link voltage and
- DVR operating with a variable DC-link voltage.

1.2.6.1 Topology with Constant DC-link voltage

A DVR with constant DC-link illustrated in Figure 1.5. This is the very basic topology from which the other topologies are derived. It employs double conversion system in which first conversion is done by an energy converter for maintaining a flat voltage profile at the DC link by converting energy from the main storage. Second conversion is done by the series converter such that it synthesis the required compensating voltage from the flat voltage maintained at the DC link.
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Figure 1.5 DVR topology with constant DC-link voltage

1.2.6.2 Topology with Variable DC-link voltage

A DVR with variable DC-link voltage illustrated in Figure 1.6 which offers simplicity as it employs only a series converter and DC link capacitor or battery bank for energy storage.

Depending upon the energy supplied to the grid and the rating of the capacitor, the voltage maintained at the DC link will vary. The effective utilization of the system depends upon the voltage maintained at the DC link and the energy saving strategies employed.
1.2.7 Topologies without Energy Storage Devices

DVRs feeding power from the grid are classified with respect to the location of the shunt converter. It may be located at the supply side or at the load side. Both passive and active shunt converters can be used. Passive diode converters will give simple topologies, but passive solutions with diodes are less controllable and cause non-linear currents.

1.2.7.1 Topology with Passive Converter at Supply Side

The supply side connected passive converter studied by Nielsen & Blaabjerg (2001) is illustrated in Figure 1.7. Due to the passive diode converter the shunt current will not be sinusoidal and DC-link voltage is poorly controllable.

![Figure 1.7 DVR based on supply-side connected shunt converter](image)

1.2.7.2 Topology with Passive Converter at Load Side

DVR with a load side connected passive converter is also taken for comparative study by Nielsen & Blaabjerg (2001) and is shown in Figure 1.8. The main advantage of a load side connected shunt converter is that the shunt converter has a restored clean voltage as the voltage is getting corrected at the supply side itself. It enables a stable charging of the DC link. One
disadvantage is the load voltages can be distorted due to the nonlinear currents drawn by the passive shunt converter.

![Diagram of DVR based on load-side connected shunt converter](image)

**Figure 1.8 DVR based on load-side connected shunt converter**

1.2.7.3 DVR with Direct AC/AC Converter

The DVR topology using a direct ac/ac converter without the DC link and energy storage devices is shown in Figure 1.9, which has got all the advantages as mentioned earlier. Since passive diode converters are not used, these are controllable and undistorted source currents are possible.

![Diagram of Direct converter based DVR](image)

**Figure 1.9 Direct converter based DVR**
1.2.8 Survey on Control of DVR

Due to the need of fast response and unsymmetrical voltage compensation, three basic control methods are discussed by Nielsen & Blaabjerg (2001) and its control strategy is shown in the Figure 1.10.

Figure 1.10 DVR control strategies

1. Pre-sag compensation method in which the supply voltage is continuously tracked at the supply side and the load voltage is compensated prior to occurrence of sag at load side. Thus load voltage remains nearly undisturbed.

2. In-phase compensation in which the compensating voltage is always in phase with the measured supply voltage regardless of the load current.

3. Energy optimal compensation in which the energy storage system is utilized efficiently. The load current is measured and the compensating voltage is generated such that energy is utilized is at a minimum.
As the thesis aims at realization of DVR without energy storage devices, the in-phase compensation and pre-sag compensation strategy is adopted for the control of DVR as the energy optimal compensation is not applicable.

1.3 OBJECTIVES OF THE THESIS

Though a few DVRs without energy storage devices already exist, they are suffering from the limited compensating range, complexity, and inability to mitigate single phase outage. The main objective of this research is to propose simple, reliable, stable and rugged topologies using direct converter with minimum number of switches, higher compensation range and with the ability to mitigate single phase outage.

1.4 OUTLINE OF THE THESIS

The thesis consists of the following chapters after the Introduction:

In chapter 2, mitigation of voltage sag and swell using single phase matrix converter is presented. Though many schemes have been proposed for various topologies of DVR, in almost all of these, there is a dependency of energy storage devices. The proposed model in this chapter replaces the conventional AC-DC-AC converter by a Matrix Converter thus avoiding bulky energy storage devices. It is able to compensate for indefinite time with very high power density.

In chapter 3, a topology to mitigate sag and swell in any one phase, is proposed by generating the compensating voltage using the power from the other two phases. The direct converter is a three phase to single phase converter constructed with 4 bidirectional switches. The performance of this topology is compared with the other existing topologies.
In chapter 4, the same topology is used as in the previous chapter. However, in order to reduce the THD of the compensated load voltage a new pulse with modulation technique is employed. Moreover it enables transport of power from one phase to the other without any tedious computation.

In chapter 5, attempt is made to design a rugged topology with reduced number of switches. It is constructed with a centre tapped series transformer and 3 bidirectional switches per phase such that the control is very simple and no PLL is required for compensation. The performance of this topology is compared with the other existing topologies.

Chapter 6 deals with a topology, to mitigate balanced sag, single outage, balanced and unbalanced swell using a multi winding transformer and a direct converter. The converter is realized using 3 bidirectional switches.

Chapter 7 deals with the mitigation of single phase voltage sag, swell and outage using a multi winding transformer and 2 bidirectional switches per phase.

Chapter 8 summarizes the results of simulation and experiments and sketches the perspectives and suggestions for future work regarding the dynamic voltage restorer.

Appendix: The Papers published during the research work are provided.