Transport and Communications Science Journal, Vol 77 Issue 7(09/2026), 1015-1023

**Transport and Communications Science Journal**

# DIRECT CURRENT CONTROL METHOD FOR SINGLE-PHASE TWO-LEVEL PWM RECTIFIERS ON HIGH-SPEED RAILWAY VEHICLES

**Pham Van Tien*, Mai Van Tham**

University of Transport and Communications, No. 3 Cau Giay Street, Hanoi City, Vietnam

ARTICLE INFO

TYPE: Research Article
Received: 23/11/2025
Revised: 26/05/2026
Accepted: 28/05/2026
Published online: 15/09/2026
https://doi.org/10.47869/tcsj.77.7.10
* *Corresponding author*
Email: vantienpham@utc.edu.vn; Tel: 0978319258 (optional)

**Abstract.** In high-speed railway traction drive systems, the deployment of Pulse Width Modulation (PWM) rectifiers represents an effective solution for mitigating harmonic pollution on the AC supply network, enhancing the power factor, and achieving energy efficiency due to the capability for seamless energy conversion between traction and regenerative braking modes. This paper investigates an instantaneous direct current control method combined with the Sinusoidal Pulse Width Modulation (SPWM) technique applied to single-phase two-level PWM rectifiers. This control method utilizes input AC current feedback to generate modulation signals, thereby offering the advantage of superior dynamic response. Furthermore, the control algorithm is simple to implement, and the DC output voltage is relatively smooth. Theoretical analysis and simulation results have validated the efficacy of utilizing active rectification, as well as the accuracy of the modulation technique and the applied control method. Based on the synthesis and systematization of relevant international literature, this paper constructs a general mathematical model of the control method and develops a simulation model to validate the theoretical foundation. Analytical and simulation results indicate that the PWM rectifier well satisfies the specified control requirements, concurrently confirming the effectiveness of the modulation technique and the applied control method. This research contributes an additional reference foundation for the research and application of high-speed rolling stock in Vietnam.

**Keywords:** PWM rectifier; Direct current control strategy; SPWM technique; AC traction drive system; High-speed railway vehicles.

## 1. INTRODUCTION

Currently, AC-DC-AC traction drive systems are predominantly employed in high-speed railway vehicles worldwide. The converter circuit topologies within these systems are primarily categorized into two types: two-level and three-level structures, with the two-level topology being the most widely adopted [1-4]. The line-side converter utilizes a Pulse Width Modulation rectifier, which draws power from the secondary winding of the traction transformer. The single-phase AC voltage from the secondary winding is converted into DC voltage by the rectifier; subsequently, a stable DC link voltage is achieved through filtering and energy storage elements. By employing PWM techniques, the phase angle of the input current drawn from the grid can be regulated, ensuring the current waveform approximates an ideal sinusoid. Simultaneously, across a relatively wide load variation range, the rectifier's power factor can be maintained close to unity. Consequently, the grid supplies only active power, thereby minimizing harmonic interference with communication signals and optimizing the utilization of the grid's transmission capacity. PWM rectifiers facilitate seamless energy conversion between traction and braking modes. Therefore, in high-power traction drive systems, the deployment of PWM rectifiers is of significant importance for energy efficiency [1,5,6].

Modulation techniques for PWM rectifiers primarily include hysteresis modulation (also known as sliding mode control), Sinusoidal Pulse Width Modulation (SPWM), and Space Vector Pulse Width Modulation (SVPWM). In railway traction drive systems, SPWM and SVPWM are widely employed. The hysteresis modulation technique is characterized by a variable switching frequency of the control devices, which limits the frequency utilization of the conducting valves and complicates filter design; consequently, it is not utilized [1,7].

Conventional PWM rectifiers employ a dual-loop control strategy, combining an outer DC voltage loop and an inner current loop. Common current control methods include indirect current control, instantaneous direct current control, and predictive direct current control. Among these, the instantaneous direct current control method is widely adopted for regulating PWM rectifiers in the traction drive systems of electric locomotives and high-speed train power cars [1,5,6].

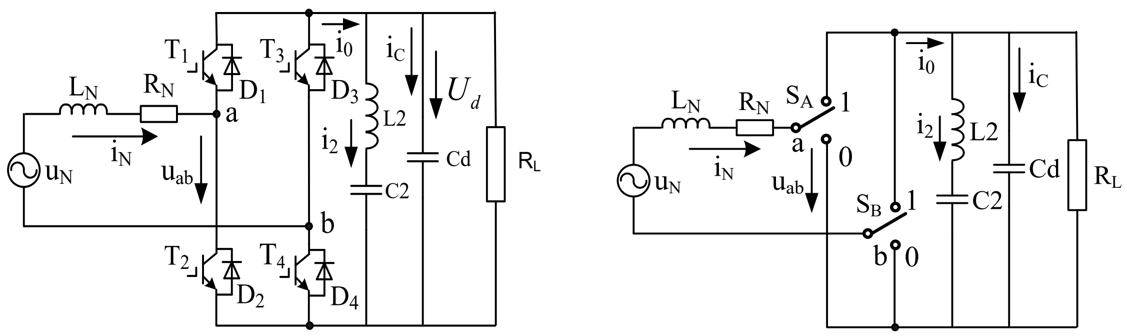
Due to objective conditions, high-speed railways have not yet been established in Vietnam. Traction systems on motive power operating on the national railway or urban railways, where present, predominantly utilize uncontrolled rectifiers rather than PWM rectifier technology [8, 9]. Several domestic research works related to PWM rectifiers include studies on regenerative braking energy recovery in urban railway operations using three-phase PWM rectifiers [10, 11], predictive control algorithms for three-phase three-level T-type PWM rectifiers [12], and sliding mode control of the current loop for single-phase PWM rectifiers [13]. In addition, there is also research on the modeling of high-speed rolling stock [14]. However, these studies have not specifically addressed PWM rectifiers for traction drive applications in railway vehicles. Currently, the North-South High-Speed Railway Project is currently being accelerated by the Government. Studies and reports have proposed selecting a power supply technology using 1x25kV AC or 2x25kV AC at 50Hz frequency, with a traction system employing VVVF-controlled induction motors [15,16]. Consequently, the proposed railway vehicles would utilize an AC-DC-AC traction drive system configuration.

From the above analyses, it can be seen that international literature has analyzed the control principles, modulation techniques, and operating characteristics of PWM rectifiers on electric rolling stock. However, there are currently no domestic studies that systematically present the theoretical foundation as well as validate this structure through simulation. In this paper, the authors synthesize the theoretical foundation from international studies, develop a simulation model, and evaluate the operating characteristics of the system, aiming to serve the research and application orientation for the high-speed railway sector in Vietnam.

## 2. MODULATION AND CONTROL TECHNIQUES FOR PWM RECTIFIERS

### 2.1. Operating principle of the Two-Level PWM rectifier

The main circuit configuration of a single-phase two-level voltage source PWM rectifier is illustrated in Fig. 1. In this schematic, $L_N$ and $R_N$ denote the leakage inductance and the secondary winding resistance of the traction transformer, respectively. The switches $T_1$, $T_2$, $T_3$ and $T_4$ constitute a single-phase fully controlled bridge rectifier circuit. The DC circuit comprises a second-order harmonic filter $L_2C_2$ and a support capacitor $C_d$. With the neutral point ($U_d/2$) of the output DC voltage serving as the reference, the voltage at point (a) or (b) relative to this neutral point can assume one of two discrete levels; for instance, when $T_1$ conducts, the value is $U_d/2$, whereas when $T_2$ conducts, the value is - $U_d/2$. Consequently, this topology is designated as a two-level PWM rectifier.




(a) Main circuit. (b) Equivalent switching circuit.

Figure 1. Circuit configuration of the two-level PWM rectifier.

To facilitate the analysis, the ideal switching functions $S_A$ and $S_B$ are defined as expressed in eq. (1) and (2), wherein 'ON' indicates that the corresponding switches are in the conducting state. By employing these ideal switching functions, the main circuit of the two-level PWM rectifier illustrated in Fig. 1(a) can be represented by the equivalent circuit shown in Fig. 1(b).

$$S_A = \begin{cases} 1 & T_1 \; or \; D_1 \quad ON \\ 0 & T_2 \; or \; D_2 \quad ON \end{cases} \tag{1}$$

$$S_B = \begin{cases} 1 & T_3 \; or \; D_3 \quad ON \\ 0 & T_4 \; or \; D_4 \quad ON \end{cases} \tag{2}$$

In each bridge leg, simultaneous conduction of the upper and lower control switches is prohibited; consequently, the switching signals for the upper and lower devices must be complementary. The rectifier input voltage $u_{ab}$, assumes three discrete levels: $U_d$, 0, and -$U_d$. This implies that the source current is either transferred to the DC circuit ($I_d = i_N$), thereby linking the DC voltage to the AC side ($u_{ab} = \pm U_d$), or the AC source is short-circuited through the switching network ($I_d = 0$), resulting in a zero input AC voltage (modulated voltage) at the rectifier ($u_{ab} = 0$). Four combinations of switching functions can be generated: $S_AS_B = 00, 01, 10, 11$. The modulated voltage can be expressed as shown in eq. (3).

$$u_{ab} = (S_A - S_b)U_d \tag{3}$$

Based on eq. (3), the equivalent circuit of the two-level PWM rectifier is derived as illustrated in Fig. 2. The voltage balance equation for this circuit is expressed as eq. (4).

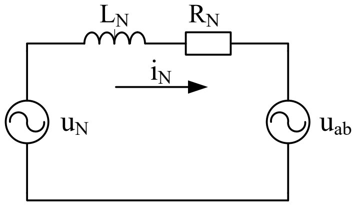



Figure 2. Equivalent circuit of the two-level PWM rectifier.

$$\boldsymbol{u}_N = L_N \frac{d\boldsymbol{i}_N}{dt} + R_N \boldsymbol{i}_N + \boldsymbol{u}_{ab} \tag{4}$$

As illustrated in Fig. 2, by appropriately adjusting the amplitude and phase of $u_{ab}$ through various control methods, the phase of the input current can be controlled to regulate the power factor and the direction of power transmission. Simultaneously, controlling the magnitude of the input current allows for the regulation of the energy transferred to the converter, thereby controlling the DC-side output voltage. Consequently, a dual-closed-loop control strategy is typically employed, combining an outer voltage loop and an inner current loop.

## 2.2. Sinusoidal pulse width modulation (SPWM) technique

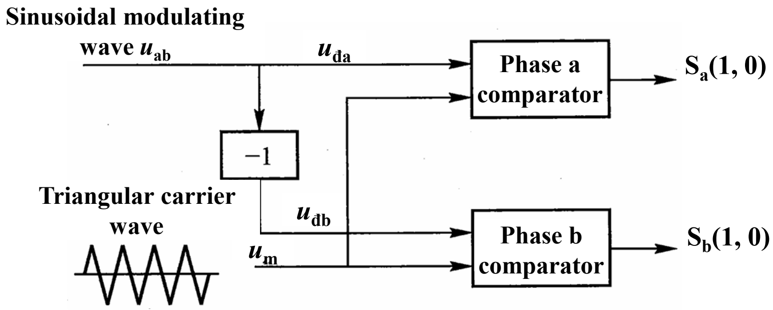



Figure 3. Diagram of unipolar SPWM for the two-level PWM rectifier.

In the SPWM technique, a sinusoidal modulating wave (reference wave) is compared with a triangular carrier wave to generate control signals for the semiconductor switches. Based on the polarity of the control signal pulses, SPWM is categorized into unipolar and bipolar modulation. Due to the issue of relatively large step changes in the output voltage associated with bipolar modulation, it is infrequently utilized for converter modulation in electric traction drive systems [1]. The implementation method of the unipolar SPWM technique for a two-level PWM rectifier is illustrated in Fig. 3. In this figure, $u_{ab}$ represents the effective modulating voltage; $u_{da}$ is the modulating wave for leg a (containing switches $T_1$ and $T_2$); $u_{db}$ is the modulating wave for leg b (containing switches $T_3$ and $T_4$); $u_{da}$ and $u_{db}$ are phase-shifted by $180^0$ relative to each other; and $u_m$ is the triangular carrier wave. The modulation is performed according to the principle that for leg a, when $u_{da} > u_m$, the switching function $S_A = 1$, otherwise it is 0; a similar logic applies to leg b.

### 2.3. Control method of the two-level PWM rectifier

International references [1, 5, 6] have analyzed the control principle of the two-level PWM rectifier; however, the presented mathematical models regarding the control method are still inconsistent. Therefore, in this section, this paper synthesizes the aforementioned references to develop a generalized mathematical model for the control method.

Based on whether the instantaneous inductor current $i_N$ is directly utilized to generate the modulating signal (modulating wave) $u_{ab}$, control methods are categorized into two types: indirect current control and direct current control.

The indirect current control method, also known as amplitude-phase control, is mathematically expressed as shown in eq. (5).

$$\begin{cases} I^*_{Nm} = K_{pu}(U^*_{d\_ref} - U_d) + \dfrac{1}{T_{iu}}\displaystyle\int (U^*_{d\_ref} - U_d)dt \\ u_{ab} = u_N - I^*_{Nm} R_N \sin\omega t - \omega L_N I^*_{Nm} \cos\omega t \end{cases} \tag{5}$$

Where: $K_{pu}$ and $T_{iu}$ denote the proportional gain and the integral time constant of the voltage loop PI controller, respectively; $U^*_{d\_ref}$ represents the reference DC output voltage; $I^*_{Nm}$ indicates the reference input AC source current; and $\omega$ is the angular frequency of the source voltage.

The direct current control strategy bears similarities to the indirect current control method; the primary distinction lies in the fact that the source-side current feedback is directly incorporated into the modulating voltage signal $u_{ab}$, hence it is designated as direct current control. This category encompasses the instantaneous direct current control method and the predictive direct current control method.

The mathematical formulation of the instantaneous direct current control method is presented in eq. (6).

$$\begin{cases} I^*_{Nm1} = K_{pu}(U^*_{d\_ref} - U_d) + \dfrac{1}{T_{iu}}\displaystyle\int (U^*_{d\_ref} - U_d)dt \\ I^*_{Nm2} = \dfrac{2 I_d U_d}{U_{Nm}} \\ I^*_{Nm} = I^*_{Nm1} + I^*_{Nm2} \\ u_{ab} = u_N - (I^*_{Nm} R_N \sin\omega t + \omega L_N I^*_{Nm} \cos\omega t) - K_{pi}(I^*_{Nm} \sin\omega t - i_N) \end{cases} \tag{6}$$

Where: $K_{pi}$ denotes the proportional gain of the proportional controller within the current control loop; and $U_{Nm}$ represents the amplitude of the input AC source voltage.

To alleviate the load on the intermediate DC-link voltage PI controller and improve the dynamic response of the PI regulator, the intermediate DC-link current $I_d$ is utilized to calculate the amplitude of the input AC source current component $I^*_{Nm2}$. The sum of this component and the component $I^*_{Nm1}$ constitutes the reference current amplitude of the input AC source, denoted as $I^*_{Nm}$.

Comparing eq. (5) and eq. (6), it is evident that the direct current control method necessitates feedback of the input AC source current $i_N$. The modulating voltage signal $u_{ab}$ incorporates an additional component $K_{pi}(I^*_{Nm}\sin\omega t - i_N)$, consequently, this method offers the advantages of superior dynamic response and rapid regulation in the presence of system parameter variations.

Regarding the predictive direct current control method, due to the current sampling period and the inherent PWM control delay, a lag phenomenon exists in the current control of the PWM rectifier. This adversely affects the dynamic performance of the current tracking control. Since the minimum delay in current control corresponds to at least one PWM switching period, the fundamental concept of predictive current control is to ensure that the actual input AC source current equals the reference current after one PWM switching period. Specifically, within any given PWM switching period ($t_k$, $t_k + T_s$), the current must satisfy eq. (7).

$$i_N(t_k + T_s) = i_N^*(t_k) \tag{7}$$

Within a switching period $T$s, the voltage across the leakage inductance $L_N$ is calculated according to eq. (8).

$$L_N \frac{di_N}{dt} = L_N \frac{i_N(t_k + T_s) - i_N(t_k)}{T_s} = L_N \frac{i_N^*(t_k) - i_N(t_k)}{T_s} \tag{8}$$

Consequently, the mathematical formulation of the predictive direct current control method is described as eq. (9).

$$\begin{cases} I^*_{Nm1} = K_{pu}(U^*_{d\_ref} - U_d) + \dfrac{1}{T_{iu}} \int (U^*_{d\_ref} - U_d)dt \\ I^*_{Nm2} = \dfrac{2I_d U_d}{U_{Nm}} \\ I^*_{Nm} = I^*_{Nm1} + I^*_{Nm2} \\ u_{ab} = u_N - I^*_{Nm} R_N \sin\omega t - \dfrac{L_N}{T_s}(I^*_{Nm}\sin\omega t - i_N) \end{cases} \tag{9}$$

Eq. (6) and eq. (9) reveal that the essence of the predictive direct current control method lies in the condition where the proportional gain of the current control loop's proportional controller is set to $K_{pi} = L_N/T_s$. Under this condition, the steady-state component $\omega L_N I^*_{Nm}\cos\omega t$ of the voltage across the leakage inductance $L_N$ is not added to $u_{ab}$ unlike in the instantaneous direct current control method. In other words, the predictive direct current control method represents a special case of the instantaneous direct current control method.

The preceding analysis demonstrates that the indirect current control method exhibits inferior dynamic performance and is therefore infrequently utilized, whereas the direct current control method offers superior dynamic characteristics. Consequently, this study adopts the instantaneous current control method, with the control principle diagram illustrated in Fig. 4, to conduct the simulations.

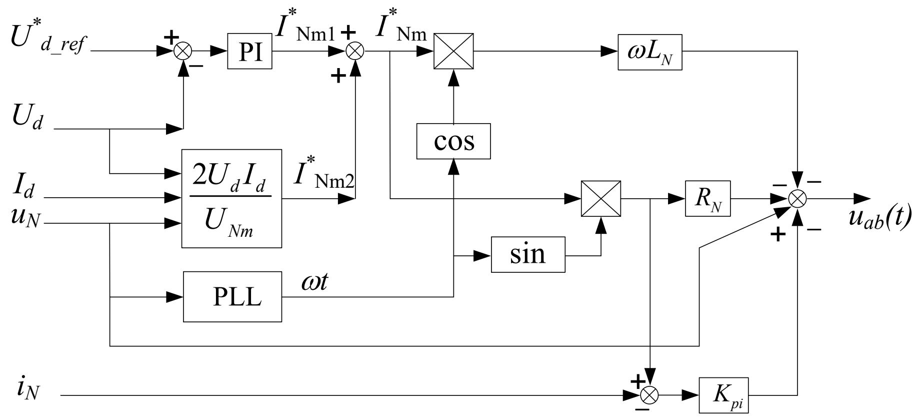
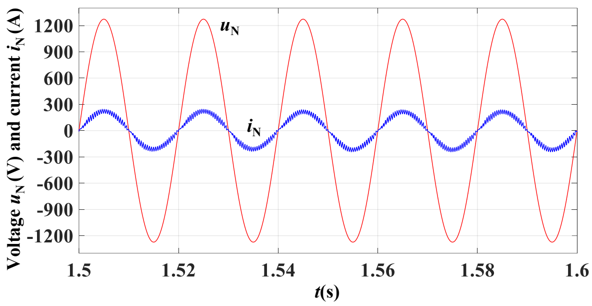


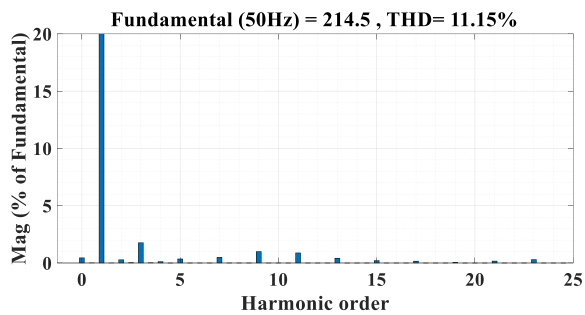

Figure 4. Principle diagram of instantaneous direct current control.

## 3. SIMULATION RESULTS

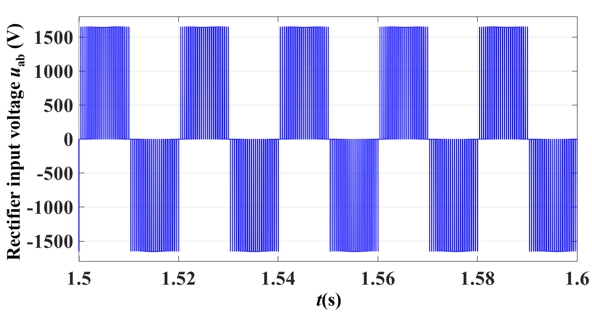
This paper utilizes the parameters of the traction drive system of the CRH1 high-speed train to conduct simulations using the Matlab/Simulink software. The specific parameters are as follows: input AC source RMS voltage $U_N = 900$V, frequency $f_d = 50$Hz; leakage inductance $L_N = 2.3$mH, resistance $R_N = 0.003\Omega$, intermediate DC-link reference voltage $U^*_{d_ref} = 1650$V, support filter capacitor $C_d$ = 8mF, second-order harmonic filter $L_2C_2$ with $C_2 = 9.22$mF and $L_2$ = 0,275mH, load resistance $R_L = 20\Omega$, and switching frequency $f_m$ = 1250Hz, the controller parameters for the voltage control loop and the current control loop are set as $K_{pu}$ =1, $T_{iu}$ = 0.01 and $K_{pi}$ = 0.68, respectively.



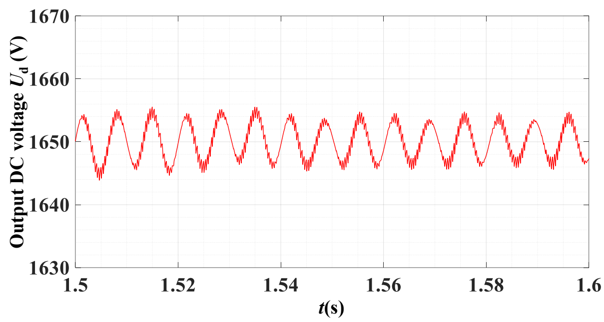

(a)




(b)




(c)

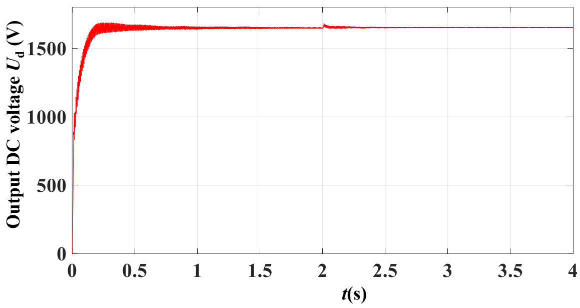



(d)

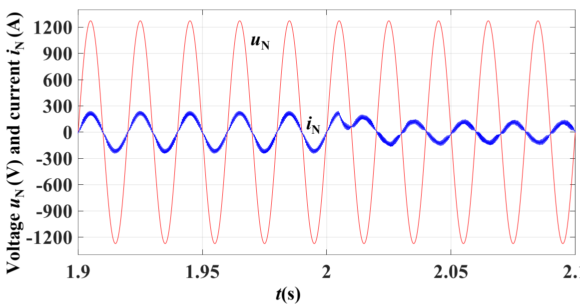
Figure 5. Simulation results of the PWM rectifier operating in rectification mode:
(a) input AC source voltage $u_N$ and current $i_N$; (b) harmonic spectrum of the input AC current $i_N$; (c) rectifier input voltage $u_{ab}$; (d) DC-side output voltage $U_d$.

Fig. 5 presents the simulation results of the PWM rectifier operating in rectification mode (traction mode). As observed in Fig. 5(a), the input AC source voltage and current are substantially in phase. Furthermore, Fig. 5(b) indicates that the Total Harmonic Distortion (THD) of the input AC source current is relatively low, at 11.15%. These factors significantly contribute to enhancing the rectifier's power factor-which reaches approximately 0.99 in the steady state-while simultaneously mitigating harmonic pollution on the power grid. Fig. 5(c) demonstrates that the rectifier input voltage $u_{ab}$ exhibits three discrete levels: *1650V*, 0, and -*1650V*, which aligns with the theoretical analysis presented earlier. The DC-side output voltage is relatively smooth and closely tracks the reference value of *1650V*. In the steady state, the voltage fluctuation range is approximately *1650±4V*, as illustrated in Fig. 5(d).

Fig. 6 depicts the simulation results when the PWM rectifier transitions its operating mode from rectification (traction mode) to inversion (regenerative braking mode). This transition is initiated by introducing a load-side back electromotive force (back-EMF) of $e_L$ = 2500V at the time instant 2.005 s. The simulation results indicate that the transition process from the traction state to the braking state occurs very smoothly. The DC-side voltage achieves stability relatively quickly, after approximately 0.25 s. Furthermore, the input AC source current rapidly shifts from being substantially in phase to being substantially in antiphase with the voltage. Consequently, in conjunction with the traction state, the rectifier facilitates bidirectional power flow, thereby enhancing energy efficiency.




(a)




(b)

Figure 6. Simulation results of the PWM rectifier transitioning from rectification (traction mode) to inversion (regenerative braking mode): (a) DC-side output voltage $U_d$; (b) input AC source voltage $u_N$ and current $i_N$.

## 4. CONCLUSION

In this study, the operating principle of the single-phase two-level PWM rectifier and the implementation of the SPWM technique were first described. Corresponding mathematical formulations were established for the indirect current control, instantaneous direct current control, and predictive direct current control methods. Subsequently, the instantaneous direct current control method, combined with the SPWM technique, was applied to the converter for simulation using Matlab/Simulink software. The simulation parameters utilized were derived from the traction drive system of the CRH1 high-speed train. The simulation results demonstrated the advantages of the PWM rectifier and validated the accuracy of the investigated modulation technique and control method.

Currently, SPWM and SVPWM are the two most widely employed PWM modulation techniques. Since this study focused solely on the former, further research on the application of the SVPWM technique is necessary. Furthermore, as three-level converters have been introduced into high-speed railway traction drive systems, investigating modulation and control techniques for single-phase three-level PWM rectifiers within such systems holds significant scientific and practical value.

## ACKNOWLEDGEMENT

This research is funded by University of Transport and Communications (UTC) under grant number T2026-CK-011.

## REFERENCES

[1]. Song Wen Sheng, Feng Xiao Yun, Control and modulation technologies of electric traction AC drives, Kexue chubanshe, Beijing, 2014.

[2]. Zhang Shu Guang, CRH1 xing dongchezu, Zhongguo tiedao chubanshe, Beijing, 2008.

[3]. Jiang Dong Jie, CRH3 xing dongchezu qianyin chuandong xitong, Tiedao jiche cheliang, 2008, 28(2), 95-99.

[4]. Zhang Shu Guang, CRH5 xing dongchezu, Zhongguo tiedao chubanshe, Beijing, 2008.

[5]. Feng Xiao Yun, Dianli qianyin jiaoliu chuandong jiqi kongzhi xitong, Gaodeng jiaoyu chubanshe, Beijing, 2009.

[6]. Zhang Xi Quan, Dianli qianyin chuandong ji kongzhi, Zhongguo tiedao chubanshe, Beijing, 2012.

[7]. Evren İşen, Comparative Study of Single-Phase PWM Rectifier Control Techniques, Mugla Journal of Science & Technology, 2021, 7(1), 44 - 51. https://doi.org/10.22531/muglajsci.870989.

[8]. Do Viet Dung, Locomotive drive, Transport Publishing House, 2021.

[9]. Do Viet Dung, Pham Van Tien, Locomotive control, Transport Publishing House, 2022.

[10]. An Thi Hoai Thu Anh, The study combining two energy-saving solutions for operating urban electric trains: tracking optimal speed profile and backing regenerative braking energy by using active rectifiers, Institution-level scientific research project, code T2022-DT-007, University of Transport and Communications, 2022.

[11]. An Thi Hoai Thu Anh, Nguyen Xuan Bien, Nguyen Van Quyen, Saving energy in urban electrified train operation: Tracking optimal speed profile and backing regenerative braking energy to utility source by active rectifiers in traction substations, Agricultural Mechanization in Asia (AMA), 53 (2022) 6145-6160.

[12]. Doan Xuan Nam, Van Tan Luong, Nguyen Van Nho, Model predictive control for 3-level t-type active rectifiers with balance capacitor voltage and reduce execution time, Journal of Science, Technology, and Food, 22 (3) (2022) 181-191.

[13]. Bui Van Huy, Sliding mode method of controlling the current loop for single-phase active rectifier, Journal of Science and Technology, 48 (2018) 8-11.

[14]. Lam Quang Thai, Nguyen Van Nghia, Quach Thanh Hai, Truong Viet Anh, Vo Truong Son, Tran Xuan Truong, Operational characteristic-based modeling of high-speed electric trains for power quality assessment in railway electrification systems, New technology and Applications in the field of Electricity - Electronics -Automation, Transport Publishing House, Ha Noi, 2026, 198-209, ISBN: 978-604-76-3354-8.

[15]. TEDI-TRICC-TEDIS Consulting Joint Venture, Pre-feasibility study report of the North-South high-speed railway project, 2024.

[16]. Nguyen Trong Nghia, Advanced technology in high-speed railway infrastructure construction: Opportunities and challenges for Vietnamese enterprises participating in the North-South high-speed railway project, Seminar on construction technology and human resource development for high-speed railway projects, University of Science and Technology - The University of Danang, 2025, 31-70.