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AN INNOVATIVE COMPENSATION NEGATIVE SEQUENCE FOR POWER QUALITY ISSUES IN TRACTION SYSTEM

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ABSTRACT

Since the beginning of railway electrification, power quality has been a main problem in railway networks because of their special characteristics. Many ways of power quality improvement have been investigated and applied to AC and DC traction systems through railway electrification history. This work proposes Railway power conditioner (RPC) is efficient in negative sequence compensation. A new power quality collaboration compensation system and strategy based on RPC is proposed in this work. The minimum capacity conducted is 1/3 smaller than traditional single station compensation. Simulation results have confirmed that the collaboration compensation system proposed can achieve a good performance at the negative sequence compensation with capacity and cost efficient. The simulation design and analysis of results are carried out in MATLAB/Simulink environment.

I. INTRODUCTION

Railway electrification has been begun in the early 20th century [1], [2]. It was embraced in many countries because of its advantages such as lower air pollution, heavy load and mass transit ability, high efficiency, and, most recently, because of reduced CO2 generation. From the start of railway electrification, power quality was a significant concern for electrification apologists, and many research studies have been dedicated to power quality improvement in rail distribution systems. In this paper, the most important articles on power quality improvement of electric railway networks are cited and classified to make them available for researchers. At first, power quality issues of rail systems are described. The most important problem is, in the case of three-phase systems, the imbalance of current because a railway load is nowadays always a single-phase load which causes a negative-sequence component (NSC) of current equal to the positive-sequence component (PSC) [3].

In former times, single-phase commutator [4] motors were used; however, during the past 50 years, single-phase rectifiers/three phase inverters are relied on combined with either three-phase synchronous or induction machines (motors/generators) which feed power back into the single-phase power system during braking operation through regeneration where the rectifier becomes an inverter and the inverter becomes a rectifier [5], [6]. The most important systems affected by railway electrification are upstream power supply networks [7]–[16], railroad signaling and communication, and telecommunication systems [17] [19]. Traction load is varying dynamically, and arcs may occur because of pantograph/centenary and switching actions. Modern drive trains rely on power electronic converters combined with transformers, which inject low amounts of current harmonics into the supply system as shown in Fig. 3.1. The great advantage of this approach is that trains can cross borders of countries, which have railway power systems with different voltage and frequency. This low quality of power may harm power system and cause the adjacent loads to malfunction. The most important power quality problems in electric railway systems have been investigated here.

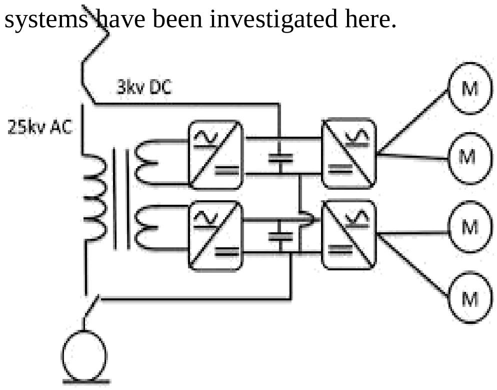

Fig 1 Modern Drive train of Locomotive, PWM Three-Phase Inverter and Three-Phase Asynchronous/Synchronous Machine with Dual Mode Voltage Capability

II. POWER QUALITY IN ELECTRIFIED RAILWAYS: STATE OF ART

Traction load is varying dynamically, and arcs may occur because of pantograph/catenary and switching actions. Modern drive trains rely on power electronic converters combined with transformers, which inject low amounts of current harmonics into the supply system [73]–[78] as shown in Fig. 1. The great advantage of this approach is that trains can cross borders of countries, which have railway power systems with different voltage and frequency. This low quality of power may harm the power system and cause the adjacent loads to malfunction. The most important power quality problems in electric railway systems have been investigated here.

2.1 System Imbalance

System imbalance is the most serious problem in electric railway power quality, because most trains are single-phase, and a single-phase load produces a current NSC as much as a PSC. If these NSCs are not attenuated, then the NSC ratio is 1, and since a traction load is large (e.g. 5-20 MW) it may harm the power system and must be compensated. The phase-shift method is investigated in, which is the most applicable NSC compensation method, of which substation connections are described in section IV. The compensation of current NSC by the means of specially-connected transformers is studied in; the conventional transformers in power industry consist of delta and wye connections, while other connections such as V-v, Scott, Multi-Purpose Balanced transformer (MPB) and etc. are used in special industries such as railway electrification; it should be noted that mass production of conventional transformers results in less price, but special transformers have better performance in this case. Some publications use different types of static voltage compensators (SVCs) to compensate NSCs of current, from fixed-capacitor/thyristor controlled-reactors (FC/TCRs) or thyristor-switched-capacitors (TSCs). The most novel commercial compensators for railway applications are investigated in which include one or two shunt converter(s) to compensate the total non-active current components. For railway loads, series compensation is not usually employed because current imbalance at the point of common coupling (PCC) should be avoided as it will result in voltage problems. An effective system for imbalance compensation besides harmonic and reactive power elimination is the co-phase system discussed.

2.2 Harmonics

Urban DC traction systems using 12-pulse rectifiers generate large amounts of 11th and 13th order harmonics, and for AC traction systems, trains use AC/DC/AC converters causing different harmonics flowing into the three-phase power system. There, also, may be a DC component injected into the AC system investigated. Current and voltage harmonicsinvestigated in are the second power quality problem of electric rail drives, which needs to be compensated. In harmonics generated by traction load are researched and modeled, and in compensation methods for harmonic reduction / elimination are proposed and studied. It is proved that specially-connected transformers act as passive filters reducing the harmonics subject to transformer type and harmonic order. An applicable method of harmonic reduction is to control the ac/dc/ac converters of traction motor drives in the train resulting in less harmonic production. A clean 27-level four-quadrant converter is proposed to be used in TSS in DC systems and a seven-cell one is investigated in that can reduce harmonics of the primary side of TSS effectively. A classic method of harmonic reduction was passive filters, an example of which is studied. Shunt active filters are the most effective method of harmonic cancellation, but they will be more expensive; therefore, in case of sensitive systems, or adjacent to sensitive loads, active filters would be a good choice, some combination of which is proposed employing passive filters to reduce the rate of active filter. Also, auxiliary train power supply draws low-frequency harmonic current, for which the compensation methods are investigated.

2.3 Reactive Power

Modern AC converters of traction motors use pulse-width modulation (PWM), which generate zero reactive power [85], and for power quality compensators, the power factor is 1 as well. In TSS, the generation/transfer of reactive/active power is required to compensate the NSCs. Consequently, NSCs in TSSs must be in anti phase with three-phase currents/voltages to eliminate reactive power. Hence, reactive power compensation and NSC compensation are not performed separately.

2.4 Voltage Problems

The most frequent problems of voltages are associated with their magnitudes. As noted before, unbalanced currents produce unbalanced voltages. Traction motors and other related loads in trains are designed to function properly with reduced voltage amplitude by 24% or increased amplitudes by 10% than the nominal voltage of electric railroad drives based on IEC 6850 and EN 50163. Therefore, current problems, as will be explained, are the problems which should be worried, but voltage problems will not harm the system operation.

2.5 Arcing

The interaction between pantograph/catenary of overhead systems or between brushes and third or fourth rail causes arcs because of dynamic latitudinal tolerance between wheels and rail. In particular, on section isolators of overhead systems or ramps of third/fourth rail arcs will occur, which can distort voltages and currents and produce a transient DC component in the AC systems causing a breakdown of dielectrics.

III. THE HAZARDS OF POWER QUALITY

PROBLEMS

Degraded power quality of rail systems may result in nearby systems malfunction. The most important hazard of power quality shortcomings applies to upstream power supply networks that can be harmed seriously as will be discussed below. Furthermore, it may harm the operation of signaling and communication systems of the railway. The impact of low power quality of traction systems on other systems is mentioned in the most important ones is:

3.1 Impacts on Signaling and Communications

Track circuits are designed to work with a special frequency that must not have any interference with the power frequency. But in presence of harmonics, communication signals may be affected by harmonic frequencies resulting in erroneous signals and faulty train positioning, which lead to a disaster. Communication cables, in turn, usually lie in parallel near the power cables. In the presence of stray currents, catenary current and return current would be unequal, causing the equivalent magnetic field in communication cables not to be zero. Therefore, it will induce voltages in communication cables and interfere with communication signals. Moreover, high-order harmonics may cause interference between communication and power systems.

3.2 Impacts on Upstream Network

The impact of power quality problems on upstream supply network investigated in many publications can be categorized to three main impacts

3.3 Decreased utilization factor

Since the traction load is a large single-phase load, it results in high current NSCs, which will flow in only two phases, and it decreases the utilization factor of the transmission line.

3.4 Malfunction of the protective system

Protection relays may operate incorrectly in the presence of harmonics and NSCs of currents and voltages. Traction load injects a large amount of harmonics and NSCs resulting in malfunction of the protective system.

3.5 Incorrect operation of transmission line control systems

Voltages and currents sampling are based on fundamental components of either voltage or current. Every control system in transmission line would work not appropriately because traction loads inject large amounts of harmonics and NSC current into the transmission lines.

IV. POWER QUALITY IMPROVEMENT METHODS

From the beginning of railway electrification, many compensation methods were investigated and applied to railway systems. More articles on compensating strategies of traction loads are reviewed and classified according to the four most important concepts, shown in Fig. 3.2 as follows.

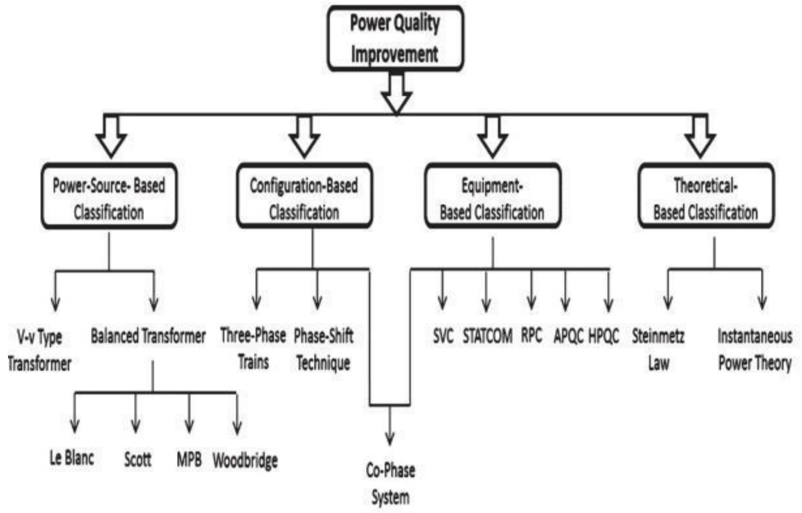

Fig 2 Power quality improvement strategy classification

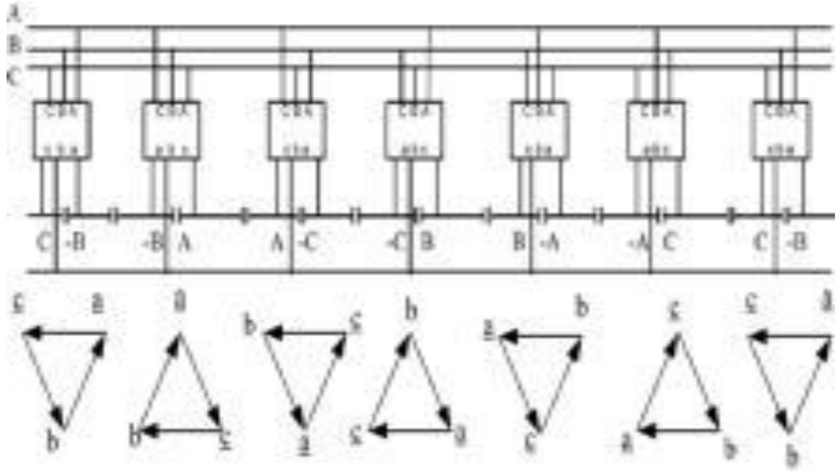

Fig 3 Phase-shift method in 7 adjacent TSSs with Yd11 and Yd5 transformers; in which each section is separated by two section isolators; each three adjacent transformers connections are designed to draw NSCs with 120 degrees phase difference, where NSC will be equal to zero for each three traction substations

4.1 Configuration Based Classification

In the first decades of the 20th century, some countries such as Italy, U.S. and Switzerland designed three-phase trains to achieve a symmetric three-phase load, which included two pantographs for two phases and running rails as the third phase. The NSC in this system was very small. But the use of second pantograph and electrifying the running rails on the ground were two serious disadvantages leading engineers to abandon this approach. As single-phase fed trains were developed the phase-shift method was applied to traction systems, in which each three adjacent TSSs connect between two different phases of the upstream network, compensating the fundamental NSC of the overall system. Phase-shift technique for delta-wye TSSs are shown in Fig. 3.3. This method effectively compensates the fundamental current NSC only when loads of each section is equal. In case of an asymmetric system (e.g. at low traffic or short lines) the NSC remains a problem. Some of the

European countries employ large single-phase synchronous generators (e.g., 140 MW) with 16 2/3 Hz at the Neckarwes the im-power plant in Germany, where the NSC is attenuated within the generator requiring a damping system (e.g., damper winding on rotor). As an alternative, power quality improvement in electric railways mostly focused on equipment-based compensation, such as static Var compensators, static synchronous compensator (STATCOM), and railway static power conditioner (RPC).

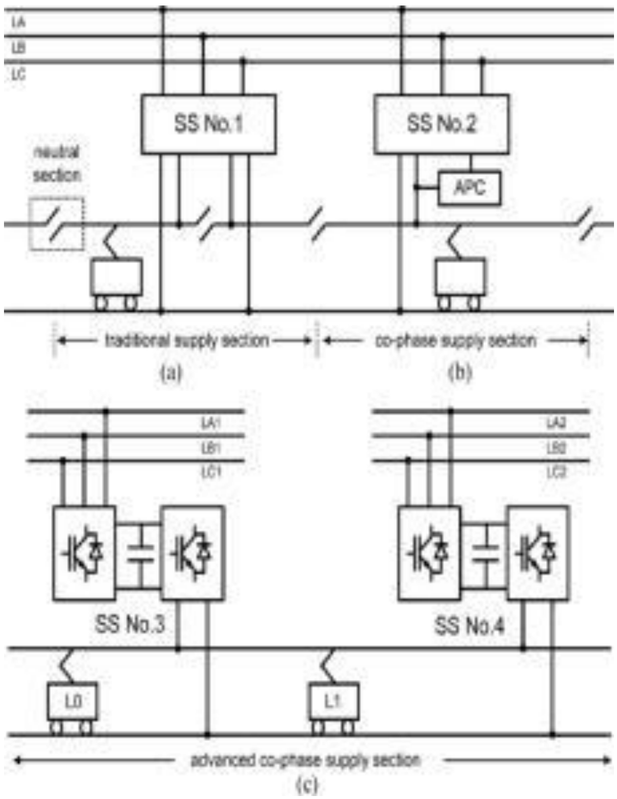

Fig 4. Advanced co-phase system compared with co-phase system and traditional supply system

Recently, equipment-based and configuration-based compensation methods have been employed to form the co-phase circuit as shown in Fig. 4. This approach minimizes all main power quality problems. Co-phase system is now an immature technology for which some improvements are studying by researchers. In this method, return circuit (i.e. running rails) is connected to one phase of the three-phase power supply system, and contact wire is fed by two other phases through Active Power Compensator (APC) as shown in Fig. 4(b), which divide power between phases to have symmetrical currents in the primary side, having the ability to compensate imbalance current, harmonics and reactive power simultaneously. An additional advantage of the co-phase system is the absence of section isolators in TSSs. This is an important aspect for high-speed trains, because section isolators limit the speed profile of the train. It can be a strong point for high-speed lines.

4.2 Power Source Based Classification

The Delta-wye type transformer is the most conventional in power industry, but in case of traction application, it generates a NSC between 50-100 % of the PSC. V-v transformer behaves from the NSC compensation point of view like Delta-wye transformer, but it saves one winding in comparison with Delta-wye. Moreover, utilization factor at full compensated load, for the V-v connected transformer can be 100% while the factor is 75.6% in

Delta-wye connected transformer,81.6% in Scott transformer, 84.5% in Le Blanc, and 82.6% in Woodbridge transformer. These advantages of the V-v transformer led designers to use V-v transformers widely, especially for high-speed trains requiring high-power TSSs. Specially-connected transformers such as Scott, Le Blanc, impedance-matching transformers, were developed and brought to commercial application during past decades, which transform orthogonal two- phase to symmetrical three-phase and can provide symmetric load of traction line sections in primary of transformers. Traction system can be supplied through different connection schemes, which are investigated for AC and DC systems. Current NSC for single-phase, V-v, Scott, Le Blanc, modified Woodbridge and Delta-wye transformers is calculated and Scott and Le Blanc transformers are compared from voltage imbalance point of view. These different connection schemes for TSS have different behaviors in case of the load power factor a comparison between these transformers has been presented using different power factor definitions. Also in case of DC railway systems, TSS can have different connections qualifying power quality parameters of the system. Those so-called balanced transformers have no fundamental NSC if loads of different sections along the line are equal. They are useful for lines with heavy traffic, but in case of low traffic lines, NSC will exist. This led designers to use some equipment-based compensation using active methods to compensate NSC

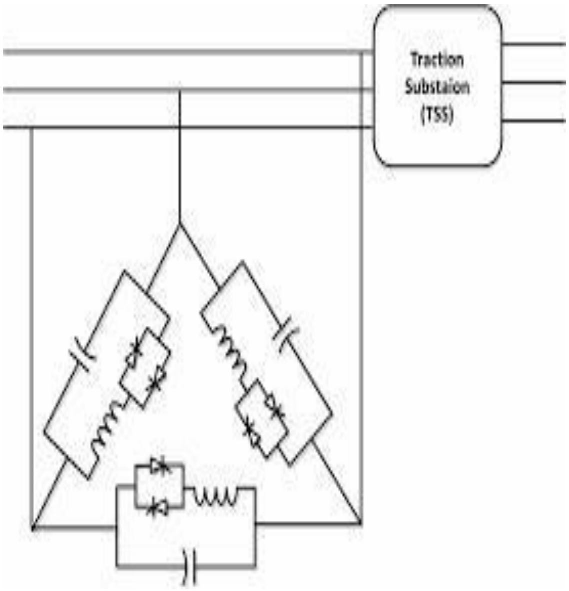

Fig 5 SVC connection to system, including fixed capacitors and thyristor controlled reactors (FC/TCR)

4.3 . Equipment Based Classification

There is some electric equipment for the improvement of power quality problems such as passive and active filters used for harmonic elimination. The SVC is used for compensation of NSC and reactive- power. RPC, Active Power Quality Conditioner (APQC) and Hybrid Power Quality Conditioner (HPQC) compensate both the current NSC and reactive power, as well as perform harmonic elimination. SVCs shown in Fig. 5, were widely used during the past decades to compensate the NSC due to its easy application and low cost compared with other active compensators NSC compensation by SVC based on Steinmetz law, control strategies of which is investigated for railway two-phase system, and for general NSC compensation. However, in this compensation scheme, there is a conflict between NSC mitigation and reactive-power reduction. If the system carries reactive power, the SVC cannot be a good compensation scheme, but most of the newer trains use PWM in their traction drives that can adjust the power factor approximately to 1. However, SVC is known as a low-cost dynamic compensator, its most important disadvantage is its effect on series and shunt resonance frequency which will impose constraints in the system. Nowadays, SVC scheme can be used in more flexible power systems (e.g. near the giant power plants) which can be economically efficient and technically enough. In late the 90s a new scheme to improve the power quality of systems was developed in Japan called RPC, in which there are two back-to-back single-phase converters with a common DC link. Each converter is designed to compensate one section along the traction line as a single-phase load and then active and reactive powers are transferred between two single-phase loads. This scheme uses 4 legs/cross branches (i.e. 8 power electronic switches) which can compensate reactive power, NSC of current and harmonics simultaneously. The precipitate growth of railway electrification imposed ways of coping to railway industry; RPC was a good response to deal with growing power quality problems of electric railway. However, size of power electronic switches is designed to be half of maximum active power of each section, which means it would have 8 big power electronic switches having giant cooling systems and auxiliary installations, and high- costs comparing with older compensators. Next generation of compensating equipment. The APQC considers the entire system as an unbalanced three-phase load and consists of three legs and six powers switches (see Fig. 3.6), but does the same as RPC, while the rating of power switches does not increase. APQC connects to the secondary of TSS through a Scott transformer which transforms the orthogonal two-phase system to a symmetric three- under steady state and transients/dynamic operation. transformers in their TSSs, so the proposed APQC is not appropriate, because voltages in the two-phase load side are not orthogonal (having 60 degrees phase difference due to V-v transformer). APQC is improved to work with V-v TSSs which is widely used throughout the traction industry. In some papers, heuristic schemes are proposed and named HPQC that combine the above listed methods with operational improvements or rating decrement approaches or both. For example a combination of shunt hybrid power filter and thyristor-controlled reactor is investigated.

4.4 Theory-based Classification

Different compensation strategies use different theoretical methods to calculate and generate compensating currents. Based on these methods compensation strategies can be classified as follows.

1. Steinmetz law

A single-phase resistive load between a and b phases which is equal to G can be symmetries by an inductive load between a and c phases equal to and a capacitive load between b and c phases equal to , as shown in Fig. 7. This law is the foundation of the SVC operation, in which compensating impedances are calculated by control unit and applied to the system through variable capacitances and/or inductors controlled by thyristors.

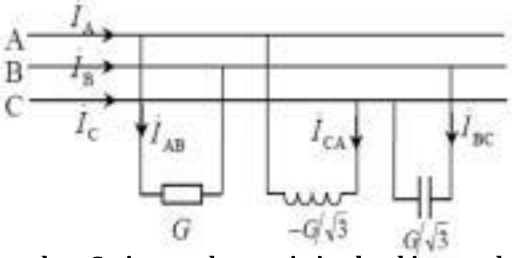

Fig 6 NSC compensation based on Steinmetz law resistive load is sampled, and then the compensator set the inductance and capacitance between two other phases as Steinmetz law

2. Instantaneous active/non-active power

It is known that active and reactive powers depend uniquely on active and reactive currents. Hence, the fundamental PSC current for the fundamental active power is calculated in this method, and it is subtracted from the total current to achieve total non-active current, called compensation currents. This theory is the basis of many compensation structures such as RPCs and APQCs. In a method for generating instantaneous real and imaginary powers is presented. This method transforms voltages and currents of three-phase system abc-variables to orthogonal two-phase system *αβ*-variables; then, real and imaginary parts of power can be separated. Using a low-pass filter, dc and ac components of p and q are calculated; thereafter, only the dc par of p is desired, and all non active parts of p (including) harmonic power, NSC, and reactive power) must be compensated, which is called p-q theory. The zero-sequence component cannot be considered in this method. Kim et al. propose the development of this method for three-phase four-wire systems and named it p-q-r theory. In electric railway systems, there is no zero-sequence component because transformers do not have a fourth wire in ac and dc systems. Therefore, in case of railway systems, there is no need for the p-q-r method. Generally, there are many methods of compensation strategies in power systems, the most applicable of which, in the railway industry, is noted throughout this paper.

V MATLAB/SIMULATION RESULTS

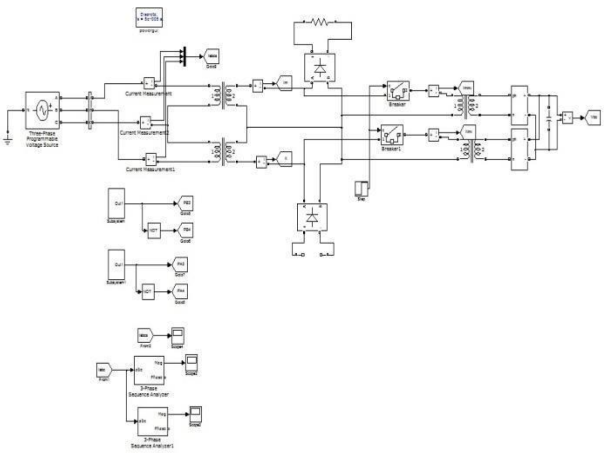

Fig 7 Simulink Model of Railway Power Quality Conditioner of Single station with RPC

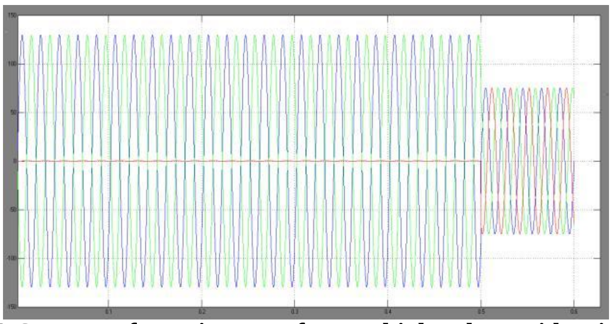

Fig 8 Current of tractive transformer high voltage side with RPC

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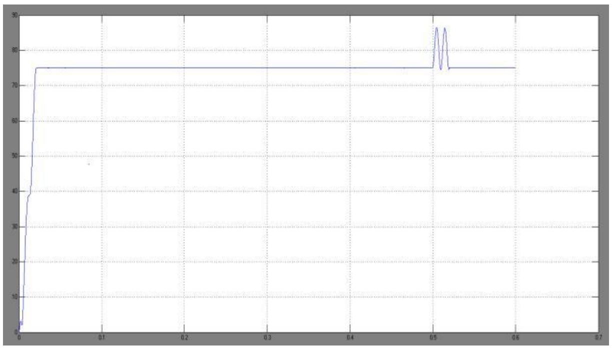
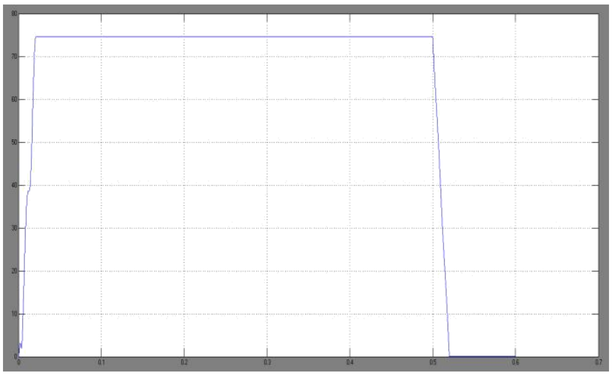


(a)



(b)

Fig 9 Compensation result under with RPC the condition of single station a) Positive sequence, b) negative sequence current

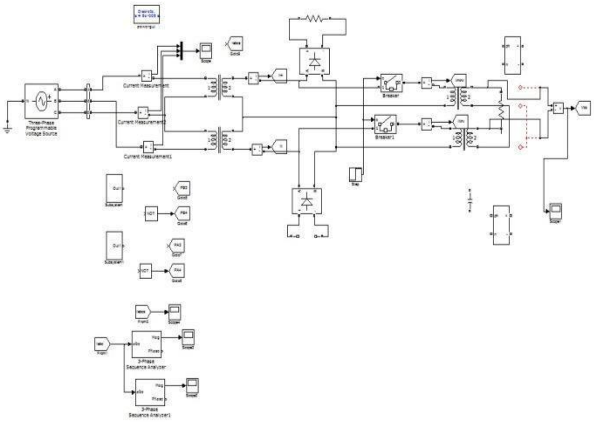


Fig 10 Simulink model of Single station without RPC

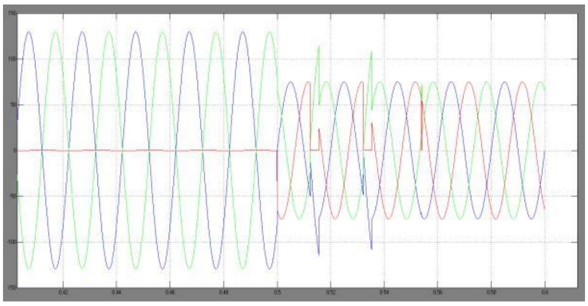
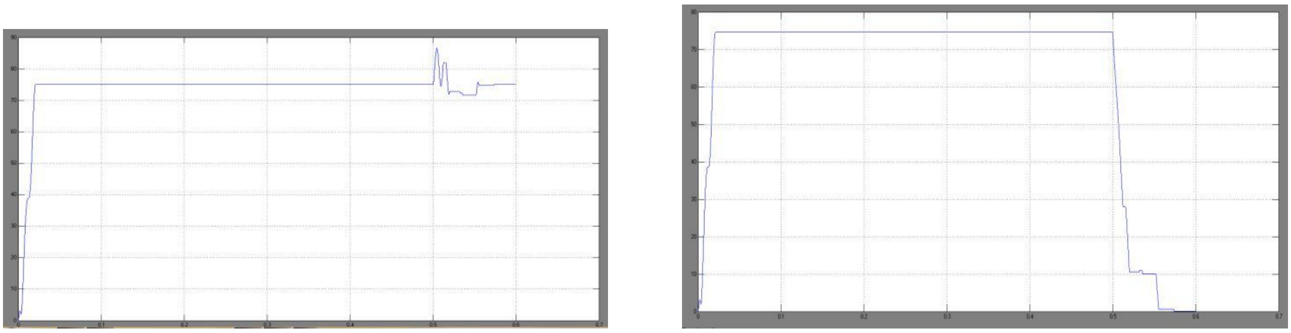


Fig 11 Simulation model Current of tractive transformer high voltage side



(a) (b)

Fig 12 Compensation result under without RPC the condition of single station a) Positive sequence, b) negative sequence current

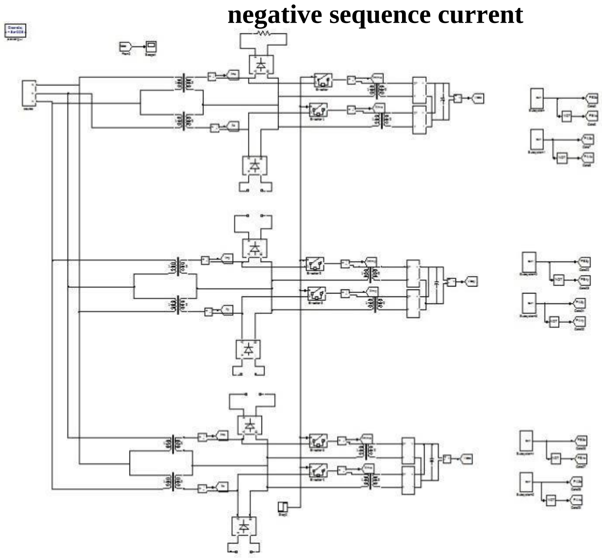


Fig 13 Simulink Model of three station of RPC3

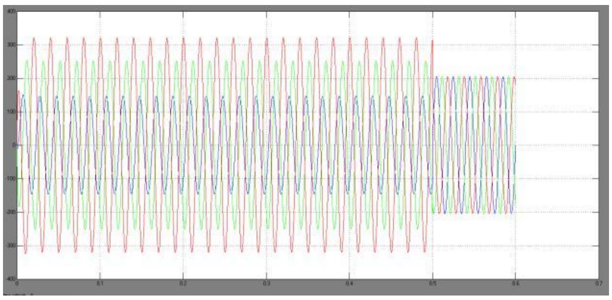


Fig 14 Three station collaboration compensation result under the condition of 2, Y, 0 three station RPC3 Current of tractive transformer high voltage side ($2/3 \leq Y \leq 1$)

VI. CONCLUSION

This paper proposes a new power quality compensation system which is composed of several railway power conditioners. The proposed system can be used to compensate negative sequence current in high speed electrified railway. A minimum installed capacity is conducted which is 2/3 of the traditional single station compensation capacity. A new compensation strategy is raised Simulation results show that the proposed collaboration compensation of railway power conditioners is effective. It can reduce compensation capacity and has a good performance at negative sequence current compensation.

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