A Novel Control Algorithm for Railway Power Quality Conditioner in AC Electrified Railway Systems

Haneol Park *, Jungho Han ** and Joongho Song †

Abstract – The AC electrified railway systems have the power quality problems such as the harmonic currents pollution, the reactive power consumption, and the load imbalance because the locomotives show the characteristics of nonlinear and single-phase electrical loads. These power quality problems have a bad effect on not only AC electrified railway systems but also other electric systems connected together. A railway power quality conditioner (RPQC) is able to provide a novel solution to these power quality problems in the AC electrified railway systems. In this paper, a novel RPQC control algorithm based on the synchronous-reference-frame (SRF) is proposed. The proposed RPQC control algorithm can compensate effectively the harmonic currents, the reactive power, and the load imbalance. The validity and the effectiveness of the proposed RPQC control algorithm are illustrated through the simulations.

Keywords: Ac electrified railway, Power quality, Active power filter, RPQC

1. Introduction

The AC electrified railway systems have the power quality problems such as the reactive power consumption and the load imbalance due to their inherent electrical characteristics of single-phase and nonlinear moving loads. Also the power electronics equipments in the AC electrified railway systems produce the large amount of harmonic currents. These power quality problems in the AC electrified railway systems have a bad effect on themselves as well as other electric systems connected together. Therefore a power quality compensator is required to maintain the proper power quality in the AC electrified railway systems. There are many researches on the power quality compensator for improving power quality in the AC electrified railway applications. Especially, a single-phase active power filter and a single-phase hybrid active power filter, being composed of a passive power filter and an active power filter, have been studied [1]. Most of the active power filters are connected in parallel with M-phase and T-phase secondary outputs of Scott transformer respectively. Although they can compensate the harmonic currents and the reactive power, the load imbalance cannot be compensated. A three-phase active power filter for power quality compensation has been proposed [2]. However, the three-phase active power filter installed at the three-phase mains requires the high-voltage rating. Another active power quality compensator, being composed of a three-phase inverter and a Scott transformer, has been studied [3]. An active power quality compensator with two single-phase inverters connected back-to-back (that is called the RPQC in this paper) has been proposed [4]. The RPQC requires no additional Scott transformer and can be operated at lower voltage level than the three-phase active power filter. In spite of these merits, there are few researches on the control of RPQC. A novel control algorithm based on SRF for the RPQC is proposed in this paper. The proposed RPQC control algorithm can properly compensate the harmonic currents, the reactive power, and the load imbalance. The effectiveness and the validity of the proposed control algorithm are demonstrated through the simulations.

2. RPQC

2.1 Structure of the RPQC

![Configuration of RPQC](image-url)
Fig. 1 shows an AC electrified railway system adopting the RPQC. The RPQC consists of two single-phase inverters sharing a DC-link capacitor. Each of the single-phase inverters is connected with M-phase and T-phase feeder of the Scott transformer.

The RPQC controller is shown in Fig. 2. The DC-link voltage for the DC-link voltage regulation, the inverter currents for the current control, and the load currents for the harmonic extraction are required as the controller inputs. The RPQC can compensate not only the harmonic currents and reactive power, but also the load imbalance by exchanging the active power deviation between M-phase and T-phase feeders through the DC-link capacitor.

2.2 Harmonic compensation

The load current of the M-phase feeder that means the current flowing into the locomotives is expressed as follows

\[ i_{M-L} = I_{m-L} \cos(\omega t - \phi) \]  

(1)

After transforming the load current in equation (1) into the SRF coordinate, the respective d-q components can be expressed as the following equations (2) and (3).

\[ I_{M-Ld} = \tilde{I}_{M-Ld} + \bar{I}_{M-Ld} \]  

(2)

\[ I_{M-Lq} = \tilde{I}_{M-Lq} + \bar{I}_{M-Lq} \]  

(3)

where, \( \tilde{I}_{M-Ld} \) and \( \tilde{I}_{M-Lq} \) are the DC values of the load current on the SRF. The DC values of the d-q axis are obtained by using the low pass filters. \( \tilde{I}_{M-Ld} \) and \( \tilde{I}_{M-Lq} \) are the AC values of the load current on the SRF, which means the harmonic contents of the load current. Therefore, when the d-q DC values are subtracted from the d-q load currents, the d-q harmonic currents to be compensated are obtained. Fig. 3 shows the method to extract the harmonic components from the load current.

2.3 Reactive power compensation

The M-phase voltage is represented as follows

\[ v_{M-L} = V_{M-L} \cos \omega t \]  

(4)

Through substituting equations (2) and (3) into equation (1), equation (5) can be derived as follows

\[ i_{M-L} = I_{M-Ld} \cos \omega t - I_{M-Lq} \sin \omega t = I_{M-L} \cos \phi \cos \omega t + I_{M-L} \sin \phi \sin \omega t \]  

(5)

Therefore, the single-phase instantaneous active power and reactive power can be described as equations (6) and (7).

\[ p_M(t) = v_{M-L} \cdot i_{M-Ld} \cos \omega t = V_{M-Ld} \cos \omega t \cdot I_{M-Ld} \cos \omega t \]

\[ = \frac{1}{2} V_{M-Ld} \cdot I_{M-Ld} \left[ 1 + \cos(2\omega t) \right] \]  

(6)

\[ q_M(t) = v_{M-L} \cdot i_{M-Lq} \sin \omega t = -V_{M-Lq} \cos \omega t \cdot I_{M-Lq} \sin \omega t \]

\[ = -\frac{1}{2} V_{M-Lq} \cdot I_{M-Lq} \sin(2\omega t) \]  

(7)
where, $V_{M-Lrms}$ and $I_{M-Lrms}$ denote the RMS value of $V_{M-L}$ and $I_{M-L}$, respectively. It is shown that the single-phase instantaneous active power depends on the d-axis current value, while the instantaneous reactive power depends on the q-axis current value. The source current, $I_{M-s}$ is made by the load current of M-phase, $I_{M-L}$ and the inverter current, $I_{M-inv}$, as in equation (8)

$$I_{M-s} = I_{M-inv} + I_{M-L}$$  \(8\)

If the q-axis value of the source current becomes zero through the compensation of the q-axis current, the corresponding reactive power can be compensated. Fig. 4 shows the control blocks of reactive power compensation algorithm.

2.4 Load imbalance compensation

It is shown in equation (6) that the single-phase instantaneous active power can be properly controlled by controlling the d-axis current. If the harmonic currents and the reactive power have been compensated by the proposed compensation algorithm, the load imbalance is provoked by a deviation between the active power load of the M-phase and that of the T-phase. For example, the load current of the M-phase is larger than the T-phase when the load of the M-phase is larger than T-phase, then the load imbalance problem is occurred. This results into that the d-axis current of the M-phase is larger than that of the T-phase. The d-axis values of the M-phase and the T-phase are equal to each other when three-phase balancing condition is considered. This load imbalance compensation can be achieved if the difference between the d-axis source currents of the M-phase and the T-phase is controlled to be zero. Fig. 5 shows the control blocks of load imbalance compensation algorithm.

2.5 DC-link voltage regulation

The DC-link voltage regulator has a role in compensating power losses of the RPQC as well as the voltage regulation. Fig. 6 shows the control blocks of DC-link voltage regulation algorithm.

2.6 Overall RPQC controller

Fig. 7 shows the structure of overall RPQC control scheme. M-phase controller and T-phase controller are fundamentally on the same structure together. However, in this paper, the T-phase controller involves the DC-link voltage regulation loop, and the sign of load imbalance compensation loop of the M-phase and the T-phase controller is opposite because the reference direction of power flow is on the T-phase. The DC-link voltage regulation and the load imbalance compensation are achieved on the d-axis and the reactive power compensation is performed on the q-axis. The harmonic currents compensation is performed on both of the d-q axis. Hysteresis current control is employed for the inverter current control.
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3. Case Study

The AC electrified railway system investigated in this paper is composed with a three-phase voltage source and a Scott transformer as shown in Fig. 8. The locomotives are considered as the non-linear circuits of the SCR bridge rectifiers, the three-phase inverters and the three-phase R-L loads. The parameters for simulation are selected as shown in Table 1.

Table 1. Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>3φ source voltage</td>
<td>250V, 60Hz</td>
</tr>
<tr>
<td>RPQC filter L</td>
<td>2mH</td>
</tr>
<tr>
<td>DC-link C</td>
<td>6000μF, 500V</td>
</tr>
<tr>
<td>T-phase R-L series load</td>
<td>1 Ω, 5mH</td>
</tr>
<tr>
<td>M-phase R-L series load</td>
<td>8 Ω, 5mH</td>
</tr>
</tbody>
</table>

3.1 Case A (without RPQC)

When RPQC is not provided, the corresponding simulation results are plotted in Fig. 9. The waveform of the load currents is not sinusoidal due to the electrical nonlinearity of the locomotives. It is known from Fig. 9 and Table 2 that the reactive power is on demand.

Fig. 7 Control block diagram of overall RPQC controller.

Fig. 8 Simulation structure of the proposed RPQC.
(a) RPQC control blocks (b) RPQC power stage

Fig. 10 shows the three-phase unbalance at primary side of the Scott transformer resulted from the single-phase load imbalance. The THD of source current is so big that the total power factor is very poor.
3.2 Case B (with RPQC)

The simulation results, when the RPQC is provided, are plotted in Fig. 11 through Fig. 13.

Even though the load currents of M-phase and T-phase contain harmonic currents, it is known from Fig. 11 that the source currents of the M-phase and the T-phase have very little harmonic components. Fig. 12 illustrates that the load imbalance is completely compensated by the RPQC. Also it is shown in Table 3 that the proposed RPQC control algorithm can compensate the harmonic currents and the reactive power satisfactorily.

<table>
<thead>
<tr>
<th>Table 3. Case B; THD and power factor</th>
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<tbody>
<tr>
<td>THD for M-phase source current</td>
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<tr>
<td>THD for T-phase source current</td>
</tr>
<tr>
<td>Displacement power factor at 3 φ source</td>
</tr>
<tr>
<td>Total power factor at 3 φ source</td>
</tr>
</tbody>
</table>

Fig. 13 demonstrates the step response of three-phase source current when the load is changed. At 0.5sec, the load of M-phase is changed up from 53% to 100% of the rated load. It is noted that the proposed RPQC control algorithm can quickly compensate the three-phase unbalance against the load step change.
4. Conclusion

The AC electrified railway systems have many power quality problems such as the harmonic currents, the reactive power consumption, and the load imbalance. These power quality problems have a bad effect on not only the AC electrified railway systems but also other electric systems connected together. Therefore, a power quality compensator is required in the AC electrified railway systems. In this paper, the RPQC for improving power quality in the AC electrified railway systems is evaluated through the case study. Also a novel control algorithm based on the SRF is proposed. The simulation results illustrate that the proposed RPQC control algorithm can properly compensate the harmonic currents, the reactive power demand, and the load imbalance.

Acknowledgements

This work is the outcome of a Manpower Development Program for Energy & Resources supported by the Ministry of Knowledge and Economy (MKE)

References


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