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An Efficient Strategy for Power Rating Reduction of Back-to-Back Converters Used in Railway Power Conditioner

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ABSTRACT

One of the most common solutions to deal with the power quality issues of electrical railway systems is employing Railway Power Conditioner (RPC). In the conventional mode of operation, the RPC power rating deployed in every Traction Power Substation (TPS) is significantly large. This paper mainly focuses on the power rating reduction of RPC through presenting a novel combinatorial compensation method. The inductive and capacitive switching algorithm retrieved from Steinmetz circuit lead to additional auxiliary balance in sequential TPS which declines the RPC function in elimination of the Negative Sequence Current (NSC). The proposed method can reduce the voltage over Sectioning Posts (SP), DC-link operation voltage, back-to-back (B2B) converters rating and installation costs. The accuracy and effectiveness of the proposed strategy are confirmed via simulation results obtained by MATLAB/SIMULINK program.

1. Introduction

With the rapid promotion of electric railway systems, especially High-Speed (HS) trains, the power quality problems in Traction Systems (TS) can damage the other consumers and equipment in Point of Common Coupling (PCC) [1-3]. Among these problems, it can be pointed to the significant amount of NSC resulted from the single-phase traction loads, lower Power Factor (PF) caused by induction based traction loads and a wide range of harmonics created by power electronic converters in locomotives acted as non-linear loads [4-7]. These problems affect the utility power systems adversely. Increase in heat and loss in transformers and transmission lines, bad impact on protection systems and failure in performance of relays, shaking and noises in generators and instability of power networks are some destructive impacts of them [8-10].

Various efforts and studies have been proposed to solve the power quality problems of TS. Special transformers like Scott, impedance-matching and Woodbridge have been used to eliminate NSC [11-13]. But, these transformers are effective when two adjacent sections in TPS have equal loads. Also, these transformers increase installation costs. In order to remove harmonics, passive filters and active power filters have been suggested, but they are also incompetent because they can't compensate NSC [14-16]. So, it was essential to have a universal compensator in TS. After years, RPC was proposed

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in Japan [17]. This system is comprised of two B2B converters and acted as an active compensation device. It can compensate harmonics, NSC and reactive power simultaneously. Since the approximate cost of passive compensation device is cheaper than the active compensation device, various researches have been done on using active compensator devices combined with passive ones [18-20]. The approximate cost of power converters is 60 USD per kVA and the power rating of installed RPQC in every TS can be larger than 10 MVA [21]. Therefore, the high cost of RPQC systems is the main barrier for implementation and promoting in AC and high-speed railway systems. However, the number of presented papers regarding of RPQC power rating reduction is too limited. Recently, a hybrid device combining active and passive compensators, called the Hybrid Power Quality Compensator (HPQC) was introduced in order to reduce operation and DC-link voltage level and thus the capacity of compensator [21, 23]. But, this method has weaknesses in compensating performance too, because the low operating voltage reduces the system efficiency. Ma *et al.* [16] proposed a simplified half-bridge based converter which leads to a decreased number of power switch in RPQC. Nevertheless, reducing the switch number in RPQC topology enhances the voltage and current stress over switches. Besides, this topology consists of two DC-link capacitors in series, which need the complex and difficult controlling system to stabilize DC-link voltages. In [24], a reducing method using TSC along with RPQC was presented to keep the power rating under the optimal value. This method has substantial disadvantages like a wide range of harmonic caused by thyristor switching and additional installation costs of TSC. In this paper, a new control strategy of RPC systems is proposed which reduces the system capacity based on NSC compensation through using the Steinmetz theory. The intelligent proposed method has not only the specifications of the previous control methods like simultaneous compensating of negative sequence current, harmonics and reactive power but also a considerable capability in diminution of RPQC power rating.

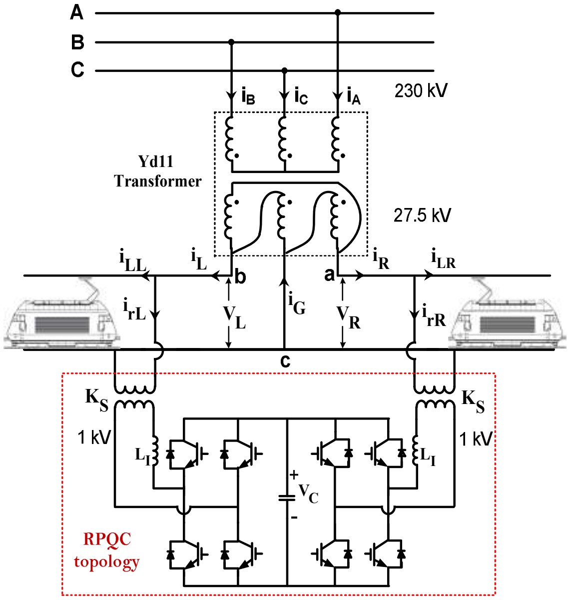


Figure 1: TPS configuration with RPC

This paper is organized as follows. Section 2 describes the configuration and operation principles of RPC. In section 3, the proposed compensation control strategy, including, choosing of TPSs configuration, connections of transformers and combinatorial compensation strategy based on the Steinmetz theory have been studied in details and compared with traditional compensation strategy. In section 4, simulation results and analysis are presented and compared. Finally, section 5 concludes this paper.

2. Operating Principles of RPC

The RPC consists of two B2B converters with a common DC-link capacitor which is installed at the secondary side of TPS and can shift active and reactive powers from one feeder to another. In other words, one of the B2B converters act as a rectifier and absorb the active and reactive power while the other one acts as an inverter and injects these powers to the adjacent section.

2.1. RPC Configuration in Traction Power Supply System

The configuration of RPC in a TPS is illustrated in Figure 1. The 230 kV three-phase high-voltage is stepped-down into two 27.5 kV single-phase voltages, which are connected to the Overhead Contact System (OCS) of two sections. As it can be seen in this figure, the RPC is comprised of two B2B converters with a common DC-link capacitor. The RPC should carry out the compensation duty for all traction network load conditions continuously. So, it is considered that there are two traction locomotives in both sides of TPS. The load currents of right and left sections (i_{LR} and i_{LL}) are forwarded to the locomotives through the OCS and a pantograph to supply the power needs of traction motors. In order to compensate NSC, harmonic and reactive power simultaneously, the currents in the secondary side of TPS (i_R, i_L) should be completely sinusoidal, symmetrical and also in the same phase of their voltages (V_R, V_L). Therefore, to achieve these purposes, the compensation currents (i_{rR}, i_{rL}) are injected to the system through interface inductances (L_I) and step-down transformers with the turn ratio of K_S.

2.2. Analysis of Compensation Principles of RPC

The configuration of Yd11 transformer is illustrated in Figure 1. In order to calculate compensation voltages and currents, the load balance ratio expressed as:

$$\zeta = \frac{\left|I_{light-load\ \mathrm{section}}\right|}{\left|I_{heavy-load\ \mathrm{section}}\right|} \tag{1}$$

The primary side phase voltages are considered as:

$$\begin{cases} \dot{V}_A = Ve^{i0} \\ \dot{V}_B = Ve^{i\frac{4\pi}{3}} \\ \dot{V}_C = Ve^{i\frac{2\pi}{3}} \end{cases} \tag{2}$$

Therefore, line-to-line voltages on the secondary side are:

$$\begin{cases} \dot{V}_R = \dot{V}_{ac} = \frac{\dot{V}_{AC}}{a} = \frac{\sqrt{3}}{a}Ve^{i0} \\ \dot{V}_L = \dot{V}_{bc} = \frac{\dot{V}_{BC}}{a} = \frac{\sqrt{3}}{a}Ve^{-i\frac{\pi}{3}} \end{cases} \tag{3}$$

Regardless of harmonics and considering PF close to 1, the currents in each section can be calculated as:

$$\begin{cases} \dot{V}_R = \dot{V}_{ac} = \frac{\dot{V}_{AC}}{a} = \frac{\sqrt{3}}{a}Ve^{i0} \\ \dot{V}_L = \dot{V}_{bc} = \frac{\dot{V}_{BC}}{a} = \frac{\sqrt{3}}{a}Ve^{-i\frac{\pi}{3}} \end{cases} \tag{4}$$

$$\begin{cases} i_A = \frac{i_R}{a} = \frac{Ie^{i0}}{a} \\ i_B = \frac{i_L}{a} = \frac{\zeta Ie^{-i\frac{\pi}{3}}}{a} \\ i_C = -(i_A + i_B) = -(\frac{Ie^{i0}}{a} + \frac{\zeta Ie^{-i\frac{\pi}{3}}}{a}) \end{cases} \tag{5}$$

According to transformer features, three phase currents of the primary side are:

The phase diagram of voltages and currents without compensation is illustrated in Figure 2(a). As seen in this figure, the currents amplitude of two sections are unbalanced as Δi for $\zeta \neq 1$ and the primary side currents are asymmetrical too. The phase A current lags phase A voltage by 30° and phase B current leads phase B voltage by 30°. The presented equations in this section can be generalized for Yd5 transformer too.

Considering the phase diagram of voltages and currents without compensation, the secondary side currents are unbalanced in amplitude as:

$$\Delta i = \left|i_R\right| - \left|i_L\right| = I\left(1-\zeta\right) \tag{6}$$

To balance the amplitude of currents, half of the current difference of the two sections should be transferred from the heavily loaded section to the lightly loaded section. This brings the currents of each section to:

$$\begin{cases} i'_R = i_R - \frac{\Delta i}{2}e^{i\delta} \\ i'_L = i_L + \frac{\Delta i}{2}e^{i\gamma} \end{cases} \tag{7}$$

δ and γ are the phase of the secondary currents which are various for different transformers. As illustrated in Figure 2(b), after transferring of this amount of current, secondary side currents (i'_R, i'_L) and consequently primary currents (i'_A, i'_B) now have the same amplitude. But three phase primary side currents of Yd11 transformer still are not symmetrical. In order to make the three-phase currents symmetrical, as illustrated in Figure 2(c), the reactive currents (i_{qr}, i_{ql}) should be added to each section. These currents can be calculated as:

$$\begin{cases} i_{qr} = tg30^\circ \times \dfrac{i'_R}{a} e^{i\frac{\pi}{2}} \\ i_{ql} = tg30^\circ \times \dfrac{i'_L}{a} e^{-i\frac{\pi}{2}} \end{cases} \tag{8}$$

These reactive currents are injected by transferring of reactive power from the lead section to the lag section. Finally, the three phase currents of primary side can be calculated as:

$$\begin{cases} i''_A = i'_A + i_{qr} \\ i''_B = i'_B + i_{ql} \\ i''_C = -(i''_A + i''_B) \end{cases} \tag{9}$$

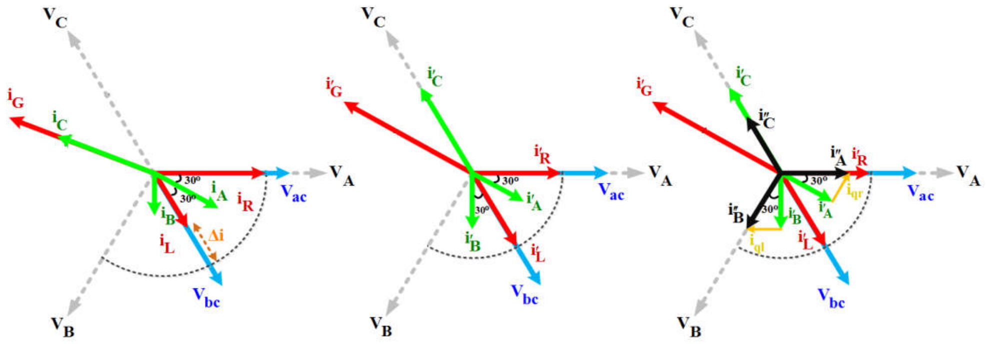
As shown in Figure 2(c), these currents are balanced and symmetrical. The compensation principles and equations for Yd5 transformer are similar.

3. Combinatorial Compensation Method

To reduce the RPC capacity through compensating harmonics and reactive power, the auxiliary compensators (i.e. passive and active filters, SVC, STATCOM) can be used. But, in the proposed strategy the capacity reduction is based on NSC compensation. Therefore, to evaluate the proposed method, at first, the RPC capacity is investigated through a conventional procedure which is based on the single station compensation method. Then, the proposed compensation method will be described and evaluated.

3.1. Configuration and Connections of TPS transformer

Different types of TPS transformers are used in electrical railway systems. The main duty of these transformers is converting a symmetrical three-phase voltage to a single phase voltage supplying traction locomotives loads. In most of the past articles related to RPC systems, three-phase V/V transformers are widely used in traction systems because of dominant power rating utilization and the simple structure compared with other traction transformers. But, if the conditions after compensation are considered symmetrical and balanced, the imbalance parameters for Yd transformer will be changed considerably. Traction transformers are evaluated and compared according to three most important factors: a) Transformer Utilization Factor (TUF), b) Line Utilization Factor (LUF), c) the current unbalance ratio (ε) [25]. As Yd transformer is a three-phase balanced transformer, its TUF and LUF are improved to 100% in balanced and symmetrical conditions; whereas TUF factor of V/V transformer declines to 87% [25]. On the other hand, Yd transformers are more common, cheaper and popular in industry comparing to V/V transformer; as a result, the Yd transformer is a better choice to put into operation with RPC in TPS. The structure of the proposed compensation system is illustrated in Figure 3. This method is based on phase rotation technique and the Steinmetz theory. Three Yd5 and Yd11 transformers with rotational phase connections are assumed one after another in six consecutive TPS.



a) before compensation

b) after active power transferring

c) after active power transferring and reactive power compensation

Figure 2: TPS voltages and currents phase diagram with balancing of currents and compensation of reactive power by RPC

The first purpose in the designing is the voltage of SPs. Reducing of these voltages can decrease the cost of in solution and protective equipment. To achieve this goal, the phase connections should be in such a way that the voltage over SPs (V_1,V_2,V_3,V_4,V_5) are close to zero.

As demonstrated in Figure 3, if the phase voltages of primary side are considered as (2), line-to-line voltages on secondary side for both Yd11 and Yd5 transformers can be calculated using the voltage vectors which are illustrated in Figure 4. These voltages are mentioned in Table 1. '*V*' is the effective value of phase voltage and '*a*' is the conversion ratio of the transformers. Considering these voltages, the voltage of five consecutive SPs can be calculated as:

$$\begin{pmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \dot{V}_3 \\ \dot{V}_4 \\ \dot{V}_5 \end{pmatrix} = \begin{pmatrix} \dot{V}_{ab\,\mathrm{Yd11}} - \dot{V}_{ba\,\mathrm{Yd5}} \\ \dot{V}_{ca\,\mathrm{Yd5}} - \dot{V}_{ac\,\mathrm{Yd11}} \\ \dot{V}_{bc\,\mathrm{Yd11}} - \dot{V}_{cb\,\mathrm{Yd5}} \\ \dot{V}_{ab\,\mathrm{Yd5}} - \dot{V}_{ba\,\mathrm{Yd11}} \\ \dot{V}_{ca\,\mathrm{Yd11}} - \dot{V}_{ac\,\mathrm{Yd5}} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{10}$$

Therefore, with this configuration, the voltage over SPs is zero.

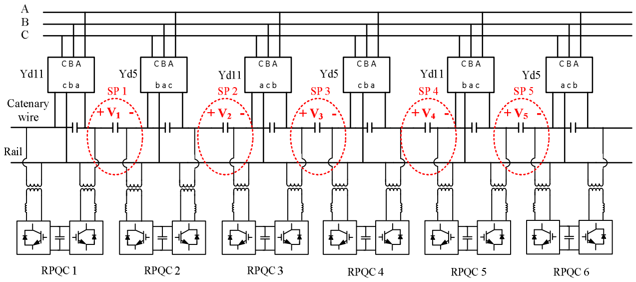


Figure 3: Electrical railway network with six consecutive TPS and RPC

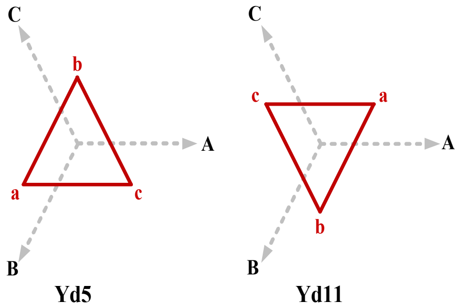


Figure 4: Primary and secondary voltage vectors of Yd5 and Yd11 transformers

3.2. Single Station Based Capacity Calculation

Normally, the RPC system's capacity is designed based on the compensation strategy for worst-case in balanced conditions. So, it is considered that there is a full-load train (maximum capacity) in one of the TPS sections and the other section has no train. Under this condition, half of the required active power for train is transferred from the no-loaded section to the full-loaded section to make the active currents of the two sections balanced in amplitude. If it is assumed that the required active power for a full-load train is P_x, the RPC should transfer $1/2\,P_X$ from no-loaded section to the full-loaded section [26].Based on Yd transformer features, in order to make the three-phase currents symmetrical or balance the currents phases, RPC should transfer some reactive power from the lead section to the lag section. As calculated in [26], the required compensation reactive power is $\frac{1}{\sqrt{3}} \times \frac{1}{2} P_X$. So, the capacities of each back-to-back converter and RPC are:

$$S_{conv} = \sqrt{\left(\frac{1}{2} P_X\right)^2 + \left(\frac{1}{\sqrt{3}} \times \frac{1}{2} P_X\right)^2} = 0.57735 P_X \tag{11}$$

$$S_{RPC} = 2 \times S_{conv} = 1.1547 P_X \tag{12}$$

S_{conv} is the converter capacity and S_{RPC} is the RPC capacity.

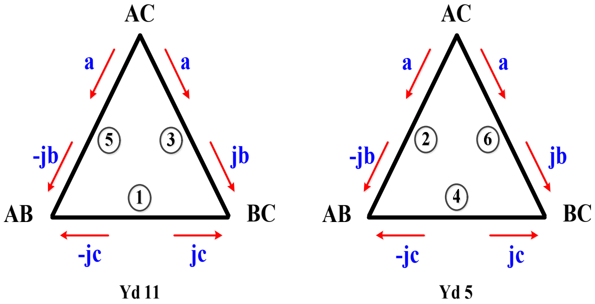


Figure 5: Active and reactive power compensation based on the Steinmetz theory

The second purpose in the designing is to balance the network based on the Steinmetz theory. It is assumed that the capacity consumed in phase AC, AB and BC is x_1, x_2, x_3, which has a relationship of $x_1 > x_2 > x_3$. In this situation, the network can be divided into two parts, one is a balanced network of minimum capacity (x_3, x_3, x_3), and the other is an unbalanced network of (x_1-x_3, x_2-x_3, 0). Considering that $X_1 = x_1 - x_3$, $X_2 = x_2 - x_3$, the network is simplified as (X_1, X_2, 0).

Setting $X_1/4$ as the reference value, the per-unit value of the simplified network is 2, Y′, 0. Here, ‘Y′’ is varying from 0 to 2. The worst-case in balanced condition is Y′=0. As illustrated in Figure 3 in the model of six consecutive TPS there is a RPC in every TPS. Since RPC could transfer active power and compensate reactive power, in Figure 5 two triangles are applied to demonstrate the principle of proposed compensation strategy based on the Steinmetz theory. One of them is used for Yd11 transformers powers exchanges and the other is used for Yd5 transformers. The apexes of the triangles are regarded as phase AC, phase BC and phase AB. The edges of the triangles are regarded as three RPC, which are affiliated to the TPS transformers. The numbers of RPC are specified in interior portions of the sides. The arrows above the edges indicate the direction of active power transfer (real part) and the reactive power transfer (imaginary part).

3.3. Collaboration Compensation Strategy

As shown in Figure 6, the compensation strategy includes three steps. At First, a quantity of active power is transferred between phases. Then, the network is being separated into a balanced network and an unbalanced network. And finally, the unbalanced network is being compensated based on the Steinmetz theory. In the Steinmetz theory, it is shown that the unbalance voltages or currents caused by connecting a resistive load between the two phases can be eliminated by installing two reactive loads, an inductance and a capacitance between the other two phases.

So, to establish the above conditions, the following equation should be satisfied:

$$b + c = \frac{2 - 3a}{\sqrt{3}} \tag{13}$$

Where ‘a’ is the amount of active power, ‘b’ and ‘c’ are the amount of reactive powers. These powers, which are transferred by RPCs determine the capacities of each back-to-back converter in six RPCs as: c, $\sqrt{a^2+b^2}$, $\sqrt{a^2+b^2}$, c, c, $\sqrt{a^2+b^2}$, $\sqrt{a^2+b^2}$. Due to the fast dynamic of traction loads and their

Table 1: Different voltage phase of Yd5 and Yd11 transformers

Secondary Voltages Vector group	$\dot{V}_{ab}$	$\dot{V}_{bc}$	$\dot{V}_{ca}$	$\dot{V}_{ba}$	$\dot{V}_{cb}$	$\dot{V}_{ac}$
Yd5	$\frac{\sqrt{3}V}{a}e^{-i\frac{2\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{i\frac{2\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{i0}$	$\frac{\sqrt{3}V}{a}e^{i\frac{\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{-i\frac{\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{i\pi}$
Yd11	$\frac{\sqrt{3}V}{a}e^{i\frac{\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{-i\frac{\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{i\pi}$	$\frac{\sqrt{3}V}{a}e^{-i\frac{2\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{i\frac{2\pi}{3}}$	$\frac{\sqrt{3}V}{a}e^{i0}$

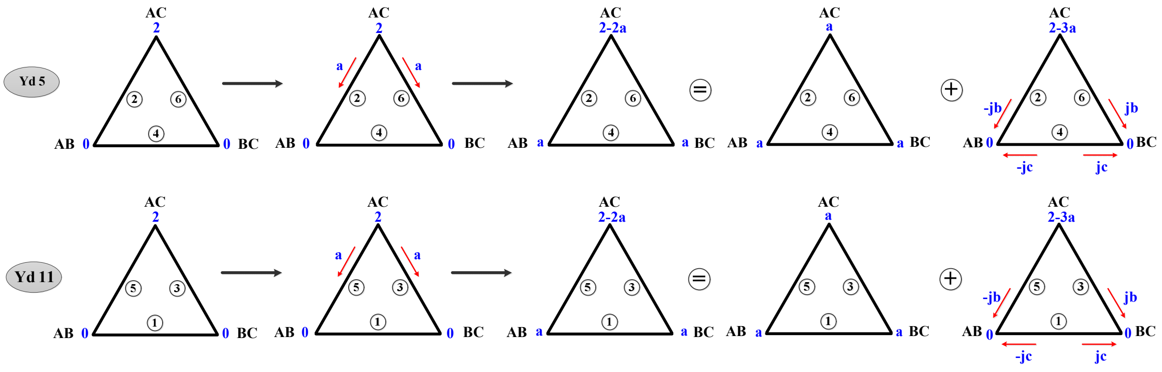


Figure 6: Steps of compensation based on the Steinmetz theory

time-varying characteristics, the installed capacity of converters should be the maximum of the above-mentioned capacities. So, the minimum capacity can be obtained when $\sqrt{a^2+b^2}=c$.

Therefore, it can be concluded that $a=\frac{1}{3},\ b=\frac{1}{3\sqrt{3}},\ c=\frac{2}{3\sqrt{3}}$. So, in this situation, the capacities of each back-to-back converter and RPC with collaboration compensation strategy are as follows:

$$S_{conv}=\sqrt{\left(\frac{1}{3}\times\frac{1}{4}P_X\right)^2+\left(\frac{1}{3\sqrt{3}}\times\frac{1}{4}P_X\right)^2}=0.09622P_X \quad (14)$$

$$S_{RPQC}=2\times S_{conv}=0.1925P_X \quad (15)$$

Table 2: Performance comparison of compensation methods

Compensation	Traditional method	Proposed method	Capacity reduction rate
Converter capacity	0.57735P$_x$	0.09622 P$_x$	83.33%
RPC capacity	1.1547P$_x$	0.19244P$_x$	83.33%

The calculated results of the converter and RPC capacities are summarized in Table 2. As seen in this table, in comparison to the traditional method the proposed method has reduced the capacity as 83.33%.

Table 3: Performance comparison of different methods

	Harmonic compensation	Reactive power compensation	NSC compensation	Power rating(p.u.)	Total cost	Specifications	
						advantages	disadvantages
Traditional RPC	✓✓	✓✓	✓✓	1.154	✓✓✓✓	High performance	High cost due to the 8 high power switches
HBRPC	✓✓	✓✓	✓✓	1.154	✓✓✓	As RPC with 4 less switches, and 1 more DC-link capacitor	High cost and complex control due to the 2 DC-
APQC	✓✓	✓✓	✓✓	1.154	✓✓✓	As RPC with 2 less switches	High cost and high voltage DC-link capacitor
Co-phase	✓✓✓	✓✓✓	✓✓✓	1.154	✓✓✓✓	As RPC without natural section isolator	High cost, complex implementation
HPQC	✓✓✓	✓✓✓	✓✓✓	1.154	✓✓✓	As RPC with additional passive equipment, better performance	High cost and low reliability due to the
Proposed method	✓✓✓	✓✓✓	✓✓✓✓	0.577	✓✓	As RPC collaborating with other RPCs, better performance, lower capacity and costs	Implementing on every 3 consecutive TPSs

3.3. Technical and Performance Comparing

Choosing a suitable compensation method for high-power and high-capacity railway systems is important specially in case of laying far from a reliable power plant [3]. In order to illustrate the main advantages of proposed method a comparing table based on the comprehensive information in [3] has been presented in Table 3. As demonstrated in the table, the low costs and low power rating of compensator are the main advantages of the proposed methods. Also due to the Steinmetz based imbalance compensation circuit implemented in proposed method, the capability of proposed method in NSC compensating is higher than others.

4. Simulation Results

In order to verify the effectiveness of the proposed compensation and control strategy, simulations based on MATLAB software have been carried out. Since the reduction of capacity is based on NSC compensation, traction loads are modelled as resistive linear load. The simulation parameters of system and traction load are shown in Table 4. The system is simulated with both traditional and proposed compensation strategies separately to prove the validity of the proposed control method.

Table 4: The parameters of simulation system

Parameter	Value
TPS transformers ratio (K$_T$)	230:27.5
Step-down transformers ratio (K$_S$)	27.5:1
Interface inductance(L$_I$)	0.5 mH
DC-link capacitors (C$_1$)	40 mF

It is considered that the power of traction load in phase AC is 4.8 MW and the other phases have no load. The three phase source currents and compensation results are shown in Figure 7. As it is presented in this figure, before compensation the network-side three-phase currents are significantly unbalanced and asymmetrical. It can be seen from the simulation results illustrated in Table 4 that the unbalanced current ratio (ε) which equals the ratio of negative sequence to the positive sequence current is about 99% before compensation. After turning on of RPC at t = 0.1 s, by transferring of power between sections, the network-side three-phase currents became symmetrical and balanced. Thus, as positive and negative sequence currents are shown in Figure 8, ε is detracted to less than 3%.

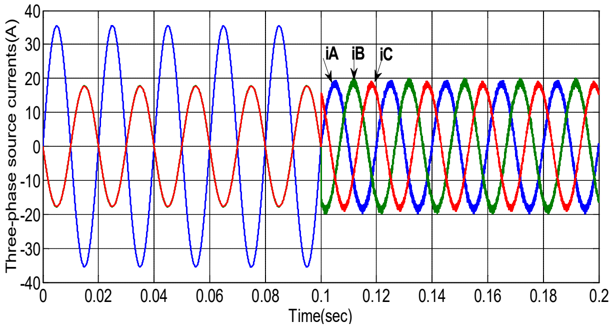


Figure 7: Network-side three-phase currents

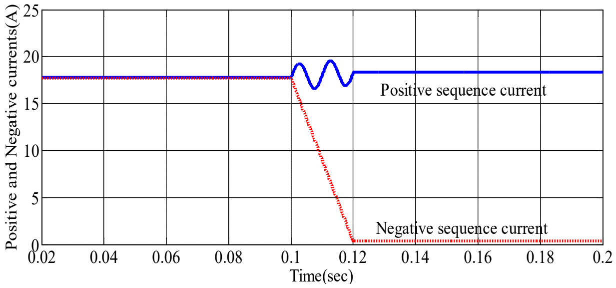


Figure 8: Positive and negative sequence currents

Figures 9-12 show the active and reactive powers transferred by the RPQC converters in both control methods. Where ‘ Pr conv ’ and ‘ Pl conv ’are the active powers of right and left converters and ‘ Q*r* conv ’and ‘ Q*l* conv ’ are the reactive powers of right and left converters in RPQC.

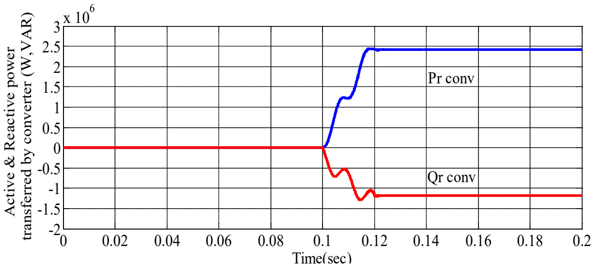


Figure 9: Active and reactive power transferred by right converter of RPQC with conventional control strategy

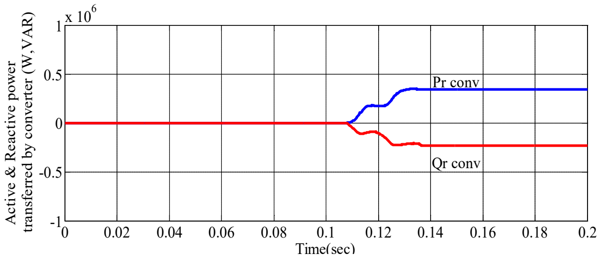


Figure 10: Active and reactive power transferred by right converter of RPQC with proposed control strategy

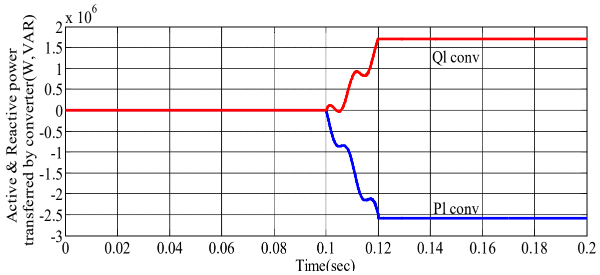


Figure 11: Active and reactive power transferred by left converter of RPQC with conventional control strategy

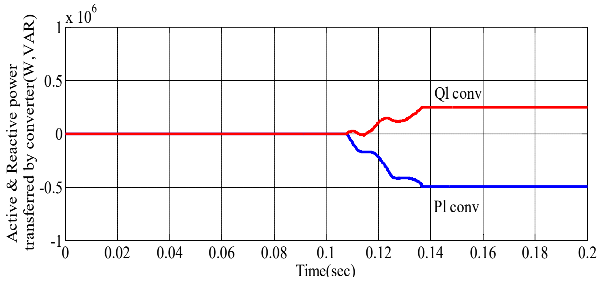


Figure 12: Active and reactive power transferred by right converter of RPQC with proposed control strategy

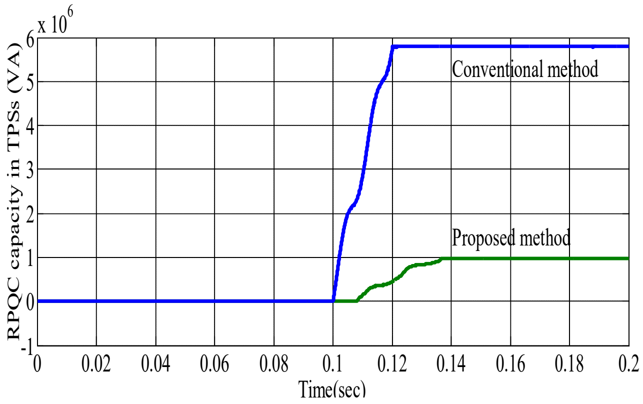


Figure 13: RPQC capacity in TPSs with conventional and proposed control strategy

The results of simulation are given in Table 5. As seen in this table, the converter and RPQC capacities in proposed method has been reduced more than 80%which satisfies the theoretical results mentioned in Table 2. Also, the satisfactory compensation results of unbalanced current ratio demonstrate the effectiveness of the proposed method.

Table 5. Performance comparison of compensation methods

Compensation strategy	Traditional method (Single station	Proposed method	Capacity reduction rate
Converter capacity (MVA)	2.91	0.561	80.70%
RPQC capacity (MVA)	5.79	0.998	82.77%
Currents unbalanced level (%)	99.1	99.1	-
Currents unbalanced level (%)	1.78	2.85	-

5. Conclusions

In this paper, a new combinatorial compensation strategy for the RPC system in AC electrical railway networks is presented. Despite having the features of the previous control methods like compensating negative sequence current, harmonics and reactive power, the proposed strategy can reduce the voltage over sectioning posts, DC-link operation voltage, the compensation system capacity and installation cost too. At first, according to the Yd transformer specifications in balanced condition, three Yd5 and Yd11 transformers with rotational phase connections are assumed one after another in six consecutive TPS so that the voltage over SPs are close to zero. Then, based on traction load translocation and using of the Steinmetz theory, the combinatorial compensation strategy is introduced which leads to capacity reduction of the compensation system and installation costs in TPSs. Finally, to evaluate the correctness of theoretical analysis of proposed control strategy, simulations are carried out for six consecutive TPSs considering traction load translocation. All the simulation results proved the functionality and effectiveness of the proposed strategy.

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