Postprint of Research on DC-Side Beat Frequency Suppression Method for EMU

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Abstract

Along with the rapid development of domestic urbanization, the demand for intercity transportation has been increasing, and electric multiple units (EMUs) have become the preferred choice for intercity traffic due to their flexible marshalling and excellent speed regulation performance. The beat frequency phenomenon in the traction converters of EMU trains can result in increased system losses, severe heating, and mechanical vibration. This paper analyzes the origin and impact of the beat frequency phenomenon based on the structural characteristics of single-phase rectifiers, comprehensively compares various suppression methods for beat frequency phenomena from domestic and international research, and provides a summary.

Full Text

Research on Suppression Method of EMU DC-Link Beat Phenomenon

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Abstract: With the rapid development of nationwide urbanization, the demand for intercity transportation has grown substantially. Electric Multiple Units (EMUs) have become the preferred choice for intercity transport due to their flexible marshalling capabilities and excellent speed regulation performance. However, beat phenomenon in EMU traction converters can lead to increased system losses, severe heating, and mechanical vibrations. This paper analyzes the origin and impact of beat phenomenon based on the structural characteristics of single-phase rectifiers, comprehensively compares various suppression methods for beat phenomenon from domestic and international research, and provides a systematic summary of their advantages and disadvantages.

Keywords: EMU, vector control, beat phenomenon, beat-less control

1 Introduction

EMUs represent an efficient transportation tool capable of implementing small marshalling and high-density operations in railway systems. Characterized by flexible composition, speed, safety, reliability, and comfort, EMUs have gained increasingly important status in transportation systems worldwide, becoming the trend in railway development.

In EMU traction drive systems, the single-phase power supply characteristic of railways causes the line-side converter to generate a pulsating voltage at twice the grid frequency in the DC-link. This pulsating voltage produces harmonic currents and torque pulsations on the motor side, which further lead to temperature rise and losses in asynchronous motors—a phenomenon known as beat phenomenon [1]. To further improve traction drive system performance, beat-less control functionality must be incorporated into the motor control module to suppress beat phenomenon.

The main circuit structure of the traction drive system is shown in Figure 1 [Figure 1: see original paper]. The system primarily comprises a pantograph, traction transformer, four-quadrant rectifier, DC-link, traction inverter, and traction motor [2]. Single-phase AC power from the catenary is transmitted through the pantograph to the traction transformer, which steps down the voltage before the four-quadrant rectifier converts it to stable DC voltage. The AC line inductor Ls primarily serves to isolate the grid voltage from the rectifier voltage, store energy, filter harmonics from the AC current, and enable reactive power transfer between the rectifier and grid. The support capacitor Cd in the DC-link stabilizes the DC voltage, suppresses harmonics, and buffers energy exchange between the AC and DC sides. The traction inverter, a critical core component of the traction drive system, converts DC voltage into three-phase AC with adjustable voltage and frequency to drive the traction motor, thereby propelling the EMU. During regenerative braking, the traction motor operates in generation mode, the inverter works in rectification mode to charge the DC-link, causing the DC-link voltage to rise, and the four-quadrant rectifier operates in inversion mode to convert DC power back to single-phase AC, feeding energy back to the power supply system through the traction transformer and pantograph, completing the conversion between mechanical and electrical energy.

Common inverters in EMUs mainly include three-level and traditional two-level inverters [3]. For instance, the CRH2 EMU employs a three-level inverter. While three-level inverters can increase DC voltage and capacity while reducing voltage and current harmonics under the same switching frequency and control method, they suffer from drawbacks such as more devices, complex control, greater mass, and lower reliability. Therefore, this paper adopts the two-level inverter for the traction drive system due to its reliable operation and ease of control [4].

This paper first analyzes in detail the causes of DC-link second harmonic voltage ripple based on single-phase rectifier characteristics, qualitatively examines the impact of beat phenomenon, then investigates suppression methods, compares various hardware and software control approaches, and summarizes their advantages and disadvantages to derive fundamental requirements for beat phenomenon suppression.

2 Traction Drive System Analysis

2.1 Main Circuit Structure

The main circuit structure of the EMU traction drive system is illustrated in Figure 1 [Figure 1: see original paper]. The system consists of a pantograph, traction transformer, four-quadrant rectifier, intermediate DC-link, traction inverter, and traction motor [2]. Single-phase AC power from the overhead contact line is collected by the pantograph and stepped down by the traction transformer. The four-quadrant rectifier then converts this to a stable DC voltage. The line-side AC inductor Ls primarily functions to isolate the grid voltage from the rectifier voltage, store energy, filter AC current harmonics, and facilitate reactive power exchange between the rectifier and grid. The DC-link support capacitor Cd serves to stabilize the DC voltage, suppress harmonics, and buffer energy exchange between the AC and DC sides. The traction inverter, as the crucial core of the traction drive system, converts DC voltage into three-phase AC with adjustable voltage and frequency to drive the traction motor, thereby propelling the EMU train. During regenerative braking, the traction motor operates in generator mode, the inverter works in rectification mode to charge the DC-link, raising the DC-link voltage, while the four-quadrant rectifier operates in inversion mode to convert DC power back into single-phase AC, feeding energy back to the power supply system via the traction transformer and pantograph, thus completing the conversion between mechanical and electrical energy.

EMUs commonly employ either three-level inverters or traditional two-level inverters [3]. The CRH2 EMU, for example, uses a three-level inverter. While three-level inverters can increase DC voltage and capacity, and reduce voltage and current harmonics under the same switching frequency and control strategy, they suffer from disadvantages including more power devices, complex control, greater weight, and lower reliability. Consequently, this paper adopts the two-level inverter for the traction drive system due to its reliable operation and straightforward control [4].

2.2 Generation of DC-Link Voltage Second Harmonic Ripple

In the AC-DC-AC traction drive system shown in Figure 1 [Figure 1: see original paper], the railway system employs single-phase industrial-frequency AC power supply, making the four-quadrant rectifier a single-phase structure.

Considering only fundamental components, the input voltage and current of the single-phase four-quadrant rectifier are defined as:

$$u_s = \sqrt{2}U_s \cos \omega_{grid} t$$

$$i_s = \sqrt{2}I_s \cos(\omega_{grid} t + \phi)$$

where U_s and I_s are the RMS values of input voltage and current under fundamental conditions; ω_{grid} is the angular frequency of the grid supply; and ϕ is the phase angle by which the rectifier line-side current lags the voltage, i.e., the power factor angle of the four-quadrant rectifier.

The instantaneous input power on the AC side can thus be obtained and simplified using trigonometric identities:

$$P_i = u_s i_s = U_s I_s \cos \phi + U_s I_s \cos(2\omega_{grid} t + \phi)$$

According to the principle of instantaneous power balance [5], assuming ideal switching devices in the rectifier and neglecting power losses, the rectifier’ s input and output powers are equal:

$$P_i = P_o$$

Assuming the actual DC bus voltage comprises a steady-state component and a ripple component:

$$u_{dc} = U_{dc} + \Delta u_{dc}$$

where U_{dc} is the DC-link steady-state voltage component and Δu_{dc} is the DC-link ripple voltage component. The four-quadrant rectifier’ s output power includes both steady-state and ripple components:

$$P_o = U_{dc} I_{dc} + U_{dc} C \frac{d\Delta u_{dc}}{dt}$$

where C is the DC-link support capacitor and U_{dc}, I_{dc} are the steady-state components of DC-side voltage and current.

Substituting equations (3) and (6) into equation (4), the steady-state components of input and output power correspond equally, as do the ripple components:

$$U_s I_s \cos \phi = U_{dc} I_{dc}$$

$$U_s I_s \cos(2\omega_{grid} t + \phi) = U_{dc} C \frac{d\Delta u_{dc}}{dt}$$

Combining and simplifying equations (7) and (8) yields the expression for the DC-link ripple voltage component:

$$\Delta u_{dc} = \frac{I_{dc}\sin(2\omega_{grid}t + \phi)}{2\omega_{grid}C\cos\phi}$$

Equation (9) shows that the amplitude of the DC-link ripple voltage component Δu_{dc} depends on the DC-side steady-state current component I_{dc}, the DC-link support capacitor C, and the four-quadrant rectifier’ s power factor angle ϕ [6-7]. EMU four-quadrant rectifiers typically employ dual-loop control strategies with transient current control to maintain high-efficiency operation and fast response, which can make the rectifier’ s power factor approximately 1 [8]. Therefore, the influence of the rectifier power factor angle ϕ can be neglected in the above expression. In this case, the ripple voltage component Δu_{dc} depends only on the DC-link support capacitor C and the steady-state current I_{dc}. Consequently, during traction drive system operation, when the DC-link voltage U_{dc} remains stable, greater output power results in larger ripple voltage. Additionally, increasing the capacity of the support capacitor C can reduce the second harmonic ripple voltage. Equation (9) also reveals that the frequency of the DC-link ripple voltage is twice the grid supply frequency—when using single-phase 50Hz AC power supply, the ripple voltage frequency is 100Hz.

2.3 Influence of Ripple Voltage on Motor Phase Voltage

Based on the above analysis, the DC-link voltage expression can be written as:

$$u_{dc}(t) = U_{dc} + \Delta U_{dc}\sin(2\omega_{grid}t + \phi)$$

For convenience in subsequent analysis, we define:

$$\Delta U_{dc} = \frac{I_{dc}}{2\omega_{grid}C\cos\phi}$$

Thus, equation (10) can be expressed as:

$$u_{dc}(t) = U_{dc} + \Delta U_{dc}\sin(2\omega_{grid}t + \phi)$$

Let the switching functions of the inverter in phases a, b, and c be S_a, S_b, and S_c, respectively. The inverter output phase voltage can then be expressed as:

$$u_{dc}(t)$$

When DC-link ripple voltage is not considered and only fundamental components are taken into account, the switching function expression becomes:

$$m\sin\omega_e t \quad m\sin\omega_e t \quad m\sin\omega_e t' \quad m\sin\omega_e t \quad ' \quad m\sin\omega_e t + \quad m\sin\omega_e t +$$

where u_a is the inverter output ideal three-phase fundamental voltage and U_{dc} is the ripple-free DC bus voltage.

Focusing on phase a in equation (13), its output phase voltage expression is:

$$u_a(t) = m \sin \omega_e t[U_{dc} + \Delta U_{dc} \sin(2\omega_{grid} t + \phi)] = \frac{m\Delta U_{dc} \cos[(2\omega_{grid} - \omega_e)t + \phi]}{2} - \frac{m\Delta U_{dc} \cos[(\omega_e + 2\omega_{grid})t + \phi]}{2}$$

where U_m is the inverter output phase voltage RMS value considering only the fundamental component; ω_e is the inverter output phase voltage frequency considering only the fundamental component; ΔU_{dc} is the ripple component amplitude; ω_{grid} is the grid supply angular frequency; ϕ is the phase angle by which the rectifier line-side current lags the voltage (the four-quadrant rectifier power factor angle); and m is the sinusoidal PWM modulation depth, with $m = U_m/U_{dc}$.

Equation (15) demonstrates that the inverter output phase voltage includes a steady-state component at frequency ω_e generated by the DC steady-state voltage U_{dc}, and ripple components at frequencies $2\omega_{grid} \pm \omega_e$ generated by the ripple voltage ΔU_{dc}. These ripple components constitute the beat frequency components in the inverter output voltage [9], produced through modulation by the pulsating DC bus and inverter switching functions. Since high-frequency harmonic amplitudes decrease with increasing harmonic order, and only fundamental frequency components are considered in the above derivation, the pulsating voltage at frequency $2\omega_{grid} \pm \omega_e$ represents the primary beat frequency component in the inverter output voltage [10-11].

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3 Suppression Methods for Beat Phenomenon

Currently, two main approaches exist for suppressing beat phenomenon: hardware methods that directly suppress DC-link ripple voltage to eliminate motor beat frequency current and torque, and software methods that incorporate beatless control strategies in the inverter to mitigate the impact of ripple voltage on the motor side. Software methods primarily include feedforward compensation, one-cycle control, and frequency compensation. The following sections compare and review several major experimental system configurations from domestic and international research, and summarize the requirements for experimental systems.

3.1 Hardware Methods

The traditional method for suppressing beat phenomenon is hardware filtering, which involves paralleling an LC filter resonant at the bus ripple frequency point on the DC bus to absorb the resonant component. The disadvantage is that the filter has large volume and mass. Additionally, increasing the support capacitor capacity can be employed. As shown in equation (9), the DC ripple voltage magnitude is related to the support capacitor capacity—the larger the support capacitor, the better the suppression effect on DC ripple voltage. When the support capacitor approaches infinity, the DC voltage can be maintained constant. However, in engineering applications, the support capacitor cannot be infinitely large, so simply increasing its capacity cannot completely suppress DC ripple.

While hardware methods can suppress the DC-side second harmonic ripple voltage, they suffer from significant drawbacks: (1) In traction drive systems, the voltage level is high while the resonant frequency is low, resulting in large volume and mass of LC filters, which not only reduces converter power density but also increases system cost. (2) Actual values of LC resonant filters used in engineering deviate from theoretical values, and these deviations prevent the filter circuit from completely eliminating the second harmonic ripple, leaving ripple voltage in the DC-link that causes energy losses in the resonant circuit due to the ripple voltage and equivalent resistance. (3) Simply increasing the support capacitor to stabilize DC voltage increases the hazard of converter short-circuit faults and reduces system stability.

3.2 Software Methods

Feedforward Compensation: The inverter output voltage is related to DC voltage and switching signals. Based on instantaneous DC voltage variations, switching signals can be modified to change the modulation wave amplitude, eliminating the influence of pulsating DC voltage on inverter output voltage [12]. The fundamental principle of feedforward compensation is real-time compensation of the modulation ratio or pulse width—precise compensation of traction inverter PWM pulses through real-time calculation to ensure the inverter can accurately modulate the voltage required by the motor even when operating under bus ripple voltage conditions, without outputting harmful beat frequency current.

In the above analysis, equation (14) represents the switching function expression before compensation. After applying feedforward compensation to the modulation ratio, the corrected switching function becomes:

$$!m\sin\omega_e t \quad !m\sin\omega_e t \quad !m\sin\omega_e t!m\sin\omega_e t \quad (!m\sin\omega_e t \quad (!m\sin\omega_e t \quad (!m\sin\omega_e t+!m\sin\omega_e t+!m\sin\omega_e t+$$

where m' is the corrected modulation depth, and:

$$!m = m\frac{u_{dc}(t)}{U_{dc} + \Delta U_{dc}\sin(2\omega_{grid}t + \phi)}$$

Taking phase a as an example, the inverter output phase voltage after switching function correction is:

$$u_a = !S_a u_{dc}(t) = mU_{dc}\sin\omega_e t$$

The expected inverter output phase voltage without DC-link ripple is:

$$u_a^* = U_m \sin \omega_e t = mU_{dc} \sin \omega_e t = u_a$$

Therefore, the corrected inverter output phase voltage component no longer contains beat frequency components. The feedforward compensation method can suppress beat phenomenon by controlling modulation ratio to adjust pulse width. When the inverter detects the DC bus second harmonic ripple voltage, it reduces modulation depth during the positive half-cycle of bus voltage ripple to decrease output voltage pulse width, and increases modulation depth during the negative half-cycle to increase pulse width [13].

The feedforward compensation scheme offers good performance and is easy to implement, maintaining equivalent area even under severe bus voltage ripple. However, for high-power, low-switching-frequency applications, if the motor speed is high and voltage amplitude has reached maximum, the adjustable margin for modulation depth is limited. Additionally, the error between actual and predicted bus voltage values is significant, and specific harmonic content increases, resulting in suboptimal compensation effectiveness.

One-Cycle Control: One-cycle control (OCC) is a nonlinear control technique for power electronic converters and represents an analog control technology. When the reference voltage signal changes, the one-cycle controller can rapidly adjust switch conduction time within one switching cycle, making the output signal average value precisely equal or proportional to the command signal [14]. One-cycle control features fast dynamic response and strong anti-interference capability.

When the traction drive system operates in the inverter multi-pulse modulation region, an integrator with reset switch can generate the inverter’ s triangular carrier reference signal, with the carrier signal amplitude varying with DC-side voltage U_{dc}. When DC-side voltage ripples, the PWM pulse width output by the one-cycle controller adjusts with U_{dc} changes. Therefore, the one-cycle control algorithm can eliminate the influence of pulsating DC voltage on inverter output voltage, and motor beat frequency current and torque can also be suppressed.

When the traction drive system operates in the inverter single-pulse modulation region, the modulation signal frequency equals the switching frequency, making traditional one-cycle control unsuitable for inverter single-pulse modulation [15]. The single-pulse modulation region’ s one-cycle control employs the volt-second balance principle, reducing pulse width during positive DC voltage ripple and increasing pulse width during negative DC voltage ripple. To precisely compensate for inverter phase voltage variations caused by pulsating DC voltage, the switching time between positive and negative pulse half-cycles must be determined. While calculating switching points is complex in digital control, analog control methods in one-cycle control do not require solving for switching times, thus simply achieving volt-second balance.

The beat-less control method using one-cycle control offers fast dynamic response, constant switching frequency, and strong anti-interference capability. However, this control method employs different controllers in multi-pulse and single-pulse modulation regions, requiring switching between different modulation regions, which increases system complexity, and involves substantial analog circuit design and control workload and complexity.

Frequency Compensation: Frequency compensation suppresses beat frequency current generated by ripple components by compensating the inverter operating frequency. The first frequency compensation method, shown in Figure 2 [Figure 2: see original paper], superimposes a time function reflecting ripple components onto the converter switching function for compensation [16].

When applied to rotor field-oriented vector control systems, frequency compensation injects ripple components into the speed loop to compensate inverter operating frequency, thereby suppressing asynchronous motor beat frequency current. The switching function before compensation can be expressed in Fourier form as:

$$S(t) = \sum_{k=odd} A_k \cos k\omega_s t$$

If a time function is used to compensate the switching function, it can be rewritten as:

$$S(t) = \sum_{k=odd} A_k \cos k[\omega_s t + \theta(t)]$$

where:

$$\theta(t) = 2\pi\Delta F_r \sin(\omega_r t + \phi_r)$$

The inverter’ s instantaneous operating frequency can then be expressed as:

$$\omega(t) = \omega_s + \Delta\omega_r \cos(\omega_r t + \phi_r)$$

where ΔF_r is the frequency compensation coefficient and ω_s is the inverter operating frequency. The inverter switching function expression becomes:

$$S(t) = \sum_{k=odd} A_k \cos k\omega_s t \cos kC \sin(\omega_r t+\phi_r)-\sin k\omega_s t \sin kC \sin(\omega_r t+\phi_r)+A_1 \cos\omega_s t+\cos(\omega_r+\omega_s)t+\phi_r \cos(\omega_r-$$

where:

$$C = 2\pi\Delta F_r/\omega_r$$

From the compensated switching function and DC bus voltage expression (3), the compensated inverter output phase voltage expression can be obtained. Taking phase a as an example:

$$u_{ao} = u_{dc}(S-1/2) = U_{dc}A_{a1}\cos\omega_s t+\Delta U_{dc}A_{a1}+A_{a1}CU_{dc}\cos(\omega_r+\omega_s)t+\phi_r-\Delta U_{dc}A_{a1}C\cos(2\omega_r+\omega_s)t+2\phi_r-\Delta$$

From equation (26), to eliminate inverter output ripple voltage, the following condition should be satisfied:

$$\Delta U_{dc} A_{a1} - A_{a1} C U_{dc} = 0$$

Thus, the frequency compensation coefficient can be expressed as:

$$\Delta F_r = \frac{\Delta U_{dc}}{2\pi U_{dc}}$$

Frequency compensation can eliminate the beat frequency phase voltage component at frequency $\omega_r - \omega_s$, but compared with the pre-compensation inverter phase voltage, it simultaneously introduces harmonic voltage at frequency $2\omega_r \pm \omega_s$ [17], which affects asynchronous motor performance.

The second frequency compensation method obtains the mathematical model of beat phenomenon through asynchronous motor modeling and analysis, and derives a beat-less control strategy based on frequency-domain analysis [18].

From the above analysis, the pulsating voltage ΔV_{dc} is the cause of beat phenomenon, while transfer functions $G_{if}(s)$ and $G_{tf}(s)$ define the relationship between beat frequency current, beat frequency torque, and slip frequency increment. In a beat-less control system, the goal is to compensate the slip frequency according to the DC voltage pulsation pattern to counteract the beat frequency current and torque generated by pulsating voltage, yielding the beat-less controller principle block diagram shown in Figure 3 [Figure 3: see original paper] [19].

In the control block diagram, the main circuit includes the traction inverter and asynchronous motor dynamic model, showing that ΔV_{dc} causes beat frequency current I_Δ and beat frequency torque $T_{e\Delta}$. In the compensation loop, $G_c(s)$ represents the beat-less controller transfer function, where pulsating voltage ΔV_{dc} can generate compensated slip frequency f_{sl}. Through compensation, the beat-less control can eliminate the beat frequency components I_Δ and $T_{e\Delta}$ produced by ΔV_{dc} in the main circuit.

From the above analysis, suppressing beat frequency current I_Δ means suppressing the gain of I_Δ/V_{dc} at the pulsation frequency point, and suppressing beat frequency torque $T_{e\Delta}$ means suppressing the gain of $T_{e\Delta}/V_{dc}$ at the pulsation frequency point. Therefore, the beat-less controller $G_c(s)$ should satisfy the relationships in equations (29) and (30), suppressing the gains of transfer functions $G_i(s)$ and $G_t(s)$ at the ripple frequency point:

$$G_i(s) = \frac{I_{ripple}}{V_{dcripple}} = \frac{G_{if}(s)}{1 + G_c(s) G_{iu}(s)} G_t(s) = \frac{T_{eripple}}{V_{dcripple}} = \frac{G_{tf}(s)}{1 + G_c(s) G_{iu}(s)}$$

where ω_{ripple} is the angular frequency at the ripple frequency point; $G_i(s)$ is the transfer function of beat frequency current after applying beat-less control; and

$G_t(s)$ is the transfer function of beat frequency torque after applying beat-less control.

Frequency compensation suppresses beat frequency current generated by ripple components by compensating inverter operating frequency. This method modifies the motor frequency command through specific algorithms to achieve beat phenomenon suppression and requires precise sampling of ripple components, offering good suppression effectiveness.

4 Conclusion

Beat phenomenon in EMU traction converters leads to increased system losses, severe heating, and mechanical vibrations. This paper first analyzed in detail the causes of DC-link second harmonic voltage ripple based on single-phase rectifier characteristics, qualitatively examined the impact of beat phenomenon, investigated suppression methods for beat phenomenon, compared hardware filtering, feedforward compensation, one-cycle control, and frequency compensation methods, summarized the principles and advantages/disadvantages of each control method, and systematically derived the origins of beat phenomenon and its suppression approaches.

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Note: Figure translations are in progress. See original paper for figures.