

MODELING AND ASSESSMENT OF THE IMPACT OF A 25 KV-50 HZ RAILWAY TRACTION POWER SUPPLY SYSTEM ON THE POWER QUALITY OF THE ELECTRICAL GRID IN VIETNAM

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ABSTRACT

This paper presents an investigation into harmonic distortion and voltage fluctuations caused by the 25 kV–50 Hz railway traction power supply system and their impact on the power quality of the Vietnamese electrical grid. A detailed traction load model representing train operating modes under Vietnamese conditions is developed in Matlab/Simulink. The study focuses on analyzing key power quality indices, including voltage fluctuations and harmonic distortion at the Point of Common Coupling (PCC). Simulation results illustrate that traction loads generate significant harmonic components and noticeable voltage sag during acceleration. These findings provide a technical basis for selecting appropriate compensation solutions such as D-STATCOM or energy-storage-integrated converters for future railway electrification projects. Furthermore, the study contributes essential insights for planning and integrating 25 kV railway systems into Vietnam's power grid with improved power quality and operational reliability.

Keywords: Harmonics, traction power supply system, non-linear loads, passive filters, power quality.

1. INTRODUCTION

Nowadays, along with the rapid development of electrified railway systems, especially railway lines employing 25 kV–50 Hz AC traction power supply systems, issues related to power quality (PQ) have become increasingly severe and have attracted significant attention from both researchers and power system operators [1–3]. Railway traction power systems are regarded as one of the largest, most rapidly varying, and highly nonlinear loads connected to the national power grid; therefore, they are capable of causing various types of disturbances and power quality degradation in the regional power network as well as in neighboring loads [4–6].

Modern electric trains employ semiconductor-based power converters (rectifiers, inverters, and traction control units), which constitute the primary sources of current harmonics, voltage waveform distortion, voltage fluctuations, phase unbalance, and large reactive power demand [6–10]. These phenomena not only directly affect the efficiency and reliability of the traction power system itself but also propagate into the supplying power grid, causing adverse impacts on transformers, transmission lines, protective devices, and other loads at the point of

common coupling (PCC). Numerous studies have demonstrated that the level of current harmonic distortion in systems with large-scale nonlinear loads often exceeds the permissible limits specified by international standards such as IEEE 519-2014 in the absence of appropriate mitigation measures [4], [11, 12].

In Vietnam, the planned development of electrified railway lines and high-speed railways in the near future imposes an urgent requirement to quantitatively evaluate the impacts of traction power systems-particularly those for high-speed trains, with the widely adopted 25 kV-50 Hz system-on the power quality of the national grid [13-15]. However, in-depth studies on detailed modeling of traction power systems and the analysis of their power quality impacts under the conditions of the Vietnamese power grid remain limited [7]. Owing to the time-varying nature of traction loads, which depend on train operating modes and the longitudinal power supply structure along the railway line, the development of accurate simulation models represents a major yet necessary challenge [14, 15].

In parallel with impact assessment, harmonic mitigation solutions-among which shunt-connected passive filters are particularly prominent-have been demonstrated to be effective, economical, and easy to implement for large-scale power systems. Previous studies have shown that passive filters can significantly reduce current harmonic distortion, improve the power factor, and decrease system losses when they are properly designed with appropriate harmonic tuning orders, reactive power ratings, and quality factors [11]. In particular, the combination of realistic nonlinear load modeling with simulations in the MATLAB/Simulink environment enables accurate evaluation of the effectiveness of the proposed technical solutions [12], [15].

Based on the aforementioned issues, this paper focuses on modeling the 25 kV–50 Hz AC railway traction power supply system and evaluating its impacts on the power quality of the Vietnamese power grid. Based on the developed simulation model, power quality indices such as voltage harmonic distortion, current harmonic distortion, and operating conditions at the point of common coupling (PCC) are analyzed and compared with the limits specified in existing standards. The research results aim to provide a scientific basis for the design, operation, and proposal of appropriate technical solutions for railway traction power systems under Vietnamese conditions.

2. METHODOLOGY

This section presents the design procedure of single-tuned passive harmonic filters for the 25 kV-50 Hz traction power supply system of high-speed railways. The research methodology consists of three subsections: modeling of the railway traction power supply system, harmonic analysis, and design of passive harmonic filters.

2.1. Electric Railway System Modelling

The traction power supply system for the 25 kV–50 Hz AC electrified railway is modeled as shown in Fig. 1. The 110kV grid is used to supply three-phase power at 110kV, 50Hz. Subsequently, the traction power substation (TPSS) is modeled to transform the 110 kV AC supply into a 25 kV–50 Hz AC supply, which is fed to the overhead contact line and delivered to the train through the pantograph.

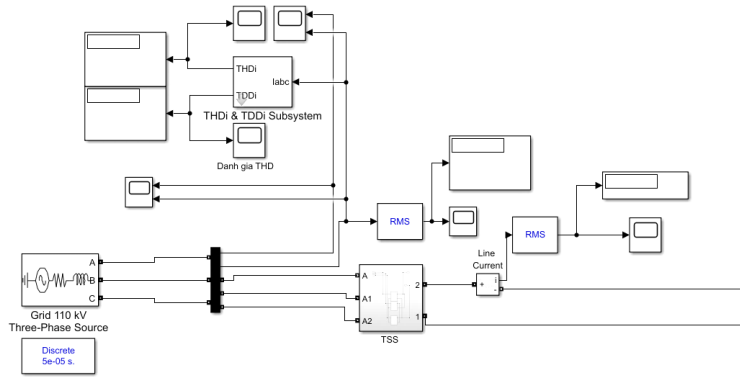


Fig. 1. Electric Railway 25 kV - 50 Hz Traction Power Supply System Modeling

The traction power substation (TPSS) of the 25 kV–50 Hz AC railway system receives electric power from the national grid. The electrical energy is stepped down and converted from a three-phase system to a single-phase system through a traction transformer, and then distributed to the overhead contact line to supply power to the train. In addition, power quality indices such as the power factor, total harmonic distortion of current (THDi), and total demand distortion (TDD) are also calculated and displayed.

The electric train supplied by the 25 kV–50 Hz AC traction power system is modeled through a chain of power-electronic energy conversion stages from the overhead contact line to the traction motor load, as shown in Fig. 2. The 25 kV single-phase AC voltage is drawn from the contact line and fed into a multi-winding traction transformer to step down the voltage to levels suitable for the downstream power converters. On the secondary side, the AC voltage is supplied to two parallel bridge rectifiers to form a DC source for the intermediate DC link. The rectified DC voltage is smoothed by a DC-link filter, consisting of a capacitor and a discharge resistor, in order to reduce voltage ripple and improve the quality of the power supplied to the traction inverter. The inverter load is modeled using a time-varying load profile, reflecting practical train operating modes such as start-up, acceleration, steady cruising, and braking. Voltage, current, and root-mean-square (RMS) measurement blocks are integrated into the model to support dynamic response analysis and evaluation of harmonic generation in the system.

This model enables accurate simulation of the electrical behavior of a 25 kV–50 Hz electric train, particularly the impact of traction rectifiers and inverters on power quality, thereby providing a solid foundation for studies on harmonic analysis, train–grid interaction, and power quality enhancement solutions for high-power AC traction systems.

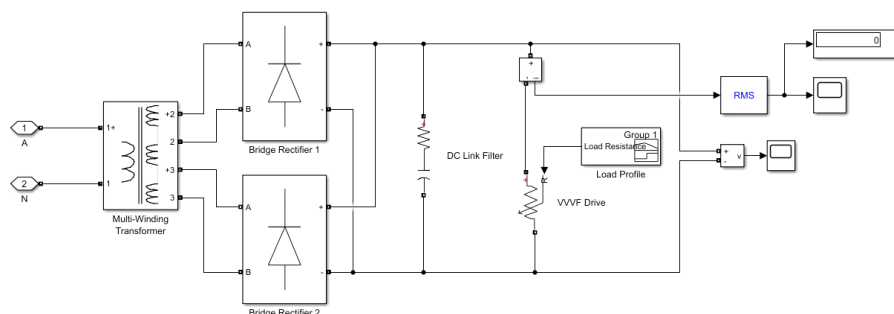


Fig. 2. Locomotive model

In order to better represent the characteristics of the Vietnamese electrical grid, the upstream power system is modeled as a 110 kV, 50 Hz transmission network supplying the

traction power substation. The substation is rated at 80 MVA and employs a Scott transformer configuration to convert three-phase power into a single-phase 25 kV traction supply.

The transmission line connecting the grid to the traction substation is modeled using typical parameters of 110 kV overhead lines in Vietnam. The equivalent line impedance is selected in the range of $Z_{line} = (0.15 + j0.4) \Omega/km$, with an assumed line length of 20–30 km, representing a medium-distance supply scenario. This corresponds to an equivalent impedance of approximately $Z_{eq} = (3 + j8) \Omega$.

Table 1. Electric train parameters

Parameters	Value
Source	110kV
Nominal voltage at the catenary	25 kV
Traction load power	5 MW
Fundamental frequency	50 Hz
Load power factor (typical for electric trains)	0.85
Fundamental load current	235.29 A

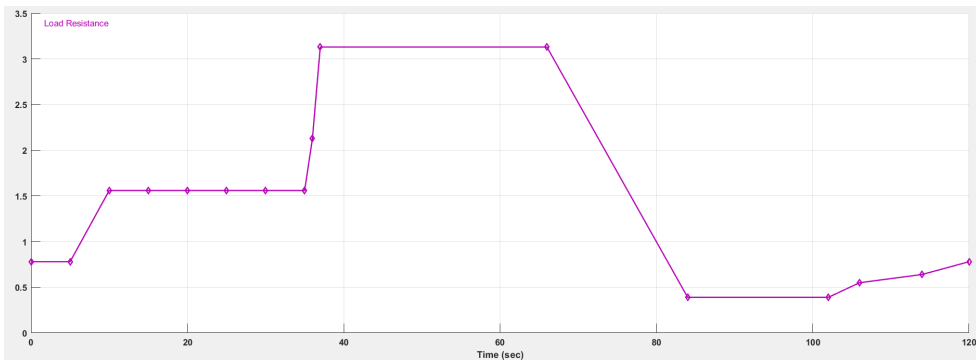


Fig. 3. Traction Train Operating Conditions

Table 2. Simulation parameters

Parameter	Description
Simulation duration	120 s
Equivalent load resistance	0.4 Ω – 3.1 Ω
Operating modes	Start, acceleration, cruising, braking, stop
Load characteristic	Large-scale dynamic nonlinear load

Fig. 3 illustrates the variation of the equivalent traction load resistance as a function of time, which is used to represent the dynamic operating conditions of a high-power electric train. Table 2. summarizes the operating modes of the electric train and their corresponding equivalent resistance levels used in the simulation. The equivalent resistance profile reflects different operating modes of the train, including starting, acceleration, cruising, braking, and stopping. A lower resistance value corresponds to higher traction power demand, while a higher resistance indicates light-load operating conditions.

During the initial starting and acceleration stage (0–10 s), the equivalent resistance decreases to approximately 0.8 Ω, indicating a high traction current required to generate large

starting torque. This operating condition leads to significant voltage drop and current distortion in the traction power system. From 10 s to 35 s, the resistance remains nearly constant at around 1.55 Ω, corresponding to a steady acceleration or medium-speed operation. In this interval, the power demand is relatively stable, and the harmonic distortion is mainly caused by the PWM-based traction converters. Between 35 s and 65 s, the resistance increases to approximately 3.1 Ω, representing high-speed cruising operation. In this mode, the traction torque requirement is reduced, resulting in lower power consumption from the grid. From 65 s to 85 s, a rapid decrease in the equivalent resistance down to approximately 0.4 Ω is observed, which corresponds to the braking or regenerative braking mode. This operating condition is characterized by abrupt power variation and bidirectional power flow, potentially causing voltage fluctuation and harmonic propagation in the traction network. Finally, during the stopping and re-start preparation stage (85–120 s), the resistance gradually increases from 0.4 Ω to 0.8 Ω, indicating reduced power demand as the train stops at the station and prepares for the next departure.

2.2. Harmonic Sources in 25 kV 50 Hz Railway Systems Analysis

Due to the nonlinear characteristics of rectifiers in the traction power system, the current drawn from the 25 kV overhead contact line contains significant harmonic components. Therefore, harmonic analysis is conducted to evaluate the levels of current and voltage distortion, as well as the impact of the train on the power quality of the AC traction power system.

In the model shown in Fig. 1, the primary-side current of the traction transformer and the current flowing in the overhead contact line are continuously measured over time. After the system reaches steady-state operation, the measured current and voltage signals are processed using an FFT analysis block to determine the harmonic spectrum and to calculate power quality indices such as Total Harmonic Distortion (THD) and Total Demand Distortion (TDD), which are defined by the following expressions:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100\% \quad (1)$$

$$TDD = \frac{\sqrt{\sum_{h=2}^N I_h^2}}{I_L} \times 100\% \quad (2)$$

Where:

I_1 : the RMS value of the fundamental component,

I_h : the RMS value of the h-th harmonic component.

I_L : is the maximum demand load current.

N: the highest harmonic order considered (typically up to the 50th order in accordance with IEEE 519).

The analysis results indicate that the current harmonic spectrum is mainly dominated by low-order harmonic components, which are characteristic of single-phase semi-controlled rectifiers, particularly the 3rd, 5th, 7th, 9th, 11th and 13th harmonics. The amplitudes of these harmonic components strongly depend on the train loading conditions and the characteristics of the DC-link filter. During start-up and acceleration modes, the THDi reaches its highest values due to the large traction current, whereas under steady-state cruising conditions, the harmonic distortion level is significantly reduced.

In addition, harmonic currents generated by the train tend to propagate back toward the traction power substation through the traction transformer, causing voltage distortion at the

point of common coupling (PCC) and potentially leading to resonance phenomena with the line and transformer impedances, as illustrated in Figs. 4 to 6. Therefore, the evaluation of THD in the developed model serves as an essential basis for investigating harmonic mitigation solutions, such as passive filters, in the 25 kV–50 Hz traction power system.

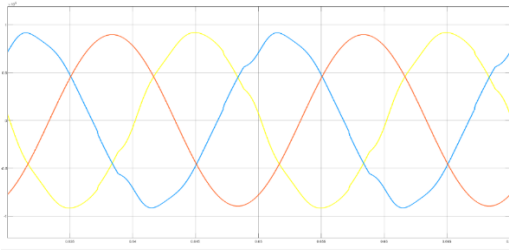


Fig. 4. Voltage waveform of the electric train before Filtering

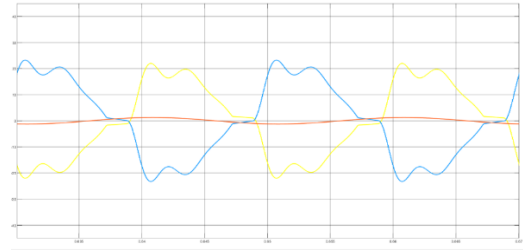


Fig. 5. Current waveform of the electric train before Filtering

The harmonic and THD analysis results obtained from the simulation model provide a fundamental basis for subsequent studies on power quality enhancement, optimization of filter design, and assessment of compliance with technical standards related to harmonic distortion in large-scale AC traction power systems.

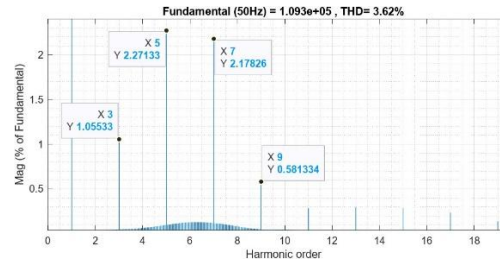
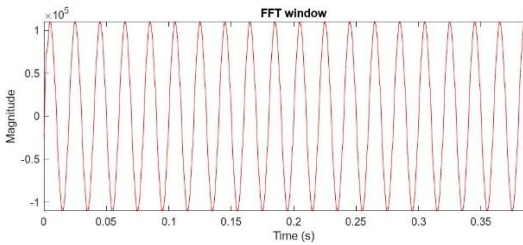


Fig. 6. Harmonic Current Distortion during Peak Hours before Filtering

2.3. Harmonic Passive Filters Design

There are various types of passive harmonic filters, such as single-tuned filters, double-tuned filters, high-pass filters, and C-type filters, whose structures are illustrated in Fig. 7. Single-tuned filters (also referred to as low-pass or band-pass filters) and high-pass filters are the two most widely applied types due to their simple design and low implementation cost. Passive filters are designed to: (i) provide reactive power compensation for the system, and (ii) tune, shape, or eliminate undesired frequency components of electrical signals. In this paper, a single-tuned passive harmonic filter is selected for design owing to its simple structure, low cost, high reliability, and high flexibility.

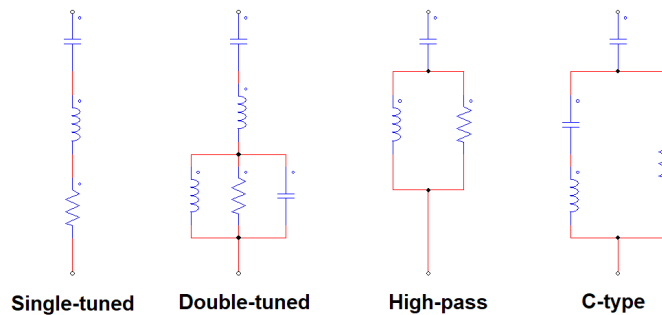


Fig. 7. Common types of passive filters

The parameters of the filter are as follows [16]:

The impedance of low- pass filter (or band-pass filter) is given by:

$$Z = R + j \left(2\pi \cdot h \cdot f \cdot L - \frac{1}{2\pi \cdot h \cdot f \cdot C} \right) \quad (3)$$

The impedance of the inductive and capacitive reactance are given by:

$$X_C = \frac{V_{ph}^2}{Q_F \cdot h} \quad (4)$$

$$X_L = \frac{X_C}{h^2} \quad (5)$$

Where Q_F is reactive power , h is harmonic number.

The quality factor of single tuned filter is:

$$Q_L = \frac{X_L}{R} \quad (6)$$

The resonant frequency is given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (7)$$

The impedance of the high-pass filter is given by:

$$Z = \frac{1}{j2\pi \cdot h \cdot f \cdot C} + \left(\frac{1}{R} + \frac{1}{j2\pi \cdot h \cdot f \cdot L} \right)^{-1} \quad (8)$$

The quality factor of the high-pass filter is:

$$Q_H = \frac{L}{R^2 C} \quad (9)$$

The resonant frequency is given by:

$$f_0 = \frac{1}{2\pi \cdot h \cdot C \cdot R} \quad (10)$$

Parameters calculation with the single tuned filter:

$$C = \frac{Q_F}{2\pi \cdot f \cdot V_{ph}^2} \quad (11)$$

$$L_h = \frac{1}{C \cdot (2\pi \cdot h \cdot f)^2} \quad (12)$$

$$R_h = \frac{2\pi \cdot h \cdot f \cdot L_h}{Q_L} \quad (13)$$

With the high-pass filter:

$$R_h = \frac{1}{2\pi.C.h.f} \tag{14}$$

A passive filter consists not only of inductance and capacitance but also includes resistance. The resistance values are used to significantly shape the filter response characteristics; however, they usually result in a considerable increase in filter losses. The quality factor characterizes the sharpness of the filter response. According to a study in [16], typical values of the low-frequency quality factor Q_L range from 25 to 100 and the typical values of Q_H range 0.5 to 2.

3. RESULTS & DISCUSSION

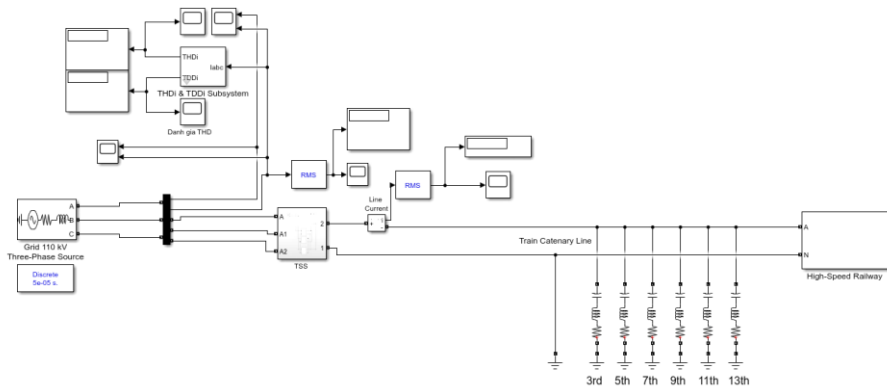


Fig. 8. Single-Tuned Harmonic Passive Filters Model

The single-tuned passive harmonic filters are connected to the electrified railway system model and simulated as shown in Fig. 8. Based on the voltage and current waveforms of the 25 kV–50 Hz traction power supply system for the electric train, the effectiveness of the single-tuned passive harmonic filters can be clearly evaluated by comparing the system responses before and after filtering. The parameters of designing passive filter are calculated according to equations from Eq. (4) to (15) and shown in Table 3.

Table 3. Parameters of designing passive filter

Harmonic order	C (uF)	L (mH)	R (Ω)
3 rd	5.1	7.36	0.17
5 th	5.1	2.65	0.1
7 th	5.1	1.35	0.07
9 th	5.1	0.82	0.05
11 th	5.1	0.55	0.04
13 th	5.1	0.47	0.048

3.1. Case without Harmonic Filters

From the unfiltered current and voltage waveforms shown in Figs. 3 and 4, it can be observed that the waveforms are significantly distorted compared to the ideal sinusoidal shape. These harmonic components increase the THD and TDD indices, adversely affecting power quality, increasing line losses, and imposing additional stress on equipment in the traction power substation (TPSS). Although the voltage waveform is less distorted than the current

waveform, oscillations and ripples caused by harmonic currents drawn by the traction load can still be observed.

3.2. Case with Harmonic Filters Installed

After the single-tuned passive harmonic filters are installed and put into operation, the waveforms exhibit a noticeable improvement in both current and voltage characteristics. The filtered current becomes smoother and closer to a sinusoidal waveform, indicating that the dominant harmonic components are effectively absorbed by the filter branches shown in Figs. 9 to 11. The amplitudes of harmonic components are significantly reduced, leading to a substantial decrease in individual harmonic distortion indices (IHDi), which consequently results in lower THDi and TDD values.

Regarding the voltage, the post-filtering waveform becomes more stable, with reduced oscillations and ripples compared to the unfiltered case. This demonstrates that mitigating harmonic currents not only improves current quality but also indirectly enhances voltage quality at the point of common coupling (PCC).

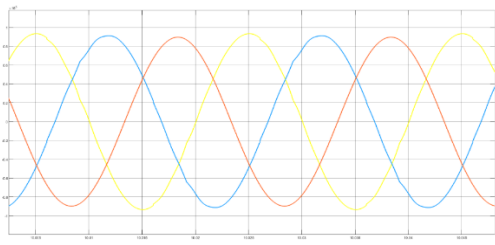


Fig. 9. Voltage waveform of the electric train after Filtering

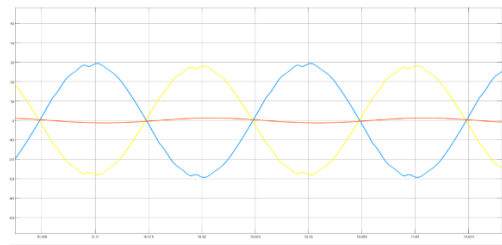


Fig. 10. Current waveform of the electric train after Filtering

The simulation results demonstrate that the application of single-tuned passive harmonic filters is an effective and feasible solution for railway traction power supply systems. The designed filters significantly reduce individual current harmonic components at characteristic harmonic orders, while enabling the THD and TDD indices to comply with the permissible limits specified in IEEE 519-2014 and circular 05/2025/TT-BCT. The improvement in current waveform quality after filtering also contributes to reduced transmission losses, enhanced operational reliability, and improved protection of electrical equipment in the traction power substation (TPSS).

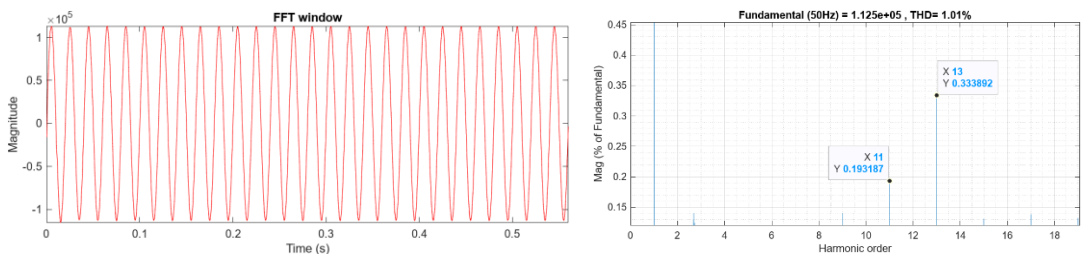


Fig. 11. Harmonic Current Distortion during Peak Hours after Filtering

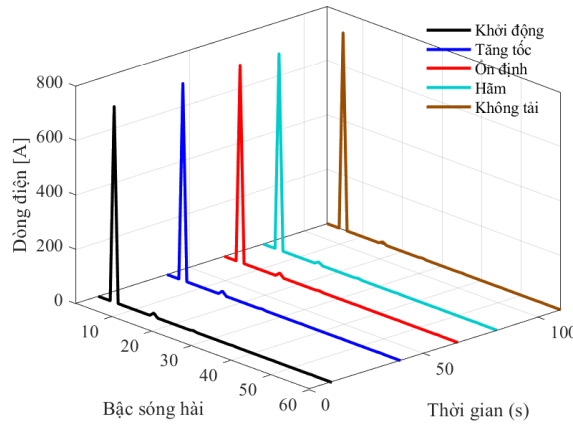


Fig. 12. Harmonic spectrum of electric train operating modes after filtering

Table 4. Comparison of thd and tdd under different operating modes

Operating Mode	THD before (%)	TDD before (%)	THD after (%)	TDD after (%)
Start-up	28.5	26.2	4.2	3.8
Acceleration	22.7	20.5	3.5	3.1
Cruising	12.3	10.8	2.1	1.9
Braking	30.8	28.6	4.8	4.2
Stop/Idle	15.6	13.9	2.8	2.4

Nevertheless, passive harmonic filters still exhibit several inherent limitations. First, the filtering capability of a single-tuned filter is effective only at a specific harmonic order; therefore, multiple parallel filter branches are required to mitigate different harmonic components, leading to increased system size and cost. Second, the performance of passive filters strongly depends on loading conditions and grid parameters, causing a degradation in filtering effectiveness under dynamic operating conditions, which are typical of traction power systems. In addition, the reactive power provided by passive filters may affect the power factor and pose a potential risk of resonance with the power grid, particularly under off-nominal operating scenarios.

Table 4 and Fig. 12 presents a comparative evaluation of THD and TDD values under different operating modes of the traction system. It can be observed that the highest harmonic distortion occurs during start-up and braking conditions due to large and rapidly varying traction currents. After the installation of single-tuned passive filters, the THD and TDD values are significantly reduced across all operating modes, ensuring compliance with IEEE 519-2014 limits and Circular 05/2025/TT-BCT. This confirms the effectiveness of the proposed filtering solution under dynamic operating conditions.

Therefore, to meet the increasingly stringent power quality requirements of modern traction power systems and high-speed railways, future research should consider more flexible harmonic mitigation and reactive power compensation solutions, such as active power filters (APFs) or distribution static compensators (DSTATCOMs) based on voltage-source converters (VSCs). These devices offer real-time adaptability, simultaneous compensation of reactive power and harmonics, and sustained filtering performance under varying load conditions, thereby promising superior performance compared with conventional passive solutions.

4. CONCLUSION

This paper presents the modeling of an electrified railway system, harmonic analysis, the design of single-tuned passive harmonic filters, and the evaluation of filter performance under peak and off-peak operating conditions. Multiple single-tuned passive harmonic filters are connected in parallel to the distribution feeders in order to simultaneously mitigate several individual current harmonic components. The obtained results indicate that the proposed single-tuned passive harmonic filter design is capable of reducing the total demand distortion (THD) to 1.01%. Consequently, the harmonic emissions from the traction power substation (TPSS) satisfy the limits specified by the IEEE 519-2014 standard and circular 05/2025/TT-BCT.

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