CHAPTER 2
LITERATURE SURVEY

2.1 Introduction

Enormous research work has already been done on the power quality conditioners and their controllers. A lot more work is still going on to make the complete automated system more efficient and reliable. This chapter includes brief literature review of power quality conditioners (mainly Dynamic Voltage Restorer) and their controllers. The performance of any control system can be improved by making it fault tolerant. The literature related to fault tolerant control systems is also a part of the chapter. The present work concentrates only on sensor fault tolerant control system for Dynamic Voltage Restorer.

2.2 Dynamic Voltage Restorer as Power Quality Conditioner

The concept of custom power was introduced by N. G. Hingorani [12]. The term is somewhat analogous to Flexible AC Transmission Systems (FACTS) since both utilizes power electronics devices, but the main difference is FACTS is for transmission systems whereas the custom power (CP) devices are used in distribution systems. Both are designed for improving quality and reliability of power but in different systems. The custom power devices are designed to improve the quality of power delivered to load therefore they are also termed as Power Quality Conditioners. Sometimes they are series connected device like DVR, sometimes they are shunt connected device like DSTATCOM, and sometimes it is the combination of shunt and series that constitute the device like UPQC.

DSTATCOM is an important shunt connected power quality conditioner, especially in the medium voltage applications for the compensation of low order harmonics. Conventional techniques used for this purpose is active power filters whose performance is deteriorate due to the limited control range and delays in digital implementation. These issues are overcome by DSTATCOM proposed in [13] for harmonic and unbalance compensation. The results have confirmed the harmonic compensation even with low switching frequency.
C. K. Sao and his colleagues have proposed a digitally controlled VSC for DSTATCOM in [14]. This digital controller had the ability to control DC as well as AC voltage simultaneously. Authors have provided a bench mark D-STATCOM that has digitally controlled VSC for studying the sinusoid. The authors have analyzed the performance of DSTSTCOM in different modes with the proposed controller in PSCAD software. The authors have also verified the Simulation results experimentally on a 10-kVA laboratory D-STATCOM.

The utility side power quality conditioning starts with the installation of the Dynamic Voltage Restorer (DVR) in United States for protecting a critical load from power system voltage disturbances. In [15] the authors have described installation and sag compensation results for a prototype DVR built by Westinghouse for EPRI. The DVR was installed in 12.47 KV systems at an automated yarn manufacturing and weaving factory.

The authors in [16] have given various interconnection equipment required for DVR installation, also already installed underground pad mounted DVR and platform mounted DVR were also discussed.

When the voltage injected by DVR is in phase with grid voltage minimum magnitude injected voltage is achieved. But for achieving minimum energy requirement some phase advance injection methods are proposed in [17].

In [18] the authors have examined the effect of inverter side filter in DVR. They investigated the influence of filter on inverter rating and proposed a scheme for filter design such that the introduction of filter should not result in excessive voltage drop and phase angle deviation.

DVR which is a series voltage injecting power quality conditioner is analyzed for closed loop load voltage and current control mode by M. Vilathgamuwa and his colleagues in [19]. The authors have proposed a multiple loop scheme for improving the damping that appears in open loop schemes. Also controller shows precise tracking of reference voltage even when load condition changes.
The capability of DVR to regulate the voltage at load terminal against unbalance and harmonics in supply is proposed in [20]. Both steady state and transient analysis of DVR operation are discussed and a series reactive injection scheme is proposed for DVR.

M. J. Newman and his colleagues have proposed [21] a selective harmonic rejection method for a medium voltage DVR system without changing the sag compensation limit of the DVR. A system Proportional Integral controller (PI) for sag compensation is improved for harmonic compensation by using resonant filters. The authors have verified the performance of the proposed scheme by analyzing it in different system conditions like unbalance, sag along with harmonic rejection. The only issue with the proposed controller was the requirement of distinct filter for each harmonic to be rejected in case of unbalance systems.

In [22] practical test results are obtained for a medium voltage level DVR at distribution test facility in Kyndby, Denmark. The authors verified the combined feed forward and feedback techniques for the controller with good transient and steady state response. The sag voltage of up-to 0.5 PU was compensated by DVR for a 400 KVA load. The saturation problem in transformer and over current in inverter, both are limited by a proposed current saturation limiting technique. Many practical problems related to transformer selection and load reference generation are also discussed by the author.

S.S. Choi and his colleagues have proposed a zero power insertion method for sag/swell compensation. So as to maintain the constant DC link voltage of Voltage Source Converter in [23]. The main issue with the proposed scheme was that it reduces the sag compensation capability of DVR.

The different topologies for DVR, like DVR without energy storage and converter in supply side, DVR without energy storage and shunt converter in load side, DVR with energy storage and variable DC link voltage, DVR with energy storage and constant dc link voltage, are compared in [24]. The authors have compared the required DVR rating for all topologies as shown in fig.2.1. It shows that load side connected converters require highest rating and variable DC link voltage DVR has lowest rating. Also experimental
results of compensation for symmetrical voltage sag of duration 100ms, without phase jump are compared as shown in table 1.

![Graph showing S_{DVR} [pu] vs Voltage sag a [pu]](image)

Fig 2.1 Overall power rating of DVR converters versus voltage sag size in PU [24]

In [25] harmonic compensation capability of already installed DVR without affecting its normal operation during sag compensation is discussed. This harmonic compensation has not involved any flow of real power (or very less), so it will not affect the DC storage available for sag compensation during transients.

The need for some advance and complex controllers for DVR are discussed in [26]. The authors raise this requirement stating the failure of simple proportional-integral (PI) method for some specific unbalance system conditions. Although the PI control scheme gives satisfactory results in majority of system conditions but it is not cost effective for rejection of harmonics for unbalance systems.
TABLE 1: COMPARISON OF THE DIFFERENT DVR TOPOLOGIES WITH THE GRADING: VERY GOOD (++), GOOD (+), POOR (-), AND VERY POOR (--) [24]

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<th>Stored Energy</th>
<th>No Stored Energy</th>
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<tbody>
<tr>
<td></td>
<td>Supply side</td>
<td>Load side</td>
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<td></td>
<td>connected converter</td>
<td>connected converter</td>
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<td>Long voltage sag duration</td>
<td>++</td>
<td>++</td>
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<tr>
<td>Deep voltage sags</td>
<td>--</td>
<td>+</td>
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<tr>
<td>Non-symmetrical voltage sags</td>
<td>--</td>
<td>+</td>
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<tr>
<td>DC-link voltage control</td>
<td>--</td>
<td>+</td>
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<tr>
<td>Size of energy storage</td>
<td>--</td>
<td>+</td>
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<tr>
<td>Grid effects</td>
<td>--</td>
<td>+</td>
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<td>Rating of charging/shunt converter</td>
<td>--</td>
<td>+</td>
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<td>Rating of the series converter</td>
<td>+</td>
<td>--</td>
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<tr>
<td>System complexity</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Cost Estimation</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Control complexity</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Sum (+)</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Sum (-)</td>
<td>10</td>
<td>4</td>
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<tr>
<td>Sum (total)</td>
<td>-3</td>
<td>4</td>
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</table>

The Repetitive controller which is based on internal model principal, was proposed in [27] for achieving zero tracking error for periodic reference signals. The different configurations of repetitive controller are analyzed in [28]. Because of its simplicity and robustness it was then utilized for many applications. For example, it was used to obtain a distortion free output from a three phase PWM inverter in [29], in [30] it was utilized to improve the power factor by tracking the output current in a three phase PWM rectifier and in [31] harmonic currents due to non-linear loads.

To protect the power electronic switches in the VSC of DVR, it is disconnected from the mains in the event of a ground fault at the load point which is called downstream fault [32, 33]. In [32] authors proposed to decrease the rate of decay of dc component of the fault current so as to reduce the sudden increase in the dc link voltage of DVR. This approach can protect the DVR from the harmful effects of downstream
fault current, but still needs a bypass switch to disconnect the DVR if the fault is not cleared by the relays in short time.

M. Vilathgamuwa and his colleagues have proposed interline DVR (IDVR) for the restoration of load side voltage in [34]. The main advantage of the proposed scheme was its ability to compensate long duration sag. In normal DVR the duration of sag that can be compensated depends on the stored energy in DC link. IN proposed scheme number of DVR are connected to different feeders connected together through a common DC link. Thus if one DVR is compensating a sag through the stored energy in DC link, another DVR is supplying energy to DC link so that long duration sags can also be compensated by the DVR. Fig 2.2 shows the IDVR in a two-feeder system.

![Fig 2.2 Schematic diagram of an IDVR in a two-feeder system of [34]](image)

The repetitive controller was introduced as controller for DVR to compensate the significant power quality issues in [35] by P. R. Sánchez and his colleagues. The main advantage of the proposed system is one controller was proposed to compensate three main voltage related power quality disturbances that are sag, unbalance and harmonics. The schematic of the proposed scheme is shown in fig 2.3. The simulation performed in PSCAD/EMTDC for a test system shows that the load voltage is maintained to reference value without any steady state error and in very less time.

A software sensor based approach for STATCOM is proposed in [36]. This method leads to very hardware of the system; also it eliminates the hardware related problem with sensors that may sometimes deteriorate performance of controllers.
The combination of STATCOM and SSSC was introduced by Gyugyi in [37] as unified power flow controller (UPFC). An analogous device for distribution systems which is the combination of DSTATCOM and DVR is UPQC i.e. Unified power Quality Conditioner. Obviously this device has the advantages of both DSTATCOM and DVR. It is able to provide series as well as shunt compensation to the system it is connected. But its high cost restricts its implementation in practical systems.

In [38] three identical control systems are used to control the injected voltage in each phase independently. The least error square (LES) filters are used to determine the phase of measured supply and load voltages. Thus PLL is not required in this method. Also this method does not neglect zero sequence components as most of the control methods for DVT do, thus it can be used for three wire as well as four wire systems.

A new Fault current interruption (FCI) method is proposed in [39]. The proposed method prevented the decrement in DC voltage of inverter while controlling the fault current. This method also used least error square (LES) filters in place of PLL.

An ultracapacitor (UCAP) based energy storage system is proposed for DVR in [40]. The proposed method removes the dependency of DVR on supply grid for compensation of sag and swell. The rechargeable ultra-capacitors are connected to dc link of inverter through a dc to dc converter. The designing of this dc to dc converter is also discussed by the author.
2.3 Fault Tolerant System

A control system is said to be fault tolerant, when it has the ability to perform acceptably in the event of some component failure. Research into fault-tolerant control has fascinated many investigators and is now the subject of broadly dispersed publications. Many conventional methods of fault tolerant are used in industries and safety critical applications like traction systems, airways etc. The main problem with these methods is they require huge amount of maintenance. One group of scholars believe that a fault tolerant system should be simple system with minimum components, while others find its fine to have a complex system. Whether simple or complex the basic requirement is, it should have the ability to maintain the performance of system within tolerance limit in the event of some component failure.

Fault-tolerant control systems are categorized in [41], according to their competencies and their behavior during fault, to make the system performance almost same as it was before the occurrence of fault. Authors also consider the performance of fault tolerant system during the transition from occurrence of component failure to restoration of system condition to normal as a significant factor. Authors also classify fault tolerant systems as active or passive systems.

The fault tolerant system design starts with the determination of components in plant whose failure could have intolerable effect on the system performance as well as stability. The analysis of component failure and their effect is an important study subject in industries. Various FMEA methods for fault tolerant systems are discussed in [42].

Many fault detection and restoration methods are proposed by the researchers. Some of these were based on conventional methods while other uses intelligent control methods like Neural Network, fuzzy logic and genetic algorithms. Fuzzy logic is a rule based computation method which is based on logical reasoning; Neural Network imitates the behavior of human brain; and Genetic Algorithm is a systemized method for random search and optimization. The combination of these powerful tools may leads to a new expert system in this field.
In any system, sensor failure can due to, calibration error; broken sensor; low in battery; connection short circuit. In [43] Szewczyk and his colleagues have theoretically analyzed all these factors in detail. The authors documented that abnormally small or large outputs of the sensor may be because of connection short circuit. Authors also recognize the calibration problem as cause for sensor failure in majority of cases. The sensor output got faulty in different manners for example, if sensor output is deviated from actual measurement by a fixed value it is an offset fault and if rate of change of sensor output did not match with rate of change of actual measurement it is a gain fault. Bychkovskiy and his colleagues in [44], and Balzano and Nowak in [45] have proposed online calibration of sensor using spatial correlation between sensors to prevent sensor failure due to calibration.

Kalman filter along with its various extensions were implemented by researchers in different applications. Kalman filters and its Multiple Model variant was used for detection of failure in digital control system for flight, through state estimation by Montgomery and Cagayan in [46]. Paul M. Frank in [47] and Thomas Kerr in [48] proposed Generalized Likelihood Ratio (GLR) method for Kalman Filter. Another extension to Generalized Likelihood Ratio was proposed by Thomas Kerr in [48]. T. V. Rama Murthy in [49], Shapiro E Y in [50] and Clark and Setzer in [51] have implemented different form of dedicated Luenberger observers for detection of sensor fault in different applications. An adaptive control approach to Sensor Failure Detection and Isolation was used by M.N. Wagdi [52]. G. Heredia and his colleagues in [53] have given a method based on observer for identification of faults in sensor and actuators of a small helicopter.

Numerous shortcomings associated with Kalman filter based sensor fault detection are discussed in [54, 55]. The concluded main problems with this method are: its operation is limited or restricted in the linear range of dynamics only, so it is measure of non-linearity in the system that governs the proper operation; also it can detect only those faults for which it is programmed in advance.
The superiority of neural network based method as compared to Kalman filter approach was discussed in [54] for aircraft control application. Napolitano and his colleagues in [55] used model based approach with neural network for identification of faults in sensor and actuators of aircraft controllers.

An outline of failure-tolerant control systems was given by Robert F. Stengel in [56]. Author also proposed artificial intelligence approach for design of fault tolerant system in addition to traditional design approaches.

Ganesh Kumar Venayagamoorthy and colleagues, [57, 58, 59] proposed three methods for sensor fault detection and restoration for SSSC. For a multi machine power system with static synchronous series compensator (SSSC), a neural network based approach was implemented in [57]. The radial basis function based optimum neural controller was proposed by the authors.

In [58] authors have verified the proposed neural controller for SSSC connected system for the IEEE 10-machine 39-bus power system. The conventional Proportional Integral (PI) was used as the controller for SSSC.

Authors proposed an auto-encoder and particle swarm optimization based missing sensor fault tolerant control system (MSFTC) in [59]. Real Time Digital Simulator and TMS320C6701 digital signal processor were used to verify the compatibility of the proposed scheme.

Abhishek B. Sharma and colleagues [60], reported instances of transient faults in sensor measurement. To understand the occurrence of sensor faults, four qualitatively different modules of fault detection methods are categorized by the authors. Rule-based methods identify the faults by using rules, based on basic information about the system. In Estimation method the faulty sensor is detected by using the correlation among different sensor data. In Time series analysis approach the current sensor output is predicted by its previous data information, which is then compared with actual sensor output for detection of faulty sensor. Learning-based method develops a model using a training set of healthy sensor readings for identification of faults in sensor.
Authors in [61] proposed a generic parameterize method for identification of permanent and intermittent faults in wireless sensor network. A multi-objective PSO is proposed for determining time between two tests and maximum number of tests required for detection of intermittent fault in sensor.

In [62] author had proposed discrete time estimator for detection of sensor fault and verified the operation on vehicle lateral dynamics. The output of estimator and system variables are used for making the system fault tolerant.

The correctness of fault detection directly depends on accuracy in prediction that determines the residual values. Therefore in [63] authors have generated steady residuals for healthy system by using cubature rule in tracking filter. The traditional method is to use Jacobin matrix in filter, thus proposed method combines the advantages of cubature rule Kalman filter and strong tracking filter for accurately detecting the sensor faults. When residual breaches the predefined threshold, the sensor is considered to be faulty.

2.4 Scope of present work

In the present work modified repetitive controller (both analog and discrete form) is proposed for control of DVR placed in low voltage distribution system. Although the LV DVR is less efficient as compare to MV DVR, the customer usually has only access to low voltage level. Also in LV systems the short circuit levels are reduced because of distribution transformers and the protection of DVR becomes easier. The FPGA based co-simulation of the controller is also proposed to verify the hardware compatibility of the control system.

Also to make complete system more reliable a missing sensor tolerant system is proposed for DVR controller. In their previous work, the authors proposed and demonstrated several missing-sensor-fault-tolerant identification and control schemes using auto-associative neural networks (auto-encoders) and particle swarm optimization (PSO). But these system uses auto associative neural network along with a complicated equation based if-else algorithm for identification of missing sensor. In the present work neural network with a very simple logic circuit is proposed for identification of missing sensor. A particle swarm optimization with auto-associative neural network is used for
restoration of missing sensor data. The MODELSIM co-simulation of PSO block with MATLAB is also proposed for FPGA verification.

2.5 Conclusion

The literature review of various power quality conditioners especially DVR is discussed. The literature review also shows the superiority of repetitive controller over other controllers in various applications. Various sensor fault detection and restoration schemes proposed by various researchers are also discussed. Basics of repetitive controller and implementation of DVR with RC compensating PQ issues with results are given in chapter 3.