Power Quality Conditioners for Railway Traction - a Review

Railway traction is a more stochastic heavy load connected system. Due to the usage of ac-dc converters and ac-ac converters, the various power quality issues become the major problems in the electric system. This paper presents a review on power quality conditioners suitable for Railway traction based on the configuration, components involved and on the technical and economic considerations. More than 120 publications are listed in the reference for quick review.

Key words: Power Quality Conditioners, Harmonics and Reactive Power Compensation, Active Filters, Shunt Hybrid filter, Power Quality

Nomenclature:
- UPQC: Unified Power Quality Conditioner
- PLL: Phase Lock Loop
- PWM: Pulse Width Modulation
- DSP: Digital Signal Processor
- SVC: Static Var Compensator
- TCR: Thyristor Control Rectifier

1 INTRODUCTION

The ac-dc converters and ac-ac converters used in the railway traction lead to various power quality problems. The major power quality problems seen in the railway traction are power factor and harmonics which leads to penalty. The traction loads are of single phase loads that lead to an unbalanced load which draws more neutral currents. Hence, the study of ideal Power Quality Conditioners for the railway traction system becomes essential to avoid the effects of power quality issues.

A study [1-15] has been done to quantify the various power quality problems in the electric networks and to analyze the power quality problems. The power quality problems due to traction loads lead to low efficiency in the system and poor power factor. In order to avoid penalty on poor power factor, capacitors are used conventionally to maintain the power factor either manually or through electronics switching.

To maintain the harmonics in the system within the limits, the passive filters [16-33] widely called Self tuned filters are used initially, which have some drawbacks such as fixed compensation, large size and resonance. Since, the traction loads are variable and increase drastically, it has led to the development of a dynamic solution called active filters [34-56].

The researchers are recently focusing on the compensation for harmonics, reactive power, load balancing and neutral current compensation [57-129].

This paper comprises a survey on various types of compensations, which are suitable for railway traction. More than 100 presentations [1-129] are studied and classified in SIX categories. The first [1-15] is on power quality indices, effects of power quality problems on the system and various algorithms for power quality analysis. The second [16-33] is about passive filters and designing of the self-tuned filters used in railway traction. The third [34-56] and fourth [57-74] deal with active filters and hybrid active filters used for power quality problems like power factor, reactive power and harmonic compensation in railway...
traction. The fifth [75-81] focuses on unified power quality conditioner, which suits various power quality problems such as power factor, reactive power compensation, voltage and load imbalance. The sixth category [82-129] deals with various compensation methods of power quality problems due to railway traction loads.

This paper mainly focuses on various control strategies and also on economic and technical considerations.

2 STATE OF THE ART

The railway traction system is connected to two phases of the three-phase system, where 110 kV is stepped-down to 21.6 kV and is connected to the load. The imbalance becomes predominant because of the single-phase load. The converters used in railways cause harmonics and poor power factor. In order to avoid penalty, capacitors and passive filters are widely used for power factor and harmonics respectively.

Researches on various power quality problems have been carried over during the past decade. Many research papers are being published with regard to measurements, analysis, causes and effects of power quality problems in power grid and traction [82-89] and the power quality compensation [90-129] in the railway traction.

The traction load is a single-phase load and hence, research has been carried out on single-phase power quality conditioners for railway traction [90-127] in various configurations and control strategies. An extensive study has been made on passive filters [16-33], active filters [34-56] and hybrid active filters [57-74, 119] based on configurations and control strategies, which also provide solution for various power quality problems in railway traction. The configurations such as shunt active filter [35-47,120], series active filter [56] and combination of series and shunt active filters are developed and simulation was done [75-81, 118, 121, 123-127] with the results.

Although traction supply is a single phase supply, a number of papers have been focused on three phase power quality conditioners for unbalanced loads, when the supply has been connected to the railway traction from the supply system through different types of transformers like V/v transformer, Scott transformer etc. There are no extensive publications on three-phase conditioners to the railway traction. Hence, many publications [48-56, 60-74, 80-81, 129] have been reviewed on three-phase power quality conditioners suitable for railway traction with many control strategies. In the three-phase power quality conditioners, active filters can be connected in series, shunt [48-57], combination of series and shunt called unique power quality conditioners [80-81] and passive filters combined with active filters [60-74, 129] are being used.

A work on the comparative study of active filters and passive filters [35, 36, 99], voltage source and current source active filters [38] were reported. Many publications for flicker [39-40,59] and many other publications [57-74, 107-129] on harmonics and reactive power compensation, voltage sag compensation and unbalanced load compensation with more terminologies such as Static Var Compensator, STATCOM, LCL etc., have been considered for literature survey.

The Power Quality Controllers for railway traction have been progressed with the development from Microprocessors to Digital Signal Processors [55, 56,62, 81] and various complex algorithms such as Particle Swarm Optimization [76], Phase Locked Loop [72, 107], Pulse Width Modulations [38, 44, 46, 75, 104, 106], Space Vector PWM [8], Proportional Integral (P-I) [35, 63, 64], Multi-level Direct PWM (122) and Prony Algorithms [48] to improve the dynamic and steady state performance of power quality conditioners.

3 CONFIGURATION

The power quality conditioners are classified based on current source inverter and voltage source inverter, shunt, series or combined on topology and on a number of phases.

3.1 Configuration based on converters

Fig.1 shows the current fed PWM based inverter structure with IGBT based converter. A PWM ac-ac converter with current source [50] provides fast response. Even though it has high response, it cannot be used for multilevel converters because of heavy losses and the need for higher power rating of capacitors.

![Fig. 1. Current-fed-PWM based active filter](image)

The other type of converter is the voltage source converter shown in Fig.2. This type of converter can be extended for multilevel configuration to improve the performance with reduced switching frequencies because of its
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3.2 Classification Based on Topology

Power quality conditioners for railway traction based on topology are classified as passive filter [16-33], active filter in series [50, 56], shunt [37,38, 40, 43,46, 47, 49, 51, 52, 54, 55, 108] and combination of active filter and passive filters connected in shunt known as hybrid filters [36, 43, 46, 62, 63, 65, 66, 67, 69, 70, 71, 73, 74, 107, 119], half bridge [112], TCR with fixed capacitors [108, 129] TCR with passive [68, 95, 98, 100], SVC with active filter [64], Series passive filter with TCR based variable impedance [61], combination of active filter both in shunt and series called unified power quality conditioners [76-81, 121, 123-127] and multilevel PQ compensators [72, 73, 75, 76, 77, 81, 122, 124,128].

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 Fig.2. Shunt active filters are mainly used at the point of common coupling of traction load, that is on the LV side of the traction station transformers to inject the equal compensating currents opposite to 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 [50, 56] as shown in Fig.3.

The unified power quality conditioner, a combination of both active filter in shunt and series [76-81, 121, 123-127] is shown in Fig.4. This type of conditioner is used for unbalanced loads, reactive power compensation and to maintain the terminal voltage. It can be configured as multilevel [77, 81, 122,124], single-phase [78, 79, 121, 123, 125, 126, 127] and three-phase [80] UPQC and hence, this type of power quality conditioner can be 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.

A hybrid filter, a combination of shunt active and passive filter is shown in Fig.5. [129]. 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 [116] to improve the performance of the compensator. LC coupling with UPQC [126] is used to reduce the unbalanced currents and harmonics and reactive power compensation with reduced converter ratings.

An Impedance-matching-transformer with multilevel converter [114] used in traction system balances the three-phase in power grid. The Shunt Hybrid Power Filter combined with Thyristor Controlled Reactor [74] is used to compensate various power quality problems with reduced cost (about 20%) and lower rating of solid state devices. Other type of hybrid filters can be found in the references [64, 68, 95, 98, 100,108, 129].

3.3 Classification based on supply

The railway traction load is a typical single-phase load and the supply has been taken on two phases from a three phase system. Since the traction load is single phase, many publications on single phase, two wire controllers for railway traction [93 – 127] have been reviewed. Even though the traction load is single phase, publications on three phase controllers for railway traction [128, 129] are also reviewed. The three phase power quality controllers are used, when the traction supply is connected to the system through various types of transformers.

3.3.1 Single phase

The power quality conditioners can be configured in active filters in shunt [35–47,120], series [56], combination of both series and shunt called unified power quality conditioners [75–81, 118, 121,123–127] and hybrid power quality conditioner [57–59, 107,108,]. A regenerative PWM rectifier system in series [104] is used to interface the traction converters to the railway power system. A two H-type UPQC with two TCR and two Thyristor controlled rectifier [124] is used to solve negative sequence and harmonics current. Single phase conditioners can be developed in multilevel [122] composing negative sequence with DC capacitors. Different kinds of transformers like Scott, Woodbridge and impedance-matching-transformers to connect three phase supply to two phase traction load system are discussed and found that Y/Δ transformers are more effective [125].

3.3.2 Three phase - three wire power quality conditioners

Publications on three-phase – three wire power quality conditioner to solve the harmonic problems and unbalance in three-phase voltage caused by negative sequences [128 – 129] due to single phase traction loads have been reviewed. Also, other publications on three-phase quality conditioners in series configuration [56], shunt [48–57] and combination of both [60 – 74, 129] have been surveyed. Three single-phase converters based on a chain circuit inverters [128] are connected to the power system through isolation transformer, where two phases are connected to two feeders of traction sub-station and the third phase is connected to the ground. The three-phase power quality conditioner can be developed in single mode or in hybrid mode like fixed capacitors combined with TCR [129], active filter with TCR [74], active filter in series with passive filters [73, 70] and series active filter with shunt passive filter [71]. These types of hybrid power quality conditioners are more popular because of cost effectiveness of the solid state devices and complexity in control.

4 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 [117 – 129] are used to derive compensating signals in terms of voltage and current. Subsequently, gating signals for the solid state devices of power quality conditioners [62, 73, 76-81] are generated using PWM techniques, hysteresis and fuzzy logic based control techniques. Then the signals to the solid state devices have been realized through Digital signal Processors, Microelectronic devices, etc.

4.1 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.

4.2 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.
4.2.1 Compensation through frequency domain

Compensating commands for frequency domain are extracted from distorted voltage and current signals through Fourier analysis [56, 67, 72, 73, 75] and Lyapunov function [61, 62, 66]. The harmonic polluted signals are analyzed 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.

4.2.2 Compensation through time domain

Various control methods to derive the compensating commands from distorted voltage and current signals through time domain are synchronous orthogonal d-q reference frame method [52, 65, 71, 74, 121], slip control [111], PSO technique [76], instantaneous p-q theory [42, 46, 47, 86, 112, 118], single variable linear controllers [81], flux base control [68], SPX algorithm of Nelder and need for optimization [64], abc-dq coordinate method [129], PLL control [72, 104, 107, 123], etc. In the above mentioned various control methods, the widely used control methods are instantaneous p-q theory [42, 46, 47, 86, 112, 118] and α-β transformation to d-q frame [63, 67]. The command signals are derived from extracted fundamental signals using α-β 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 can be found in [42-52,57-68, 72-75,112-123].

4.3 Getting signals to solid state devices of power quality conditioners

The control signals to the solid state devices in terms of voltage or current are generated based on the derived compensating commands. The PWM voltage or current control, phase shifted PWM current control, Multi direct PWM current control, Regenerative PWM, Space Vector PWM and Fuzzy based current control are implemented for switching of solid state devices in power quality conditioners either through hardware or software (in DSP-based).

5 SELECTION OF COMPONENTS AND DIFFERENT FEATURES OF POWER QUALITY CONDITIONERS

The railway traction load is high rated and hence, the selection of solid state device is very much essential. Even though GTO are used for high rated, IGBT is the ideal one because of its characteristics. The inductor (L) is normally used to act as buffer between the supply and power quality conditioner. The selection of the inductor is important for an optimum operation of power quality conditioners. Large amount of dc supply is injected into the system when small value of inductor is selected. The tracking of the compensating current will be difficult when large value of inductor is selected. Hence, the optimum value of inductor selection is necessary. Selection of DC line capacitor is another important parameter for the optimization of power quality conditioners [54]. Large fluctuations and large ripples are observed for small values of capacitors. When large values of capacitors are selected, the cost and the size of the capacitor are increased, even though the fluctuations and ripples are reduced.

In general, power quality conditioners are used to compensate voltage and current harmonics. In addition, sometimes, they may be used for reactive power compensation, unbalanced current, flickers and for voltage regulation. For voltage problems such as voltage sag, fluctuations and voltage unbalance, the power quality conditioners are connected in series [50, 56]. For current related problems such as reactive power compensation, current unbalance etc., the power quality conditioners are connected in shunt [35, 57, 120]. If it is required for both the above problems, the power quality conditioners are to be connected both in series and shunt configuration [60-81, 118, 121, 123-127, 129].

6 TECHNICAL AND ECONOMIC CONSIDERATION

Even though technical literature is being developed since 1971, it has not been possible to develop power quality conditioners for higher rated railway traction because of the cost complexity in solid state devices, complex control strategies, etc. Later, many developments like passive filters connected with active filters [36, 58, 60, 62, 63, 65-67, 69-74,107, 119], Thyristor Controlled Reactor coupled with fixed capacitors [108] and TCR combined with static hybrid active filter [129] 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 [117]. In these types of conditioners, passive filters are used to compensate low order harmonics and active filters for higher 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 cost effective and economic power quality conditioners for a high rated traction supply.
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 and listed in Table 1.

7.1 Power quality conditioners 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 most suitable for current harmonics. Combining active filter with passive filter in shunt is 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 most suitable for the current based compensation, while hybrid active filters combined with passive filters may be preferred for combined compensation with reduced cost.

7.2 Power quality conditioners for voltage based compensation

The compensation for voltage harmonics, voltage balancing, voltage flickering reduction, voltage sag and dips are based on the voltage. The series type active filters are most suitable for voltage based compensation. The power quality conditioners for voltage based compensation are listed in the order of preference in Table 1.

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 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 few combination of compensation like voltage and current harmonics. The selection of power quality conditioner for this type of compensation is listed in Table 1 in the order of preference.

| Compensation for specific application | Power quality conditioner for railway traction |
|--------------------------------------|-----------------------------------------------|
| Current Harmonics                    | Active filter in series **  ***  ***            |
| Reactive Power                       | Active filter in Shunt ***  **  *              |
| Load balancing                       | Hybrid Active Filter/SVC * **  *               |
| Neutral current                      | Active filter both in series and shunt (UPQC) **  * |
| Voltage Harmonics                    | **  ***  *                                    |
| Voltage Regulation                   | **  *  *                                      |
| Voltage Balancing                    | ***  **  *                                    |
| Voltage Flicker                      | **  ***  *                                    |
| Voltage Sag and Dips                 | ***  *  *                                    |
| (1+2)                                | ***  **  *                                    |
| (1+2+3)                              | **  *                                         |
| (1+2+3+4)                            | *                                             |
| (5+6)                                | *                                             |
| (5+6+8+9)                            | **  *                                         |
| (1+5)                                | **  *                                         |
| (1+2+5+6)                            | * **                                          |
| (6+7)                                | **  *                                         |
| (2+3)                                | *                                             |
| (2+3+4)                              | *                                             |
| (1+2+7)                              | **  *                                         |
| (1+3)                                | *                                             |
| (1+4+7)                              | * **                                          |
8 CONCLUSION

It is seen that, there is difficulty in maintaining the power quality at the consumer’s end and in turn the consumers may pay penalty directly or indirectly. An exclusive review on power quality conditioners for railway traction provides a clear idea to researchers, engineers and consumers. It provides suggestions to the consumers to select a suitable power quality conditioner based on its application and cost.

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