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A Novel Collaboration Compensation Strategy of Railway Power Conditioner for a High-Speed Railway Traction Power Supply System

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Abstract— **High-speed train traction power supply system causes serious negative current problem. Railway power conditioner (RPC) is efficient in negative sequence compensation. A novel power quality collaboration compensation system and strategy based on RPC is proposed in this paper. 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.**

Keywords-RPC; Collaboration compensation; Unbalance compensation; Minimum capacity

I. INTRODUCTION

With the rapid development of high-speed railway in China, power quality has become a major concern for traction supply system [1]. Compared with normal electrification railway locomotive load, high-speed locomotive load has some characteristics, such as big instantaneous power, high power factor, low harmonic components and high negative sequence component. A large amount of negative current is injected into grid [2], which causes serious adverse impact on power system, such as increasing motor vibration and additional loss, reducing output ability of transformers and causing relay protection misoperation [3]. These adverse impacts threaten the safety of high-speed railway traction supply system and power system. Therefore, it's necessary to take measures to suppress negative current.

Many methods and power quality compensators are studied in order to solve the issue of power quality. The traditional methods adopted to suppress negative current are as follows: (1) Connect unbalanced load to different supply terminals;(2) Adopt phase sequence rotation to make unbalanced load distributed to each sequence reasonably;(3) Connect unbalanced load to higher voltage level supply terminals; (4) Use balanced transformers such as Scott transformer and impedance balance transformer [4]. These methods have some effects on reducing unbalance degree, but they are lack of flexibility and can't adjust dynamically.

Recent years, high-voltage, large-capacity Static Var Compensator (SVC), Active Power Filter (APF) and Static Compensator (STATCOM) have become focus on power quality compensation of electrified railway [5]-[7]. However, these methods all need high-voltage transformers which increase cost. APF is effective in suppressing harmonic currents in electrified railway but rarely used in negative sequence compensation [8]. An active power quality compensator (APQC) with a impedance-matching balance transformer or a Scott transformer is proposed in [9] to compensate negative-sequence current, harmonics and reactive current. Reference [10] and [11] put forward a proposal of Railway Power Conditioner (RPC), RPC can make comprehensive compensation of negative sequence components, harmonics and reactive power. Reference [12] carries a dual-loop control strategy in order to improve the control effect and performance of RPC. Taken into account the disturbance and variation of electrified railway environment, a recursive proportional-integral control based on fuzzy algorithm is adopted to realize a fast and smooth tracking to reference current. Reference [13] raises a method of setting up two groups of thyristor control reactors (TCR) and two groups of thyristor control 3rd harmonic wave filter besides RPC. The RPC is used to transfer active power; the reactive power is supplied by the TCR and the filter. These works prove that RPC is a effective way to solve the power quality problems in railway system. But the compensator capacity is still too big to make RPC into practice.

To reduce the high compensator capacity, this paper puts forward a new railway negative unbalance compensation system based on the thought of multiple RPC collaboration compensation. This method realizes a minimum compensation capacity which is strictly proved, which reduces 1/3 capacity compared with traditional single station RPC compensation method. The simulation results have verified the correctness of the method proposed in this paper.

II. RPC Structure and Analysis of Compensation Principle

The structure of RPC is shown in Fig.1. Three phase 220kV voltage is stepped down into two single-phase power supply voltage at the rank of 27.5kV by V/V transformer. RPC is made of back-to-back voltage source converters and a common dc capacitor, which can provide stable dc-link voltage. Two converters are connected to secondary arms of V/V transformer by step down transformer. Two converters can transfer active power from one power supply arm to another, supply reactive power and suppressing harmonic currents.

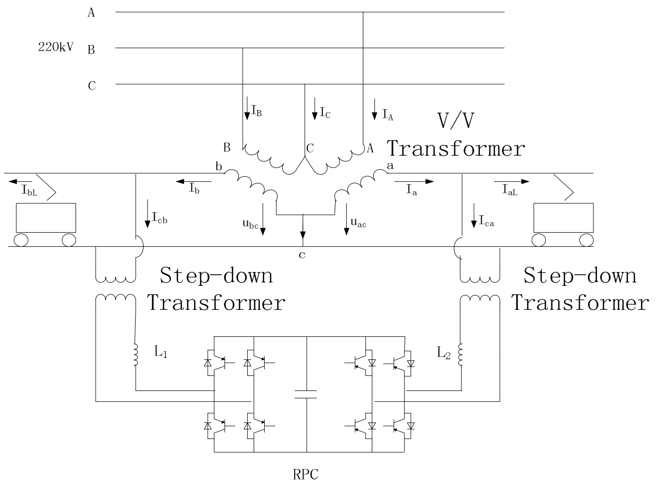


Figure 1. Traction power system with a three-phase V/V transformer and a RPC

The right feeder section in Fig.1 is denoted as *a*-phase power arm, while that the left side is *b*-phase power arm. The corresponding phases on the primary side are denoted as Phase A and Phase B, respectively. Since using four-quadrant pulse rectifiers to feed electrical locomotives, the power factor of high speed electrical locomotive is close to 1. Set U_A as the reference value. Assume that the fundamental current vector of *a*-phase power arm is $\dot{I}_{aL}$ and the fundamental current vector of *b*-phase power arm is $\dot{I}_{bL}$. $\dot{I}_{aL}$ and $\dot{I}_{bL}$ are shown as follows:

$$\begin{cases} \dot{I}_{aL} = I_{aL} e^{-j30^\circ} \\ \dot{I}_{bL} = I_{bL} e^{-j90^\circ} \end{cases} \tag{1}$$

The turns ratio of V/V transformer is *K*, so the three currents of the high-voltage side are shown as follows:

$$\begin{cases} \dot{I}_A = \dfrac{\dot{I}_{aL}}{K} = \dfrac{I_{aL}}{K} e^{-j30^\circ} \\ \dot{I}_B = \dfrac{\dot{I}_{bL}}{K} = \dfrac{I_{bL}}{K} e^{-j90^\circ} \\ \dot{I}_C = -(\dot{I}_A + \dot{I}_B) \end{cases} \tag{2}$$

Before RPC compensation, *a*-phase power arm has load current $\dot{I}_{aL}$ and the *b*-phase power arm has load current $\dot{I}_{bL}$. Assume that $I_{aL} \geq I_{bL}$, the three phase current is shown in Fig.2 .

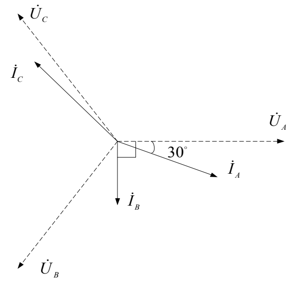


Figure 2. Three-phase current phase diagram without compensation

It is obvious that three phase current is unbalance before compensation. Use RPC to shift $\frac{1}{2}(I_{aL} - I_{bL})$ from *a*-phase to *b*-phase. Then, the current of two power arms are compensated to I'_{aL} and I'_{bL} , and they have an equal amplitude of $\frac{1}{2}(I_{aL} + I_{bL})$ and an angle difference of $\pi/3$. The unbalance level is 50% now.

On the basis of active power transfer, RPC should compensate a certain quantity of capacitive reactive current I_{caq} on the power arm *a* and a certain quantity of inductive reactive current I_{cbq} on the power arm *b*, which can make the current of *a*-phase power arm lead the corresponding voltage $\pi/6$. At this point, the reactive current should be calculated as follows:

$$I_{caq} = I_{cbq} = \frac{1}{2}(I_{aL} + I_{bL}) \tan 30^\circ \tag{3}$$

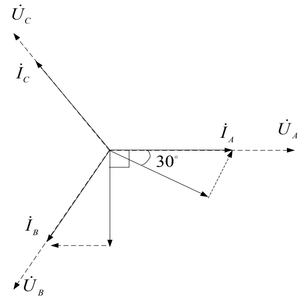


Figure 3. Three-phase current phase diagram after adjusting active and reactive power by RPC

After the compensation, the currents I_A and I_B have the same amplitude, as shown in Fig.3, and their angle difference is $2\pi/3$. The C phase current I_C can be obtained as $I_C = -I_A - I_B$. The primary side of traction transformer has a balance three-phase current after active power shift and reactive power compensation. It is similar when $I_{aL} < I_{bL}$. The common expression of RPC compensation current is:

$$\begin{cases} \dot{I}_{ca} = \dfrac{1}{2}(I_{bL} - I_{aL}) e^{-j30^\circ} + \dfrac{1}{2\sqrt{3}}(I_{aL} + I_{bL}) e^{j60^\circ} \\ \dot{I}_{cb} = \dfrac{1}{2}(I_{aL} - I_{bL}) e^{-j90^\circ} + \dfrac{1}{2\sqrt{3}}(I_{aL} + I_{bL}) e^{j180^\circ} \end{cases} \tag{4}$$

$\dot{I}_{ca}$, $\dot{I}_{cb}$ --the equivalent current of RPC converters of *a*-phase arm and *b*-phase arm at the voltage of 27.5 kV.

III. PRINCIPLE OF COLLABORATION COMPENSATION

Since phase sequence rotation is widely adopted in traction power supply system, 3 stations collaboration compensation is mainly discussed in this paper. The structure of 3 stations collaboration compensation is shown in Fig.4.

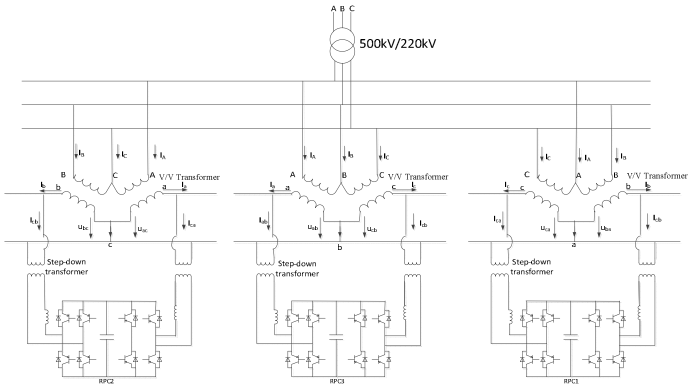


Figure 4. Schematic diagram of collaboration compensation of three stations

The capacity in phase CA, AB and BC is *x,y,z* , which has a relationship of *x>y>z*. The network of *x,y,z* can be divided into two parts, the one is a balanced network of *z,z,z* , the other is an unbalanced network of *x-z, y-z, 0*. Assume that $X = x - z$, $Y = y - z$, the original network is simplified as $X, Y, 0$. Set *X*/2 as the reference value, the p.u. value of the simplified network is 2, Y',0. Y' is varying from 0 to 2.

The extreme case is Y' =0. The optimize compensation strategy is shown below:

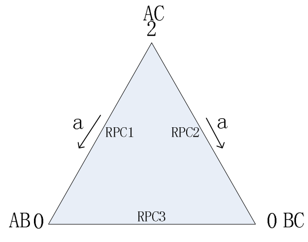
A. Single RPC compensation

Based on the compensation strategy of RPC, when there is a maximum capacity in one of the traction feeder arms, RPC transfers $\frac{1}{2} * \frac{X}{2}$ active power from one traction feeder arm to another. And then compensates $\frac{1}{2\sqrt{3}} * \frac{X}{2}$ reactive power to both traction feeder arms based on Steinmetz theory. So the compensation capacity of single RPC is:

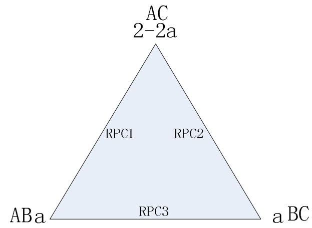
$$S = \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2\sqrt{3}}\right)^2}\ \frac{X}{2} = 0.2885X \tag{5}$$

B. Three stations collaboration compensation

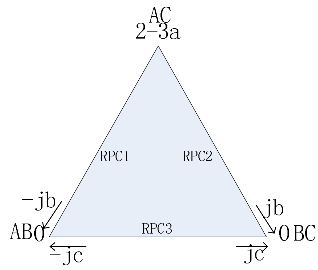
The simple model of 3 stations structure is shown in Fig.5. Since RPC could transfer a quantity of active power and compensate reactive power, a triangle is applied to illustrate the principle of collaboration compensation: apexes of the triangle are regarded as active load in Phase-AC, Phase-BC and Phase-AB, and edges of the triangle are regarded as three railway power conditioners. The arrows mean the delivery of active power (real part) and compensation of reactive power (imaginary part) . There are three steps to compensate. Firstly, transfer a quantity of active power. Secondly, separate the network into two parts: a balanced network and an unbalanced network. And last, make compensation to the unbalanced network based on the Steinmetz theory.



(a)Active power delivery



(b)Three phase power after active power delivery



(c) Reactive power compensation based on Steinmetz theory

Figure 5. Compensation strategy under the condition of 2,0,0

According to the Steinmetz theory, fully compensation should satisfy the relationship of $b + c \geq \frac{2 - 3a}{\sqrt{3}}$. The capacity of three RPC is $\sqrt{a^2 + b^2}$, $\sqrt{a^2 + b^2}$, c , separately. The installed capacity will be the maximum of the three RPC capacities above. So we can obtain the minimum installed capacity when $\sqrt{a^2 + b^2} = c$.

The results can be conducted that $a = \frac{1}{3}, b = \frac{1}{3\sqrt{3}}$, and the minimum capacity is $S_{\min} = \sqrt{a^2 + b^2} = c = \frac{2}{3\sqrt{3}}$. This is a fully compensation but the station where RPC2 installed is capacitive. To avoid this condition, RPC1 supply inductive reactive power with the value of *b*, and RPC2 supply capacitive reactive power with the value of *b*, too. So the capacitive condition is avoided and the system keeps balance at the same time.

Working condition of three stations is shown in Fig.6. The ellipses stand for different traction feeder arms, the squares stand for RPC which connect to traction feeder arms. The arrows stand for active power transfer and reactive power compensation.

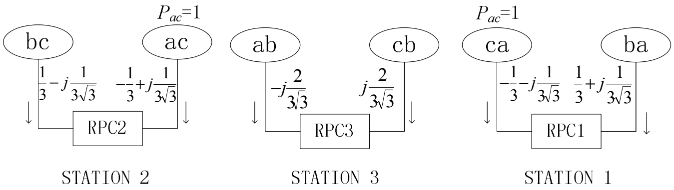


Figure 6. Working condition of three stations which supply active power and reactive power.

Three stations collaboration compensation minimum capacity is :

$$S_3 = \sqrt{\left(\frac{1}{3}\right)^2 + \left(\frac{1}{3\sqrt{3}}\right)^2}\,\frac{X}{2} = \frac{2}{3\sqrt{3}} * \frac{X}{2} = 0.1925X\,, \quad (6)$$

which is 2/3 of the capacity of single RPC compensation. Tab.1 shows the compensation capacity of the two strategies.

TABLE I. COMPARISON OF TWO COMPENSATION METHOD

Compensation mode	Single station	Three station collaboration compensation
RPC capacity	0.2885*X*	0.1925*X*

It can be proved that this installed capacity (0.1925*X*) can satisfy any condition when *Y′* varying from 0 to 2.

If there is *N* stations connect to one 220kV bus, *N* may be 3*n*, 3*n*+1 or 3*n*+2 (*n*=0,1,2…). When *N*=3*n*, it means there are n sets of 3-stations compensation. When *N*=3*n*+1, it means there are n sets of 3-stations compensation and a single station compensation. When *N*=3*n*+2, it means there are *n* sets of 3-stations compensation and 2 single station compensation.

IV. SIMULATION RESULTS

Simulation is done to proof the correctness of the theory by MATLAB/Simulink.

A. Single RPC Compensation

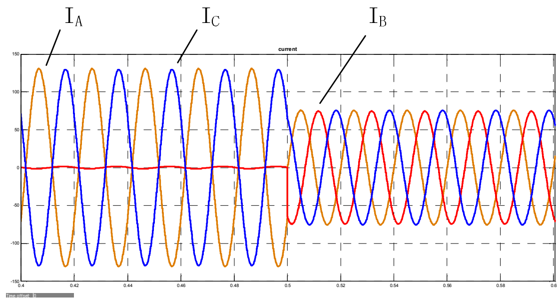
Assume the maximum load capacity appears at *a*-phase power arm, that is $P_{AC}=1$. The base capacity is $P_{base}=20MW$, and the short-circuit capacity is 750MVA. The power of *b*-phase locomotive load is 0. The *a*-phase load was switch on at 0*s*, the compensation system ran at 0.5*s*. The simulation schematic diagram is shown in Fig.1. The simulation parameters are as follows: three phase voltage of the system is 220kV; the frequency is 50Hz; the ratio of V/V transformer is 8:1; the ratio of step down transformer is 40:1; the capacitor of RPC at DC side is 100000 μF, and the value of L_1 and L_2 is 3mH and 2mH respectively.

Fig.7 (a) is the simulation current waveforms before and after three-phase negative sequence current compensation at 220kV side when locomotive load is under *a*-phase power arm. Fig.7 (b) is sequence analysis of current waveform. It can be seen from Fig.7 that before the compensation the current of Phase B I_B is zero, and the phase current I_A and I_C have the same amplitude and an angle difference of 180° . Meanwhile, the negative sequence component is equal to positive sequence component. The unbalance level is defined :

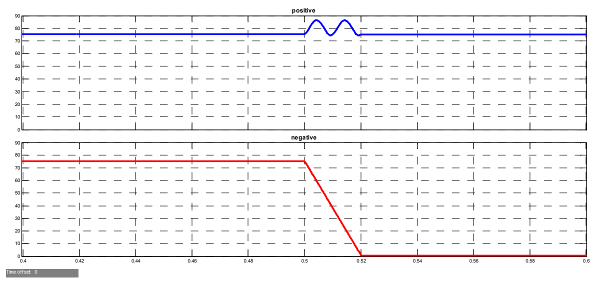
$$\varepsilon_I = \frac{|\dot{I}_-|}{|\dot{I}_+|} \times 100\% \qquad (7)$$

$|\dot{I}_-|$, $|\dot{I}_+|$ --modulus of negative and positive current

The unbalance level before the compensation is 100%. The three phase currents become balanced after the compensator was carried out and the unbalance level was reduced to 0.



(a) Current of tractive transformer high voltage side



(b) Positive sequence and negative sequence current

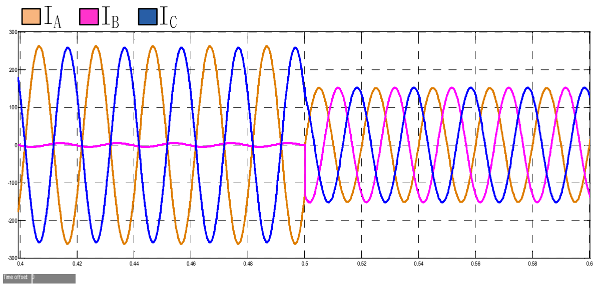
Figure 7. Compensation result under the condition of single station

B. Three Station Collaboration Compensation

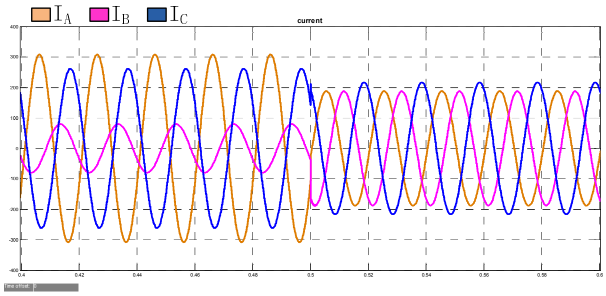
Set three station collaboration compensation for example. Fig.4 shows the schematic diagram of three station collaboration compensation. Three typical conditions are taken into consideration :

$$1)\mathrm{Y}=0;\ \ 2)\,0 \le Y \le \frac{2}{3};\ \ 3)\,\frac{2}{3} \le Y \le 1\,.$$

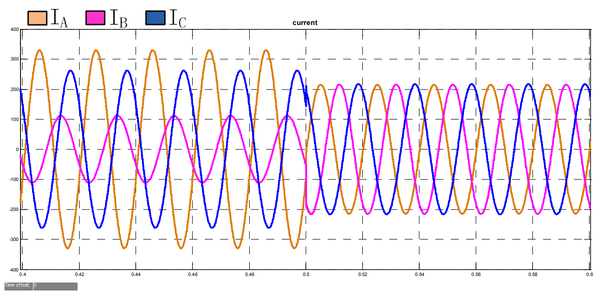
The simulation parameters are the same as single station compensation. Simulation results are shown in Fig.8. Fig.8 (a) shows the waveform before and after compensation when the maximum locomotive load appears at the Phase-AC at the condition of *Y*=0. The situation before compensation is almost the same as single station compensation, except for that the load is twice as much as single station locomotive load. With the use of compensator, the unbalance level was changed from 100% to 1%.Fig.8 (b) is the waveform when $0 \le Y \le \frac{2}{3}$, Y appears at Phase AB. Compensator was put into operation at 0.5*s*. The unbalance level was reduced from 71% to 7%. The waveform when $\frac{2}{3} \le Y \le 1$ is shown in (c). The unbalance level was reduced from 60% to 2%. It can be seen from the simulation that there is a serious unbalanced condition before the compensation. The collaboration compensation network is effective in reducing the negative current(the unbalance level is reduced below 8%). The error may come from the loss of power electronic components and isolation transformers. The unbalance level before and after the compensation is listed in Tab. 2.



(a) Current of tractive transformer high voltage side(Y=0)



(b) Current of tractive transformer high voltage side($0 \le Y \le \frac{2}{3}$)



(c) Current of tractive transformer high voltage side($\frac{2}{3} \le Y \le 1$)

Figure 8. Three station collaboration compensation result under the condition of 2,Y,0

Table II. UNBALANCE LEVEL BEFORE AND AFTER COMPENSATION

	Y=0	$0 \le Y \le \frac{2}{3}$	$\frac{2}{3} \le Y \le 1$
Before Compensation	100%	71%	60%
After Compensation	1%	7%	2%

V. 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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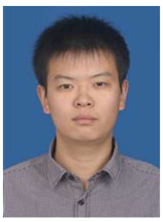
BIOGRAPHIES



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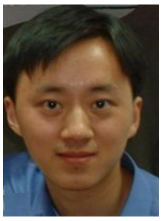

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