CHAPTER 2
LITERATURE SURVEY

2.1 INTRODUCTION

The various non-linear loads in the grid lead to different power quality problems. The major power quality problems are power factor and harmonics which lead to penalty. The traction loads are single phase loads that lead to an unbalanced load which draws more neutral currents. Hence, the study on ideal Power Quality Conditioners becomes essential to avoid the effects of power quality issues. The application of power quality conditioners has drawn more attention among the researchers, engineers and industrialists in the recent years to avoid the penalty imposed directly or indirectly.

2.2 BACKGROUND STUDY

The power quality issues have emerged as major challenges for the suppliers as well as the consumers. Hence, the researchers have concentrated on the various issues and their effects. The power quality disturbances (Siahkali 2008) are categorised as continuous and discrete disturbances. The global and individual power quality indicators with maximum and minimum values to help the operators to assess are presented.

By installing a monitor on the supply of traction load, the voltage and current characteristics of the power qualities are studied (LIU Yu-quan et al. 2011). The unbalanced three phase current is the worst affecting factor of the system due to its harmonic content and negative sequence current. Field
measurement on power factor, switching transients and harmonics provide useful data in designing of filters (Gopalakrishnan et al. 2002) to improve the power factor and harmonic suppression as per the IEEE 519-1992 standards.

Voltage unbalance leads to overheating, which in turn leads to winding insulation degradation (Arfat Siddique 2004). Six type of voltage unbalance and its effects on stator loss, rotor copper loss in Induction motors are studied. A technique to detect disturbances in time varying power frequency has been proposed (Cristiano Augusto Gomes Markques et al. 2011) using sampling. It has advantages over the cost, robustness and in mechanism dealing with frequency deviation.

A methodology is proposed (Martin Valtierra- Rodriguez et al. 2014) with dual neural network to detect and classify the single and combined power quality issues such as sags, swells, outages, harmonics as well as inter harmonics. It has the advantages in detecting the issues even when they appear simultaneously. In this, the signal is analysed through ADALINE and the signal spectrum is obtained for each sample and the algorithm used is variable step- size least mean square algorithm to minimise the error. Due to the power quality problems like harmonics and low power factor, penalty is being imposed. Hence, the literature survey has been done on various power quality conditioners based on

1. Topology
2. Classification based on supply
3. Control strategies
4. Technical and Economic Consideration
5. Selection based on specific applications

More number of research papers have been taken for literature survey in this work.
2.3 CLASSIFICATION BASED ON TOPOLOGY

The power quality conditioners are classified as passive filter, active filter, series filters, shunt filter, series and shunt filters, unified power quality conditioner, etc based on the topology.

To suppress the transients (Paul A Cart Wright 1952), passive compensators are developed using T-transformer instead of series capacitors which are used to improve steady state voltage. He Yi- Hong et al. (2013) have developed double tuned filter to reduce the cost and area of the group of single tuned filters when used to compensate multiple frequency harmonics in a power system. A new method has been proposed based on resonance frequency to reduce the amounts of computation and has been proved in power system simulation.

Shuja Khan et al. (2011) have designed a passive filter for the induction motor has been designed after detecting the harmonics in the current drawn by the induction motor. The passive filter has been experimented in different approach i.e., in series, shunt and series shunt with induction motor for the suitability and it is finally suggested that the parallel passive filter is the most suitable not only to suppress the harmonics, but also to supply the reactive power for the improvement of power factor.

Tuning factor and quality factor derived through bode-plot in designing single tuned passive filter (Young-Sik Cho et al. 2011) avoid side effects from parallel resonance. The performance of the filter is verified with three rectifier load using different order filter and the reduction of harmonic content is proved in percentage.

A shunt filter is designed with the field measurement at Zinc plating rectifier, MIG welding, induction hardening, etc (Gopalkrishnan et al.)
2002) to improve the power factor after carrying out the load flow analysis through ETAP simulation. The shunt filter is designed with tuned LC by considering loss minimisation and better harmonic performances. The advantages and disadvantages on various methods used in signal analysis for power quality issue are compared (Granados-Lieberman 2010). Similarly, the advantages and disadvantages on various algorithms are used for classifying the power disturbances. It is concluded that the combination of the techniques improves the results.

The shunt type active filter is normally used for various power quality problems such as reactive power compensation, current harmonics and imbalanced currents and is shown in Figure 2.1. Shunt active filters are mainly used at the point of common coupling of load that is on the LV side of the traction station transformers to inject the equal compensating currents opposite to the phase for harmonics and reactive power. The series active filters are connected in series with the incoming supply to compensate the voltage harmonics and to maintain the terminal voltage (Eddy C Aeloiza et al. 2003; Yuan Chang & Liu Jinjun 2007) and are shown in Figure 2.2.

Figure 2.1 Voltage-fed active filter
The unified power quality conditioner, a combination of both active filter in shunt and series is studied (Kashefikaviani 2009) and is shown in Figure 2.3. This type of conditioner is used for unbalanced loads, reactive power compensation and to maintain the terminal voltage. It can be
configured as multilevel and three-phase UPQC (Shankar et al. 2014), and hence, this type of power quality conditioners are considered as an optimum controller for railway traction. Since, railway traction is a high capacity service, the main drawbacks of this type of conditioner are high cost and complexity in control because of large number of static devices.

![Hybrid filter, a combination of shunt active and passive filter](image)

**Figure 2.4 Hybrid filter, a combination of shunt active and passive filter**

A hybrid filter, which is the combination of shunt active and passive filter is shown in Figure 2.4 and is dealt by Wang Dan & Yang (2012). Usage of this type of conditioner will reduce the rating of the solid state devices and in turn reduce the cost of the conditioners (about 5%). LCL is used with back to back converter by Keng-Weng Lao & Man-Chung Wong (2013), to improve the performance of the compensator. LC coupling with UPQC by Dai Ning Yi & Lao (2013) is used to reduce the unbalanced currents and harmonics and reactive power compensation with reduced converter ratings.
Na Ding & Zeliang Shu (2011) have introduced an impedance-matching-transformer with multilevel converter. The system balances the three-phase in power grid when used in traction system.

Figure 2.5 depicts the survey of literature performed on power quality conditioners based on topology.

![Classification based on Topology](image)

**Figure 2.5 Distribution of literature survey based on topology**

### 2.4 CLASSIFICATION BASED ON SUPPLY

The loads in the grid are either single phase or three phase systems. Hence, a detailed study has been made on power quality conditioners classified under single phase and three phase systems.

Figure 2.6 shows the literature survey performed on power quality conditioners based on supply.
Techniques used for the measurement of Ultrasonic velocity are classified into two categories. They are continuous wave methods and pulse techniques.

2.4.1 Single Phase

Longhua Zhou & Qing Fu (2009) have proposed MPQC for power quality issues in railway traction. The MPQC has two H-bridge single phase inverters with DC link capacitor. MDPWM control strategy is used. It is informed that the MDPWM control strategy is equal to two level SVM control strategy. Simulation is done through MATLAB/SIMULINK. The linking impedance in H-bridge converter is taken as locomotive load for simulation and proved the performance of MPQC with the MDPWM control strategy in power quality compensation.
A cascade system which consists of TCR and single tuned filter has been proposed by Salchifar & Ranjbar (2009) for various power quality problems in electrified traction system. Fuzzy controller for firing angle of TCR and PLL as control strategy has been proposed. Simulation is done through MATLAB to prove the performance of the proposed system in reactive power control.

Majianzong et al. (2009) have proposed Static Var Compensator which has TCR, passive filter and fixed capacitor to resolve the power quality problems in electrified traction supply. Various power quality issues in the traction supply have been studied and analysed. Improvement in power factor has been proved through the actual measurement by connecting the proposed system.

A new railway power conditioner with two TCR and third order harmonic suppressor TCR has been proposed by LU Fang et al. (2011) to compensate the power quality issues in railway traction. The phase angle of the power supply has been changed by the TCR, whereas, the third order harmonic content is reduced by the third order harmonic suppressor. The equivalent circuit of the proposed system has been analysed both in frequency domain and in harmonic domain. Simulation is also done by PSIM 6.0 to prove the reduction in rating of active part, effective reduction in harmonic content and compensation of negative sequence.

Dai et al. (2012) have proposed HPQC to resolve the power quality problems in railway traction supply. The HPQC contains two number single phase converter connected back to back. One of the converters is connected to the feeding phase through LC filter and the other one is connected to the other phase through a coupling transformer. The HPQC is proposed in such a way that all the three phase currents in the grid are balanced. The harmonic content is controlled by the α-phase, whereas β-phase is used to control the DC
Since, low DC voltage is enough to operate the HPQC, the rating of the HPQC is reduced. Simulation is done through PSCAD/EMTDC and proved that all the three phase currents are balanced apart from the compensation in reactive power and harmonics.

Keng-Weng Lao et al. (2012) have proposed a hybrid power quality compensator for high speed traction with low DC voltage to reduce the rating of the compensator. Instantaneous pq theory is used to control the proposed system and the simulation is done through PSCAD/EMTDC. LC filter connected on α-phase has been tuned to compensate the fifth order harmonics that is predominant in railway traction. Through the simulation, it is found that HPQC’s operating voltage is only within the range of 68% to 70% when compared to the conventional power compensator.

A system having an LC filter connected to SVC to reduce the harmonics generated by the traction loads is introduced by Chang Min et al. (2012). In this system, harmonic and negative magnetic potential has been eliminated using the ampere turn balance principle. Since, the LC filter is used for reduction in harmonics and SVG is used for elimination of negative sequence current, the compensator cost and the installation cost reduction have been proved through simulation.

Dan Wang et al. (2012) have experimented on the management of SVC in railway traction for power quality problems. The SVC proposed has a thyristor controlled reactor and fixed capacitors. Based on Steinmetz balancing theory, open loop control for reactive power and closed loop control for voltage are used to control the SCV. The signals dq arrived from current and voltage signals of supply side have been used to calculate the susceptance value for compensation. High accuracy has been achieved through voltage closed loop control. Finally, simulation is done through
PSCAD/EMTDC and is found that the three-phase unbalance is effectively controlled along with the harmonic problem.

Keng-Weng LAO et al. (2013) have designed the LCL type filter to suppress the harmonic content produced by the Railway Power Quality Conditioner used for compensation. The LCL type filter has been modelled mathematically and analysed. The simulation is done through PSCAD and verified. The Railway Power Quality Conditioner has converters connected back to back and used to compensate the reactive power and unbalance in system and harmonics. The electronic devices used in this conditioner generate harmonics and are fed into the grid. Hence, the LCL type filter has been introduced in series with the conditioner. Simulation is done on the LCL type filter with fixed capacitor on one side and small rated capacitor on the other side and is proved to perform better.

Ning Yi Dai et al. (2013) have proposed HRPC by introducing the LC filter in one phase between the traction supply and the converter. The LC filter is introduced to reduce the dc link voltage. p-q theory is used to control the conditioner. Simulation is also done through PSCAD with RPC and HRPC using RL load for traction load. It is proved that even though the RPC and HRPC performed the same, the cost of HRPC and power loss in HRPC is reduced. The dc voltage is also found low.

Y/Δ traction transformer has been studied by Alireza Ghassemi et al. (2013) for power quality problems in the electrified traction. Various kinds of transformers have been analysed on the performance in electrified traction against the power quality problems. Compensation theory with PI control is used to calculate reference voltage and is studied. All the electrical parameters are measured and the commands for compensation are derived from the current signal and in turn the gating signals are generated. Finally,
simulation is also done with different load capacities to prove the performance of the Y/Δ transformer.

A novel structure of a single phase UPQC-DG is developed (Mokhtarpour et al. 2013) for various power quality problems. The proposed system has two cyclo converters with a three phase high frequency transformer and a full bridge inverter. The cyclo converter is directly connected to the grid in which, one is acting as a series active filter and the other one is shunt active filter. Input output feedback linearisation is the control system to generate the reference signals. Dynamic and state space analysis is also done for the proposed system. Simulation and experimental setup have been done to study the performance of the proposed system.

Keng-Weng Lao et al. (2015) have proposed the hybrid power quality conditioner for railway traction to reduce the dc link voltage in power quality compensation. The dc link operation voltage is to be enhanced to have better power quality compensation and hence a study is done relating the dc link voltage and compensation capability. The control signal is derived through linear operated hysteresis PWM method. Analysis has been done through PSCAD simulation and an experimental setup. Since, the cost of the inductive coupled RPC is high, the capacitive coupled RPC has been proposed. The performance of the proposed hybrid power quality conditioner is found to be not satisfactory for the power factor beyond some limit and hence it has been concluded that specific dc link capacitor has to be selected depending on the load capacity.

A single phase multilevel inverter has been proposed by Malathy et al. (2016) with reduced number of switches. The proposed single phase multilevel inverter has 3 unidirectional switches with 3 dc sources.
An active power flow controller combined with a single phase traction transformer has been proposed by Min Wu Chan et al. (2016) to solve the power quality problems raised by the traction loads. Based on the power balance principle, the compensation currents for the PFC are calculated. Mathematic modelling of the co-phase transformer has been studied for the calculation of compensation currents. The performance has been studied through the simulation.

### 2.4.2 Three Phase

Yuan Chang and Liu JinJun (2007) have introduced a new control system for an active filter to reduce the cost and complication in conventional control methods. Through this control system, the voltage injected by the active filter is controlled for the harmonic suppression. To have proper operation of active filter on reactive power, the dc side voltage is made indispensable. The idea is to prove the reduction in the cost of the compensation and control system through simulation, even when the high pass filter is removed. Since, the line voltage is taken as reference, it is concluded that the line current can be taken for reference for effective control of current harmonics.

Shoji Fukuda et al. (2008) have introduced an auxiliary supply system so that the square wave voltage is an input to a 12-phase controlled rectifier to suppress the possible harmonics generated by the 12-phase controlled rectifier. A single phase inverter with pulse width modulation having variable output voltage has been introduced for auxiliary supply. Through simulation, the usefulness of the proposed system is verified for reduction of 11\textsuperscript{th} and 13\textsuperscript{th} order harmonics and that the VA rating of the proposed system is only 5\% of the 12-phase converter.
An Luo et al. (2009) have proposed a 3-phase, 3-wire compensation system having combined Active filter and Static Var Compensator. In this system, the Thyristor controlled reactor is connected in delta along with the passive filter connected in star to form the SVC. The active filter is used to reduce the harmonic content generated by the harmonic load and the TCR is used to suppress the resonance between the passive filter and the power grid, whereas, the passive filter is used for power factor improvement. PI control is used for improved performance of the SVC. To optimise $K_P$ and $K_I$, accelerated simplex algorithm is adopted. Finally, experiments have been carried out with a prototype model with DSP based controller for 200 kVA load to prove the performance of the proposed system. Simulation is done through PSIM software to find out the performance of the proposed system with the reduction of harmonic content, reactive power compensation and power factor improvement.

Salem Rahmani et al. (2009) have proposed a non-linear control technique to have a better dynamic response of 3-phase, 3-wire shunt hybrid filter on power quality problems. The shunt hybrid filter is the combination of an active filter and passive filter. PI controller has been used to control the dc bus voltage. Mathematical transformation for the shunt hybrid filter and ‘dq’ reference frame transformation has also been done. Simulation is done through MATLAB to study the performance of the shunt hybrid filter in the proposed non-linear technique and the performance is proved.

The characteristics of the hybrid active filter are analysed by An Luo et al. (2010) with injection circuit. The PI control based on iterative learning control algorithm is used for steady state performance of the hybrid active filter. Fuzzy reasoning based on current error referred in D-type learning law is used in dynamic performance of the hybrid active filter. The
proposed system performance is studied after implementing in a steel plant in China.

A 3-phase, 3-wire hybrid passive filter consisting of the passive filter in series with the TCR base impedance filter is proposed by Abdelhamid Hamadi et al. (2010) for harmonic and reactive power compensation. The rating of inductance in passive filter has been reduced by using mutual – inductance design concept. Lyapunov’s stability and Barbalat’s Lemma based adaptive control is used as control strategy. Simulation is done to prove the performance of hybrid filter towards load variation resonance and power factor with both delta connection and star connection TCR. The same is carried out for both voltage source and current source non-linear loads.

Na Ding & Zeliang Shu (2011) have proposed a 3-phase, 3-wire RPC to improve the power quality issues in electrified railway system. The RPC has three separate single phase chain circuit inverters. All the three single phases are connected in star such a way to make 3-phase, 3-wire system. In that, two phases are connected to two feeders and one phase is connected to the ground. The control strategy phase shifted carrier PWM is used for RPC switching. Simulation is carried out with the proposed system to prove the balancing of the current in all the three phases even if it is unbalanced loads.

A 3-phase, 4-wire hybrid multi converter conditioner is proposed (Maria Isabel Milanes Montero et al. 2011). The proposed conditioner has an active filter and a hybrid filter in parallel. The hybrid filter has an active filter and a passive filter tuned for a particular harmonic order in series and a hybrid filter is used for resonance effect where as the active filter is for higher order harmonics. A collaborative control strategy based only on sensing the load current is used and hence it reduces the number of sensors. PI controller is used for the selection of converter based on the load current. It is proved that
Improvement in output waveform has been done through hybrid multilevel converter (Cesar A. Silva et al. 2011) with dc link voltage control scheme. The proposed converter has 3-phase, 3-wire conventional inverter with a single-phase H-bridge inverter in series on each phase. PLL algorithm is used in H-bridge converter to transfer maximum active power to the capacitor. The DC link voltage is controlled by the regenerative operation. The performance is studied through MATLAB/SIMULINK and hardware setup with TMS320C6713 processor and DSP control. It is suggested that the proposed control system can be used for cascade H-bridge to avoid isolated input transformer.

A 3-phase, 3-wire hybrid filter for harmonic suppression and reactive power compensation is proposed (An Luo et al. 2012). The proposed hybrid filter has TCR and RITHAPF. RITHAPF has an active filter and a passive filter in series. The proposed hybrid system is proved to be useful for medium rated grid voltage with reduction in initial investment cost. Frequency – selective predictive current control and π – aimed smith predictor are used for RITHAPF current delay. Simulation is done with PI controller and FSPCC to prove that FSPCC performed better. Finally, simulation and application in industries prove the performance of the proposed filter in load imbalance and in harmonic current suppression.

A 3-phase, 4-wire hybrid active filter coupled with LC filter controlled by dc adaptive dc-link voltage is introduced (Chi-Seng Lam et al. 2012) to reduce switching loss and noise in reactive power compensation. The minimum dc-link voltage is arrived based on the mathematical relationship between the range of the reactive power compensation and dc-link. The active and reactive reference current is derived through instantaneous power.
compensation control block. The minimum dc-link voltage range is controlled by adaptive DC link voltage control. Finally, PWM control is used to generate control signals. Simulation is done through PSCAD/EMTDC and the prototype model is also implemented to study the performance of the proposed system. It is found that the initial cost of the proposed system is not reduced because the working range is based on the specification alone.

AVIK Bhatta Charya et al. (2012) have introduced parallel operation of the active filter operating both in low and high frequency for better performance. Voltage source inverters are used and one-pair of converters is removed from each inverter. Since, only two passive filters are used, it is found optimal in eliminating low order harmonics. Higher order harmonics are eliminated by the two active filters. The low frequency inverter operates in feed forward mode whereas the high frequency inverter operates in feedback mode. Simulation is also done to reveal that the low frequency inverter controls the reactive power whereas the high frequency inverter is for the harmonics of the load and harmonics generated by the low frequency inverter. Prototype hardware is also implemented to analyse the performance.

Shijukumar et al. (2013) have proposed a modular power electronic transformer to solve the power quality issues in the traction. The proposed power electronic transformer is designed in such a way that the fundamental frequency supply is converted to high frequency supply and in turn reduced to the frequency supply with DC link capacitor which is provided in between 6-pulse converter. When the power electronic transformer replaces the conventional transformer, the weight and size are reduced to a great extent. The harmonics reduction using this type of transformer is only on the incoming side, but has harmonics on the output side which is lesser than the traditional transformer.
Velmurugan et al. (2013) have introduced a 3-phase hybrid multilevel inverter to have control over voltage sag and to compensate reactive power harmonics and negative sequence currents. PD technique has been used for modulation of 7 level output. Current control scheme and voltage control scheme are used to control the shunt active filter and the series active filter respectively. Synchronous reference frame theory is used for signal with phase locked loop and PWM generator. Simulation is done through MATLAB/SIMULINK with non-linear balanced load and non-linear unbalanced load and it is found that the THD of source voltage is controlled within the IEEE limits.

A current controller for the shunt active filter has been developed by Andrea Tilli et al. (2015) to extend the application of SAF to large transients and over loaded system. Anti windup approach is proposed for current control. Closed loop and suitable feed forward action are used in this approach. Harmonic reference manager is used to control input saturation with reference correction. Simulation and hardware setup have been done to study the effectiveness of the proposed controller.

A three phase, three limb coupled inductor has been proposed (Asharf Ali Khan et al. 2015) to solve the commutation problem for PWM AC-AC converters. To increase the power density of the converter, three coupled inductors are integrated by a three-phase, three limb coupled inductor. The analysis of the proposed scheme has been done on the boost type converter alone and is also suggested that the above scheme can be extended to buck and buck-boost converters. The dead time in PWM signals is eliminated in the proposed system because the frequency of the filter inductor is almost twice the switching frequency and thus the odd harmonics are eliminated. The prototype model has been experimented both in separate inductors and coupled inductor on unbalanced resistive load. The same is
extended (Mukhzan Mbeen Ali 2016) for the Bridgeless Boost AC-DC converter.

A three phase multilevel converter based railway power conditioner has been proposed (Fujun Ma et al. 2016) to balance the three phase supply feeding the traction. The proposed system has four H-Bridge links with inductor filter connected to the traction supply. The capacitor voltage is regulated using integrated control strategy. The triggering signals for the proposed system are derived through the PWM controller. Simulation is done and found that the two phase compensation currents are distributed because of no dc bias.

2.5 CONTROL STRATEGIES

Control strategy is very important for effective compensation by the power quality conditioner. The control strategy is being implemented in three stages. Primarily, the signals like power factor, current, voltage and frequency are collected through CT, PT and sensors. Then, the received signals are converted into instantaneous signals. Later, various methods are used to derive compensating signals in terms of voltage and current. Finally, gating signals for the solid state devices of power quality conditioners are generated using PWM techniques, hysteresis and fuzzy logic based control techniques. Then the signals to the solid state devices have been realised through Digital Signal Processors, Microelectronic devices, etc.

The literature survey performed on power quality conditioners based on control strategy is presented in Figure 2.7.

2.5.1 Signal Conditioning

To implement the control algorithm in open loop or closed loop, voltage and current signals on 110 kV side and 25 kV side are measured and
converted into instantaneous signals. To compensate the power quality problems in the railway traction, the control signals to the solid state devices are generated from the above instantaneous signals. PTs or Hall Effect sensors or isolation amplifiers can be used to measure voltage. CTs or Hall Effect sensors can be used to measure current. The hardware or software based type filters are sometimes used to filter voltage and current signals to avoid noise problems.

![Classification based on Control Strategy](image)

**Figure 2.7 Distribution of literature survey based on control strategy**

### 2.5.2 Compensating Signal Derivation

Frequency or time domain based control strategies have been developed in terms of voltage and current compensating signals. These are very essential for steady state performance of the power quality compensators and to control the rating of the solid state devices.
2.5.3 Compensation through Frequency Domain

Compensating commands for frequency domain are extracted from distorted voltage and current signals. The harmonic polluted signals are analysed using Fourier or Lyapunov transformation and the compensating harmonic components are derived. The switching frequency of the solid state devices in the power quality conditioners is generally kept more than the highest compensating harmonic frequency for effective compensation. The online Fourier transformation is usually used for high response time.

Lyapunov function control technique based on energy is developed (Salem Rahmani et al. 2012) for 3-phase, 3-wire shunt active hybrid filter for balanced non-linear loads. PI controller is used to control dc voltage in shunt hybrid filter whereas Lyapunov function control technique is used for steady state and dynamic performance. A prototype model is developed using dSPACE DS1104 control board and the performance is studied. Through the study, it is found that the proposed control scheme does not fully compensate the reactive power but has effective performance in both the transient and steady state operation.

2.5.4 Compensation through Time Domain

The command signals are derived from extracted fundamental signals using $\alpha-\beta$ transformation. The compensating commands are derived after extracting the load current and the reference supply current, where the desired value and reference value are maintained in the controllers like P-I controller and sliding mode controllers. Various other types of controllers to derive the compensating commands from distorted voltage and current signals through time domain are synchronous orthogonal d-q reference frame, slip control, PSO technique, instantaneous p-q theory etc.
Artificial neural network is used for self tuning parameters of power system stabilizer (Ravi Segala et al. 2003) to prove the superiority over the conventional and robustness on wide variation in loading. On investigation, it is proved that nine neurons in one hidden layer are adequate and sufficient.

Li Xiaqing & Zuo Li (2007) have introduced a new control method which consists of PID along with phase locked loop for STATCOM to compensate the harmonics in electric traction loads. Arithmetic control has been derived to have a direct influence on compensation. The capacitance voltage involving energy exchange has been controlled within range using arithmetic control to have a good performance of STATCOM.

A discrete time linear control strategy has been proposed (Javier et al. 2012) for multilevel 3-phase UPQC. Control strategy used is global controller and local controller. Feed forward and feed backward loops are available for series compensator control. Output is taken to the local series current distribution control scheme. The global shunt compensator loop is used to control the power factor by modifying the angle between voltage and current. The output of this controller is taken for local distribution controller to modify the amplitude. Analysis is done through simulation and by implementing prototype model and is found that the steady state performance is satisfactory.

A non-linear derivative control strategy is developed (Abdel hamid Hamadi et al. 2013) for 3-phase, 3-wire shunt hybrid filter. PI control is used to control the dc bus voltage and the load current tracking and the regulation of voltage by non-linear derivative control. The feedback linearisation theory is used to control the ac current through the inner loop and the dc voltage through the outer loop. Simulation is done to study the response of the shunt hybrid filter in harmonic compensation and in load variation of non-linear
loads with reduced ratings confirmed through hardware set on dSPACE DS1104 control board.

Haneol Park et al. (2011) have proposed the synchronous reference frame based control algorithm for RPQC to have effective compensation for various power quality issues. d-axis is used for load imbalance and DC link voltage whereas q-axis is used for reactive power control. The inverter current control is done through hysteresis current control. Simulation is done for traction load with RPQC and the proposed control algorithm through MATLAB/SIMULUX to show the performance on the compensation of the power quality issues and to prove the improvement in THD and power factor.

Decoupling compensation control theory has been introduced to RPC by Ying Dong Wei & Qurong Jiang (2008) to utilise RPC optimally for compensation of reactive power and negative phase sequence current along with the reduction in harmonic current. Reactive power priority control strategy based algorithm is proposed for negative phase sequence current. Finally, the optimum performance of RPC with decoupling control strategy is proved through geometric knowledge.

An algorithm to schedule energy and to mitigate power quality issues has been developed (Mingguo Hong et al. 2014). The algorithm supports the operating schedule of the equipment in the commercial building. Energy control has been carried out in three tier hierarchical control. The voltage and frequency regulations have been carried out in primary control. Secondary control gives the set points to the primary control based on the decision done in the tertiary control. MPPT and PQ control are used in primary control. Case studies have been performed and simulation is done with AIMMS, open DSS and PSCAD.
The shunt active filter has been controlled (Panigrahi et al. 2015) through linear quadratic Gaussian Servo controller. Through this controller, the error between the output current and the variation is reduced by using linear quadratic regular and Kalman filter. The tuning difficulty of the PI controller is improved by Kalman filter. To make dc link capacitor voltage steady at set point, reference generation scheme has been adopted. Simulation and hardware setup have been studied on balanced supply voltage with steady state load condition and the load impedances are increased by 50%.

Shankar et al. (2014) have proposed a new unified control technique for UPQC for various power quality problems. SVPWM along with genetic algorithm control technique have been used. Genetic algorithm is used to determine the firing angle and SVPWM is used for significant optimisation. SVPWM is used to control PWM and to minimise the THD. Simulation is done with 3-phase non-linear load for harmonic compensation and voltage disturbances like sag and swell and it is proved that the waveform is optimised by SVPWM and the output by SA. It is suggested to use charging current and 12-DGBT with two capacitors midpoint grounded for effective system operation.

A novel control strategy for multi level converters capable to manage the capacitor voltage has been developed (Marco A Perez et al. 2015). Decomposition strategy is used in this control scheme. Reference of DC current is arrived from the capacitor voltage and is controlled by adding compensation values. Later, PWM is used to generate gate pulses for the converters. Output of the PI controller is divided by the input current reference so as to get voltage reference. Hence, even when the current reference is small, reference for the generation of the gate signals is predominant and thus the current reference is replaced by the voltage reference which is the output of the voltage controller. Experimental set up is
carried out to find the effect of energy component, control of capacitor voltage and the impact of the voltage controller on output current.

Direct adaptive control technique based on command generator tracker has been developed (Rajesh Kumar Patjoshi et al. 2015) for a 3-phase, 3-wire unified power quality conditioner. The command generator tracker is reference control law to regulate DC link capacitor voltage. Direct adaptive control technique is used to reduce the error between the output and the signal to be controlled and hence provides better tracking performance. Simulation has been done with the proposed technique and the performance has been compared with the conventional PI controller on dynamic condition. Later, proved experimentally and also in real time situation.

A predictive control algorithm has been proposed (Jin-Hyuk Park et al. 2016) for power factor correction converter with conduction mode detection method. Since, the duty cycle is calculated based on the next current state using the slope of the inductor current, the proposed predictive control algorithm has been proposed both in discontinuous conduction mode and continuous conduction mode. Since, the optimum duty cycle has been calculated accurately by the predictive method and directly applied to the control circuits, the proposed predictive control algorithm is found to be more accurate compared to the conventional PI controller, due to the usage of CCM, DCM and MCM for various loading patterns. Simulation is done through PSIM software to validate the performance of the proposed algorithm without the usage of MCM and using only CCM and DCM.

The performance of the various power quality controllers such as DVR, DSTATCOM and UPQC have been studied (Mohammed Abdul Ahad Yahiya et al. 2016) using PI controller and fuzzy logic controller. The switching signal is generated by PI controller. Signals are measured at every interval to find error and the output is generated to activate the signals for
every phase. Simulation is done to study on DVR for voltage regulations, DSTATCOM to compensate voltage level and compensation of various power quality issues by UPQC with PI and fuzzy logic controller.

Sliding mode controller for series active power filter has been proposed (Sushree Diptimayee Swain et al. 2016) which is more robust and stable.

PI control based on Falb-Wolovich has been developed (Johnny Chhor et al. 2016) for a modular shunt connected power condition system. The proposed system has two individual modules. One is the power module for active and reactive power control and another one is the high frequency model to control harmonic distortion. The proposed control strategy along with the proposed system has been simulated through MATLAB to prove the moderate switching frequencies.

Reactive power compensation has been done with FC and TCR (Yuval Beck et al. 2016) with an invariant control system. The invariant control system receives the input voltage and converts to sinusoidal voltage after eliminating the constant component and the zero crossing voltage have been initiated. Simulation is also done to ensure that the load reactive power change range is close to the network by maintaining the power co-efficient.

Synchronous reference frame control algorithm has been developed (Venkata Reddy Kota 2016) for MULTI STATCOM for harmonic suppression. In synchronous reference frame, inverse transformation of a-b-c to d-q-o is used for load current transformation. The DC link voltage is kept constant and PI is used to compensate the loss of active part. Simulation has been done on the 3-phase, 3-wire system with SRF control to study the performance.
Frequency adaptive capability based on repetitive control for the shunt active filter has been presented (LI Lanfang et al. 2016). The steady state compensation accuracy is improved by the proposed control strategy. The phase detection is done by PLL and the reference current signals are produced by the reference current calculator and then the repetitive controller in DSP is implemented so as to improve the performance of the shunt active filter in compensation of harmonics.

Jinwei He (2016) has proposed the co-ordinate control method for dual inter facing converters for harmonic current compensation. Load is directly connected to the first converter through the shunt capacitor to enhance the voltage waveform through closed loop. PLL is used to control parallel converters.

A novel control strategy by combining fuzzy logic with vector PI control for 3-phase hybrid power filter is developed (Subhra Chandran Behera et al. 2016) to mitigate the harmonics. The hybrid filter has series active filter and passive filter. The PI vector PI controller is based on harmonic selective algorithm and fuzzy logic controller based on human thinking. PI controller is used to provide stable output and fuzzy logic controller for command signal. Simulation has been done on the proposed system with the proposed control system.

### 2.6 TECHNICAL AND ECONOMIC CONSIDERATION

Even though technical literature has been developed since 1971, it has not been possible to develop power quality conditioners for higher rated railway tractions because of the cost complexity in solid state devices, complex control strategies, etc. Later, many developments like passive filters connected with active filters (Hideaki Fujita & Hirofumi Akagi 1990), Thyristor Controlled Reactor coupled with fixed capacitors (Wang & Dan...
Yang 2012) and TCR combined with static hybrid active filter (An Luo et al. 2009) for reactive power compensation with the reduction in the rating of the solid state devices have been developed. To reduce the installation cost, the UPQC is connected to load connected phase via LC branch and coupling transformer to the other phase by Dai et al. (2012). In these types of conditioners, passive filters are used to compensate low order harmonics and active filters for high order harmonics. The size and cost of the power quality conditioners have been reduced by using these types of power quality conditioners. Hence, these are the cost effective economic power quality conditioners for a high rated traction supply.

2.7 SELECTION OF POWER QUALITY CONDITIONER FOR SPECIFIC APPLICATIONS

Selection of power quality conditioners based on the application requirement is an important task for the consumers as well as the scientists for voltage and current based compensation. The criteria for selection of power quality conditioner is discussed here and listed in Table 2.1.

2.7.1 Power Quality Conditioner for Current Based Compensation

The compensation for current harmonics, reactive power, neutral currents and load balancing are based on the current. An individual user may select conditioners for individual compensation or for the combination. The active filters are the most suitable for current harmonics. Combining the active filter with the passive filter in shunt is the most suitable because of the reduction in cost due to the low rating of solid state devices in power quality conditioners. The shunt type active filters can be used in reactive power compensation for varying loads and capacitors for fixed loads. Load balancing and neutral current compensation can be done by shunt type active filters. Shunt type active filters are the most suitable for the current based
compensation, while hybrid active filters combined with passive filters may be preferred for combined compensation with reduced cost.

2.7.2 Power Quality Conditioners for Voltage Based Compensation

The compensation for voltage harmonics, voltage balancing, voltage flickering reduction, voltage sag and dips reduction are based on voltage. The series type active filters are the most suitable for voltage based compensation. The power quality conditioners for voltage based compensation are listed in the order of preference in Table 2.1.

2.7.3 Power Quality Conditioners for Voltage and Current Based Compensation

Almost all the voltage and current based power quality problems are present in all the railway tractions because of single phase load and usage of AC-DC converters and AC-AC converters. Hence, the combination of both series and shunt type active filter, usually called Unified Power Quality Conditioner (UPQC) is the most suitable one for this type of compensation. This type of conditioner can be used for individual compensation, but the cost of the conditioner is too high because of its high rating solid state devices. Hence, these conditioners can be used for a few combination of compensation like voltage and current harmonics. The selection of power quality conditioner for this type of compensation is listed in Table 2.1 in the order of preference.
Table 2.1 Selection of Power Quality Conditioners for specific application

<table>
<thead>
<tr>
<th>Compensation for specific application</th>
<th>Power quality conditioner for railway traction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Active filter in series</td>
</tr>
<tr>
<td>1. Current Harmonics</td>
<td>**</td>
</tr>
<tr>
<td>2. Reactive Power</td>
<td>***</td>
</tr>
<tr>
<td>3. Load balancing</td>
<td>*</td>
</tr>
<tr>
<td>4. Neutral current</td>
<td>**</td>
</tr>
<tr>
<td>5. Voltage Harmonics</td>
<td>***</td>
</tr>
<tr>
<td>6. Voltage Regulation</td>
<td>***</td>
</tr>
<tr>
<td>7. Voltage Balancing</td>
<td>***</td>
</tr>
<tr>
<td>8. Voltage Flicker</td>
<td>**</td>
</tr>
<tr>
<td>9. Voltage Sag and Dips</td>
<td>***</td>
</tr>
<tr>
<td>10. (1+2)</td>
<td>***</td>
</tr>
<tr>
<td>11. (1+2+3)</td>
<td>**</td>
</tr>
<tr>
<td>12. (1+2+3+4)</td>
<td>*</td>
</tr>
<tr>
<td>13. (5+6)</td>
<td>**</td>
</tr>
<tr>
<td>14. (5+6+8+9)</td>
<td>**</td>
</tr>
<tr>
<td>15. (1+5)</td>
<td>**</td>
</tr>
<tr>
<td>16. (1+2+5+6)</td>
<td>*</td>
</tr>
<tr>
<td>17. (6+7)</td>
<td>**</td>
</tr>
<tr>
<td>18. (2+3)</td>
<td></td>
</tr>
<tr>
<td>19. (2+3+4)</td>
<td></td>
</tr>
<tr>
<td>20. (1+2+7)</td>
<td>**</td>
</tr>
<tr>
<td>21. (1+3)</td>
<td></td>
</tr>
<tr>
<td>22. (1+4+7)</td>
<td>*</td>
</tr>
</tbody>
</table>

Note: * Indicates suitable  
** Indicates more suitable  
*** Indicates Most Suitable.
2.8 SUMMARY

A detailed literature survey has been performed on various power quality conditioners to resolve the various power quality issues which makes the maintenance of power quality difficult at the consumers’ end and which in turn leads the consumers to pay penalty directly or indirectly. An exclusive review on the power quality conditioners provides a clear idea to the researchers, engineers and consumers. It provides suggestions to the consumers to select a suitable power quality conditioner based on its application and cost.

An Luo et al. (2009) have proposed a 3-phase, 3-wire compensation system having combined the active filter and the Static Var Compensator (SVC). In this system, the Thyristor Controlled Reactor is connected in delta along with the passive filter which is connected in star to form SVC. The passive filter is used for power factor improvement. The active filter is used to reduce the harmonic content generated by the harmonic load and the TCR is used to suppress the resonance between the passive filter and the power grid.

Na Ding & ZeliangShu (2011) have proposed a 3-phase, 3-wire Railway Power Conditioner (RPC) to lessen the power quality issues in electrified railway system. The RPC has three separate single phase chain circuit inverters. All the three single phases are connected in star to make 3-phase, 3-wire system. In that, two phases are connected to two feeders and one phase is connected to the ground. Phase shifted carrier Pulse Width Modulation (PWM) is used for RPC switching. Simulation is carried out with the system to prove the balancing of the current in all the three phases even if it is an unbalanced load.
A modified 3-phase, 3-wire system conditioner to reduce the harmonic content and to compensate the reactive component is proposed. The proposed conditioner has a shunt hybrid power filter with a Thyristor controlled reactor to reduce the ratings of the semiconductor devices when used for high rating loads.