A Hybrid Negative Current Compensation System for High-speed Railway Power System

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***Abstract*—The high-speed railway load is a single-phase load with high power, which can generate large negative sequence current (NSC). Many compensation methods have been applied to compensate NSC which is a big power quality problem of railway power supply system, and each method has its own characteristics. A hybrid compensation system is proposed in this paper. The system consists of two different compensation methods. One is based on railway power conditioner(RPC) with modular multilevel converter(MMC) structure(MRPC), and the other is based on Steinmetz compensation principle with magnetic static var compensation (MSVC). The MRPC has a fast response speed but expensive price, while the MSVC has a low response speed but much cheaper price. Compared with MRPC-ONLY compensation method, the hybrid compensation system has a lower cost by reducing the compensation capacity of MRPC with MSVC. Firstly, the compensation principles of the hybrid compensation system is analyzed in detail. Then, the collaboration control strategy of compensation system is proposed. Moreover, the cost of the hybrid compensation system and the MRPC-ONLY compensation method are compared. Finally, simulation and experiment results are both presented to verify the effectiveness of the hybrid compensation system and its control method.**

Keywords—Negative sequence current, hybrid compensation, modular multilevel converter, railway power conditioner

I. INTRODUCTION

The development of high-speed railway becomes more and more significant in many countries around the world, because of its advantages, such as high energy efficiency, economy and environmental protection [1]. Since the high speed electric locomotive is a high power single-phase load, it can cause serious negative sequence issue which may make the generating set nearby vibrate and heated, the working condition of three-phase asynchronous motor deteriorate, the relay protection malfunction and so on [2]. Recently, there are two methods, optimizing the structure of the traction power supply system and installing compensation devices, to deal with the power quality issues including negative sequence issue [3]. The latter method is utilized more generally, because it is a cheaper method which is easier to realize in the existing power supply system. In [4], SVC was utilized to compensate NSC according to the Steinmetz compensation principle. In this method, three SVCs are respectively installed in phase AB, BC and CA. The structure is simple, but the responding speed is slow. The compensation effect is not very well when the load changes quickly. The railway power conditioner (RPC), firstly proposed by Japanese scholar, can compensate the NSC by transport active power and compensate reactive power. RPC can resolve NSC issue well, even if the load changes quickly. However, the cost of RPC is high [5]. The extensive studies of the RPC are done in recent years. RPC was utilized in V/V electric traction system and the compensation strategy was studied [6]. To enhance the cost-efficiency and reliability of RPC, a novel compensating system named asymmetric double LC-coupled railway power flow conditioner (ALC-RPFC) is proposed in [7]. In [8], a hybrid electrical magnetic power quality compensator (HEMPQC) based on magnetic static var compensator (MSVC) and hybrid power quality compensator (HPQC) is proposed to make the active compensation capacity minimum and lower the cost. All of the RPC compensation methods need a step-down transformer, which increases the costs and the install space.

MMC proposed in [9], which is utilized for high voltage direct current transmission (HVDC) at the very beginning, can connect the power grid with high voltage rating directly, without a transformer. The transformerless characteristic of MMC attracts the attention of some researchers who are interested in the unbalance compensation of the railway. A new transformerless four-leg topology is suggested for NSC compensation, the modular multilevel converters (MMC) based on the half-bridge converters in [10]. MMC-based railway traction power conditioner (RTPC) is proposed in [11], which is characterized by modular multilevel cascaded structure. The RTPC consists of four H-Bridge links and output filter inductors, which can be connected to 27.5kV traction feeders in co-phase supply system directly. An improved model predictive control of RTPC is proposed in [12]. An active power conditioner (APC) is implemented by using a three-phase modular multilevel converter (MMC) to improve the power quality at the grid side in [13][14]. Reference [15] presents a simplified quantitative comparison of five previous modular RPC topologies for unbalance compensation in V/V and SCOTT traction systems, aiming for an optimal selection of the compensators.

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According to these researches, MMC with three arms can compensate NSC well without transformers. However, the cost of MRPC is still a little high. In this paper, a novel hybrid compensation system is proposed to reduce the cost of NSC compensation devices and maintain the compensation effect at the same time. The compensation system consists of a MRPC and three MSVCs, as shown in Fig.1, which can respond fast and lower the cost. Then, the system structure, the compensation principle of hybrid compensation system, and the cooperative control strategy are studied.

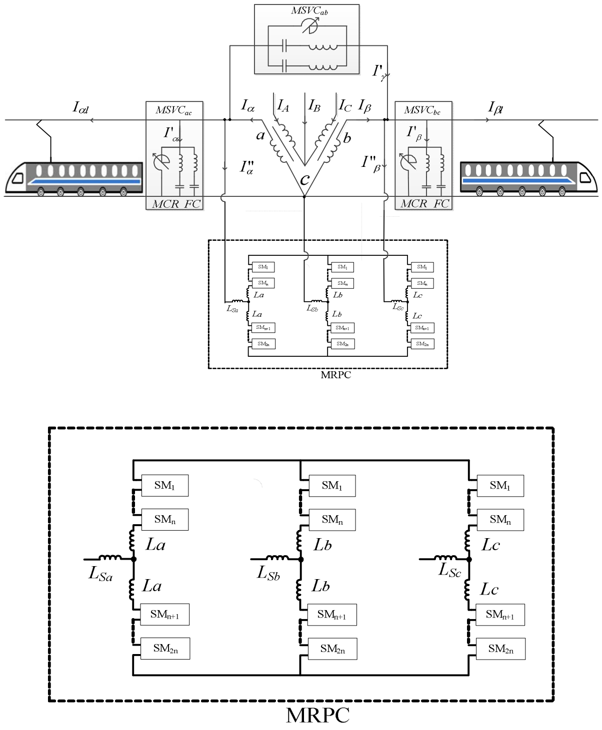


Fig. 1. The topology diagram of the hybrid compensation system

In the following, the structure of hybrid compensation system will be discussed in Section II. In Section III, the compensation principle of the hybrid compensation system is analyzed. In Section IV, the install capacity and cost is analyzed and compared with the MRPC-ONLY compensation method. The collaboration control strategy is studied in Sections V. Section VI gives the results of simulation and experiment. Finally, the conclusion is given in Section VII.

II. THE STRUCTURE OF HYBRID COMPENSATION SYSTEM

The structure of the proposed hybrid compensation system is shown in Fig.1. The system consists of two parts: one low capacity MRPC and three high capacity MSVCs with third and fifth-harmonic-tuned LC passive filter. The MRPC connected to V/V transformer's secondary power supply arms through coupling inductors without the step-down transformers is used to compensate the transient negative sequence component. The MSVCs installed to the three-phase output ports of the V/V transformer's secondary sides are used to compensate the steady-state negative sequence component. Since the MSVC can absorb and issue a certain amount of continuously adjustable reactive power, it can compensate the NSC according to the Steinmetz compensation theory.

III. COMPENSATION PRINCIPLE

A. *Compensation Principle of MSVC*

According to the symmetrical component method, the negative sequence compensation currents generated by the MSVCs are

$$\begin{bmatrix} \dot{I}^{-}_{MSVC} \\ \dot{I}^{+}_{MSVC} \end{bmatrix} = \frac{\sqrt{3}}{3} \begin{bmatrix} \frac{\sqrt{3}}{2} - j\frac{1}{2} & -j & \frac{\sqrt{3}}{2} + j\frac{1}{2} \\ \frac{\sqrt{3}}{2} + j\frac{1}{2} & j & \frac{\sqrt{3}}{2} - j\frac{1}{2} \end{bmatrix} \begin{bmatrix} \dot{I}'_{\alpha} \\ \dot{I}'_{\beta} \\ \dot{I}'_{\gamma} \end{bmatrix} \quad (1)$$

The negative sequence components generated by the MSVCs are $\dot{I}'^{-}_{\alpha}$, $\dot{I}'^{-}_{\beta}$ and $\dot{I}'^{-}_{\gamma}$:

$$\begin{cases} \dot{I}'^{-}_{\alpha} = \frac{\sqrt{3}}{3}\left(\frac{\sqrt{3}}{2} - j\frac{1}{2}\right) \times \dot{I}'_{\alpha} = \frac{\sqrt{3}}{3}\dot{I}'_{\alpha}\angle -30^{\circ} \\ \dot{I}'^{-}_{\beta.} = -\frac{\sqrt{3}}{3} j \times \dot{I}'_{\beta} = \frac{\sqrt{3}}{3}\dot{I}'_{\beta}\angle -90^{\circ} \\ \dot{I}'^{-}_{\gamma} = \frac{\sqrt{3}}{3}\left(\frac{\sqrt{3}}{2} + j\frac{1}{2}\right) \times \dot{I}'_{\gamma} = \frac{\sqrt{3}}{3}\dot{I}'_{\gamma}\angle 30^{\circ} \end{cases} \quad (2)$$

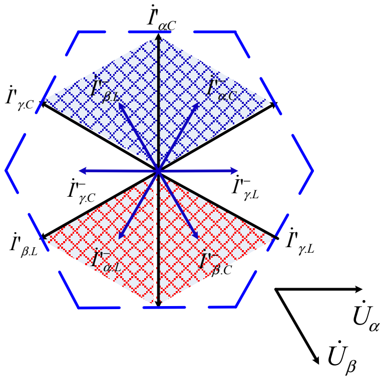


Fig. 2. The negative sequence compensation vector diagram of three-phase MSVC compensation network

The MSVC can absorb and issue a certain amount of continuously adjustable reactive power. So, the MSVC compensation network can generate 6 different negative sequence components. Each component has a 60°phase angle that different from the adjacent one, as it is shown in Fig. 2. The shadow areas are the compensation range of the MSVC.

B. *Compensation Principle of MRPC*

Assume that the voltage phase of the phase-α is 0. The output active power component currents of the two-phase bridge arms of the MRPC are $I^{"}_{\alpha.p}$ and $I^{"}_{\beta.p}$, respectively. The output reactive power component currents are $I^{"}_{\alpha.q}$ and

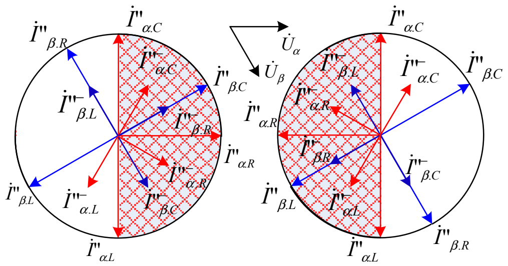
$I''_{\beta.q}$, respectively. According to the symmetrical component method, the output NSC components are

$$\begin{cases} \dot{I}''^{-}_{\alpha} = \frac{\sqrt{3}}{3}\left(\frac{\sqrt{3}}{2} - j\frac{1}{2}\right) \times \dot{I}''_{\alpha} = \frac{\sqrt{3}}{3}\dot{I}''_{\alpha}\angle -30^\circ \\ \dot{I}''^{-}_{\beta} = -\frac{\sqrt{3}}{3} j \times \dot{I}''_{\beta} = \frac{\sqrt{3}}{3}\dot{I}''_{\beta}\angle -90^\circ \end{cases} \tag{3}$$

Then, the NSC component are

$$\begin{aligned} \dot{I}''^{-} &= \dot{I}''^{-}_{\alpha} + \dot{I}''^{-}_{\beta} \\ &= \frac{\sqrt{3}}{3}(I''_{\alpha p}\angle -30^\circ + I''_{\alpha q}\angle 60^\circ + I''_{\beta p}\angle 30^\circ + I''_{\beta q}\angle -60^\circ) \\ &= \dot{I}''_{\alpha} \end{aligned} \tag{4}$$

Namely, the NSC generated by the MRPC is equal to the output current of the phase-T bridge arm. The compensation NSC of MRPC is shown in Fig. 3.



(a)The absorbing active power (b)The issuing active power

Fig. 3. The NSC vector produced by MRPC

C. *Compensation Principle of the Hybrid System*

The total compensation current is that the output current of MSVC plus the output current of MRPC. The negative sequence compensation vector diagram is shown in Fig. 4.

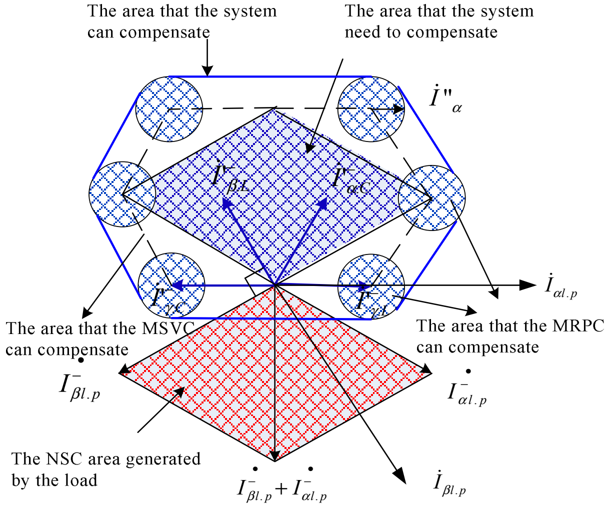


Fig. 4. The negative sequence compensation vector diagram

According to the vector diagram, the hybrid system can resolve the unbalance issue theoretically.

IV. ANALYSIS OF INSTALL CAPACITY AND COST

A. *The capacity analysis*

In this paper, MSVC is used to reduce the capacity of MRPC. In an extreme case, the load of ac side reaches the maximum and the MRPC can not compensation the NSC completely. It is assumed that the active power current issued by MRPC is $I_{MRPC.p}$. After the active power transfer, the active power current of the two power arms is respectively $I'_{\alpha l.p} = I_{\alpha l.p} - I_{MRPC.p}$ and $I'_{\beta l.p} = I_{\beta l.p} + I_{MRPC.p}$, which generate the NSC:

$$\begin{cases} I'^{-}_{\alpha l.p} = \frac{1}{\sqrt{3}}\left(I_{\alpha l.p} - I_{MRPC.p}\right) \\ I'^{-}_{\beta l.p} = \frac{1}{\sqrt{3}}\left(I_{\beta l.p} + I_{MRPC.p}\right) \end{cases} \tag{5}$$

According to the power factor, the compensation currents of MSVCs satisfy the following relationship:

$$I'_{\alpha} + I'_{\beta} + I'_{\gamma} = 0 \tag{6}$$

Then, an expression can be derived, which is:

$$\begin{cases} \frac{1}{2}I'^{-}_{\alpha} + \frac{1}{2}I'^{-}_{\beta} - I'^{-}_{\gamma} = \frac{\sqrt{3}}{2}I'^{-}_{\alpha l.\mathrm{p}} - \frac{\sqrt{3}}{2}I'^{-}_{\beta l.p} \\ \frac{\sqrt{3}}{2}I'^{-}_{\alpha} + \frac{\sqrt{3}}{2}I'^{-}_{\beta} = \frac{1}{2}I'^{-}_{\alpha l.p} + \frac{1}{2}I'^{-}_{\beta l.p} \end{cases} \tag{7}$$

The output current of MSVCs can be conducted:

$$\begin{cases} I'_{\alpha} = \frac{1}{\sqrt{3}}\left(I_{\beta l.p} + I_{MRPC.p}\right) \\ I'_{\beta} = \frac{1}{\sqrt{3}}\left(I_{\alpha l.p} - I_{MRPC.p}\right) \\ I'_{\gamma} = \frac{1}{\sqrt{3}}\left(I_{\alpha l.p} - I_{MRPC.p}\right) - \frac{1}{\sqrt{3}}\left(I_{\beta l.p} + I_{MRPC.p}\right) \end{cases} \tag{8}$$

As the active power current issued by MRPC is $I_{MRPC.p}$, the active power transferred by MRPC is that $P_{MRPC} = I_{MRPC.p} \bullet U$

So, the compensation capacity of MSVCs are respectively:

$$\begin{cases} Q_{\alpha.MSVC} = \frac{1}{\sqrt{3}}\left(I_{\beta l.p} + I_{MRPC.p}\right) \bullet U - \sqrt{S^2_{MRPC} - P^2_{MRPC}} \\ Q_{\beta.MSVC} = \frac{1}{\sqrt{3}}\left(I_{\alpha l.p} - I_{MRPC.p}\right) \bullet U - \sqrt{S^2_{MRPC} - P^2_{MRPC}} \\ Q_{\gamma.MSVC} = \frac{2}{\sqrt{3}}\left(I_{\alpha l.p} - I_{\beta l.p} - 2I_{MRPC.p}\right) \bullet U \end{cases} \tag{9}$$

the total install capacity of MSVCs is

$$\begin{aligned} Q_{\mathrm{Total}} &= \frac{2}{\sqrt{3}}\left(I_{\alpha l.p} - I_{MRPC.p}\right) \bullet U - 2\sqrt{S^2_{MRPC} - P^2_{MRPC}} \\ &\quad + \frac{2}{\sqrt{3}}\left(I_{\alpha l.p} - I_{\beta l.p} - 2I_{MRPC.p}\right) \bullet U \\ &= \frac{4}{\sqrt{3}}I_{\alpha l.p} \bullet U - \frac{2}{\sqrt{3}}I_{\beta l.p} \bullet U - 2\sqrt{3}P_{MRPC} - 2\sqrt{S^2_{MRPC} - P^2_{MRPC}} \end{aligned} \tag{10}$$

According to the derivative of P_{MRPC}, when the expression (11) is satisfied,

$$\frac{P_{MRPC}}{\sqrt{S_{MRPC}^2 - P_{MRPC}^2}} = \frac{P_{MRPC}}{Q_{MRPC}} = \sqrt{3} \qquad (11)$$

the minimum total install capacity of MSVCs satisfies the following expression

$$Q_{\text{TotalMin}} = \frac{4}{\sqrt{3}} I_{\alpha l.p} \bullet U - \frac{2}{\sqrt{3}} I_{\beta l.p} \bullet U - 4S \qquad (12)$$

Therefore, if MRPC can not compensate NSC completely, the install capacity of MSVC reaches the minimum when the proportion of active power and reactive power issued by MRPC is $\sqrt{3}$.

B. *The cost analysis*

The comparison of different compensation strategies is shown in Tab.I.As the cost of MSVC per unit capacity is 1/8 as much as the MRPC's, assuming that the cost of MSVC per unit capacity is *m*, then the MRPC's is 8*m*. According to the capacity in Tab.I, the cost of the MRPC-ONLY compensation strategy will be 125.8*m*, while the cost of the hybrid compensation strategy will be 60*m*. Hence, compared with traditional MRPC-only method, the proposed hybrid compensation system can save nearly 50% cost.

TABLE I THE INSTALLED CAPACITY OF DIFFERENT COMPENSATION TOPOLOGY

Compensation Topology	**Installed Capacity of MRPC**	**Installed Capacity of MSVC**
MRPC ONLY	15.725MVA	0
Hybrid Compensation	3.4642MVA	32.332MVAR

V. COLLABORATION CONTROL STRATEGY

The control strategy is that the compensation current comes from both MRPC and MSVC. When the traction load keeps steady, the compensation current mainly comes from MSVC which is cheaper. When a sudden change of the traction load happens, the additional compensation current first comes from MRPC which can respond quickly, and then the MSVC compensation current increase while the MRPC compensation current decrease. However, the total of the two currents is fixed, which equals to the reference compensation current. The control diagram is shown in Fig.5. The control system includes three parts: the detection of the reference current, MSVC control and MRPC control. To completely eliminate the NSC, the expected compensation currents are

$$\begin{cases} i_a^{\exp}(t) = \dfrac{\sqrt{2}}{2} I_{L1p} \sin\left(\omega t - \dfrac{\pi}{6}\right) + \dfrac{\sqrt{2}}{2\sqrt{3}} I_{L1p} \cos\left(\omega t - \dfrac{\pi}{6}\right) \\ i_b^{\exp}(t) = \dfrac{\sqrt{2}}{2} I_{L1p} \sin\left(\omega t - \dfrac{\pi}{2}\right) - \dfrac{\sqrt{2}}{2\sqrt{3}} I_{L1p} \cos\left(\omega t - \dfrac{\pi}{2}\right) \end{cases} \qquad (10)$$

where, I_{L1p} and I_{L1q} are the fundamental active and reactive load currents root-mean-square(RMS) values, respectively [8]. The PI control is used in the control of the MSVC and the constant voltage control is used in the control of the MRPC. simulation and experiment

VI. SIMULATION AND EXPERIMENT

A. *Simulation of the hybrid system*

Simulations using MATLAB/Simulink are done to verify the feasibility and availability of the hybrid compensation system. The following cases have been simulated.

- Case 1: Steady State Simulation

Fig. 6 and Tab II shows the steady state simulation result. It demonstrates that the NSC is well compensated by the MSVC and the compensation result is satisfied.

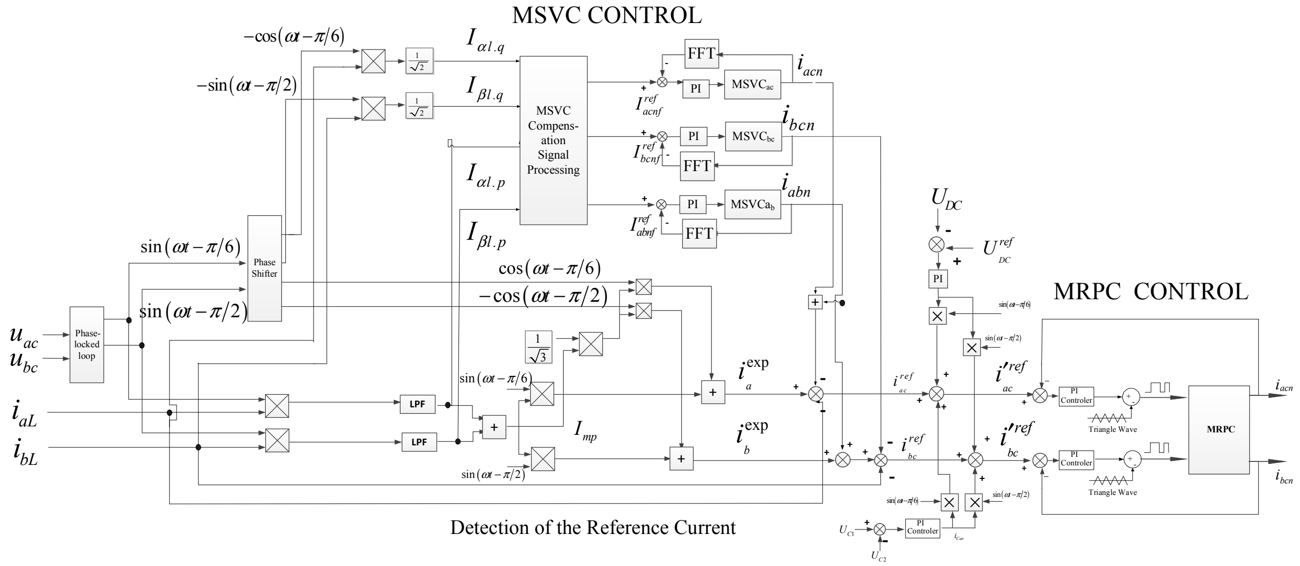


Fig. 5. Control diagram of the hybrid compensation system

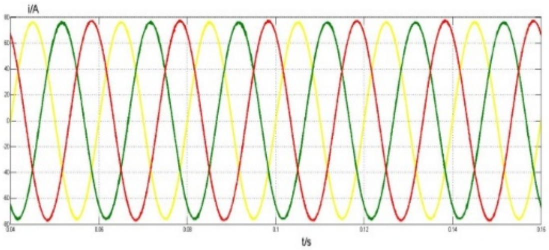


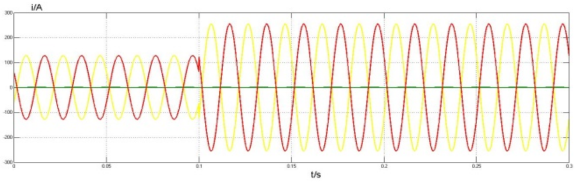
Fig. 6. The 3-phase current after compensation

TABLE II PARAMETERS OF THE CASE

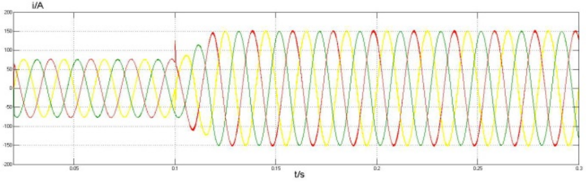
Current	I_A	I_B	I_C	I_+	I_-
Before	90.54A	0.0096A	90.54A	73.94A	73.94A
After	53.6A	53.6A	54.2A	76.12A	0.6388A

- Case 2: Transient State Simulation

The simulation results in Fig.7 indicate that the compensation system also has a good performance at transient states. Fig.8 shows that the output current of the MSVC increases slowly, while the output current of the MRPC increases at first and then decreases.

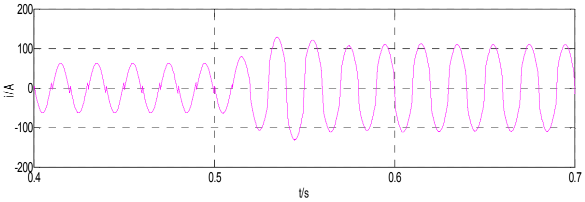


(a) Before

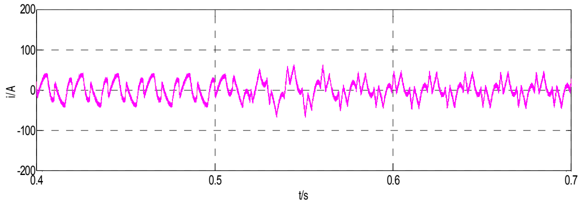


(b) After

Fig. 7. Comparison of the 3-phase current before and after compensation



(a) MSVC



(b) MRPC

Fig. 8. The output currents of the MSVC and MRPC

B. *Experiment of the hybrid system*

For further validation of the proposed hybrid compensation system, a low capacity physical platform of MRPC and MSVC have been built in a laboratory. The experiment platform of the hybrid system is shown in Fig. 9. The power rating of the main transformer with turn ratio of 380V:220V is 10 kVA. The MSVC capacity is 2000 var. The load capacity is 1300W. The coupling inductance is 10mH. The submodular consists of two 1200V 50A IGBTs and a 450V 2200μF capacity. TMS320F2812 DSP from TI company is used as the controller of the hybrid compensation system. All of the control programs are run in the DSP which output the control signals. In Fig.10 (a), before compensation, because the loads are concentrated on ac-phase, only A-phase and C-phase have mutually reverse

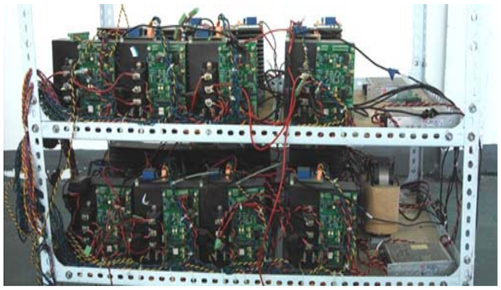
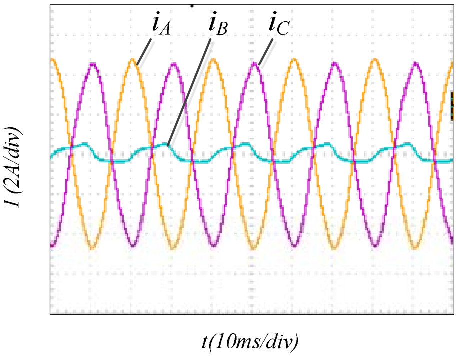
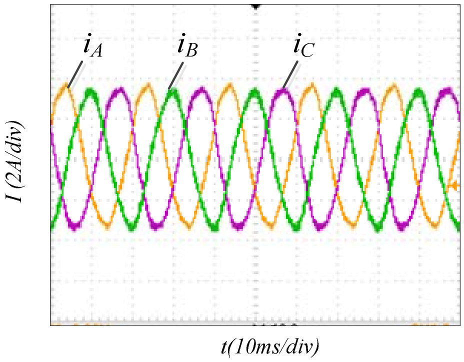


Fig. 9. Experiment Platform



(a) Before



(b) After

Fig. 10. The experiment results

currents in the primary winding of the simulated V/V traction transformer. After MRPC and MSVCs are fully invested based on the collaboration control strategy, the three-phase current waveform of primary winding of main transformer are shown as Fig.10 (b), the negative sequence component of which are completely compensated.

VII. CONCLUSION

To make the compensation of unbalance issue in the high-speed railway power system, a hybrid compensation system is proposed. Compared with the MRPC-ONLY compensation structure, the hybrid compensation system can reduce the capacity of the compensation devices to lower the cost and maintain a good compensation effect meanwhile. The topology of the system is presented and the collaboration compensation principle of the hybrid compensation system is analyzed with a good transient response characteristic. Finally, simulations and experimental results verify that the proposed hybrid compensation system has a good compensation performance with a lower cost. The proposed hybrid compensation system has a good compensation character, but the currents of three arms of MMC has an uneven distribution, which is not good for the compensation devices to work for a long time.

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