Power Quality Issues and Solutions in Electrified Railway Traction System

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Abstract-Many advancements in electrified railways have been made in recent years around the world. Power quality has become a serious issue with AC powered railways as technology has progressed. Negative sequence current, harmonic current contamination, load imbalance, and reactive power consumption, are all issues with this technology. A huge portion of negative current is introduced into the grid, causing serious effects on the power system, like motor vibrations and other extra losses; protective relay mis operation; and reduced transformer output capability. The railway traction power supply and electricity system are both intimidated by such effects. As a result, harmonic current and negative sequence current must be suppressed. Many approaches and power quality compensators are utilized to confront the problem of power quality in electrified railways. This study explains why power quality concerns have arisen in the rail network, their consequences, and how well we can thoroughly compensate for these issues.

Keywords-*Power Quality (PQ), Electric railways traction, Traction Power System (TPS), Public Power System (PPS), Negative Sequence Current*

I. INTRODUCTION

The present era represents a period of technological advancement and development. With fast evolution, the demand for high-quality power has increased. In everyday life, transportation is critical to everyone's well-being. The Indian railway system is one of the country's most extensive transport networks. The expansion of electrified railways in India demonstrates a successful solution for increasing capacity of public transit. Indian Railways implemented electric powered railways in 1957 [12]. With electric railways, concerns about power quality arise, as traction demand is considered a dynamic and a non-linear load. This peculiarity generates a huge number of harmonics, subharmonics, and currents in the negative sequence current (NSC). In this context, a massive amount of negative current is introduced into the grid, having a detrimental effect on the power system by causing motor vibrations and added losses; reducing the output capability of the transformer; and causing the protective relay to malfunction. This has a chilling effect on the power systems as well as the railway traction supply [1-4]. These issues result in a variety of issues, including motor vibration, an impact mostly on efficiency and performance of transformers, noise, malfunctioning protective systems, and an impact on sensitive relays. As a result, it is required to compensate for poor power quality in the traction system. As a result, harmonic current and negative sequence current must be suppressed. Numerous approaches and PQ compensators are utilised to address the problem of power quality in electric railways. Therefore, in context, this article discusses the PQ challenges associated with railway electrification, and also strategies for improving PQ which can be either conventional or based on innovative power electronics. The article's primary objective is to have an outline of the PQ phenomenon during railway electrification, as well as the novel tactics used to improve PQ.

II. RAILWAY TRACTION SYSTEM

The traction system is supplied by the state utility, which provides three-phase power at 110/220 kV. Because the traction overhead equipment (OHE) requires a 25 kV supply, only two phases are received and converted to a single phase 25 kV via a transformer located at the traction substation. This transformer is known as traction transformer which converts the two phase into single phase at 25 kV. This 25kV is sent to the OHE from the feeder and then to the loco via the pantograph located on the loco's roof. When many locomotives operate concurrently at a substation, a voltage drop occurs at the OHE. As a result, the motor operates inefficiently, as a huge amount of current is pulled from the line. The complete traction structure can be considered in three sections: three-phase power supply, locomotive system, and traction substation.

a. *Traction substation:* Through a 1-Φtransformer, 110/220 kV is stepped down to 25 kV at the traction substation. From 3-Φ systems, the 25 kV AC voltage is taken as a 1-Φ system. One transformer link is permanently securely earthed and serves as a return.The traction substation is made up of several protection devices in addition to the transformer. It includes things like a circuit breaker, transformer protection, and lightning arrestor among other things. This 25 KV is then delivered to the feeder, which is ultimately connected to the OHE line.

Figure 1.Traction Substation Configuration [7]

b. 3-Φsupply system:

The power generated from the producing station is routed through a 3-Φ phase distribution network to a grid substation. The voltage level of a 3-Φ distribution system is 132 kV or 220 kV from normal. However, because the Indian railway approved the 25 kV system, the existing 3-Φ phase voltage must be reduced to 25 kV. To step down the 220/132 kV to 25 kV, the step-down transformer is linked to any 2 phases of a standard 3-Φ phase circuit. In a 3-phase system, this leads to a voltage drop and an imbalance. The OHE connection wires are supplied from A-B, B-C, and C-A at periodic intervals (approximately 40-60 km) at the traction substation for load balancing mostly on power network. The next substation is supplied from the b-c phase if one phase is supplied from A-B. This form of phase combination has no effect on the system's phase sequence. A dead zone across two successive sections supplied from two separate kinds of phases is supplied to prevent a short circuit between both the phase's neutral section or dead zone.

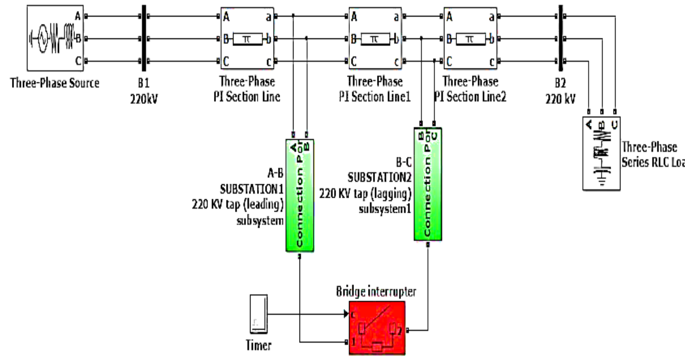

Figure 2. Indian Railways' 25 KV Traction System Typical Feeding Arrangement [7]

Figure 2 depicts two substations fed from separate phases with a bridge interrupter in the middle. The bridge interrupter allows the loco to smoothly transition from A-B to B-C phase.

c. *Locomotive Subsystem:* Locomotives use a traction transformer to obtain a 25kV, 50Hz Ac power supply from a 3- Φ grid of 110/220kV. The following graphical representation (fig 3) shows how a locomotive works. The locomotive gathers 25kV AC from OHE using a pantograph [7], as illustrated in the diagram. Traction motors turn this electrical energy into mechanical energy in a controlled manner. In a traditional locomotive, a roof-mounted pantograph collects 25000V single phase, which is then stepped down by a transformer inside the locomotive. A circuit breaker is installed on the roof for safety reasons. Full-wave silicone rectifier converts this supply to DC, which is subsequently fed to traction motors via smoothing reactors. The locomotive has six motors. DC motors are commonly utilised in locomotives. Variation in AC input voltage to the rectifier via an on-load tap changing mechanism on the primary side of the traction transformer regulate speed and torque. The ARNO converter receives a 380 V, single phase feed from the loco transformer's auxiliary winding and transforms it to 380 V, 3-Φ. This 3-Φ power is used to power blowers that cool traction motors, as well as loco transformers, silicon rectifiers, smoothing reactors, compressors, and vacuum generators that pile up air pressure.

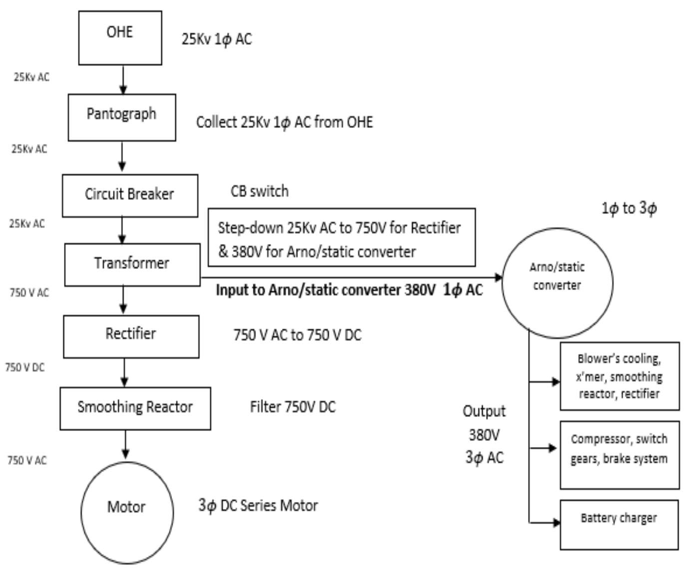

Figure 3. Locomotive Block Diagram

This configuration in loco throws the system off balance, causing NSC to occur in the system and inject NSC into the grid. Because to the presence of NSC, the AC input current to the silicon rectifier is harmed, and the DC output is also harmed. Harmonics and subharmonics were introduced into the system by the nature of nonlinearity. Odd harmonics are present when NSC is present. This problem has an impact on the power system's performance. Engineers are quite concerned about finding a solution to this problem.

III. PERILOUS EFFECTS OF POWER QUALITY

Rail systems with deteriorated power quality may cause surrounding systems to fail. One of most serious threat posed by power quality issues is to upstream power distribution networks, that can be severely impacted, as it will be detailed further below. Moreover, it may jeopardise the railway's signalling and communications networks. [19,28-30,40,58-61] discuss the effects of low traction power quality on various systems, the most notable of which are:

a. Signalling and Communication Consequences: Track circuits are built to operate at a specific frequency which should not interfere with power frequency. Harmonic frequencies may alter transmitted signal in the existence of harmonics [19,41], leading in inaccurate signals and poor train alignment, culminating in a disaster. In addition, communication lines are generally run in parallel with power lines/cables. Return current and Catenary energy would be uneven in the existence of stray currents, leading the corresponding magnetic field in communication cables to not be zero. As a result, voltages will be induced in communication cables, interfering with the signals of communication [68]. Furthermore, high-order harmonics may create power system and communication interference.

b. Upstream Network Effects: The influence of power quality issues on the upstream supply network has been studied in a number of studies [34,49,60] and can be divided into three categories:

- *Inappropriate transmission line control system functioning:* Voltages and currents are sampled depending on their fundamental components. Every control system in a transmission line would operate incorrectly as a result of the immense amount of NSC current and harmonics injected into transmission lines by traction loads.
- *Failure of the protective system:* In the existence of harmonics and NSCs in voltages and currents, protection relays may function erroneously. Traction load generates a huge number of harmonics and NSCs, which causes the protection mechanism to malfunction.
- *Reduced utilisation factor:* Because the traction load is a huge single-phase load, it leads to high current NSCs that flow in just two phases, lowering the transmission line's utilisation factor [40].

IV. POWER QUALITY IN ELECTRIFIED RAILWAYS

Because of catenary/pantograph and switching activities, the traction load varies dynamically, and arcs may form. As demonstrated in Figure 4, modern drivetrain components rely on power converters in combination with transformers to introduce low levels of current harmonics into supply system [14,15,32,46,48,51]. This method has the significant advantage of allowing trains to cross borders between nations with diverse railway power systems in terms of frequency and voltage. This poor power quality could affect the power system that causes neighbouring loads to fail. Thus, the most serious power quality issues in electric railway systems were addressed.

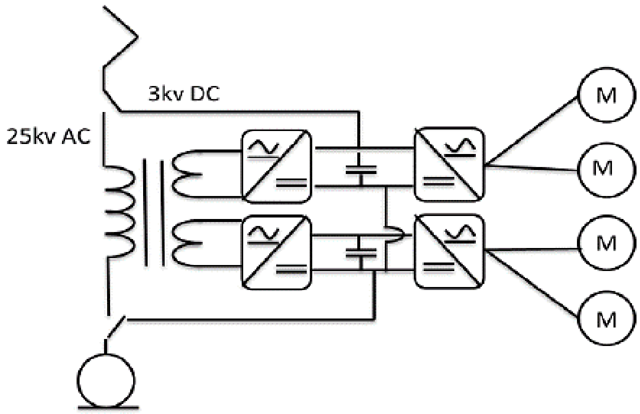

Figure 4. Modern locomotives having a PWM 3-Φ inverter and a three-phase synchronous/asynchronous machine that can run at both high and low voltages. [17].

a. Harmonics: Urban DC traction systems employing 12-pulse rectifiers generate a significant quantity of 11th and 13th order harmonics, while AC traction systems employ AC/DC/AC converters, resulting in the introduction of distinct harmonics into the 3 Φ phase power system. Additionally, a DC component may have been inserted into the AC system examined in [64]. Harmonics in voltage and current are the second power quality issue with electric rail drives that must be corrected for in [31,39,40,52,65,67]. Harmonics induced by traction load are investigated and modelled in [65], and harmonic elimination/reducing compensating methods are proposed and explored in [20,22,24,50]. It has been demonstrated that transformers coupled in a specific manner act as passive filters, lowering harmonics depending on the harmonic order and transformer type [40,42,47,53].Harmonic reduction can be accomplished by controlling the ac/dc/ac converters on the train's traction motor drives [31,52,66], leading in less harmonic generation. A clean 27-level 4-quadrant converter is designed for use in TSS in DC systems [48], while a seven-cell converter is examined in [43], both of which are capable of successfully reducing the major side harmonics of TSS. Shunt active filters are by far the most effective technique of harmonic cancellation, but they are also the costliest; consequently, for sensitive systems or adjacent to sensitive loads, active filters are a great option; some mixture of passive and active filters is proposed in [34-36], with passive filters used to slow down the rate of the active filter. Additionally, the supplemental train power supply generates low-frequency harmonic current, in which [36] investigates the compensatory approach.

b. System Imbalance: System imbalance is by far the most critical issue in terms of electric rail power quality, as the majority of trains are single-phase, and a single-phase load generates nearly that much current NSC as a PSC [62,63]. If such NSCs are not suppressed, the NSC ratio is 1, and given the size of a traction load (e.g., 5-20 MW), it may cause damage to the power system and therefore must be compensated [49,57]. [35] investigates the phase-shift approach, which is the most widely applied method for NSC compensation, and section IV describes the substation connections. The compensation of current NSC using particularly linked transformers is researched in [30,38,47,53,55,59]; traditional transformers inside the power sector use wye and delta connections, whereas special transformers like Scott, V-v, and Multi-Purpose Balanced transformer (MPB) are being used in special industry sectors like railway electrification; this should be mentioned that while traditional transformers are less expensive mass production, special transformers are more expensive. Several papers [44,56,60] demonstrate the use of several kinds of static voltage compensators (SVCs) to correct for NSCs of current, including thyristor-switched capacitors (TSCs) and fixed-capacitor/thyristor-controlled reactors (FC/TCRs). The most innovative commercial compensators for rail applications are examined in [1,3,18,25,30,45,49], which employ one or two shunt converters to correct for the entire non-active current components. Series compensation is typically not used with railway loads as current imbalance at the point of common coupling (PCC) must be minimized to avoid voltage difficulties. Apart from removing reactive power and harmonic, the co-phase scheme outlined in [1,13,14,15,23,25] is an excellent system for compensating for imbalances.

c.Reactive Power: Modern traction motor AC converters employ pulse-width modulation (PWM), which produces no reactive power [21], and power quality compensators also have a power factor of one [30,50]. In TSS, active/reactive power generation/transfer is supposed to compensate for the NSCs. As a result, to reduce reactive power, NSCs in TSSs must be in phase with three-phase currents/voltages. As a result, reactive power and NSC compensation are not conducted independently.

d. Arcing: Arcs are formed when the catenary/pantograph of overhead systems interacts with the third or fourth rail, or when brushes engage with the third or fourth rail due to the dynamic latitudinal tolerance between rail and wheels [28,33]. Arcs will occur in particular on overhead system isolators and third/fourth rail ramps, distorting voltages and currents and introducing a transient DC component into AC systems, resulting in dielectric breakdown.

e. Voltage Problems: The most common issues with voltages are related to their magnitudes. Unbalanced currents result in unbalanced voltages, as previously stated. Depending on EN 50163 and IEC 6850, traction motors as well as other associated loads in trains are supposed to perform correctly with voltage amplitudes that are 24 percent lower or 10 percent higher than that of the nominal voltage of electric railroad drives. As a result, current problems must be concerned, as it will be detailed, but voltage problems would not impair the system's performance.

V. ENHANCING POWER QUALITY OF ELECTRIC RAILWAY TRACTION

Since the inception of railway electrification, numerous approaches for overcoming PQ degradation on the PPS side have indeed been deployed and researched. The following approaches were implemented some generations earlier and are still in use today in a variety of traction substations throughout the globe. The following subsections provide an overview of the conventional approaches used to enhance the PQ.

4.1 Conventional Methods

Since the inception of railway electrification, numerous approaches for overcoming the PQ degradation on the PPS side have been employed and researched. The following procedures were implemented some decades ago and are currently being used at several traction substations globally. The following subsections provide an overview of the conventional strategies used to enhance the PQ.

a.Employing Adjacent Power Transformers for Phase Shift
To prevent short circuits between phases, the overhead catenary lines are sectioned into electrically isolated sections using this technology. The non-electrified regions are known to as neutrality sections (NSs), and they can span many kilometres [27].Every zone all along catenary line is single-phase, with phase alternation occurring at every traction substation. This is a time-honoured and cost-effective method of achieving phase balance [2]. When electrified portions are not loaded equally, existing NSCs are drastically decreased, but still exist due to asymmetrical 3 Φ currents [17].Alternating phases does not completely resolve the current imbalance problem unless the loads on every electrified segment are equal. Furthermore, this design precludes load sharing between nearby single-phase (1Φ) power transformers. Figure 5 illustrates the phase-shift approach in three single-phase traction substations.

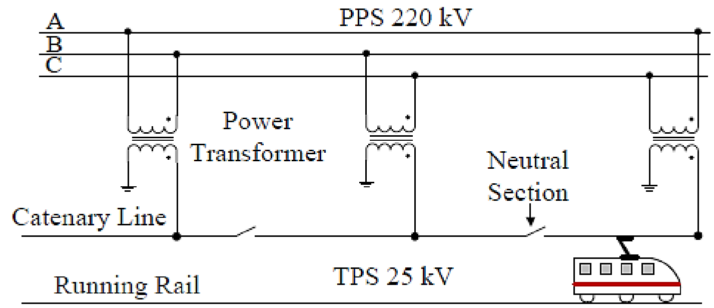

Figure 5. A phase-shift methodology used to switch between PPS phases. [2]

b. 3-Φ Electric Trains: The 3-Φ asynchronous motors have been used all over the world for traction over the last few decades. A few TPSs have indeed been built with two catenary lines and 3-Φ AC power, as well as the third and/or fourth rails. The primary thing that made this framework hard was that it needed three conductors, that made the overall cost much more. There were 3-Φ AC traction systems that ran at 16.7 Hz and 3.6kV for the hillside lines. Italy was the main user of these systems. To make this system work, the traction load throughout this case had to be 3-Φ. The main benefit of this process was that the PPS didn't have to deal with a lot of NSCs. Even though, to use a 2nd pantograph and energising the rails have been the primary reasons to give up on this idea.

c. *EmployingPassive Power Filters:* Passive filters have a straightforward assembly and are composed of passive components like capacitors and inductors. These filters had first been utilised in 1940 to decrease harmonic current injection into the TPS from locomotive converters [5]. This was the technique of power factor adjustment and harmonic reduction that was frequently utilised in railway electrification. Such passive power devices can usually be used in conjunction with a balanced power transformer or power electronics compensator to reduce the compensator's power rating, cost, and volume [6].Passive power filters come in a variety of configurations, including single-tuned, double-tuned, and third-tuned [13]. Generally, these filters are capable of reducing the appearance of low-order harmonics(– for example, the 5th and 7th), but the damping passive filter has indeed been suggested to remove higher order harmonics [13]. Paralleling passive filter banks was suggested to maintain harmonic distortion within tolerable ranges.However, this method may need a large amount of space for installation, in addition to the high operational cost. Another issue was the progressive change in filter settings caused by heat or longevity, which resulted in incorrect filter functionality. When using passive power filters, a compensation system cannot perform a unitary power factor correction if the reactive power of the TPS changes often. Each passive filter's set capacitor value cannot completely compensate for reactive power, as these devices are incapable of tracking dynamic changes over time [13].

d. *Employing Balanced 3-Φ Power Transform:* Certain types of 3 power transformers are well-known for their employment in 2-Φ power systems and rail distribution channels. This is due to the fact that some technological properties, such as the potential to reduce NSCs mostly on PPS side, may assist in PQ advancement.The LeBlanc, Scott, Woodbridge power transformers, and impedance matching, are among the most frequently used balanced transformers. Whenever the electrified portions have same loads, the NSCs of the currents supplied in the PPS are ignored [23]. In terms of balanced transformer, harmonic distortion, can be an intriguing choice, as they can result in the cancellation of some harmonics [6]. In addition, even though the load sections are equally loaded, complex winding configurations and an unequal number of turns across each phase might lead in an unbalanced situation [17].There are certain downsides to balanced power transformers which should be considered. To begin, these power transformers' material utilisation factors (copper and iron) are relatively poor in comparison to conventional V/V (unbalanced) power transformers. Furthermore, because LeBlanc and Scott power transformers have no neutral point in their own primary windings, the required voltage insulation levels are just too high and expensive [16]. Scott power transformer links are shown in Fig 5(a), while LeBlanc power transformer connections are shown in Fig 5(b). In China, the impedance matching power transformer seen in Fig 5(c) is the most widely utilised.For two-phase railway traction power delivery, the Woodbridge power transformer often necessitates two extra autotransformers [6,16].

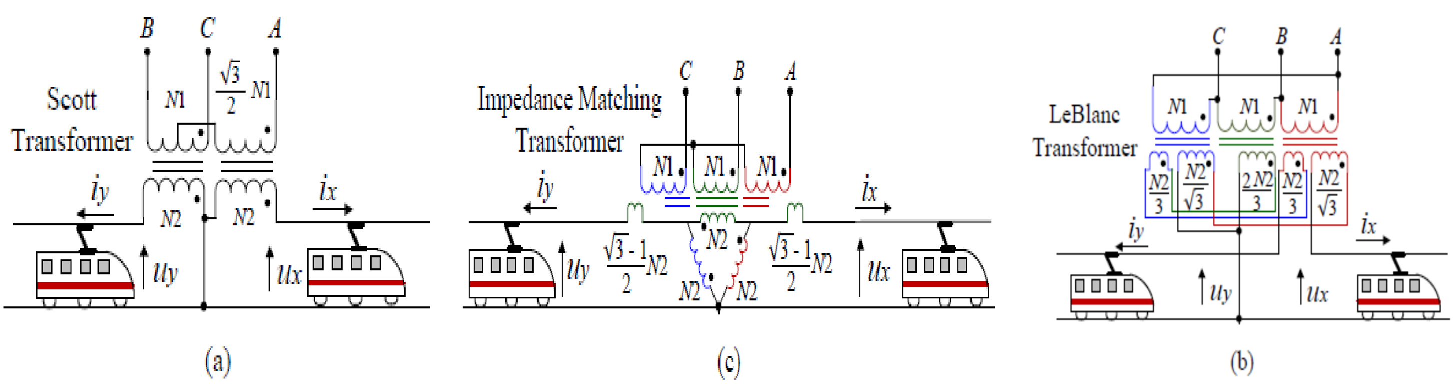

Figure5. Railway power transformers that are balanced; (a) Scott transformer; (b) LeBlanc transformer; (c) Impedance matching transformer [2].

In comparison to balanced power transformers, The design of an imbalanced V/V power transformer is fairly straightforward, and it can be overloaded [8].As a result, it is commonly employed in railway applications.

4.2 Power Electronics Technology-Based Methods

Since the 1970s [5], particularly with the observed progress in power electronics devices, power generation compensators depending on the power electronics technology have been put into service in order to enforce dynamic compensation. The power electronics-based strategies used to increase the PQ of PPS are described in this paper.

a. STATCOM: Static Synchronous Compensator(STATCOM) devices have indeed been dubbed the "next generation of power rectifiers" [11]. Mostly on AC side, a voltage source converter (VSC) with DC-link inductances, a capacitor, and a coupling transformer is present.STATCOM devices are suitable for usage at medium voltages and frequencies of 50/60 Hz. As a result, they are typically manufactured in greater numbers than SVCs devices. The STATCOM device is linked in parallel with PPS in Fig. 6. The STATCOM can be connected and unplugged without compromising with the functioning of the traction substation due to its parallel connection.As a result, the STATCOM operation will have no effect on the railway. substation's resilience or readiness. Additionally, because the STATCOM does not require an internal power supply, it provides no active power.In another sense, STATCOM would be accountable for trading reactive power with the PPS and therefore will require no active power. As a result, the volt-ampere (VA) rate of the STATCOM can be significantly lower than the traction substation [4].STATCOM, as compared to the SVC, is a bidirectional reactive power compensator that provides a quick response time, improved load capacities, lower harmonic content, and a much more efficient system design.

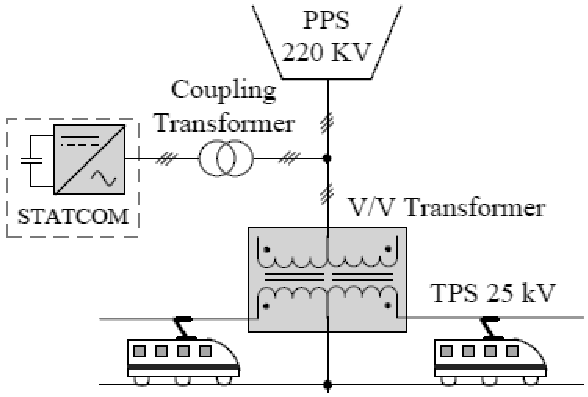

Figure6. A step-down coupling transformer connects the STATCOM to the PPS. [2].

b.SVC: The Static VAr Compensator (SVC) can be installed via a step-down transformer at the PPS, as illustrated in Fig. 7.

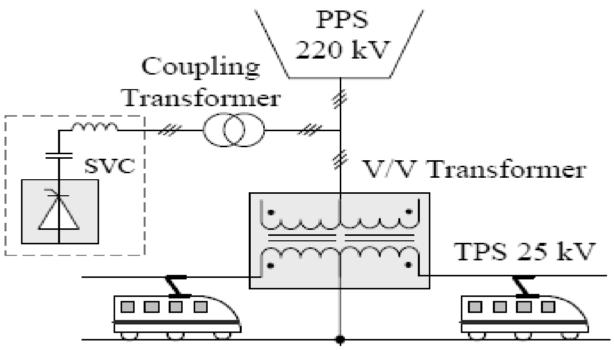

Figure 7. A step-down transformer connects the SVC compensator to the PPS[2].

The SVC is now known as a compensator possessing low-cost since it has the potential to lower the system's power factor when used to compensate for NSCs. In other words, while applying the SVC, there is a compromise amid NSCs compensation and the power factor correction. If the system has reactive power, the SVC is useless as a compensation. As a result, because there are many SVC kinds on the market, manufacturers are continuously customising the SVC to match each customer's individual needs.

c. RPC: In electrified trains, Rail Power Conditioner *(*RPC) seems to be a very efficient topology for overcoming the bad impacts of currents, harmonics, and NSCs. The system is made up of two single-phase, back-to-back converters with a single DC-link, as shown in Fig. 8. Every converter is connected to a load segment through a step-down coupling transformer.

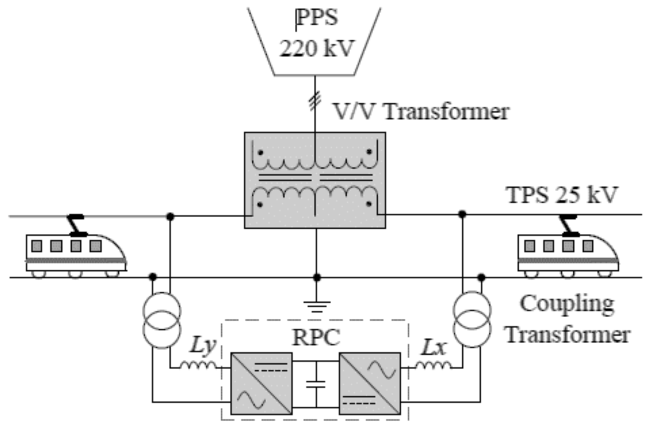

Figure 8. Step-down coupling transformers connect the RPC compensator to the TPS. [2].

The RPC has the ability to balance the active power consumed by the TPS's primary feeder two-phases. This can be accomplished by transferring half of load active power disparity from the heavily laden to a light load region [14,16]. However, balancing the active power utilized by two phases is inadequate to achieve balanced current flow there in PPS. The RPC compensates for reactive power due, including one RPC converter producing capacitive reactive power as well as the other compensating for inductive reactive power [10]. Unlike the SFC, the PPS does not conduct a frequency conversion because the load power is provided predominantly by a Scott or a V/V power transformer; however, the load sections can be overloaded, which is a benefit of using the V/V power transformer [9,10]. Moreover, by using a co-phase RPC framework, the NSs risk can be minimised [17]. Table provides a comparison of the above-mentioned compensator techniques in rail electrification. In the new proposed RPC topologies, the MMC is used to eliminate the necessity for two step-down coupling power transformers [8-10].

*d. SFC:*As shown in Fig. 9, the Static Frequency Converter *(*SFC) is made up of a *3-Φ* AC/DC converter linked back-to-back to a *1- Φ* DC/AC converter with a single DC-link. Harmonic currents can't travel from the TPS to the PPS because of SFCs. In other terms, locomotive harmonics are not transmitted to the PPS [8-10]. Furthermore, because SFCs may display the *1-Φ* load mostly on TPS as a balanced *3-Φ* load on the PPS, they can readily solve the difficulty of NSCs [8-10].

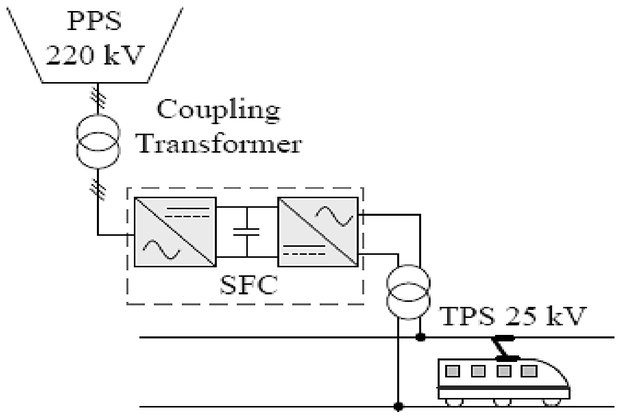

Figure 9. SFC system in railway electrification [2].

As a result, NSCs and harmonics compensation are regarded as intrinsic behaviours when the SFC is used. If a significant number of SFCs are used to supply the catenary line, they must be capable of operating in all four quadrants and getting adequate power ratings to feed the locomotives with the entire amount of power they require [11]. In contrast to other power compensators, the SFC technique is generally more expensive than the other structures as it must be rated for the entire train power, while other power compensators should be only rated for a portion of the load power [17]. The SFC method is also substantially more expensive than that of the other systems because it must be rated for the entire train power. According to the unique and creative topologies, the SFC should be based on a modular multilevel converter (MMC), which can be connected directly to higher voltage levels, hence eliminating the need for coupled transformers.

4.3 Considerations for Choosing the Right Compensation

Selecting the correct level of power quality is a critical decision in the construction of a rail network, and it varies greatly based on the system's requirements and conditions. The following are the most crucial characteristics that qualify the system's compensation programme.

- Power flow (having the power to regenerate or not).
- Number of pulses (for example 6/12 pulses for DC railway).
- Size, cost, efficiency, and weight.
- Interference with signalling and communication systems due to electromagnetic interference.
- Environmental variables (altitude, ambient temperature, humidity, types of cooling, pollution level, etc.).
- Need for required degree of power quality from a PCC perspective (permissible current, harmonics, and power factor for NSC).

Additionally, there are certain additional decisive aspects that affect the compensation approach, such as the DC-link capacitor/voltage level i.e., for active compensators, the step-down transformer used to compensate for switch rating decrement, and a specified standard.

VI. CONCLUSION

By comparing locomotive and traction system operation, we can determine why and how this power quality problem happened in the system, how it manifested itself in the system, and the impact of power quality concerns on the entire network.Future research should focus on optimising power quality by the application of these forms of power quality improvement techniques in an optimal system configuration.

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