Amirkabir University of Technology
(Tehran Polytechnic)
Vol. 45, No. 1, spring 2013, pp. 9- 15

Amirkabir International Journal of Science& Research
(Electrical & Electronics Engineering)
(AIJ-EEE)

Power Quality Improvement in Traction Power Supply Networks

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ABSTRACT

AC railway traction loads are usually huge single phase loads. As a result, a significant amount of Negative Sequence Current (NSC) is injected into utility grid. Moreover, harmonics and consumption of reactive power are further power quality problems that the supply network is encountering. In this paper, a compensation strategy with the aid of Railway Power Conditioner (RPC) is proposed to overcome the above-mentioned problems. Firstly, different kinds of traction transformers are evaluated and Y/Δ traction transformer is chosen. Then, a compensation strategy is initiated that is valid for all kinds of traction transformers and a control system is proposed based on that. Finally, the correctness of the analysis and proposed strategy is verified by the simulation results using Matlab/Simulink software.

KEYWORDS

Power Quality, Negative Sequence Current (NSC), Electrified Railway, Railway Power Conditioner(RPC), Traction Transformer.

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1- INTRODUCTION

By the development of electrical railway networks as a centerpiece of transportation across the globe, the supplying power network has been encountering severe power quality problems. These problems are mainly: (1) Negative sequence current which is resulted by utilizing huge single-phased traction loads in a symmetrical 3-phased network. (2) Considerable level of the reactive power. This consuming amount of power is due to the inductive motors and older generation of adjustable speed drives (ASDs) with low power factors, but it is also one of the adverse results of the existence of / in an asymmetrical load in a 3-phased system. (3) Harmonic and sub-harmonics. Traction loads are treated as non-linear loads which cause harmonics in the power supply system [1-4]. Meanwhile, the mentioned drawbacks would lead in some other problems in power network system like increasing the loss in transformers and transmission lines and decrease their effective capacities, disturbance in protective relay operation and etc [5-6].

To overcome the above-mentioned problems, numerous devices and methods have been proposed and imposed in the traction systems. For instance, to reduce the negative sequence current, customized transformers like Scott, Woodbridge and impedance matching balance traction transformer are employed in traction substations [7] but they are usually inefficient if the normal loads at the two arms of substation's feeders become unbalanced, which is highly prevalent in the electrical railway networks.

Static Var Compensator (SVC) is another device that has been proposed for the traction systems to compensate the reactive power. However, it is not economical to install this device on the high-voltage side. Moreover, it plays as a non-linear load and creates current harmonics which makes it an inappropriate candidate as a compensator in the traction systems [8]. Additionally, conventional active power filters (APFs) are not widely employed in large scale in traction systems as well, because they are not able to compensate negative sequence current effectively and they have high expense, complicated control systems and other technical restrictions [9-10].

RPC was firstly introduced by researchers at the Railway Technical Research Institute in Japan as a device to compensate the negative sequence current [10-11]. It consists of two back-to-back converters with a common dc-link capacitor. Meanwhile, by selecting a proper control technique, harmonics and reactive power can be compensated to a very high extent, as well.

Different kinds of transformers can be employed in traction substations and consequently RPC configuration varies with each of them. Most of the current studies focus on RPC with Scott and V/V transformers [11-13]. However, Y/Δ transformers are rarely considered as a candidate for the traction substation [14]. In this paper, it is shown on condition that the negative sequence current is compensated by RPC, Y/Δ transformer becomes more efficient and a preferable choice to work with RPC. In addition, compensation equations will be shown and verified by the simulation results.

2- RPC PRINCIPLES

A. Selecting proper transformes

Different types of transformers such as single-phase, V/V, Scott and Y/Δ used in traction substations to change a symmetrical 3-phase voltage into a single phase voltage.

The traction transformers can be compared according to three following factors which are defined in [15-16]: (1) Transformer Utilization Factors (TUF) (2) Line Utilization Factors (LUF) (3) negative-sequence current index (R): which is the ratio of negative-sequence effective current to the positive sequence effective current as shown in (1)?

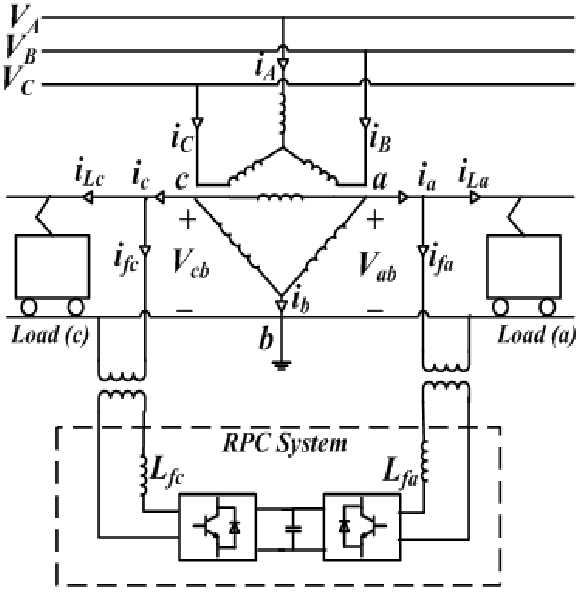

Fig. 1. Traction substation with RPC system

All the above factors depend on balance degree (η) which is defined as:

$$\eta = \frac{\left| I_{light-load\ \ side} \right|}{\left| I_{heavy-load\ \ side} \right|} \qquad (1)$$

Table 1. shows TUF, LUF and R for four different kinds of traction transformers. As it can be inferred from it, the best performance belongs to Scott transformer but it is a special, complicated and costly transformer which is not very commercial in the traction systems. Likewise, the single-phase transformer has the highest level of negative-sequence current index (R). Moreover, the Y/Δ transformer has the lowest TUF among all transformers. As a result, V/V transformer becomes the most common traction transformers on the whole.

On the other hand, if the negative sequence current was compensated by a compensator (such as RPC), the imbalance parameters would be changed considerably. As it can be seen in Table 2, in the case of symmetrical 3-phase condition, the Y/Δ transformer's TUF and LUF are improved to 100%, while TUF has declined in V/V transformer to 87%. The Y/Δ transformer is also more common, ordinary, cheaper and more available device comparing to V/V transformer.

Therefore, the Y/Δ transformer can be considered as a better option to put into the operation with RPC in traction substations. Despite of this fact, RPC has been mostly reported with V/V and Scott transformers and its compensation principle with Y/Δ transformer has not been studied thoroughly in the literature, to the best knowledge of the authors. In this paper, a compensation system, based on RPC and using Y/Δ transformer is presented to eliminate the negative sequence current, suppress harmonics and compensate the reactive power, simultaneously.

TABLE 1. TRACTION TRANSFORMERS IMBALANCE PARAMETERS

Imbalance Parameter	*Traction Transformer*			
	Single phase	*V/V*	*Y/Δ*	*Scott*
TUF	$\frac{1+\eta}{2}$	$\frac{1+\eta}{2}$	$\frac{1+\eta}{2.64}$	$\frac{3(1+\eta)}{3+2\sqrt{3}}$
LUF	$\frac{1+\eta}{2\sqrt{3}}$	$\frac{1+\eta}{3}$	$\frac{1+\eta}{2.64}$	$\frac{1+\eta}{2}$
R	1	$\frac{\sqrt{\eta^2-\eta+1}}{\eta+1}$	$\frac{\sqrt{\eta^2-\eta+1}}{\eta+1}$	$\frac{\eta-1}{\eta+1}$

B. RPC Compensation Theory

All the compensation methods for RPC in the previous literatures have usually considered the primary voltages as the reference for deriving compensation equation. Because of that, the phase angles of secondary voltages are different and the equations cannot be generalized about the various transformers. Consequently, these compensation equations are just valid for a specific configuration of RPC with a particular traction transformer. In this paper, a simple compensation theory is proposed to generate RPC reference currents. As a result, these generated reference currents are independent from the type of traction transformers. Thus, by this compensation method, the RPC system can be installed with all different kinds of traction transformer without any requirement to reset control parameters.

As it can be seen in Fig. 1, the primary side of transformer is in Y-type connection and there is Δ-type connection in the secondary side. Similarly, V_{ab} and V_{cb} are line-to-line voltages on the secondary side and supply the traction loads. The current returns to substation, flowing through the rail tracks. The phase 'b' is connected to rail tracks. The neutral (star point) physically exists in the star side. In the delta side physically the neutral point does not exist so it cannot be brought out. The delta side neutral is the imaginary point 'n' (geometrically found). Therefore $\dot{V}_{an}, \dot{V}_{bn}$ and $\dot{V}_{cn}$ (or briefly $\dot{V}_a, \dot{V}_b$ and $\dot{V}_c$) are assumed as phase voltages in the secondary side. These voltages, as it can be seen in Fig. 2, can be considered as the secondary reference voltages as follows:

$$\begin{aligned} \dot{V}_a &= V_p \angle \theta_a \\ \dot{V}_b &= V_p \angle \theta_a - 120^\circ \\ \dot{V}_c &= V_p \angle \theta_a + 120^\circ \end{aligned} \tag{2}$$

where V_p is the effective value of phase voltage and θ_a is the phase angle of $\dot{V}_a$.

TABLE 2. V/V AND Y/Δ TRANSFORMERS IMBALANCE PARAMETERS AFTER COMPENSATION

Traction Transformer	*Imbalance Parameter*		
	TUF	*LUF*	*K*
V/V	87%	100%	0
Y/Δ	100%	100%	0

Line-to-line voltages on the secondary side are also :

$$\begin{cases} \dot{V}_{ab} = V_{La} \angle \theta_{ab} \\ \dot{V}_{cb} = V_{Lc} \angle \theta_{cb} \end{cases} \tag{3}$$

where V_{La} , V_{Lc} are $\dot{V}_{ab}$ *and* $\dot{V}_{cb}$ effective value voltages and θ_{ab}, θ_{cb} are the phase angles of them, respectively. As it is shown in Fig. 2, the $\dot{V}_{ab}$ always lags $\dot{V}_{cb}$ by 60° In addition, because of four-quadrant PWM converters, which are widely adopted in new generation locomotives, the power factor of loads is assumed approximately to be unity. Therefore, the loads currents are:

$$\begin{cases} \dot{I}_{La} = I_{Lap} \angle \theta_{ab} \\ \dot{I}_{Lc} = I_{Lcp} \angle \theta_{cb} \end{cases} \tag{4}$$

where I_{Lap} and I_{Lcp} denote the effective currents of loads in '*a*' and '*c*' feeders, respectively. In order to alleviate the negative sequence current, the three transformer secondary currents ($\dot{I}_a$, $\dot{I}_b$ *and* $\dot{I}_c$) should have the same peak values and with a phase separation of 120° from each other. Furthermore, to compensate the reactive power simultaneously, $\dot{I}_a, \dot{I}_b$ *and* $\dot{I}_c$ should be in phase with the phases of their corresponding phase voltages $\dot{V}_a, \dot{V}_b$ *and* $\dot{V}_c$, respectively.

To put the above theory into action, assume the loads active powers as follows:

$$\begin{cases} P_{La} = E \cdot |I_{La}| \cdot \cos \varphi_a \\ P_{Lc} = E \cdot |I_{Lc}| \cdot \cos \varphi_c \end{cases} \tag{5}$$

Where *E* is the line-to-line effective secondary voltage and due to the loads unity power factors, $\cos\varphi_a = \cos\varphi_c = 1$. Since the reactive power is supposed to be compensated, all the apparent power of a Y/Δ transformer (S_T) should be equal to the total load's active powers. Moreover, Elimination of the negative sequence current requires that all the three transformer secondary currents after compensation have same values of $|i_a| = |i_b| = |i_c| = I_s'$. Thus:

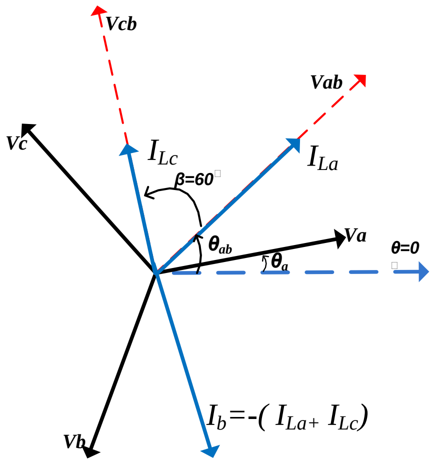

Fig. 2. phasor diagram before compensation

$$S_T = \sqrt{3}E.I_s' \qquad (6)$$

$$\begin{cases} S_T = P_{La} + P_{Lc} \\ \sqrt{3}EI_s' = E.I_{Lap} + E.I_{Lcp} \end{cases} \qquad (7)$$

As a result, the I_s' can be calculated as:

$$I_s' = \frac{I_{Lap}+I_{Lcp}}{\sqrt{3}} \qquad (8)$$

Hence, the transformer secondary currents after the compensation would be:

$$\begin{cases} i_a' = \frac{\sqrt{2}}{\sqrt{3}}(I_{Lap}+I_{Lcp})\sin(\omega t+\theta_a) \\ i_c' = \frac{\sqrt{2}}{\sqrt{3}}(I_{Lap}+I_{Lcp})\sin(\omega t+\theta_a+120^\circ) \\ i_b' = -(i_a'+i_c') = \frac{\sqrt{2}}{\sqrt{3}}(I_{Lap}+I_{Lcp})\sin(\omega t+\theta_a-120^\circ) \end{cases} \qquad (9)$$

As it is shown in Fig.3, the three complementary transformer secondary currents are found as a symmetrical 3-phase system. Thus, the RPC reference currents (i_{fa} and i_{fc}) could be calculated as:

$$\begin{cases} i_{fa} = i_a' - i_{La} \\ i_{fc} = i_c' - i_{Lc} \end{cases} \qquad (10)$$

These reference currents for two back-to-back converters are needed to be tracked by a precise control system.

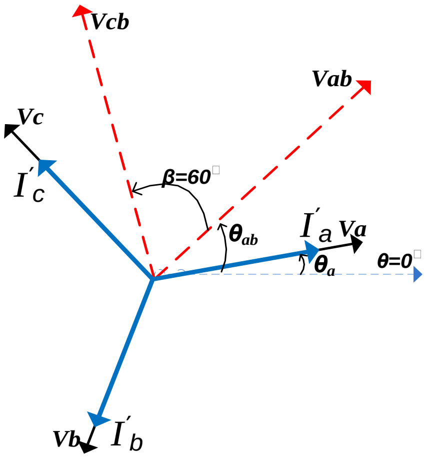

Fig. 3. phasor diagram after compensation

C. RPC Control Implementation

Control strategy is the heart of the RPC system and it is put into action in three steps. First, the desired parameters are measured, then compensating commands in terms of current are derived and finally the gating signals for power semi-conductor devices of RPC should be generated [17].

To yield the RPC reference currents, active component of loads currents (I_{Lap} and I_{Lcp}) is required to be derived. However, the loads currents consist of active, reactive and harmonic components as it is shown in (11). One method to derive the active component is multiplying the loads currents by their corresponding synchronous voltages. The results consist of DC and AC components. The DC parts can be easily extracted from an appropriate filter. The other advantage of this method is to eliminate harmonic components that lead to the reduction of Total Harmonic Distortion (THD) of source currents dramatically.

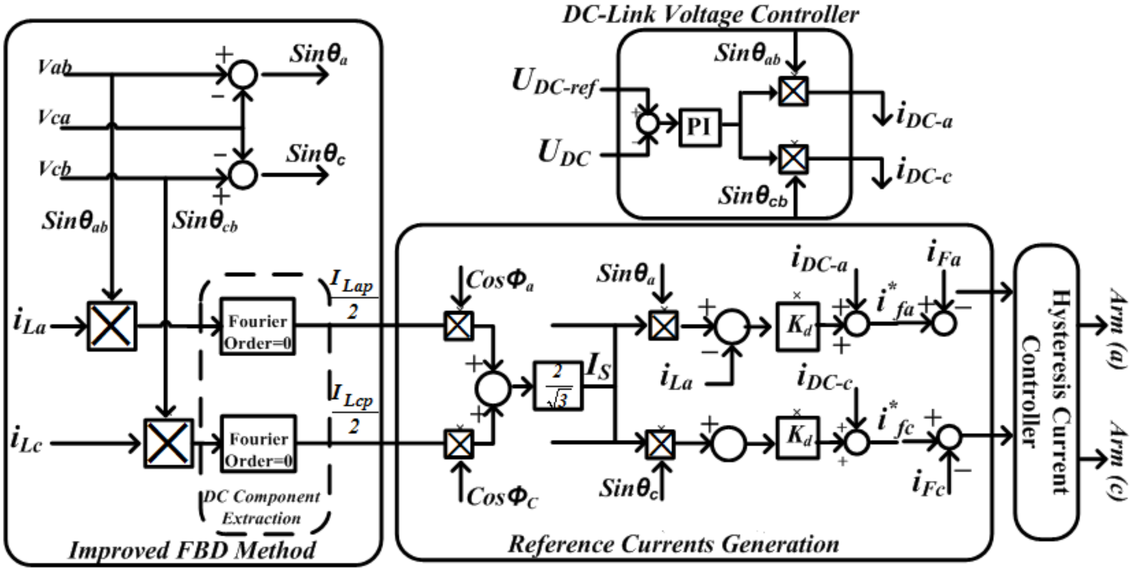

Fig. 4. RPC Control Block Diagram

$$
\begin{aligned}
i_{La} &= \sqrt{2} I_{Lap}.\sin(\omega t + \theta_{ab}) + \sqrt{2} I_{Laq}.\sin(\omega t + \theta_{ab} - \frac{\pi}{2}) \\
&+ \sum_{h=2}^{\infty} I_{Lah}.\sin(h\omega t + \theta_{ah}) \\
i_{Lc} &= \sqrt{2} I_{Lcp}.\sin(\omega t + \theta_{cb}) + \sqrt{2} I_{Lcq}.\sin(\omega t + \theta_{cb} - \frac{\pi}{2}) \qquad (11) \\
&+ \sum_{h=2}^{\infty} I_{Lch}.\sin(h\omega t + \theta_{ch})
\end{aligned}
$$

In addition, the phase voltage on the secondary side can be easily calculated by the following equations:

$$
\begin{cases}
\dot{V}_a = \dfrac{\dot{V}_{ab} - \dot{V}_{ca}}{3} \\
\dot{V}_c = \dfrac{\dot{V}_{ca} - \dot{V}_{bc}}{3}
\end{cases}
\qquad (12)
$$

Fig. 4 shows the block diagram of the control system of a RPC. As it is depicted, the phase of $\dot{V}_a$ and $\dot{V}_c$ are available with the aid of Phase Lock Loop (PLL) devices. Afterward, the amplitude of transformer secondary currents must multiply by their corresponding phases. Finally, the RPC reference current is calculated.

To track the RPC reference current properly, a high performance current controller is essential. Therefore, a hysteresis controller is proposed in this article for the RPC system which had a satisfactory functioning [18].

One of the other crucial aspects of the RPC control system is stabilizing the DC-link capacitor voltage. The transfer of active and reactive power is not perfectly achievable without a reliable and constant DC-link voltage and any fluctuation in DC-link voltage will cause distortion in RPC currents.

TABLE 3. SIMULATION PARAMETERS

Simulation parameter	value
Network Phase-To-Phase Voltage	*230kV*
Traction Transformer Turns Ratio	*230:27.5*
Step-Down Transformer Ratio(K_f)	*27.5:1*
L_{fa} , L_{fc}	*1 mH*
DC-Link Capacitor	*0.08F*
Grid Impedance	*R=0.2ω , L=1 mH*

In order to avoid the mentioned drawback, as it is illustrated in Fig. 4, a PI controller is adopted in this system. PI controller obtains both the measured capacitor DC voltage and desired reference voltage, and creates a proportional current [19]. Afterward, the current must become in the phase with loads current phase and finally added to RPC reference currents to guarantee the stability of the DC-link capacitor voltage.

3- SIMULATION AND RESULTS

In order to verify the proposed compensation method and theoretical analysis, a simulation is carried out using MATLAB/Simulink. Simulation parameters are shown in Table 3. Since the power factor of load are assumed nearly 1 , the traction loads are modeled by resistance. Likewise, owing to take the current harmonic component into account, a non-controlled rectifier is added to the traction loads. As it was mentioned before, the functioning of RPC control system is independent of the vector group of Y/Δ transformer. However, a Y/Δ11 is selected as a traction transformer in these simulations.

The RPC switched on at 0.1s, but it is connected from the beginning of simulation to the network. This causes that the DC-link capacitor starts to be charged through the diodes of the converters before the switches become turned on. This precharge action prevents from the occurrence of overvoltage in DC-link capacitor and high-peak transient charging current.

Two different cases are simulated in this part:

Case (1): Assuming only 'a' phase power arm had locomotive load but 'c' phase power arm didn't, the following simulation results would verify the proposed strategy. The power of the traction load is supposed to be 3.2MW with a THD of 12.3%. The loads currents (i_{La}, i_{Lc}) and RPC reference currents (i_{fa}, i_{fc}) are illustrated in Fig. 5. The network currents on the primary side (i_A, i_B, i_C) are also shown in Fig. 7. As it can be seen from it, after turning RPC compensation device on, at 0.1s, the networks currents became almost symmetrical as R is reduced from 94% to 2.4%. Harmonics were also greatly suppressed as the THD of i_{La} is 12.3% but the THD of i_a is fallen to 2.6%. The simulation results before and after compensation are depicted in Table 4.

TABLE 4. V/V AND Y/Δ TRANSFORMERS IMBALANCE PARAMETERS AFTER COMPENSATION

Simulation Results	case(1)		case(2)	
	Before compensation	After compensation	Before compensation	After compensation
Source Current THD	**12.3%**	**3.1%**	**12.3%**	**2.3%**
Negative-Sequence	**94%**	**2.8%**	**46%**	**2.4%**
Power Factor (1)	**0.85**	**0.988**	**0.92**	**0.992**

(1) Power Factor is measured from the PCC point at the supplying network.

Case (2): In the second case, it is assumed that both 'a' and 'c' phases have the same loads of 3.2MW and with a THD of 12.3%. The loads currents, RPC reference currents and network currents on the primary side are illustrated in Fig. 6 and Fig. 8, respectively. As it can be seen in Table 5. the simulation results are satisfactory in this case as well.

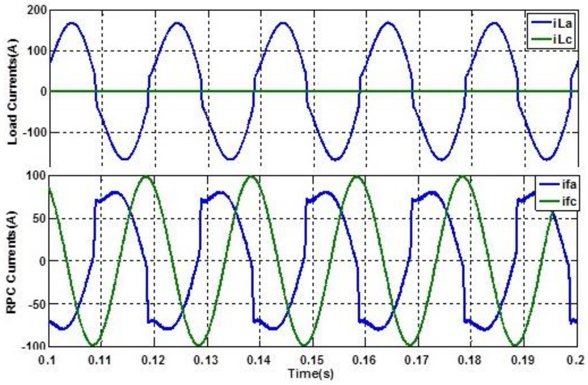

Fig. 5. The loads and RPC reference currents (case1)

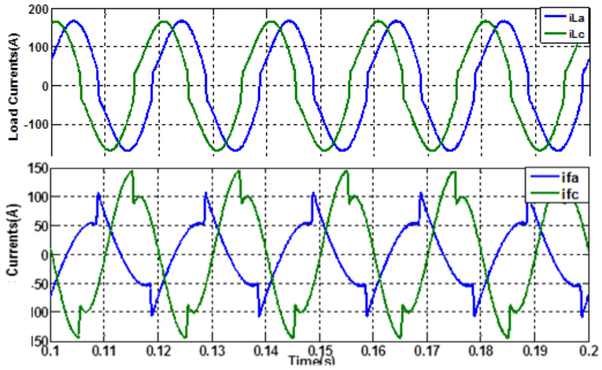

Fig. 6. The loads and RPC reference currents (case2)

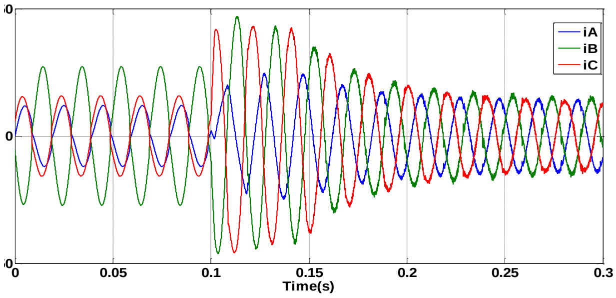

Fig. 7. Source currents (case 1)

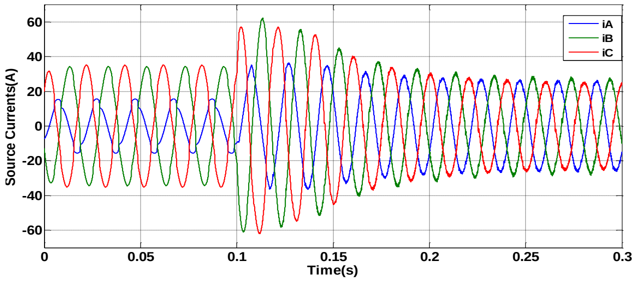

Fig. 8. Source currents (case2)

4- CONCLUSION

I this paper, a compensation strategy with the aid of Railway Power Conditioner (RPC) is proposed to overcome the power quality problems. Since RPC configuration varies with each of traction transformers, firstly different kinds of traction transformers were compared with each other according to their TUF, LUF and R and it was shown that Y/Δ is the most appropriate choice to utilize with RPC. Then a simple and general strategy, which is valid for all kind of traction transformers, was presented to compensate negative sequence current, harmonics and reactive power, simultaneously. Afterward, the corresponding RPC reference currents were generated and a hysteresis method was selected as a current controller to track them. Similarly, a PI controller was adopted to stabilize DC-link capacitor voltage which plays an indispensable role in RPC performance. Finally, two different cases were simulated and in both of them, all the major power quality factors were improved significantly as negative sequence current index fell just under 3%, power factor was improved to approximately 0.99 and THD of supply current declined under 3%. These simulation results have confirmed the validity of theoretical analysis and control strategy.

5- REFERENCES

[1] P. Marian, N. B. Ioana and G. Sirbu, “Solution for the Power Quality Improvement in a Transportation System”, in 14th International Power Electronics and Motion Control Conference, EPE-PEMC, pp. 32- 37, 2010.

[2] R. E. Morrison, “Power quality issues on ac traction systems”, in 9th International Conf. Harmonics and Quality of Power, pp. 709- 714, 2000.

[3] H. E. Mazin and W. Xu, “Harmonic cancelation Charactristics of Specially Connected Transformers”, Electric Power Systems Research, vol. 79, No. 12, pp. 1689- 1697, 2009.

[4] H. Lee, C. Lee, G. Jang, and S. Kwon, “Harmonic analysis of the korean high-speed railway using the eight-port representation model”, IEEE Trans. Power Del., vol. 21, No. 2, pp. 979– 986, Apr, 2006.

[5] P. C. Tan, P. C. Loh, and D. G. Holmes, “Optimal impedance termination of 25-kv electrified railway systems for improved power quality”, IEEE Trans. Power Del., vol. 20, No. 2, pp. 1703– 1710, Apr, 2005.

[6] C. P. Huango, C. J. Wu, Y. S. Chuang, S. K. Peng and M. H. Han, “Loading Characteristic Analysis of Specially Connected transformers Using Various Power Factor Definitions”, IEE Trasaction on Power Delivery, vol.21, No. 3, pp. 1406- 1413, July, 2006.

[7] J. Chen, W. Lee, and M. Chen, “Using a static var compensator to balance a distribution system”, IEEE Trans. on Ind. Appl., vol. l35, No. 2, pp. 298– 304, Mar./Apr, 1999.

[8] R. E. Morrison, D. G. Holmes, P.C. Tan, “voltage form factor control and reactive power compensation in a 25 kV electrified railway system using a shunt active filter based on voltage detection”, in power electronics and drives systems conference, pp. 605- 610, 2001.

[9] D. Grahame Holmes P. chin tan, “A robust Multilevel Hybrid Compensation System for 25 kV Electrified Railway Application”, IEEE Transactions On Power Electronics, vol. 19, No. 4, pp. 1043- 1052, July, 2004.

[10] Y. Mochinaga, M. Takeda, and K. Hasuike, “Static power conditioner using GTO converters for ac electric railway”, in Proc. Power Convers. Conf., Yokohama, Japan, pp. 641– 646, Apr, 2002.

[11] H. Morimoto, M. Ando, Y. Mochinaga, and T. Kato, “Development of railway static power conditioner used at substation for shinkansen”, in Proc. Power Convers. Conf., Osaka, Japan, pp. 1108– 1111, Apr, 2002.

[12] A. Luo, W. Chuanping, J. Shen, Z. Shuai, M. Fujun, “Railway Static Power Conditioners for High-speed Train Traction Power Supply Systems Using Three-phase V/V Transformers”, IEEE Trans. Power Del., vol. 26, No.10, pp. 2844– 2856, Oct, 2011.

[13] M. Fujun, A. Lou, X. xiayong, W. Jingbing, W. Chuanping, Z. Canlin, Z. Yin, “The Compensation and Control Analysis of Railway Static Power Regulator”, 10th Electrical and Control Engineering (ICECE), pp. 4391- 4394, 2010.

[14] S. T. Senini and P. J.Wolfs, “Novel topology for correction of unbalanced load in single phase electric traction systems”, in Proc. IEEE 33th Annu. Power Electron. Spec. Conf., pp. 1208– 1212, Jun, 2002.

[15] M. Kalantari, M. J. Sadeghi, S.Farshad, S.S. Fazel, “ Modeling and Comparison of Traction Transformes Based on the Utilization Factor Definitions”, International Review on Modeling and Simulations (I.RE.MO.S.), vol. 4, No.1, pp 342- 351, Feb, 2011.

[16] H. Q. Wang, Y. J. Tian and Q. C. Gui, “Evaluation of negative-sequence current injecting into the public grid from different traction substation in electrical railways”, in Proc. 20th Int. Conf. Exhib. Elect. Distrib., Prague, Czech Republic, pp. 1– 4, Jun, 2009.

[17] K. Alhaddad, A.chandra Bhim singh, “A review of active filters for power quality improvement”, Industrial Electron, vol. 4, No. 5, pp. 960- 969, May, 1999.

[18] P. A. Dahono, “New hysteresis current controller for single-phase full-bridge inverters”, Power Electronics, IET, vol. 2, No. 5, pp. 585- 594, 2009.

[19] M. K. Mishra, K. Karthikeyan, “A Fast-Acting DC-Link Voltage Controller for Three-Phase DSTATCOM to Compensate AC and DC Loads”, IEEE Trans. Power Del., vol. 24, No.4, pp. 2291– 2299, Oct, 2009.