Research on a novel power quality conditioner with PV for electrified railway

Q Wang¹, C Z Zhang¹,² and Y H Shu¹

¹Hubei Key Laboratory for High-efficiency Utilization of Solar Energy and Operation Control of Energy Storage System, Hubei University of Technology, Wuhan 430068, China

E-mail: longmarch_zhang@163.com

Abstract. With the fast development of electric railway, harmonics and reactive power problems caused by electric locomotive load remains to be further improved. This paper presents a novel power quality conditioner based on multiple H-bridges with photovoltaic power. The proposed structure utilizes a hybrid cascaded 81-level converter in series with a PWM converter to achieve a high-voltage and large-capacity power quality conditioner, and photovoltaic power connects with the DC bus side of the hybrid cascaded 81-level converter to reduce active consumption for electric railway. The fundamental voltage of the hybrid cascaded 81-level converter is controlled by the traction network. The active component of the PWM converter output current is controlled by DC link voltage of the hybrid cascaded 81-level converter, and its reactive and harmonic components are controlled by reactive and harmonic currents from the load. The system structure, working principle and control method of the novel power quality regulator are analysed. A single-phase traction system simulation model is built in MATLAB/Simulink. Simulation results are presented to verify the feasibility and effectiveness of the proposed PQC.

1. Introduction
Railway transportation industry plays an important role in promoting the development of national economy. In recent years, electrified railway system has been greatly developed due to its strong transportation capacity, high-speed, small impact from natural conditions and high safety coefficient [1,2]. However, the electrified traction power supply system works in the power supply mode of single-phase power frequency AC, and electric locomotive has the special load characteristics, which can not only result in power quality problems, such as voltage fluctuation, harmonics, and reactive power in traction power system, but also cause the transformer to overheat and instrument failure. Moreover, it can threaten the safety and stable operation of the power grid through the injection of public network through traction substation [3,4]. Therefore, it is of important significance to govern the electric power quality of electrified railway, especially in the high-speed electrified railway.

Up to now, the solutions for improving the power quality of traction power supply system for electrified railway emerge in endlessly, mainly including optimizing power supply systems and adding compensation devices [5,6]. The latter is the dominant trend. In the early period, passive compensators were installed on locomotives. But this method can only filter out harmonics within a certain frequency range. In addition, it is affected by system impedance, and exists a danger of harmonic amplification and resonance [7,8]. Hence, later research focuses on various types of active
compensator, containing hybrid active filters [9], railway power conditioner (RPC) based on multiple technique and multi-level technology [10-13]. In [14], the study introduced a hybrid cascade 27-level converter to achieve higher voltage level power quality regulation. However, for a 27.5 kV power system, the DC side consumes too much energy and the switching device need high withstand voltage. In [15], usage of a transformer reduces the voltage level of compensation system’s main circuit, but since it is difficult for high-power and high-voltage transformer to obtain precise high-frequency characteristics, high-frequency response of harmonic compensation performs poor. Afterwards, a power quality compensation system combining a three-phase voltage source converter (VSC) with a thyristor switched capacitor (TSC) was proposed in [16] to reduce VSC capacity. There are two sets of TSC to compensate most non-functional amount, while VSC compensates harmonics, negative sequence and residual reactive power component. In [17], the static var compensator (SVC) completes most of the reactive power compensation, and the RPC compensates for the rest of reactive power, harmonics and transfers active power, which aim for reducing the active part capacity. To further optimize compensation capacity and improve compensation performance, flexible dc voltage control was used in railway hybrid power quality conditioner [18]. However, these hybrid topologies are complicated. The study in [19] proposed a RPC based on half-bridge converter. Compared with the traditional RPC, the structure is simple and the number of power switching tube can be reduced by half, but the increase of capacitors’ number can lead to voltage-balancing problem and the control is more complicated. Moreover, a new high-speed railway compensation system with the structure of full-bridge multilevel can eliminate the DC bus capacitance and can be directly applied to the negative sequence compensation of the Scott transformer traction power supply system [20]. However, it needs extra control to suppress circulating current. In [21], modular multilevel converters for the V/V and SCOTT traction systems also have the circulation problem to solve.

Considering that traditional H-bridge power compensators are difficult to adapt to the traction network voltage and capacity levels, this paper presents a novel Power Quality Conditioner (PQC), which consists of a hybrid cascade of 81 level converters, a PWM converter and photovoltaic power. The cascaded 81-level converter is equivalent to a controlled voltage source, and undertakes the main power of the system. The PWM converter is equivalent to a controlled current source, which withstands low voltage. The voltage source is in series with the current source to achieve photovoltaic power generation and power quality regulation. First, this paper analyzes the system structure and working principle of the new type of PQC, and then studies the command signal operation method and the current tracking control method. Finally, the simulation confirms that the novel PQC can not only improve the power quality of the electrified railway power supply system, but also contribute to the promotion of large-capacity photovoltaic integration capacity, and help the energy saving and consumption reduction of the electrified railway system.

2. System structure and working principle

2.1. The topology structure of the novel PQC

Figure 1 shows the novel PQC topology of electrified railways. The effective value of the traction network voltage is 27.5 kV. $i_0$, $i_1$, and $i_r$ are traction bus current, load current and compensation current of the novel PQC, respectively. $U_{dc}$ is the DC side voltage of the voltage source, and $U_d$ is DC side voltage of the current source. The voltage source is a hybrid cascaded 81-level converter. Its four H-bridges share the same DC bus and generate 81 levels through transformers with a ratio of 1:3:9:27. The DC bus is connected with PV units. Photovoltaic arrays use a triple boost converter to achieve maximum power point tracking. The current source is a PWM converter, and it can realize power quality adjustment of 27.5 kV electrified railway system in a low-voltage environment.

Figure 2 depicts the equivalent circuit of PQC. The voltage source is equivalent to a structure, which contains a controlled voltage source $U_2$ in series with an inductor L. L is the sum of the short circuit impedance of the voltage source transformer. The current source part can be equivalent to a controlled current source $i_r$, and the electric locomotive load part is equivalent to a current source $i_k$. 
Figure 1. Topology of the novel railway power quality conditioner.

Under the steady-state condition, the fundamental component of the output voltage of the voltage source is the same as that of the traction network, so the main power of the system is supported by the voltage source, and because the switch frequency of the voltage source is very low, the active power loss is low in the process of power conversion. Furthermore, the current source works in low voltage environment, and the switching frequency of the device is high, which can improve the dynamic characteristics of the current tracking control. Due to the small power capability of the current source, the total active power loss of the new type of PQC power conversion is relatively small. Consequently, the novel PQC can reduce the active power loss, accelerate the dynamic response of the compensation system in the application of the electrified railway and improve the permeability of the photovoltaic system in the railway system.
The working mechanism of hybrid cascade 81 level converter

The voltage source of the novel PQC is composed of a hybrid cascade 81-level converter and transformers, and the specific structure is that the four H-bridge AC sides are cascaded by transformers of different transformation ratios. The transformation ratio of the four transformers from top to bottom is \(1: k, 1: 3k, 1: 9k\) and \(1: 27k\) (\(k\) is the transformer ratio factor). After the H-bridge is cascaded through the transformer, an 81-level voltage can be generated by the appropriate modulation strategy. All the levels are shown in Table 1.

Table 1. 81 levels of hybrid cascade multilevel converter.

| Synthetic level | 1 level | 3 level | 9 level | 27 level | Synthetic level | 1 level | 3 level | 9 level | 27 level |
|-----------------|---------|---------|---------|----------|-----------------|---------|---------|---------|----------|
| -40             | -1      | -1      | -1      | -1       | 5               | -1      | -1      | 1       | 0        |
| -39             | 0       | -1      | -1      | -1       | 6               | 0       | -1      | 1       | 0        |
| -38             | 1       | -1      | -1      | -1       | 7               | 1       | -1      | 1       | 0        |
| -37             | -1      | 0       | -1      | -1       | 8               | -1      | 0       | 1       | 0        |
| -36             | 0       | 0       | -1      | -1       | 9               | 0       | 0       | 1       | 0        |
| :               | :       | :       | :       | :         | :               | :       | :       | :       | :        |
| 0               | 0       | 0       | 0       | 0         | 36              | 0       | 0       | 1       | 1        |
| 1               | 1       | 0       | 0       | 0         | 37              | 1       | 0       | 1       | 1        |
| 2               | -1      | 1       | 0       | 0         | 38              | -1      | 1       | 1       | 1        |
| 3               | 0       | 1       | 0       | 0         | 39              | 0       | 1       | 1       | 1        |
| 4               | 1       | 1       | 0       | 0         | 40              | 1       | 1       | 1       | 1        |

By the generation method of 81-level voltage in Table 1, the fundamental voltage \(U_2\) of the voltage source can be closer to the fundamental voltage of the traction network by calculating the pulse sequence. Figure 3 shows the voltage waveform of the voltage source output and the grid voltage. Since the grid voltage \(u_s\) passes through the middle point of each step of the 81-level voltage \(U_2\) and the voltage value of each step is \(U_{dc}\), the amplitude of the grid voltage is \(40.5kU_{dc}\). The mathematical relationship between the fundamental amplitude value \(U_m\) of the output voltage and the DC side bus voltage \(U_{dc}\) of the voltage source is as follows:

\[
U_m = 40.5kU_{dc} \tag{1}
\]

Figure 3. Voltage waveform of 81-level and grid-side.

In the electrified railway single-phase traction network, the traction bus has a rated voltage of 27.5 kV. Due to the fluctuation of locomotive load, the effective value \(U_s\) of the traction network voltage is also undulate, and its variation range is 20 kV~29 kV. If \(U_m\) and \(k\) are given, the real-time required
value of the dc bus voltage $U_{dc}$ in the voltage source can be derived from equation (1).

According to figure 3, a cycle of the single-phase AC voltage of the traction network is divided into 162 time points. Due to the symmetry of time, only switching times in a quarter of a cycle need to be calculated, and the switching time of one cycle can be deduced as:

\[
\alpha_i = \begin{cases} 
0 & i=0 \\
\frac{1}{2\pi} \sin^{-1} \left( \frac{2i-1}{81} \right) & i = 1,2,...,40 \\
0.5 - \alpha_{i_1} & i = 41,42,...,80 \\
0.5 + \alpha_{i_2} & i = 81,82,...,120 \\
1 - \alpha_{i_3} & i = 121,122,...,160 \\
1 & i=161 
\end{cases}
\]

where $T$ is cycle, $\alpha_i$ is cycle ratio, $t_{i+1}$ is switching time of a cycle.

**Figure 4.** Output voltage waveforms of each H-bridge.

By setting the dwell time of each step, a nearly sinusoidal voltage waveform can be obtained. Supposing that $k$ is 2/3 in equation (1), figure 4 shows output voltage waveform of each H-bridge of voltage source in a cycle. As can be seen from figure 4, the output voltage frequency of every H-bridges converter side of the voltage source through the transformer is different. When the voltage of traction network acts as the modulation fundamental wave, the output frequency of the H$_5$-bridge is 50 Hz. Other output voltage frequencies are less than 900 Hz. Through Fourier analysis, fundamental voltage amplitudes of H$_2$, H$_3$, H$_4$ and H$_5$ are 235.8 V, 1.222 kV, 6.253 kV and 31.112 kV, respectively.
In consequence, the power percentages of four transformers are 0.6%, 3.1%, 16.6% and 79.7%. Because the AC side transformer of H4-bridge bears the largest proportion of the power, but the switching frequency is only the power frequency, there is less power loss in voltage source.

2.3. PWM converter working mechanism
The current source of the PQC is a PWM converter, whose structure is the same as conventional parallel APF. On the one hand, it tracks the command current and generates a current with same amplitude but opposite phase in comparison with the harmonic and reactive components of the load current to inject into the traction network. On the other hand, usage of the active component of its output current controls the DC bus voltage of the voltage source to remain stable.

The AC voltage of conventional APF is the traction network voltage, while the AC side of the current source of the novel PQC withstands the voltage difference between the traction network voltage and the 81-level output voltage of the voltage source. The peak value is only $kU_{dc}$. When the voltage $U_2$ of the voltage source output is close to the fundamental voltage of the traction network, the voltage amplitude on the AC side of the current source is very low. Therefore, the DC bus voltage requirement of the current source is also very low. The current source operates in a low-voltage environment. In this way, the switching frequency of the current source can be enhanced without increasing the power loss greatly, so the PQC has good dynamic characteristics when applied to a high voltage distribution network.

3. Control strategy of the novel power quality conditioner
The overall control block diagram of the PQC is shown in figure 5. During the soft-start stage, the voltage source and current source DC bus capacitors are charged through a pre-charge circuit. After completing the pre-charging, the normal operating mode starts and the photovoltaic power supply is switched on. By adjusting the current source active current to achieve a stable control of the voltage source DC bus voltage. The system uses a double closed-loop control strategy based on voltage loops and current loops. The current source mainly includes reference current calculation, current inner loop tracking control, and SPWM modulation based on triangular carrier comparison. In addition to the pulse timing calculations given in the previous section, the voltage source section relies on the voltage outer loop to keep the DC-side voltage stable.

![Figure 5. Control block diagram of the PQC.](image-url)

3.1. Single-phase harmonic and reactive current detection method
In a single-phase system, detection methods for the reference current are mainly divided into time domain and frequency domain detection. The system is based on time-domain detection and uses single-phase instantaneous reactive power theory to separate harmonic and reactive components. The specific methods are as follows:

Assuming that traction voltage is not distorted, traction voltage $u_s$ can be expressed as:

$$u_s(t) = U_s \cos \omega t$$  \hspace{1cm} (4)

where $U_s$ is the effective value of the traction network voltage, $\omega$ is angle frequency.

By means of Fourier series decomposition, traction current containing harmonic component can be modeled as:

$$i_L(t) = \sum_{n=1}^{\infty} \sin(n\omega t - \phi_n) = I_p \sin \omega t \cos \phi_1 + I_q \cos \omega t \sin \phi_1 + \sum_{n=2}^{\infty} I_n \sin(n\omega t - \phi_n)$$  \hspace{1cm} (5)

where $\phi_n$ is phase angle, $I_n$ is current amplitude.

For convenience of the analysis, $I_1 \cos \phi_1$ is replaced by $I_p$, and $I_q \cos \phi_1$. Thus,

$$i_L(t) = I_p \sin \omega t + I_q \cos \omega t + \sum_{n=2}^{\infty} \sin(n\omega t - \phi_n)$$  \hspace{1cm} (6)

When $(t-T/4)$ instead of $t$, $i_L'$ is given in

$$i_L'(t) = -I_p \cos \omega t + I_q \sin \omega t - \sum_{n=2}^{\infty} \cos(n\omega t - \phi_n)$$  \hspace{1cm} (7)

Based on equations (6) and (7), the error value is as follows

$$i_L(t) \sin \omega t - i_L'(t) \cos \omega t = I_p + \sum_{n=3}^{\infty} \cos(n\omega t - \phi_n)$$  \hspace{1cm} (8)

From equation (8), DC component $I_p$ can be obtained by using low-pass filter, whose cut-off frequency is less than three times of fundamental frequency. So the fundamental active current is

$$i_p(t) = I_p \sin \omega t$$  \hspace{1cm} (9)

Besides, harmonic and reactive current is calculated

$$i_h(t) + i_q(t) = i_L(t) - i_p(t)$$  \hspace{1cm} (10)

Figure 6 shows the detection algorithm of harmonic and reactive current.

3.2. System control strategy

As is shown in figure 4, the novel PQC utilizes CPLD to generate the switching pulse signal of the voltage source according to the phase, frequency obtained by the phase-locked loop and equation (2).
By combining the voltage value of the traction network, the synchronization signal and equation (1), the reference value $U_{dc}^*$ of the DC bus voltage in the voltage source can be calculated.

Outer voltage loop maintains the DC side voltage constant. By comparing $U_{dc}^*$ with the feedback value $U_{dc}$, the error signal is handled by the PI regulator. Hence, the current source fundamental active current amplitude $i_d^*$ is obtained, and then multiplies by the synchronization signal to get the reference value $i_{DG}^*$ of the current source fundamental active current.

Current inner loop control achieves command current tracking. The reference current generated by the harmonic and reactive power detection link is added to the reference value of the fundamental active current to obtain the command current. The error between the command current and the current feedback value of the grid-connected current in the current source is controlled by the PI regulator to obtain the modulated wave signal, and then use the SPWM modulation to obtain the switching pulse signal of the current source. Finally, the turn-on and turn off of the switching device is controlled via the driving protection circuit.

4. Simulation and results analysis

![Simulation model of 27.5 kV electrified railway traction network power supply system.](image)

**Figure 7.** Simulation model of 27.5 kV electrified railway traction network power supply system.

**Table 2.** Main parameters of simulation.

| Parameter                          | Value          |
|------------------------------------|----------------|
| System capacity                    | 10 MVA         |
| AC voltage in traction net         | 27.5 kV        |
| Transformation ratio in H2 bridge side | 3:2           |
| Transformation ratio in H3 bridge side | 1:2           |
| Transformation ratio in H4 bridge side | 1:6           |
| Transformation ratio in H5 bridge side | 1:18          |
| $U_{dc}^*$                          | 1440 V         |
| Capacity of PV system              | 3 MW           |
In order to validate the correctness and effectiveness of the new scheme, a simulation model for the 27.5 kV electrified railway traction network power supply system is established in MATLAB/Simulink, as shown in figure 7. The main simulation parameters are given in table 2. Simulations are implemented under different working conditions, including before and after the addition of the new PQC and photovoltaic power.

Figure 8 shows the voltage waveform and FFT analysis of the voltage source of the novel PQC. It can be seen that the voltage fundamental amplitude is 38.8 kV and the waveform distortion rate is 1.03%. The output voltage waveform of the voltage source is basically consistent with the voltage waveform of the power grid. Therefore, the current source withstands a relatively small voltage, ensuring that the current source operates in a low-voltage environment.

![Voltage waveform and FFT analysis of the voltage source](image)

Figure 8. Simulation results of the voltage source: (a) voltage waveform of the 81-level, (b) FFT analysis of the voltage source.

Figure 9 displays the power factor change curve for different operating conditions, and table 3 provides the results of FFT analysis of the grid-side currents before compensation, after compensation, as well as after the addition of photovoltaic. It is known from the above charts that grid-side current distortion is up to 8.65%, and the power factor is only about 0.89 before the compensation device is put into operation. Adding the new PQC at 0.2 seconds, the total harmonic distortion rate of grid-side current drops to 2.04%, and the power factor increased to 0.99. The power quality of the system is greatly improved and complies with the national power quality standards. When photovoltaic power is added at 0.4 seconds, the photovoltaic power supply provides some active power to the electric locomotive. This causes that the fundamental wave amplitude of the grid-side current is greatly reduced from 307.7A to 150.7A. The total harmonic distortion rate remains below 3%, and the factor of the traction network is close to 1. It indicates that the PQC has good compensation ability for the grid current.
**Figure 9.** Power factor curve under different working conditions.

**Table 3.** Fundamental amplitude and THD of grid-side current.

| Different working conditions | Net side current amplitude | Net side current THD | Net side power factor |
|-----------------------------|----------------------------|----------------------|-----------------------|
| Before compensation         | 343 A                      | 8.65%                | 0.89                  |
| After compensation          | 307.7 A                    | 2.04%                | 0.99                  |
| After adding photovoltaic   | 150.7 A                    | 1.64%                | 0.99                  |

**Figure 10.** Grid-side Current and voltage waveforms without and with compensation.

**Figure 11.** Grid-side current and voltage waveforms before and after adding PV.

Figure 10 shows the simulation waveforms of voltage and current on the grid-side before and after compensation. To see the phase difference visually, voltage value is decreased to 1/100. From figure 10, the distortion of grid current is obvious and its lag is behind the voltage before compensation. The current waveform on the grid side is significantly improved after adding the new PQC at 0.2 seconds, and tends to be steady within one period. Figure 11 shows the simulation waveforms of the voltage.
and current on the grid side before and after putting the PV power supply into the system. The photovoltaic system enters a new steady state within 1.5 cycles after adding PV power supply at 0.4 seconds, indicating that the system has good dynamic response characteristics.

5. Conclusion
A new type of power quality regulator with photovoltaic power has been presented in this paper. The system is composed of a hybrid cascaded 81-level converter, a PWM converter and photovoltaic power. The DC side is connected by a triple boost converter with a PV array, and the DC voltage fluctuation is very small. Hybrid cascaded 81-level inverter operates at low switching frequency, which undertakes main power of system. The PWM converter works in high frequency and low voltage environment in series with voltage source to realize the regulation of power quality of the system.

The simulation model of PQC with PV generation system has been built in Matlab/Simulink, and the results show that the new PQC performs very well in suppressing harmonic and compensating reactive power and has fast dynamic response. The input of photovoltaic power supply is propitious to further optimize the power quality of traction network, and promotes the development of photovoltaic industry. Meanwhile, it has great significance for energy saving and emission reduction of electrified railway system and the management of power quality of higher power grid.

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