Modeling and Control of Railway Static Power Conditioner Compensation based on Power Quality Standards

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Abstract—**Most control algorithm for Railway Static Power Conditioner (RPC) is developed based on full compensation requirement and has no relationship with power quality standards. There are actually tolerances in power quality that full compensation may not be required. However, the relationship between RPC compensation and power quality standard is complicated and less study has been done. In this paper, the relationship between RPC compensation and power quality standard is being modeled. This makes RPC compensation more flexible so as to reduce the compensation capacity and cost. Simulation verifications are done using the electromagnetic power transient software PSCAD®/EMTDC^{TM}.**

Keywords-power quality, traction power, system unbalance, reactive power, compensation

I. INTRODUCTION

Railway transportation is especially important for city and country developments. Among all, electrified railway is preferred over others since it is safer, cleaner and more efficient. However, power quality problems have always been one of the important concerns in electrified traction power supply [1]-[3]. For instance, major traction power problems in AC electrified railway include system unbalance, reactive power and presence of harmonics. Unbalanced locomotive loadings inject large amounts of negative sequence currents into the power grid, causing system unbalance which may damage the power devices. Since locomotive loadings are mostly inductive, reactive power are present in the system source, indicating inefficient usage of apparent power provided by the grid side. Moreover, increasing usage of power electronics in locomotives also leads to the harmonic problems, which may result in additional heat and power loss.

Concerning the power quality problems introduced above, IEEE and IEC have both developed standards for their tolerances [4]. It is important that traction power supply should satisfy these standards, otherwise it may cause damages to the system or penalties may be imposed. Various power quality compensators have thus been proposed for compensation in order to meet these standards. Railway Static Power Conditioner (RPC) is one of them which can provide unified power quality compensations [5]-[7]. A typical RPC is composed of one back to back converter with a common DC link, and is connected across the two single phase outputs of traction substation transformer, providing compensation for the primary grid side.

So far, most of the RPC control is developed based on full compensation requirement, and has no relationship with power quality standard. However, this technique may not be an economic solution. Since there are tolerances on the power quality standards, there are possibilities that the compensation target can be adjusted for lower compensation capacity and cost. Unfortunately, the relationship between RPC compensation and power quality standard is complicated and less study has been done concerning this topic.

In this paper, a control algorithm for RPC in co-phase traction power supply system is derived based on power quality standards for co-phase traction power supply system power quality compensator. A brief inroduction is given in section I. In section II, details of the co-phase traction power supply system under investigated are described, together with system modeling. The proposed RPC control algorithm based on power quality standards is presented in section III while PSCAD simulation verifications are done in section IV. Finally, a conclusion is provided in section V.

II. SYSTEM DESCRIPTIONS AND MODELING

The schematic of a typical co-phase traction power supply with V/V substation transformer and RPC is shown in Figure 1. The V/V substation transformer is used to transform power from three phase gird into two single phase outputs, namely Vac and Vbc phase. As introduced above, the power quality compensator RPC is composed of one back to back converter with a common DC link and is connected across the secondary side of the V/V substation transformer, providing compensation for the primary side. Locomotive loadings are connected across Vac phase only, leaving Vbc phase unloaded. The system quantities are defined as follows. It is assumed that three phase primary current rms values are I_A, I_B and I_C respectively; while the secondary current rms are defined as I_a, I_b and I_c. The load current rms is defined as I_L and the Vac

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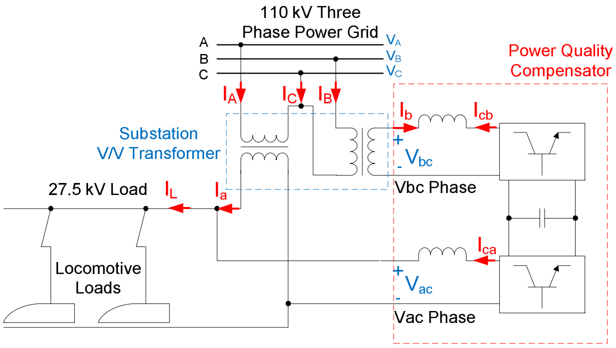


Figure 1 A typical schematic of co-phase traction with RPC

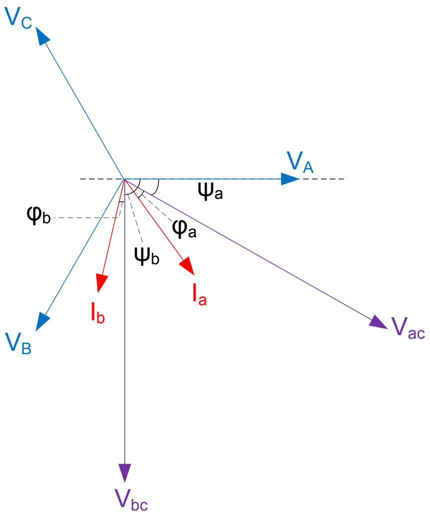


Figure 2 Vector diagram showing physical definitions of co-phase traction power during study

phase and Vbc phase compensation current rms are I_{ca} and I_{cb}. Furthermore, the voltage rms at of Vac and Vbc phase arec V_{ac} and V_{bc} respectively.

The other physical definitions of the system are shown using vector diagram in Figure 2. It is assumed that the phase angle of V_{ac} and V_{bc} is lagging the primary voltage V_A by ψ_a and ψ_b respectivley; while the phase angle of I_a is lagging V_{ac} by φ_a and that of I_b is lagging V_{bc} by φ_b. These definitions are important for understanding of the following analysis.

The system is modeled first before attempting to derive the control algorithm for power quality compensator. In the analysis, the system is divided as linear combination of fundamental and harmonic models, in which the former one may be used to interpret system unbalance and reactive power problems, while the latter can be used for investigations of harmonics in the system.

A. System Unbalance and Negative Sequence

As introduced above, system unbalance in co-phase traction power supply is caused by injection of negative sequence current by unbalanced locomotive loading. Since compensation is done at the secondary side of the substation transformer, the system unbalance model is represented in terms of secondary side parameters. Different system parameters may be defined as shown in (1).

$$\begin{cases} \dot{V}_{ac} = V_{ac}e^{-j\psi_a}, & \dot{I}_a = I_a e^{-j(\psi_a+\varphi_a)} \\ \dot{V}_{bc} = V_{bc}e^{-j\psi_b}, & \dot{I}_b = I_b e^{-j(\psi_b+\varphi_b)} \\ \left|V_{bc}\right| = \left|V_{ac}\right| \end{cases} \tag{1}$$

First, system unbalance in co-phase traction power is investigated. It is stated in IEEE standard that system unbalance is defined as the ratio (%) of negative sequence current to positive sequence current in the system. Therefore, modeling of system unbalance is equivalent to modeling of positive and negative sequence current. According to the method of symmetrical components, the zero, positive and negative sequence components may be determined by (2), where F_{a0}, F_{a2} and F_{a1} then refers to zero, negative and positive sequence respectively and F_a, F_b and F_c are the three phase components.

$$\begin{bmatrix} \dot{F}_a \\ \dot{F}_b \\ \dot{F}_c \end{bmatrix} == \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} \dot{F}_{a0} \\ \dot{F}_{a2} \\ \dot{F}_{a1} \end{bmatrix} \tag{2}$$

where $\alpha = e^{+j\frac{2\pi}{3}} = e^{+j120^o} = -\frac{1}{2} + \frac{\sqrt{3}}{2}j$

$$\begin{bmatrix} \dot{I}^0 \\ \dot{I}^- \\ \dot{I}^+ \end{bmatrix} = \frac{1}{3K} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ -\dot{I}_a - \dot{I}_b \end{bmatrix} \tag{3}$$

$$\begin{cases} \dot{I}^0 = 0 \\ \dot{I}^- = \dfrac{1}{\sqrt{3}K}\left[I_a e^{-j(\psi_a+\varphi_a)} \cdot e^{-j30^o} + I_b e^{-j(\psi_b+\varphi_b)} \cdot e^{-j90^o}\right] \\ \dot{I}^+ = \dfrac{1}{\sqrt{3}K}\left[I_a e^{-j(\psi_a+\varphi_a)} \cdot e^{+j30^o} + I_b e^{-j(\psi_b+\varphi_b)} \cdot e^{+j90^o}\right] \end{cases} \tag{4}$$

The zero, positive and negative sequence component in co-phase traction power system may then be obtained by further manipulations, and the result is shown in (3). By substituting (1) into (3), the equations shown in (4) can be obtained. These are also the expressions for estimation of system unbalance in co-phase traction power supply.

B. Reactive Power and Power Factor

Besides system unbalance, presence of reactive power in the power source should also be avoided or minimized. In traction power system, the reactive power mainly comes from inductive traction loading. Power Factor is a commonly used parameter for presence of reactive power. It is stated clearly in IEEE standard that power factor is an important parameter for presence of reactive power in a system. Power factor is defined as the ratio of the active power P and apparent power S, where their relationship with reactive power Q satisfies the equation $S^2 = P^2 + Q^2$ in harmonic free system. In co-phase traction power supply, the power factor of primary grid side is of interest and is modeled.

The three phase power factor in co-phase traction power may be modeled, as shown in (5). Notice all parameters used are from the secondary side of the transformer for easier derivation of compensation control algorithm.

$$\begin{aligned} PFA &= \cos\left(0^o + \psi_a + \varphi_a\right) \\ PFB &= \cos\left(-120^o + \psi_b + \varphi_b\right) \\ PFC &= \cos\left(-240^o + \tan^{-1}\left(\frac{I_a \sin\phi_a + I_b \sin\phi_b}{-I_a \cos\phi_a - I_b \cos\phi_b}\right)\right) \end{aligned} \tag{5}$$

where $\phi_a = \psi_a + \varphi_a$ and $\phi_a = \psi_a + \varphi_a$

C. System Nonlinearity and Harmonics

Another important concern in co-phase traction power is the harmonic problem. It is caused by usage of nonliner components in traction power load. Harmonic in co-phase traction power supply is being investigated using the harmonic model. The harmonics at secondary side of substation transformer can be modeled by (6), where I_h refers to the harmonic current, and $2 < n \le \infty$.

$$I_h = \sqrt{\sum_{n=2}^{\infty} I_n^2} \tag{6}$$

III. DERIVATION OF PROPOSED CONTROL ALGORITHM

After system modeling, the next step is to develop the RPC control algorithm for co-phase traction power. The ultimate goal is to derive the required compensation power from RPC, and thus the compensation current I_{ca} and I_{cb} according to the requirement. Details of this derivation are given in this section.

Based on the model developed above, the control algorithm of power quality compensator in co-phase traction power can be derived. The mathematical expression in (7) can thus be obtained from (4), (5) and (6).

$$\begin{cases} PFA = \cos\left(30^o + \varphi_a\right) \\ PFB = \cos\left(-30^o + \varphi_b\right) \\ PFC = \cos\left(-240^o + \tan^{-1}\left(\dfrac{I_a \sin\phi_a + I_b \sin\phi_b}{-I_a \cos\phi_a - I_b \cos\phi_b}\right)\right) \\ Unbalance: \left|\dot{I}^-\right| = \dfrac{1}{\sqrt{3}K}\sqrt{I_a{}^2 + I_b{}^2 + 2I_aI_b\cos\left(-120^o + \varphi_a - \varphi_b\right)} \\ I_h = \sqrt{\sum_{n=2}^{\infty} I_n^2} \end{cases} \tag{7}$$

where $\phi_a = \psi_a + \varphi_a$ and $\phi_a = \psi_a + \varphi_a$

In (7), the values of PFA, PFB and PFC may be chosen according to the power factor standard while I^- may be selected according to the system unbalance tolerance. However, there are still not enough conditions to derive the required values of I_a and I_b with (7) alone. Another constraint is thus added according to conservation of active power. In other words, under ideal case, no active power should be stored in the power quality compensator. These may be expressed mathematically as (8).

$$I_a \cos\varphi_a + I_b \cos\varphi_b = I_L \cos\varphi_L = I_{Lp} \tag{8}$$

Solving (7) and (8), the corresponding values of I_a and I_b can be obtained. The compensation current reference I_{ca} and I_{cb} can thus be determined by taking the load current I_L into account, as shown in (9).

$$\begin{cases} \dot{I}_{ca} = \dot{I}_L - \dot{I}_a \\ \dot{I}_{cb} = -\dot{I}_b \end{cases} \tag{9}$$

The required compensation power may be deduced when the phase volage V_{ac} and V_{bc} are known. The required compensation power is defined as follow. The required active and reactive RPC compensation power for Vac phase is defined as p_{ca} and q_{ca}, while that for Vbc phase are p_{cb} and q_{cb}. The computed required compensation power is an expression as the form shown in (10). Instataneous active power is contributed by current in phase with the voltage, while instantaneous reactive power is contributed by current having 90 degrees phase differrence with the voltage. The values of K_1, K_2, K_3 and K_4 may then be determined.

$$\begin{bmatrix} p_{ca} \\ q_{ca} \\ p_{cb} \\ q_{cb} \end{bmatrix} = \begin{bmatrix} K_1\overline{p}_L + \widetilde{p}_L \\ K_2\overline{p}_L + q_L \\ K_3\overline{p}_L \\ K_4\overline{p}_L \end{bmatrix} \tag{10}$$

The instantaneous active and reactive load power, p_L and q_L, are computed using the instantaneous pq theory developed by

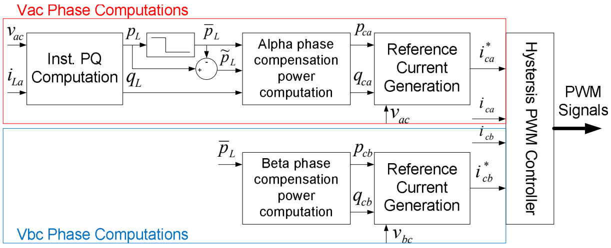


Figure 3 Block diagram showing the control system of power quality compensator in co-phase traction power

Akagi. Notice that $\bar{p}_L$ refers to the fundamental part of p_L while $\tilde{p}_L$ refers to oscillatory portion of p_L.The values of coefficients K_1, K_2, K_3 and K_4 in (10) are known.

Shown in Figure 3 is the control block diagram for co-phase traction power quality compensator. The load instantaneous active and reactive power is computer using insatantaneous pq theory. The alpha and beta phase compensation power may be computed according to the power quality standards and the equations in (7), (8), (9) and (10).

IV. SIMULATION VERIFICATIONS

In order to verify the performance of the RPC control algorithm, simulation verifications are done using PSCAD®/EMTDC^{TM}. It is a new powerful electromagnetic time domain transient simulation environment and study tool. The simulation schematics, as decribted in this paper, are shown in Figure 4. The circuit parameters for simulation are shown in Table I for reference.

For instance, simulations are done for two conditions, A) Full compensation; B) Compensation with power factor standard of 0.87 (Macau Standard). The former one is chosen for comparison with existing full compensation control algorithm, while the latter one is chosen to simulate the condition where RPC is control is derived based on Macau power quality standard.

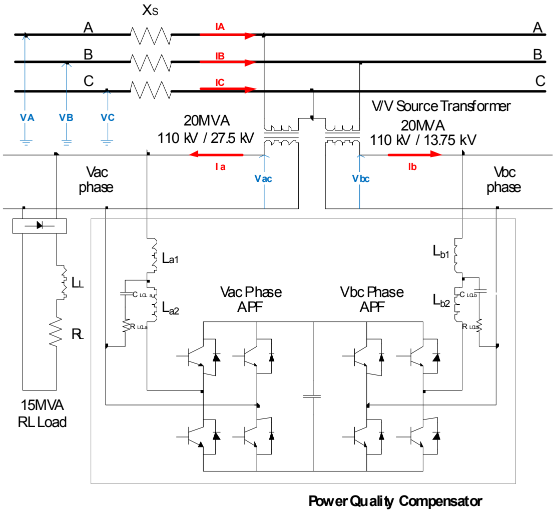
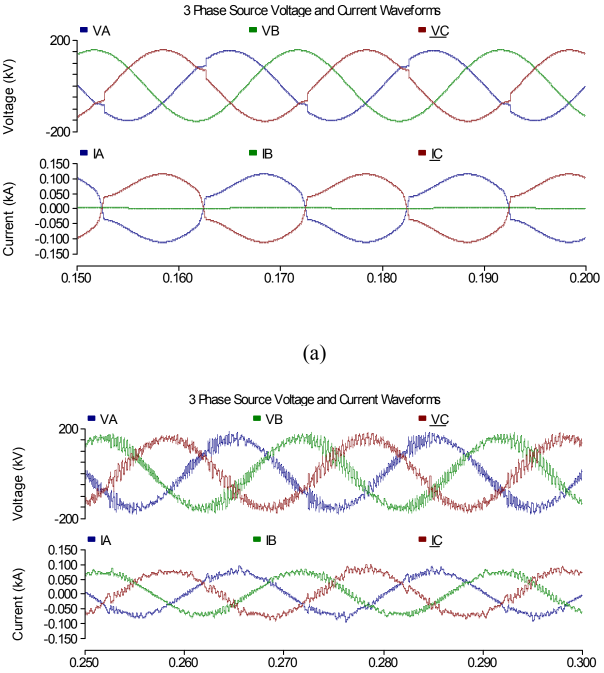


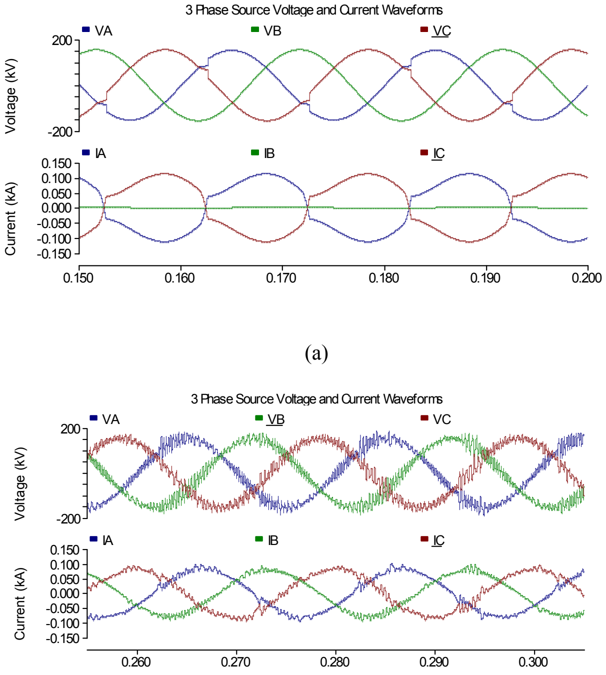
Figure 4 Circuit schematics of co-phase traction power with power quality compensator for simulation verifications



(a)

(b)

Figure 5 Three phase power voltage and current waveforms: (a) without compensation; (b) with RPC (PF desired =1.0)



(a)

(b)

Figure 6 Three phase power voltage and current waveforms: (a) without compensation; (b) with RPC (PF desired =0.87)

TABLE I. CIRCUIT PARAMETERS IN SIMULATIONS

Circuit Parameter	Descriptions
Vac Coupling Inductance 1 L_{a1}	3.4 mH
Vac Coupling Inductance 2 L_{a2}	3.4 mH
Vac LCL Capacitance C_{LCLa}	5 uF
Vac LCL Damped Resistance R_{LCLa}	20 ohm
DC Link Capacitance C_{dc}	10000 uF
Vbc Coupling Inductance 1 L_{b1}	4 mH
Vbc Coupling Inductance 2 L_{b2}	4 mH
Vbc LCL Capacitance C_{LCLb}	5.63 uF
Vbc LCL Damped Resistance R_{LCLb}	20 ohm

A. Full Compensation

According to full compensation requirement, the system source current should be balanced (0% system unbalance) and harmonic-free, with power factor of 1.0. The required compensation power computed from (7) and (8) based on this requirement is shown in (11), which is equivalent to those computed from previous researches. The simulated waveforms captured are shown in Figure 5. It can be observed that without RPC, the system suffers from system unbalance, reactive power and harmonics; after RPC full compensation, the system source is balanced, reactive power and harmonic free. The system performances under this condition are also summarized in Table II.

$$\begin{bmatrix} p_{ca} \\ q_{ca} \\ p_{cb} \\ q_{cb} \end{bmatrix} = \begin{bmatrix} 0.5\bar{p}_L + \tilde{p}_L \\ 0.2887\bar{p}_L + q_L \\ -0.5\bar{p}_L \\ -0.2887\bar{p}_L \end{bmatrix} \tag{11}$$

B. Compensation with power factor of 0.87 (Macau Standard)

Secondly, simulations are done to investigate the performace of co-phase traction power RPC with control algorithm designed according to Macau standard. In other words, the system source is balanced, with reactive power of 0.87 and harmonic free. Shown in (12) is the result computed from (7) and (8) according to this requirement.

$$\begin{bmatrix} p_{ca} \\ q_{ca} \\ p_{cb} \\ q_{cb} \end{bmatrix} = \begin{bmatrix} 0.3364\bar{p}_L + \tilde{p}_L \\ 0.0053\bar{p}_L + q_L \\ -0.3364\bar{p}_L \\ -0.5720\bar{p}_L \end{bmatrix} \tag{12}$$

TABLE II. POWER QUALITY PERFORMANCES OF CO-PHASE TRACTION POWER WITHOUT RPC AND WITH RPC FULL COMPENSATION (PF=1.0)

Items	Without compensation			With RPC compensation (PF=1.0)		
	A	B	C	A	B	C
Power Factor	0.65	0.87	0.98	0.9994	0.9999	0.9996
Current THD (%)	17.0	---	17.0	5.07	3.67	5.69
Current Unbalance (%)	99			2.18		

TABLE III. POWER QUALITY PERFORMANCES OF CO-PHASE TRACTION POWER WITHOUT RPC AND WITH RPC COMPENSATION (PF=0.87)

Items	Without compensation			With RPC compensation (PF=0.87)		
	A	B	C	A	B	C
Power Factor	0.65	0.87	0.98	0.87	0.88	0.88
Current THD (%)	17.0	---	17.0	4.98	3.99	5.65
Current Unbalance (%)	99			2.18		

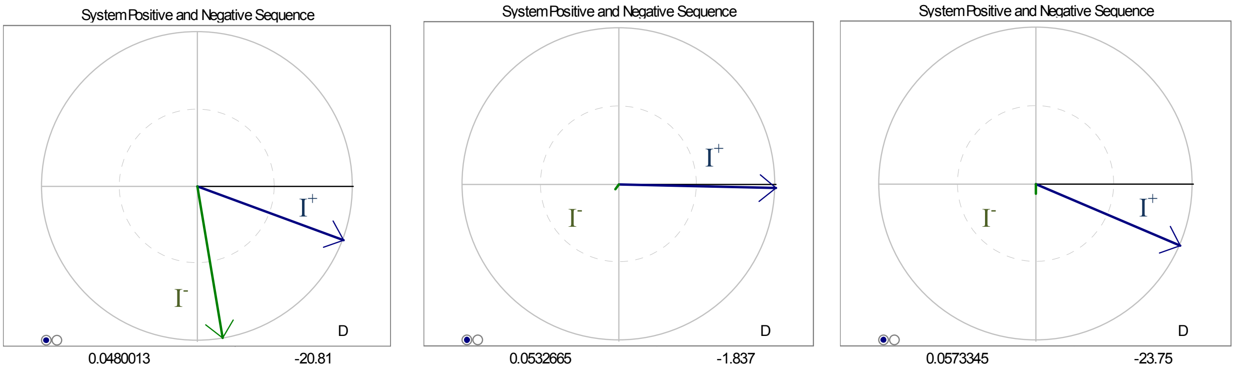
TABLE IV. ESTIMATION OF COMPENSATION CAPACITY ACCORDING TO POWER QUALITY STANDARDS

Items	With RPC compensation (PF=1.0)	With RPC compensation (PF=0.87)
Alpha phase current rms (A)	441.04	245.98
Beta phase current rms (A)	339.40	370.11
Total Capacity Reduction (VA)	21%	

The simulated waveforms captured are shown in Figure 6. Simulated performances under this condition can be found in Table III. Compensation performance can be adjusted according to the power quality standard using proposed control algorithm.

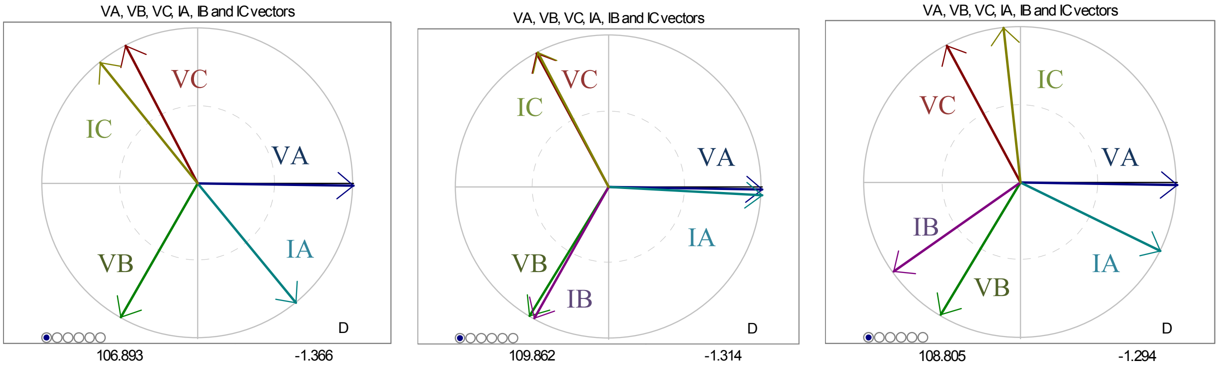
In order to estimate the compensaiton capacity using the proposed RPC control algorithm, the alpha and beta phase compensation current rms under the two conditions mentioned are also measured and are shown in Table III. It can be observed that there is a total of 21% reduction in compensation capacity when the power factor requirement is adjusted to 0.87, compared to full compensation.

Besides waveform capturing, PSCAD®/EMTDC™ also provides built in FFT module for investigations using vector diagram. Shown in Figure 7 and Figure 8 are the vector diagram obtained via simulation. It provides another tool for measuring the performance of the system. It can be observed from the figures that with full RPC compensation, the source current is in phase with the source voltage, while for RPC compensation according to Macau Standard (power factor of 0.87). These show the effectiveness and advantages of proposed RPC control algorithm.



(a) (b) (c)

Figure 7 System source positive and negative current vectors obtained via simulation: (a) without compensation; (b) with RPC (PF=1.0); (c) with RPC (PF=0.87)



(a) (b) (c)

Figure 8 System source voltage and current vectors obtained via simulation: (a) without compensation; (b) with RPC (PF=1.0); (c) with RPC (PF=0.87)

V. CONCLUSIONS

In this paper, a control algorithm of RPC in co-phase traction power is developed based on power quality standards. In order to achieve so, the relationship between co-phase RPC compensaiton and power quality is being modeled. This makes compensation more flexible that full compensation may not be required so as to reduce the compensation capacity and cost. After development of RPC compensation control algorithm according to power quality standards. PSCAD simulations are done to verify its performance. It is found that the RPC compensation performance can satisfy power quality standard. It is found that there is an estimated toal of 21% reduction in compensation capacity with Macau power quality standard compared to full compensation.

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REFERENCES

[1] P. E. Sutherland, M. Waclawiak, and M. F. McGranaghan, “System impacts evaluation of a single-phase traction load on a 115-kV transmission system,” *IEEE Trans. Power Delivery*, vol. 21, issue 2, pp. 837 – 844, 2006.

[2] H. Y. Kuo; and T. H. Chen; “Rigorous evaluation of the voltage unbalance due to high-speed railway demands,” *IEEE Trans. Vehicular Technology*, vol. 47, issue 4, pp. 1385 – 1389, 1998.

[3] D. C. Howroyd,. “Public-supply-system distortion and unbalance from single-phase a.c. traction,” in *Proceedings of the Institution of Electrical Engineers*, vol. 124, issue 10, 1977, pp. 853-859,.

[4] IEEE Standard 519-1992, “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”

[5] Z. Shu, L. Xie and Q. Li, “Single-phase back-to-back converter for active power balancing, reactive power compensation and harmonic filtering in traction power system”, IEEE Trans. Power Electronics, Issue 99, 2010.

[6] Zeliang Shu; Shaofeng Xie; and Qun-zhan Li, “Development and Implementation of a Prototype for Co-phase Traction Power Supply System”, *Asia-Pacific Power and Energy Engineering Conference (APPEEC),* 2010, pp:1-4.

[7] S. T. Senini, P. J. Wolfs, “Novel topology for correction of unbalanced load in single phase electric traction systems,” in *Power Electronics Specialists Conf., 2002. pesc 02. 2002 IEEE 33rd Annual*, vol. 3, June 2002, pp. 1208–1212.,