Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

The Hysteresis Control Strategy of Modular Multi-Level Railway Power Conditioner

Shijun Li [1, 2]*, Longfu Luo [4], Jiayi Yang [3], Fumei Wu [4], Yanping Li [1]
[1]College of Electrical & Information Engineering, Hunan Institute of Engineering, Xiangtan, Hunan, China
[2]College of Electrical and Information Engineering, Hunan University, Changsha, Hunan, China
[3]School of Electrical Engineering Shaoyang University, Shaoyang, Hunan, China
[4]Swan College of Central South University of Forestry and Technology, Changsha, Hunan, China
*Corresponding Author.

Abstract:

Complex control progress, large amounts of calculation and complex modulate strategy is the problems when modular multi-level railway power conditioner (MPRC) improves the quality of electric energy in traction network. In order to overcome these problems, this paper constructed the dc hysteresis control strategy of MPRC on the basis of dc-ac electric hysteresis control strategy. In this strategy, the closest electric level approximation principle is used to output port voltage to offset high voltage on the traction side, and the current error is used to modulate sub-module pulse signal of bridge arm on the compensation side to realize the no static tracking of compensation current. The new hysteresis control strategy has some advatages: easily debugging, small amount of calculation, strong robustness. The simulation results verified the correctness and effectiveness of the proposed control strategy.

Keywords: *Railway power conditioner, Hysteresis control strategy, Modular multi-level conditioner, Electrified Railway, Reactive power compensation.*

I. INTRODUCTION

With the rapid development of electrified railway, the negative order and harmonic problems in traction power supply system are becoming more and more prominent [1]. In order to improve the power quality of traction power supply system, a series of control strategies have been proposed [2-5].Compared with other strategies, the flexibility and superiority of two-phase power integrated railway power regulator proposed by Japanese scholars has been widely recognized. [6-7]

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

Traditional railway power regulation apparatus adopts two electric-level structure, which needs the auxiliary step-down transformer and multiple ways to connect to the grid because the structure is restricted by the withstand voltage of single device. Its disadvantages are: large, complex and covering large area. [8]. In order to compensate for the above shortcomings, relevant scholars proposed the modularized multi-level railway power conditioner based on the structure of the Modular Multilevel Converter, which can make the traction side connect to the grid directly. [9].

At present, MRPC control is mainly based on the control strategy of the three-phase system MMC device. The suitable modulation for the MMC is mainly carrier phase-shifting modulation cascade, closely electric-level approximation, carrier stack-up, etc... The harmonic content is big in closely electric-level approximation when the electric-level is low, carrier phase-shifting modulation and carrier stack-up needs to modulate each module, which is complex. Not only that, these modulation strategies require complex current controllers to obtain the modulation wave, the control system is complex, the response is slow, and the robustness is poor [10].The current loop usually used are PI, PR and repetitive control. Different from the conventional three-phase MMC system, the MRPC system is two-single-phase structure, except the transmission of the fundamental wave is active, the harmonic and reactive power are compensated and negative.

To simplify the control strategy of MRPC, improve the flexibility and robustness of the system, the equivalent circuit of MRPC bridge arm is constructed on the basis of analyzing the working principle of MRPC. According to the closely electric-level approximation principle, the MRPC output port voltage to offset the high voltage on the traction side, and the MRPC multi-level current control is transformed into two level control of the upper and lower bridge arm modules. Compensation arm current is controlled by hysteresis control. This control strategy does not need to obtain the modulation wave, so the control is simple, the response is fast, the robustness is strong and the debugging parameter is less.

II. ANALYSIS OF STRUCTURE AND PRINCIPLE OF MRPC SYSTEM

2.1 System Structure

Fig 1 is the structure diagram of MRPC system.110kv (or 220 kV) three-phase power grid is transformed into a two-phase 27.5 kV traction grid by traction transformer to power the locomotive. The MRPC structure is composed by two single-phase MMC back to back (Fig 2 is the MRPC phase structure). MRPC can directly connect to the traction power supply arm on both sides without a transformer. The reasonable control of the MRPC can realize the active balance on the side of the two arms, and achieve reactive power and harmonic compensation, and the compensation algorithm can be referred to [11], which is not repeated here.

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

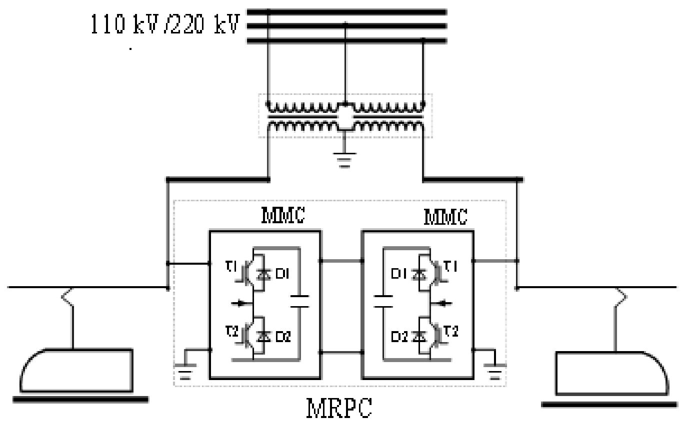


Fig 1: The system structure of MRPC

2.2 Operating Principle

The structure of the α and β phases of the MRPC is consistent, and we chose one of them to analyze, as shown in Fig 2. The structure of each sub-module on the bridge arm is shown in the imaginary box in the picture.

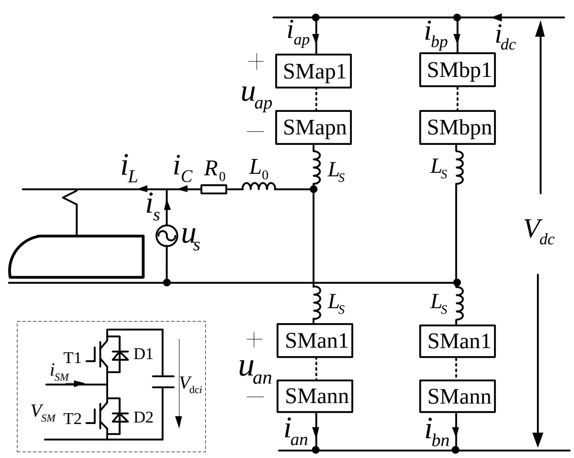


Fig 2: The system structure of MRPC's one side

The u_s, i_s is respectively the voltage, currect of traction arm, i_L is the load current, i_c is the compensation current of MRPC, V_{dc} is the voltage on the DC side of MRPC, and L_s, R_s, L_0 and R_0 are respectively the resistance, inductance of bridge arm, resistance and inductance of gird side of MRPC.

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

Subscript p, n represents upper and lower bridge arm parameters, u_{jp}, u_{jn} and i_{jp}, i_{jn} are respectively the voltage and current of the upper and lower bridge arm of j phase (j=a, b, indicating the two bridge arms of one phase of MRPC, and the following analysis is consistent).

Refer to Fig 2, according to kirchhoff's voltage law, the MRPC AC side expression is as follows:

$$u_c = u_s + L_0 \frac{\mathrm{d}i_c}{\mathrm{d}t} + R_0 i_c \tag{1}$$

Similarly, the MRPC dc side can be expressed in the following mathematical expressions:

$$\begin{cases} \frac{1}{2}V_{dc} = u_{jp} + L_s \frac{\mathrm{d}i_{jp}}{\mathrm{d}t} + R_s i_{jp} + u_j \\ \frac{1}{2}V_{dc} = u_{jn} + L_s \frac{\mathrm{d}i_{jn}}{\mathrm{d}t} + R_s i_{jn} - u_j \end{cases} \tag{2}$$

In the equation (2), the two equations are reduced and added respectively to obtain the MRPC ac side port and the dc side voltage equation.

$$\begin{cases} u_c = \frac{1}{2}(u_{jn} - u_{jp}) + \frac{L_s}{2}\frac{\mathrm{d}i_c}{\mathrm{d}t} + \frac{R_s}{2} \cdot i_c \\ V_{dc} = (u_{jp} + u_{jn}) + 2L_s \frac{\mathrm{d}i_z}{\mathrm{d}t} + 2 \cdot R_s i_z \end{cases} \tag{3}$$

Among them, i_c= (i_{jn}-i_{jp})/2, i_z= (i_{jp}+i_{jn})/2.The two are respectively the compensation current of MRPC and the inner circulation of the bridge arm.

According to equation (1) and equation (3), the compensation current i_c control can be realized through reasonablely control of upper and lower bridge arm voltage u_{jp}, u_{jn} .(in essence, it is to control the number of the sub-module putting into the upper and lower bridge arm Nn(t) and Np(t))

2.2.1 Integrated control strategy for MRPC current hysteresis

The input module of the upper and lower bridge arm is equivalent to the controlled voltage source. According to formula (1) and equation (3), the equivalent circuit of the single arm can be obtained. The equivalent circuit is shown in Fig 4:

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

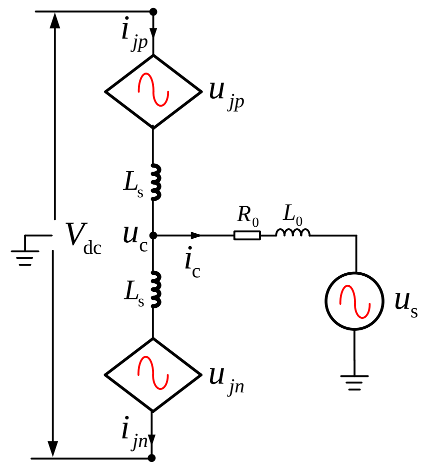


Fig 3: A equivalent circuit diagram of MRPC's one bridge arm

In Fig. 3, $u_{jx}(x=p,n)$ is the output voltage of upper and lower bridge arm. Traditional MMC bridge arm control needs to obtain the modulation wave according to the current controller, and then modulates each sub-module according to the modulation wave .Because traction voltage is higher, upper and lower bridge arm has more than one sub-modules, and the hysteresis control determine the on or off of the switch by the error value of the compensation current, which can't control multiple modules, and this is the main reason why current hysteresis control is difficult to be applied into the MMC. In order to apply current hysteresis control to MMC, the following should be done. Firstly, we need u_{jx} output can offset the port voltage u_{c1} of the high voltage u_s on the traction side (as shown in Fig 4 (a)). At this time, the compensation current i_c=0. So u_{jx1} output does not affect the compensation current i_c. Secondly, when the high voltage u_s on the traction side is offset, the whole equivalent circuit single-phase bridge arm can be equivalent to the equivalent circuit as shown in Fig 4 (b), in this case the voltage on the traction side u_s=0, that means we can produce compensation current i_c through control each sub-module u_{jx2} by current hysteresis control only on the basis of the error value of compensation current. Therefore, as shown in Fig 5, the output voltage of the upper and lower bridge arm $u_{jx}(x=p, n)$ is mainly composed of the u_{jx1} and the u_{jx2}, the former is used to offset the high voltage on the traction side u_s , the later is used to control the compensate current i_c. The specific implementation is as follows:

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

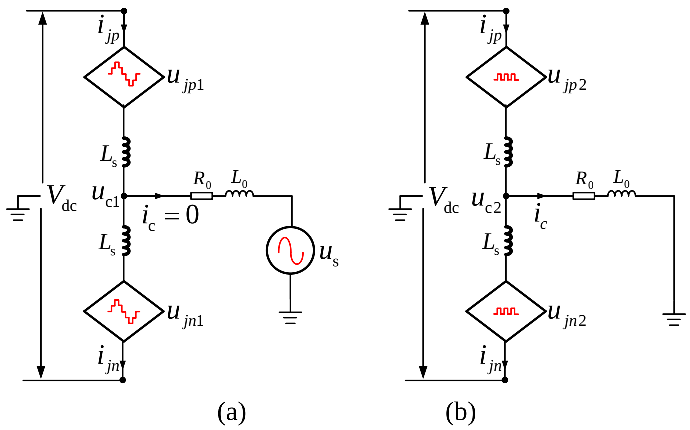


Fig 4: Decoupled equivalent circuit diagram

(a) u_{jx1} control

The purpose of u_{jx1} is to offset most of voltage on the traction side u_s to make the compensation current i_c can be produced by each single sub-module. According to the closely electric-level approximation principle, the input module of the upper and lower arm of the MRPC must satisfy the following formula so as to generate a uniform port voltage with u_s:

$$\begin{cases} N_{p1}(t) = \dfrac{N}{2} + \mathrm{round}(\dfrac{u_s}{u_{SM}}) \\ N_{n1}(t) = \dfrac{N}{2} - \mathrm{round}(\dfrac{u_s}{u_{SM}}) \end{cases} \tag{4}$$

In equation (4), $N_{p1}(t)$, $N_{n1}(t)$ respectively are the number of sub-modules putting into the upper and lower bridge arm, N is the total number of the sub-module put by the bridge arm, u_s is the voltage on the traction side, u_{SM} is the capacitor voltage of sub-module, and round is the integral function.

(b) u_{jx2} control

When the sub-modules of the upper and lower bridge arm are input according to equation (4), the output port voltage of MRPC u_c can offset most of the high voltage on the traction side u_s. According to the equivalent decoupling circuit diagram 4(b), the output voltage equation can be expressed as follows:

$$\frac{1}{2}(u_{jn2} - u_{jp2}) = (L_0 - \frac{L_s}{2})\frac{\mathrm{d}i_c}{\mathrm{d}t} + (R_0 - \frac{R_s}{2})i_c \tag{6}$$

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

To facilitate analysis, we make:

$$\begin{cases} u_{\text{ceq}} = \frac{1}{2}(u_{jn2} - u_{jp2}) \\ L_{\text{eq}} = L_0 - \frac{L_{\text{s}}}{2} \\ R_{\text{eq}} = R_0 - \frac{R_{\text{s}}}{2} \end{cases} \tag{7}$$

Substituting equation (7) into equation (6), equation (6) can be equivalent to:

$$u_{\text{ceq}} = L_{\text{eq}} \frac{\text{d}i_{\text{c}}}{\text{d}t} + R_{\text{eq}} i_{\text{c}} \tag{8}$$

There is no effect of the high voltage on the traction side in equation (8), L_{eq}, R_{eq} are small, so a small u_{ceq} is enough to produce corresponding compensation current i_{c}, using the current hysteresis to control upper and lower bridge arm sub-module duty ratio can generate corresponding compensation current i_{c}.

Fig 5 is the principle of hysteresis control. According to PWM homalographic principle, $u_{\text{ceq}}=\delta u_{\text{SM}}$. The δ is determined by error value of compensation current and ring width h. If Δi_{c} is bigger than the upper limit value of h, the inductive current should be reduced, and δ=0 at this time; if Δi_{c} is smaller than the lower limit value of h, then the inductive current should be enlarged, and δ=1 at this time; if Δi_{c} is within the value of h, then δ remain unchanged.

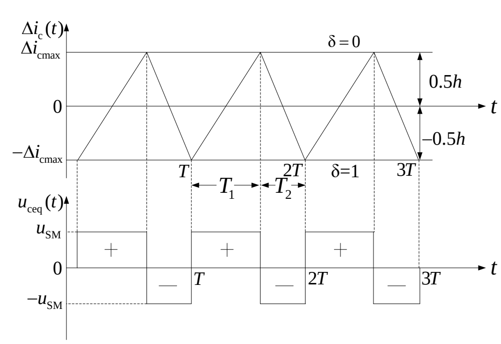


Fig 5: The hysteresis control schematic diagram

In combination with (a) and (b) analysis shows that the core idea of MRPC hysteresis control is that

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

using u_{jx1} to produce the port u_c consistent with the voltage on the traction side u_s, according to the closely electric-level approximation principle, so that the multiple electric-level control of compensation current i_c can be changed into two electric-level control by upper and lower bridge arms. Through the directly control of sub-modules u_{jx2} of the upper and lower bridge arms by current hysteresis control, the compensation current i_c can be produced. In combination with u_{jx1}, u_{jx2}, the number of sub-modules $N_p(t)$, $N_n(t)$ putting by upper and lower bridge arms is as follows:

$$\begin{cases} N_p(t) = \dfrac{N}{2} + \mathrm{round}(\dfrac{u_s}{u_{SM}}) + \delta \\ N_n(t) = \dfrac{N}{2} - \mathrm{round}(\dfrac{u_s}{u_{SM}}) - \delta \end{cases} \tag{9}$$

Among them, $i_c=(i_{jn}-i_{jp})/2$, $i_z=(i_{jp}+i_{jn})/2$.The two are respectively the compensation current of MRPC and the inner circulation of the bridge arm.

According to equation (1) and equation (3), the compensation current i_c control can be realized through reasonablely control of upper and lower bridge arm voltage u_{jp}, u_{jn} .(in essence, it is to control the number of the sub-module putting into the upper and lower bridge arm Nn(t) and Np(t))

III. INTEGRATED CONTROL STRATEGY FOR MRPC CURRENT HYSTERESIS

Fig 6 shows the control system diagram of MRPC based on current hysteresis control. First of all, detect the locomotive load $i_{\alpha L}$, $i_{\beta L}$ on α, β traction sides, and obtain the compensation current set value i_c of two arms. In order to stabilize dc voltage V_{dc}, a small amount of work is superimposed on the compensation current given value i_c .*.Secondly, detect the voltage u_s on the traction side, obtain the number of sub-modules putted by upper and lower bridge arms according to the closely electric-level approximation principle, offsetting most of the voltage u_s on the traction side.

Then, obtain the error value Δi_c of compensation current, and get the δ value of sub-module of upper and lower bridge arms through current hysteresis and so as to get the total number of sub-modules $N_p(t)$, $N_n(t)$ needed to be put by upper and lower bridge arms. Finally, the pulse signal of the submodule is obtained by the capacitor voltage.

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

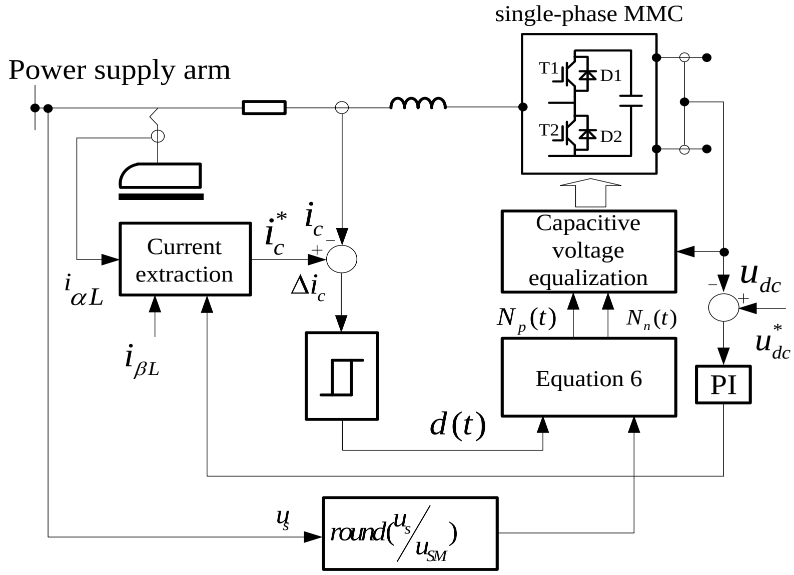
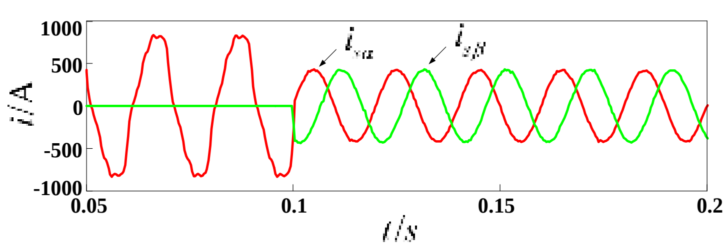


Fig 6: the MRPC control system based on hysteresis control

IV. SIMULATION ANALYSIS

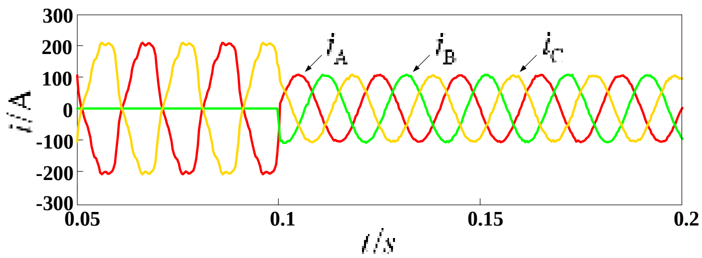
In order to verify the correctness and rationality of the control strategy proposed in this paper, the simulation model was built in Simulink with reference to Fig 1.

Fig 7 shows the current waveform of secondary side current of traction transformer, three-phase current of the grid, he current on the compensation side of α phase before and after the MRPC inputt (t= 0.1s inputting MRPC). Fig 8 is the power quality indexes before and after MRPC input. From the figure, after the input of MRPC, the secondary side current of traction transformer is balanced, the wave is sine, the three-phase current unbalance degree on grid side reduced from 1 to below 1%, the total harmonic distortion rate is reduced from 12% to below 12%, the power factor near to 1, so the power quality improved considerable. In addition, it can be seen from Fig 8 (c) that the compensation side current can quickly respond to the compensation current instruction value after the MRPC is input, which indicates the correctness and rationality of the construction control strategy in this paper.

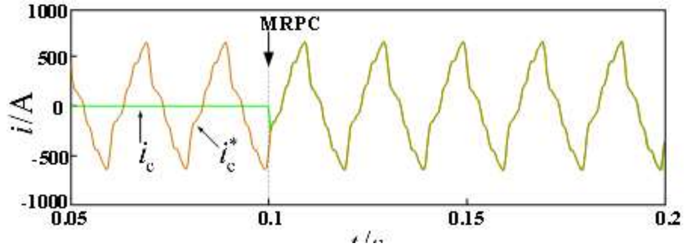


Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

(a)Secondary side current of traction transformer

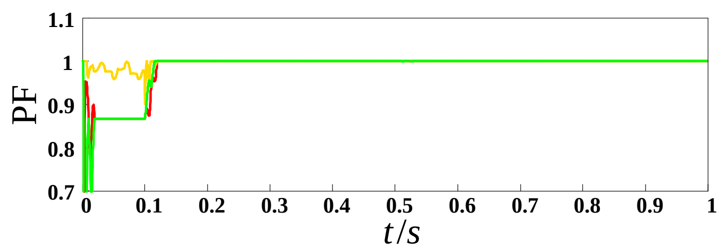


(b)Three phase current at grid side

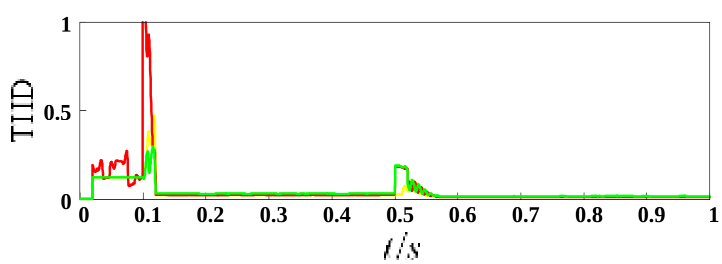


(c) α Phase compensation current

Fig 7: the waveforms of MRPC before or after compensation

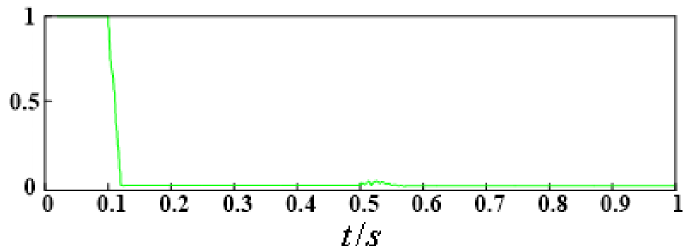


(a) Power factor



(b) Total harmonic distortion rate

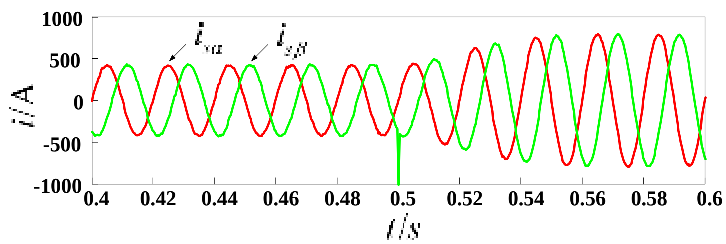
Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021



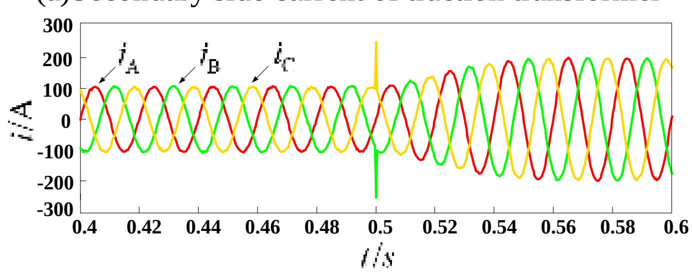
(c) Current unbalance

Fig 8: The transient waveforms under load fluctuation

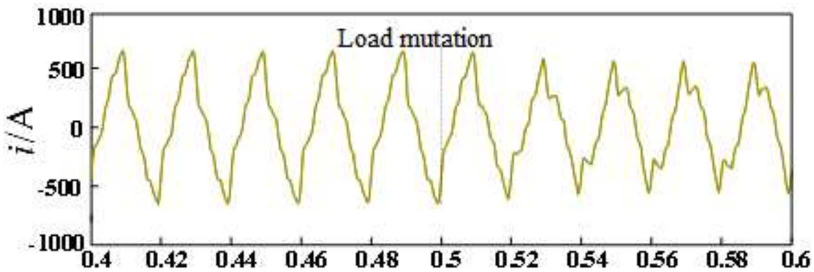
Fig 9 shows the current waveform of secondary side current of traction transformer, three-phase current of the grid, the current on the compensation side of α phase in the load fluctuation condition (t=0.5s, the input load of the β phase is 13.75mw).From the picture, under the condition of load fluctuation, the compensation current of MRPC can well track the given value, the two phases on secondary side of traction transformer is balanced, the wave is sine, and the three-phase current on grid side is symmetry without distortion. The transition is smooth, the transient time is short, and there is no obvious impact and distortion waveform. The above shows that the MRPC can be well balanced on both sides of the traction, compensating for harmonic and reactive power even under load fluctuation.



(a)Secondary side current of traction transformer



(b)Three phase current at grid side



(c) α Phase compensation current

Fig 9: The transient waveforms under load fluctuation

V. CONCLUSION

In order to improve the MRPC, this paper proposed a direct current hysteresis control strategy based on the principle of MRPC to realize fast and reliable tracking of compensation current. Second, this paper pointed out the core idea of direct current hysteresis control strategy of MRPC is using the closely electric-level regulation to offset the voltage on traction side, and control the needed conpensation current of upper and lower bridge arm through hysteresis strategy. Finally, through the analysis of the switching frequency of MRPC direct current hysteresis control, the paper analyzed and pointed out that the switching frequency of modularized multilevel with hysteresis control is improved to some extent compared with the two-level structure.

ACKNOWLEDGEMENTS

This paper is supported Project supported by Scientific Research Fund of Hunan Provincial Education Department(19A108), and provincial natural science foundation of Hunan (2019JJ40059)AND collaborative education project of industry university cooperation of the Ministry of Education (201902143006) (2019003020) (201902145014),and Hunan teaching reform project(HNJG-2021-1350) ,and Doctoral Talent Research Fund(20RC002),and Xiangtan enterprise science and technology special expert project(CG-TPZJ20211019), and Xiangtan science and technology innovation project(CG-YB20211019)

REFERENCES

[1] Zhao Y, Dai NY, Bao A. Application of three-phase modular multilevel converter (MMC) in co-phase traction power supply system. Transportation Electrification Asia-Pacific. IEEE. 2014:1-6

[2] Hu S, Zhang Z, Li Y, et al. (2015) A New Railway Power Flow Control System Coupled With Asymmetric Double LC Branches. IEEE Transactions on Power Electronics, 30(10):5484-5498

Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
September-October 2021 Page No. 632-644
Article History: Received: 22 July 2021 Revised: 16 August 2021 Accepted: 05 September 2021 Publication: 31 October 2021

[3] Uzuka T, Ikedo S, Ueda K. (2004) A static voltage fluctuation compensator for AC electric railway. Power Electronics Specialists Conference PESC 04. 2004 IEEE 35th Annual, vol. 3, pp. 1869-1873, June 2004
[4] Research on the Influence and Management of the Electrified Railway Traction Substation on Power System. Proceedings of the CSEE, 2011, S1: 77-82
[5] Research on Hysteresis-band Current Tracking Control of Grid-connected Inverter. Proceedings of the CSEE, 2006, (09): 108-112
[6] Integrative Compensation Method of Negative Phase Sequence and Harmonic for High-speed Railway Traction Supply System With V/v Transformer Proceedings of the CSEE, 2010, 16:111-117
[7] Study and Application of a New Power Quality Combined Compensation System for Electrified Railway, Transactions of China Electrotechnical Society, 2009, 03:189-194
[8] Richardeau F, Pham T. Reliability calculation of multilevel converters: theory and applications. IEEE Transactions on Power Electronics, 2013, 60(10): 4225- 4233
[9] Remus T, Marco L, Pedro R. Grid converters for photovoltaic and wind power systems. ChiChester: IEEE Press, 2011
[10] Richardeau F, Pham T. Reliability calculation of multilevel converters: theory and applications. IEEE Transactions on Power Electronics, 2013, 60(10): 4225- 4233
[11] Raygani S, Tahavorgar A, Fazel S, et al. Load flow analysis and future development study for an AC electric railway. IET Electrical Systems in Transportation, 2012, 2(3): 139-147