Research on electrified railway power router based on 81 level conversion technology

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Abstract. On the premise of realizing the application of renewable energy power generation in traction power supply system, aimed at the problems of power scheduling and operation cost in the traction network of 27.5 kV electrified railway, a kind of electrified railway energy router device based on 81 level conversion technology is proposed. The device adopts 81 level converter to realize the high voltage, high power quality and high power demand of grid-connected converter for electrified railway energy supply system. The energy dispatching mode of voltage-phase angle is adopted to ensure the normal power supply of electric locomotive and the voltage support of traction network. At last, the bidirectional converter of the energy storage unit realizes peak cutting and valley filling of energy and ensures the stability of renewable energy generation. Based on the theoretical study of the topology, technical principle, energy scheduling calculation and control strategy of the new electrified railway power router, the device was simulated and verified, and the effectiveness of the electrified railway power router technical solution was verified.

1. Introduction
In the current development of China's railway operation, electrified railway has become the mainstream of development due to its characteristics of convenient power supply, high efficiency and low environmental pollution. However, as the electric locomotive belongs to the nonlinear load of high power resistance, it has not only a enormous demand for the power supply of the traction network, but also has a serious impact on the power quality of the traction network. Therefore, on the premise of saving energy and reducing operating costs, it is a hot research direction for the development of electrified railway to launch an energy device that can make the traction network of electrified railway match the operation of electric locomotive and create a high power quality power supply system.

The reference [1] back-to-back photovoltaic power generation systems can supplement the active power of the electrified railway and compensate the reactive power. However, due to the instability of distributed power generation, the energy supply of the device will be unstable and the system security will not be guaranteed. Therefore, it cannot be directly used in the electrified railway in practice, and it is necessary to add energy storage part to the system to ensure the normal operation of the traction network. As shown in the study of flywheel energy storage on peak cutting and valley filling of electrified railway in reference [2], adding the energy storage part can indeed improve the safety and stability of power generation. In reference [3], a new railway power regulator containing supercapacitor energy storage was proposed, which not only realized peak cutting and valley filling,
but also promoted the utilization rate of regenerative braking energy. However, its working mode is more complex and the experimental conditions are more stringent. In reference [4], on the premise of the back-to-back electrified railway power quality device as the basic topology, feedback and power grid working conditions are incorporated into the scope of power quality compensation, which not only solves the problem of low primary side power factor and power quality, but also avoids the high installation cost of energy storage device. However, the algorithm is complex and the dynamic performance needs to be improved. In order to improve the efficiency of the system, the selection of grid-connected converter is also diversified. When applied to high-power equipment such as electrified railways, multi-level converters such as diode clamp type [5], flying capacitor type [6] and H-bridge cascade type with DC power supply [7] have the advantages of low output voltage distortion rate and suitable for high voltage and high power places. However, the difficulties in potential balance, too many dc power supply and complex control algorithm are the main factors that limit the development and application of these traditional converters.

In electrified railway, reasonable energy control mode can not only peak cutting and valley filling for electrified railway traction network, but also improve the safety of traction network operation. The voltage-frequency droop control mentioned in reference [8] is not applicable in electrified railway due to the need to stabilize the power frequency in spite of the high flexibility of adjustment. The virtual flux control method designed in reference [9] effectively avoids the problems of traditional droop control in grid-connection frequency by adopting the flux - phase angle control strategy. But its complicated control mode and various parameter calculation make it difficult to popularize it. Reference [10] proposes a control method that can achieve accurate active power allocation and frequency recovery based on the study of voltage-frequency, but additional control should be added to the frequency recovery. It can be seen from the current researches on droop control that there are still some problems such as harmonics, large distortion rate and high loss. Although the theoretical research on droop control is relatively mature, further research is needed in the practical application such as electrified railway [11]. Therefore, for the application of electrified railway and other high-power applications, both the topological structure and control mode of new energy supply still need to be improved and adjusted.

In order to promote the application of renewable energy power generation in electrified railway power supply systems, realize the peaking and valley filling of energy, the voltage support of the traction network and the improvement of the traditional grid-connected converter are difficult to adapt to the traction network voltage and capacity level, and solve the problem of power quality and control’s complexity, this paper proposes a new type of electrified railway power router device. In this paper, the topological structure of the new power router device and the working mode of the 81 level converter are analyzed theoretically. Then, the power scheduling parameter calculation and the overall energy control strategy are studied. Finally, the effectiveness of the new power router is verified by matlab/simulink simulation.

2. Discussion
In the current development of electric locomotives in China, CRH series locomotives occupy a large proportion. When entering the station, the relevant parameters of different types of locomotives are shown in table 1. It can be concluded from the table that the electric locomotive has a higher energy supply level for the traction network, and the active power and reactive power required by different locomotives are different (in the case of CRH2 locomotive, the power factor is basically stable at 0.97), thus The difficulty of energy scheduling is further increased. Therefore, under the premise of meeting the power supply requirements of electric locomotives, it is of great significance to realize a green and safe electrified railway system.
Table 1. Related parameters of different types of locomotives.

| Type | CRH1 | CRH2 | CRH3 | CRH5 |
|------|------|------|------|------|
| Traction power (KW) | 5500 | 4800 | 8800 | 5500 |
| capacity of passengers served (person) | 670 | 610 | 601 | 604 |
| Operating speed (Km/h) | 200 | 200 | 330 | 200 |
| Power configuration | 2(2M+1T)+(1M+1T) | 4M+1T | 2(2M+1T) | (3M+1T)+(2M+2T) |

3. System structure

As shown in figure 1, the device’s main circuit topology is composed of distributed power converter (I), distributed energy storage converter (II), the dc bus capacitor (III) and the 81 level converter (IV). Device using distributed power converter as the main power supply of electrical energy router interfaces, distributed energy storage converter to achieve the peaking and valley filling of energy and dc bus capacitors realize filtering, dc bus voltage support and ac/dc power decoupling, and the 81 level converter is used to realize the high voltage, large capacity and high power quality output of the power router.

![Figure 1. Main circuit topology.](image)

4. Working principle of power router

4.1. Working principle of 81 level converter

The 81-level converter of the power router is composed of four sets of parallel h-bridge ac side
passing through the corresponding transformer, and then the four sets of transformers are connected to the grid side in series. The transformer ratio of the four sets of transformers is 1:1, 1:3, 1:9 and 1:27 from top to bottom. By controlling the on-off action time of H Bridges in each group, the 81 level combinations shown in table 2 can be obtained.

Table 2. 81 levels generating method.

| synthetic level | Level 1 | Level 3 | Level 9 | Level 27 |
|-----------------|---------|---------|---------|----------|
| -40             | -1      | -1      | -1      | -1       |
| -39             | 0       | -1      | -1      | -1       |
| :               | :       | :       | :       | :        |
| 0               | 0       | 0       | 0       | 0        |
| :               | :       | :       | :       | :        |
| 39              | 0       | 1       | 1       | 1        |
| 40              | 1       | 1       | 1       | 1        |

![Output voltage waveform of power router and 3 sets of transformers on the grid side.](image)

Figure 2. Output voltage waveform of power router and 3 sets of transformers on the grid side.

In a traction network frequency cycle shown in figure 2, in order to make the output voltage $U_{81}$ of the power router meet the quality standard of the power supply voltage of the traction network, the voltage of the traction network under ideal state $U_s$ can be divided into 81 parts, so that the sine wave
can be divided into 81*2 horizontal lines. Starting from the horizontal line passing through the origin, each two adjacent horizontal lines are made to intersect the vertical line of the traction grid voltage, and the vertical line that can be divided by the traction grid voltage is a stepped vertical line of 81-level voltage. By analogy, the ideal 81-level voltage waveform can be obtained. Combined with the level combination of Table 1, the corresponding four sets of H-bridge voltage waveforms can be derived. Assuming that the voltage of the dc bus capacitor is \( U_{dc} \), then the height of each lattice step is \( U_{dc} \). In Figure 2, the relationship between the output voltage \( U_{81} \) of the power router and the voltage \( U_{dc} \) of the dc bus capacitor can be expressed as:

\[
U_{81} = \frac{81U_{dc}}{2}
\]  

As shown in Figure 2, \( U_{81} \) has 162 stepped vertical lines in one power frequency cycle, which means that there are 162 different working switching moments. According to the symmetry principle of the sinusoidal function, it is only necessary to calculate the working time within 0.05 s, the switching time \( t_{i+1} \) (\( i = 0, 1, 2, ..., 161 \)) of the entire period can be derived as:

\[
t_{i+1} = \frac{T}{2} \alpha_i
\]

Combined with Table 1 and formula (2) and (3), the software operation of DSP+CPLD sets the action time of 16 IGBTs, so that the power router can output an 81-level voltage similar to a sine wave.

4.2. Power router power scheduling principle

Assuming that the 81-level converter output voltage and the grid-side voltage are \( U_{81} \angle \alpha_1 \), \( U_S \angle \alpha_2 \), respectively, the sum of the transformer short-circuit impedance and line impedance is \( X \). The active power and reactive power transmitted to the grid are \( P \) and \( Q \), respectively. The effective values of active current and reactive current are:

\[
I_a = \frac{P}{U_S}
\]

\[
I_s = \frac{Q}{U_S}
\]

Let \( \alpha = \alpha_1 - \alpha_2 \), so it can be approximately obtained that the active power and reactive power output of the power router to the traction network can be divided as:

\[
P \approx \frac{U_{81}U_S}{X} \sin \alpha
\]

\[
Q \approx \frac{U_{81}^2 - U_{81}U_S}{X} \cos \alpha
\]
(6) and (7), the active power is mainly regulated by the phase angle difference $\alpha$ between the voltage of 81 level converter and the traction net. The reactive power is mainly regulated by the voltage difference between the output voltage of the power router and the traction network, and for the energy storage function of the power router, The process is opposite to the above, the output power of the traction net is charged to the device through the bi-directional converter in the power router, thereby realizing the bidirectional flow of energy and the peak cutting and valley filling of the traction net.

The power router device realizes power scheduling by adjusting the voltage $U_{dc}$ across the dc bus $C_1$, and the phase angle difference $\alpha$ between the 81 level converter and the traction network. The scheduling mode is described below with reference to figure 3. From the figure, it can be seen that when the electric locomotive enters the station, the output voltage $U_{81}$ of the power router is increased by increasing $U_{dc}$, so that made it to be higher than the traction network voltage $U_s$, and the 81 level converter is scheduled at the same time. The sync pulse angle makes the output voltage phase lead the traction network voltage $U_s$. It can be seen that the power router would transmit active power and inductive reactive power to the traction network, which not only provides the required energy for the locomotive, but also compensates the reactive power of the locomotive load, and improves the power factor of the traction network. It can be seen from the b diagram that after the electric locomotive exits the station, the output voltage of the power router is reduced by reducing the $U_{dc}$, so that $U_{81}$ is smaller than $U_s$, then changing the synchronous pulse angle of the 81 level converter. The output voltage phase lags behind the traction network voltage $U_s$. It can be known that the active power emitted by the traction network will be transmitted to the electrical energy router to supplement the energy of the distributed energy storage unit and realize the peak cutting and valley filling of energy. At the same time, the electrical energy router can also compensate the reactive power of the traction network and realize the voltage support of the traction network.

![Diagram](image)

**Figure 3.** Power router power scheduling control principle.

5. **Power router power scheduling control strategy**

It can be seen from figure 4 that after calculating the output voltage and the synchronization pulse angle of the power router by the required power, firstly, using the proportional relationship between the dc bus voltage and $U_{81}$ (formula (1)), the dc bus voltage value to be scheduled at this time is calculated. The calculated value is set as the reference value $U_{dc^*}$. The modulated wave signal is obtained by the double closed-loop control of the dc bus voltage actual value $U_{dc}$ and the actual current value $i_d$ of the input energy storage bidirectional converter, and then the SPWM modulation method is used to form a pulse signal of the bidirectional DC/DC (or AC/DC) converter. In order to achieve the control of the dc bus voltage, Then, the calculated sync pulse angle is subtracted from the traction network voltage phase angle, and the obtained offset angle $\alpha$ is used as a reference value to control the output voltage phase of the 81 level converter through the phase shifting. Through the joint control to achieve the peak cutting and valley filling of energy and power scheduling in traction network.
6. Simulations
In order to verify the effectiveness of the power router in the field of electrified railway, this paper established a simulation model on the matlab/simulink simulation platform. Main simulation parameters are as follows: the distributed generation and distributed energy storage unit adopt the simulation modules of photovoltaic power generation and ultracapacitor respectively. The rated power generation capacity of the power generation unit is 2 MVA, and the output voltage of the energy storage unit is 600 V, assuming that the electric locomotive needs to dispatch active power and reactive power of 1 MW and 1 Mvar respectively from the power router, the rated power of the energy storage unit is set at 1.41 MVA, distributed energy storage converter adopts bidirectional Buck/Boost converter. The transformer ratio is 1:3:9:27 in turn. According to rated power, transformer short circuit impedance, traction network voltage and other parameters, the DC side voltage reference value of the power router when the power is supplied under the rated power state is 1023 V, and the phase angle difference $\alpha$ is 3.6°. When the power router stores energy under the rated power state, the dc side voltage reference value is 905 V, and the phase angle difference $\alpha$ is -2.2°. The IGBT switching frequency of the bidirectional DC/DC converter is 10 kHz.

6.1. Verification of corresponding output waveform when locomotive enters the station

![Figure 4. Block diagram of the control system.](image-url)
Figure 5. Output waveform of the power router in generation state. (a) waveform comparison, (b) output voltage distortion rate, (c) Active power and (d) reactive power.

After the locomotive enters the station, by dispatching the required power of electric locomotive, figure 5(a) is a comparison of the voltage waveforms of the power router and the traction network when the power router is supplied at the rated power. The FFT analysis is performed on the output voltage of the power router. In figure 5(b), it can be seen that the output step wave distortion rate is only 1%, which achieves the effect of delivering high-quality power for the traction network, and at the same time, through the output power measurement, it is also observed from the diagrams c and d that the device can basically reach the require of power scheduling, achieve the energy supply to the locomotive and the voltage support to the traction net.

6.2. Verification of corresponding output waveform when locomotive exits the station

After the locomotive exits the station, the power required by the power router can be scheduled when the traction network is under no load or the device is under generation deficiency. Figure 6(a) is a comparison of the voltage waveforms of the power router and the traction network during power scheduling when the power router is storing energy at rated power, it is also observed from the diagram b and c that the required scheduling power can be basically reached, achieves the peak cutting and valley filling of the energy and the reactive compensation of the traction net during no-load, and also ensures the stability of renewable energy generation.

It is verified by the above two sets of simulation waveforms that the new electrified railway power router can meet the needs of the electrified railway system and realize energy supply and voltage support while realizing the application of renewable energy power generation in the traction power supply system. It enables energy to flow in both directions, cut peaks and fill valleys, and ensure the stability of renewable energy generation and maximize energy utilization. However, the disadvantage lies in the voltage-phase angle-based control method adopted by comprehensive consideration. When performing power scheduling, the single parameter change will both affect the active power and the reactive power, at the same time, considering that the control parameters have not reached the optimal conditions, there still need some improvement in the dynamic performance of the system.
Figure 6. Output waveform of power router in energy storage state. (a) Output voltage waveform comparison, (b) Active power and (c) Reactive power.

7. Conclusions

- The 81-level converter part of the electrified railway power router can reduce the output step wave distortion rate to 1%. Compared with the multi-level converter used in the traditional electrified railway energizing device, when generating the same multi-level voltage, the new electrified railway router uses only four sets of H-bridges, and the cost is greatly reduced. Also the voltage and switching loss of the tube is reduced by 19.96% (for the switch tube with the maximum withstand voltage in the H-bridge).

- The new electric energy router can not only solve the problem of energy supply and voltage support of the traditional renewable energy power supply system in the electrified railway (it can provide active power and reactive power of 1 MW and 1 Mvar respectively), but also ensure the stability of renewable energy power generation by peak cutting and valley filling of the traction network.
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