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Research Article

Negative Sequence and Harmonic Currents Compensation in High-Speed Electric Railway

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Abstract: In order to solve the power quality problem of negative-sequence and harmonic currents in high-speed railway traction systems, a novel power quality compensator is proposed, which is constituted by railway static power conditioner (RPC), two thyristor-controlled reactors and two thyristor-controlled 3rd filters. The RPC contains two converters which are connected back-to-back by sharing the DC link and is only used to transfer active power and suppress harmonics. The thyristor-controlled 3rd filters are used to suppress 3rd harmonic current and change the phase angle of power supply current.

The thyristor-controlled reactors are as the same used to change the phase angle of power supply current. The proposed power quality compensator has small capacity and low cost. Furthermore, based on the working principle of the proposed power quality compensator, its equivalent electrical models are established in fundamental and harmonic domain respectively. Simulation results are provided to demonstrate that the negative-sequence currents is zero and the THD of power arm current is reduced from 14% to 3%, after the proposed power quality compensator is run.

Keywords: Negative-sequence current compensation; harmonic currents suppression; high-speed electric railway; novel power quality compensator.

INTRODUCTION

With the development of electrified railway in China, Power quality becomes a major concern for AC electrified railway power supply system's[1]. As for China's high-speed railway, it will be continuous operation for more than 350 kilometres per hour. Because of the rapid development of the power electronic switching device, the DC-AC-DC PWM modulation was adopted by high-speed electric trains, as a result, the power factor can reach to 0.98 and it is no need for the compensation of reactive power. However, there are a large amount of the negative-sequence current and harmonic currents which have a broad spectral range. So these negative sequence and harmonic currents are a direct threat to the public power grid and the safe operation of its own[2]. In order to solve the issue of power quality in the general and high-speed electrified railway, many methods and power quality compensators are studied. Static Var Compensators (SVC) can be used to balance a distribution system[3], but the SVC should be connected to the 110kV or 220kV high-voltage side of the traction system, which increases the requirement on voltage rating. General active filters are effective in suppressing harmonic currents in electrified railway[4, 5], but cannot compensate negative-sequence currents. An active power quality compensator (APQC) with an impedance matching balance transformer and an Scott transformer is proposed in[6] to compensate negative-sequence, harmonic and reactive currents. Japanese scholars in 1993, proposed a the electrified railway power regulator (Railway Static Power Conditioner, RPC) notion in the literature[7,8] that RPC based on the switching devices is connected between two secondary output phases of traction transformer, which has the ability to control two-phase active, reactive power and harmonic currents. But the capacity of RPC is large and cost too much. For power quality problem of high-speed electrified railway, this paper presents a new type of power quality compensation system, which is mainly made of railway regulator RPC, two sets of thyristor-controlled reactor and two sets of thyristor-controlled 3rd filter. Based on the working principle of the proposed power quality compensator, its equivalent electrical models are established in fundamental and harmonic domain respectively. The simulation results confirm the correctness of the contents of this paper, and also reflect the new power quality compensation system has the low cost, stability characteristics and good prospects for engineering applications.

SYSTEM STRUCTURE

The structure of proposed power quality compensator, which suitable for high-speed electrified railway systems, is shown in **Fig.1,**

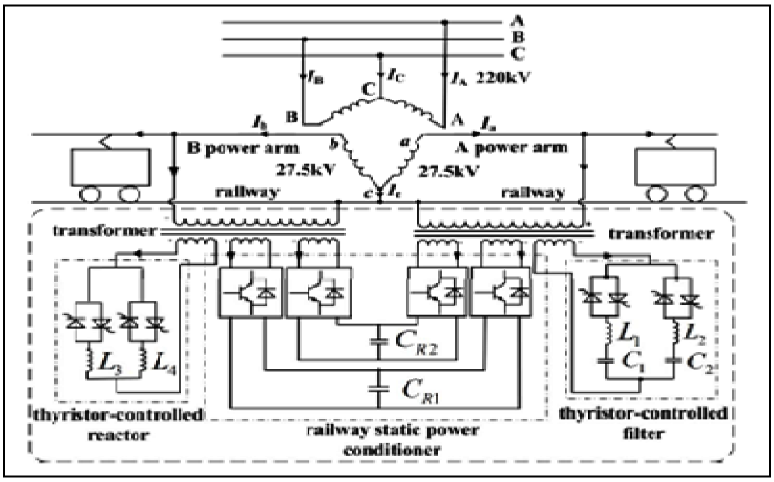


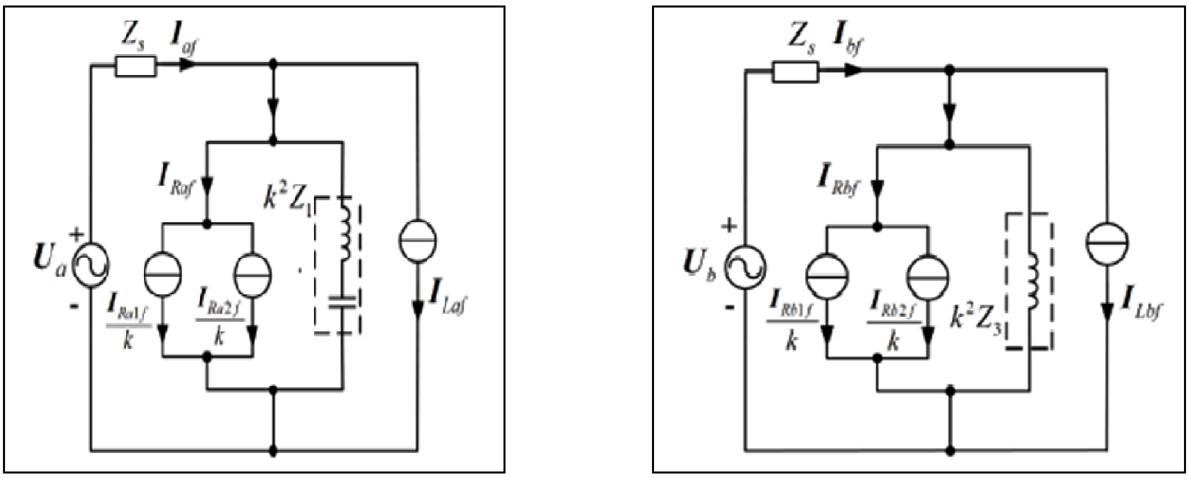
Fig 1: Structure of novel power quality compensator

The compensator is constituted by the three parts: railway power regulator consisting of two single-phase H bridge inverter which is linked by the capacitor CR1 and CR2; two sets of thyristor-controlled reactor constituting by the inductors L3 and L4; two sets of thyristor-Controlled 3rd single tuned filter constituting by the inductors L1, L2 and capacitor C1, C2. The transformer is a single-phase three-winding step down transformer. The railway power regulator makes a connection with two power supply arms of the V/V traction transformer's second side by step-down transformer. Thyristor-controlled 3rd single-tuned filter is installed under a phase-leading power arm. Thyristor-controlled Reactor is installed under b phase-lagging power arm. When the locomotive load is under A power arm, the 3rd filters composed of L1, C1 and inductor L3 are switching on respectively. When the locomotive load is under B power arm, then 3rd filters composed of L2, C2 and inductor L4 are switching on respectively.

In this new structure, in order to reduce the capacity of active part of RPC and improve the stability of entire compensation system, RPC is only used to transfer active power. The thyristor-controlled reactor and 3rd filters provide reactive power. And here thyristors only play the role of switch, so they do not generate additional harmonics. Because the 3rd filter is capacitive in fundamental wave, thyristor-controlled 3rd filters and thyristor-controlled reactor are equivalent to the function of SVC, which can provide capacitive and inductive reactive power for power supply system. In Fig.1, *IA* , *IB* , *IC* means the three-phase current of the original edge of the traction transformer V/V; *Ia* , *Ib* , *Ic* means the three-phase current of the Vice-edge.

UNIFIED EQUIVALENT ELECTRICAL MODEL OF THE PROPOSED COMPENSATOR

Unified equivalent electrical model in fundamental Domain: Corresponding to the secondary winding of traction transformer, RPC can be equivalent to two controlled current sources respectively. As a result of the four-quadrant PWM rectifier control, locomotive power factor is close to 1, and it has a little of Low-frequency harmonic. so locomotive load can be equivalent to a fundamental source and a harmonic current source in parallel. In this section we only discuss the fundamental domain; the harmonic domain will be discussed in the next section. So locomotive load can be an equivalent to a fundamental current source in this section. The fundamental equivalent circuit of the novel power quality compensator under A and B power arms is shown in **Fig.2.**



(a) Fundamental domain equivalent circuit of A power arm

(b) Fundamental domain equivalent circuit of B power arm

Fig 2: Equivalent electrical model of the novel power quality compensator in fundamental domain

In **Fig.2,** the two H-bridge inverters in parallel under A and B power arms share the fundamental output current I_{Raf} , I_{Rbf} equally together. I_{af} and I_{bf} are fundamental current of A, B power arms respectively. I_{Ra1f}/k and I_{Ra2f}/k are the fundamental current of the two inverters under A power arm when converted to 27.5kV side. I_{Rb1f}/k and I_{Rb2f}/k are the fundamental current of the two converters under B power arm when converted to 27.5kV side. U_a , Z_1 and I_{Laf} are A power arm voltage of traction transformer vice-side, impedance of 3rd filter and fundamental current of locomotive respectively. U_b, Z_3 and I_{Lbf} are B power arm voltage of traction transformer vice-side, reactor resistance and fundamental current of locomotive respectively.

Because the line fundamental impedance Z_s is far smaller than the equivalent impedance $2k Z_1$ of 3rd filter and the equivalent impedance $2k Z_3$ of the reactor, we neglect the divergence effect of the line fundamental impedance and consider it as a short circuit. The following equations can be obtained from the equivalent circuit diagram:

$$\begin{cases} I_{af} = I_{Raf} + I_{Laf} + \dfrac{U_a}{k^2 Z_1} \\ I_{bf} = I_{Rbf} + I_{Lbf} + \dfrac{U_b}{k^2 Z_3} \end{cases} \tag{1}$$

Where,

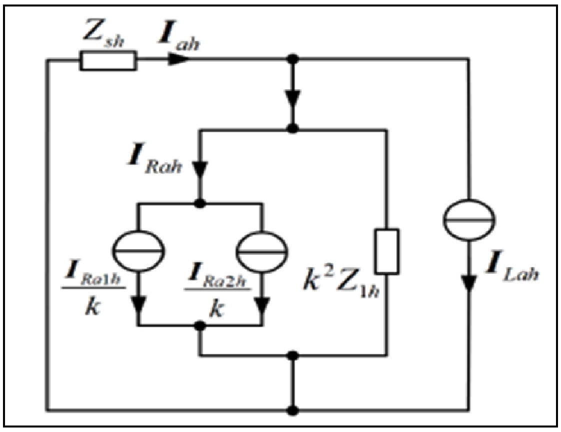
$$\begin{cases} I_{Raf} = 2\dfrac{I_{Ra1f}}{k} = 2\dfrac{I_{Ra2f}}{k} \\ I_{Rbf} = 2\dfrac{I_{Rb1f}}{k} = 2\dfrac{I_{Rb2f}}{k} \\ Z_1 = j\omega L_{1(2)} + \dfrac{1}{j\omega C_{1(2)}} \\ Z_3 = j\omega L_{3(4)} \end{cases} \tag{2}$$

In the above equations, ω is the fundamental angular frequency. $L1$ (2) expresses the inductance of $L1$ or $L2$, $C1$ (2) expresses the capacity of $C1$ or $C2$, and $L3$ (4) expresses the inductance of $L3$ or $L4$. When locomotive load is under a power arm, switch on the filter composed of $L1$ and $C1$ under A power arm and $L3$ under B power arm simultaneously. When locomotive load is under B powered arm, switch on the filter composed of $L2$ and $C2$ under A powered arm and $L4$ under B powered arm simultaneously. From equation (1) and (2), the value of $Z1$ and $Z3$ can be derived.

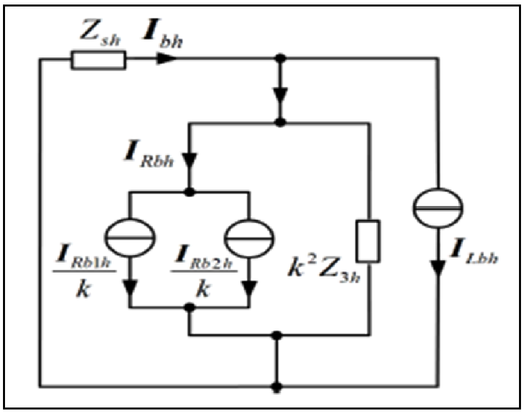
In **Fig.1**, in order to reduce the capacity of active devices and the cost, RPC is only used to transfer active power. Maximum active power is half of the active power difference between A, B power arms, that is （ $I_{Laf} - I_{Lbf}$）/2 (set it as the standards of transferring active current). Transfer active current from the power arm with smaller load to the other arm. In order to improve the reliability of the system, RPC's transferring current size could be further reduced toη (η < 1) times of the standard active current. so the capacity of the active part can be further reduced. At this point, RPC's transferring active current expression can be drawn as follows:

$$\begin{cases} I_{Raf} = \dfrac{1}{2}(I_{Lbf} - I_{Laf}) \times \eta \\ I_{Rbf} = \dfrac{1}{2}(I_{Laf} - I_{Lbf}) \times \eta \end{cases} \tag{3}$$

Unified equivalent electrical model in Harmonic domain: A harmonic domain equivalent circuit of the new power quality compensation system under A, B power arms is shown in Fig.3 respectively. I_{ah} , I_{Rah} , Z_{1h} , I_{Lah} are the line harmonic current under A power arm, the harmonic current shared by the two inverters, reactor impedance in harmonic domain and locomotive harmonic current respectively. I_{Ra1h} and I_{Ra2h} are the two respective inverters harmonic current under A power arm. I_{bh} , I_{Rbh} , Z_{3h} , I_{Lbh} are the line harmonic current under B power arm, the harmonic current shared by the two inverters, reactor impedance in harmonic domain and locomotive harmonic current respectively. I_{Rb1h} and I_{Rb2h} are the two respective inverters harmonic current under B power arm. Z_{sh} is the line harmonic impedance.



(a) Harmonic domain equivalent circuit of a power arm



(b) Harmonic domain equivalent circuit of b power arm

Fig 3: Equivalent electrical model of novel power quality compensator in harmonics domain

According to the basic principles of the circuit, the formulas can be drawn from **Fig.3:**

$$\begin{cases} I_{ah} = I_{Lah}\dfrac{k^2 z_{1h}}{z_{sh}+k^2 z_{1h}} + I_{Rah}\dfrac{k^2 z_{1h}}{z_{sh}+k^2 z_{1h}} \\ I_{bh} = I_{Lbh}\dfrac{k^2 z_{3h}}{z_{sh}+k^2 z_{3h}} + I_{Rbh}\dfrac{k^2 z_{3h}}{z_{sh}+k^2 z_{3h}} \end{cases} \quad (4)$$

To achieve the effect of harmonic suppression, it should be as follows:

$$\begin{cases} I_{ah} = 0 \\ I_{bh} = 0 \end{cases} \quad (5)$$

From equation (4) and (5), the formula can be calculated:

$$\begin{cases} I_{Rah} = -I_{Lah} \\ I_{Rbh} = -I_{Lbh} \end{cases} \quad (6)$$

Drawn from the equation (3) and (6), the total fundamental current I_{Ra} and harmonic current I_{Rb} of the inverter under the two power arms can be derived as follows:

$$\begin{cases} I_{Ra} = I_{Raf} + I_{Rah} = \dfrac{1}{2}(I_{Lbf} - I_{Laf}) \times \eta - I_{Lah} \\ I_{Rb} = I_{Rbf} + I_{Rbh} = \dfrac{1}{2}(I_{Laf} - I_{Lbf}) \times \eta - I_{Lbh} \end{cases} \quad (7)$$

Furthermore, the output current expressions ***IRa***1, ***IRa***2, ***IRb***1, ***IRb***2 of each inverter under A, B power arm can be got in equation (8). As long as the inverter output current of two power arm is under control, then the new power quality compensator can suppress harmonics and compensate negative-sequence currents successfully.

$$\begin{cases} I_{Ra1} = I_{Ra2} = \frac{1}{4}(I_{Lbf} - I_{Laf}) \times \eta - I_{Lah} \\ I_{Rb1} = I_{Rb2} = \frac{1}{4}(I_{Laf} - I_{Lbf}) \times \eta - I_{Lbh} \end{cases} \tag{8}$$

SIMULATION CIRCUIT MODEL

The simulation analysis of the proposed compensation system on the application of the high-speed electrified traction supply system is given by PSIM6.0. The simulation schematic diagram is shown in **Fig 4.** The simulation parameters are as follows: Three-phase voltage of the system is 220kV. The frequency is 50Hz; the ratio of V/V traction transformers is 8:1. The ratio of step-down transformer is 35:1.The load is AC-DC-AC electric locomotives having the capacity of 4.8MW. The capacitor of RPC at DC side is 100000uF, and the values of L_3 and L_4 are 3.396mH and 1.371mH respectively. 3rd filter parameters of L_2 and C_2 are 105.3mH and 10.7F respectively when converted to 27.5kV side.

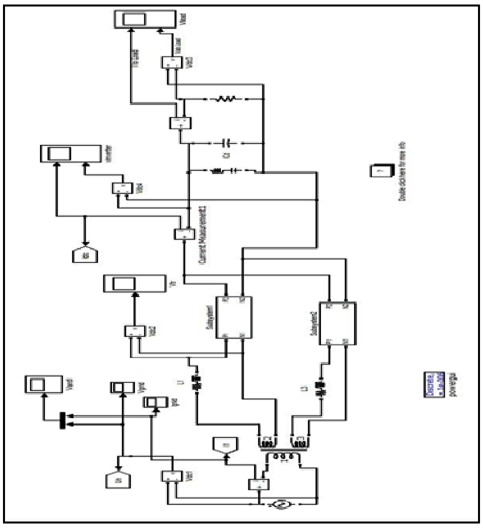


Fig 4: Simulation Circuit Model

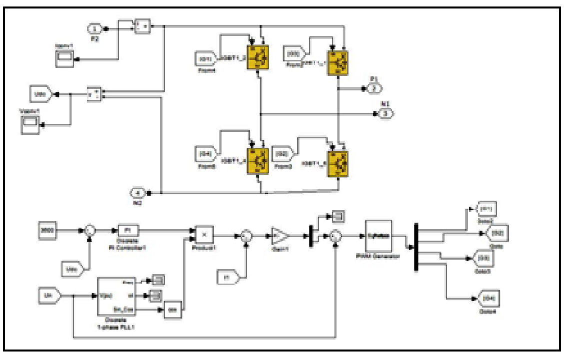


Fig 5: Subsystem1

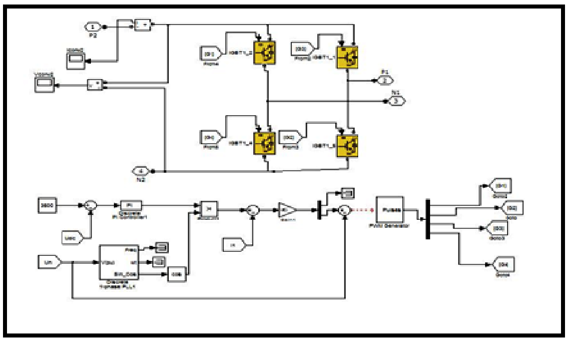
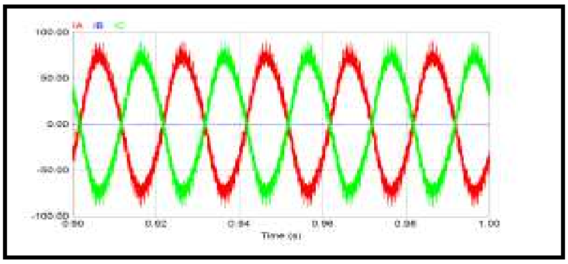
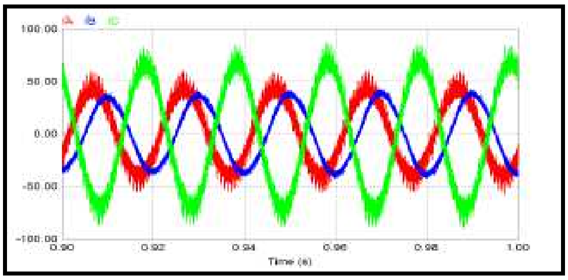


Fig 6: Subsystem2

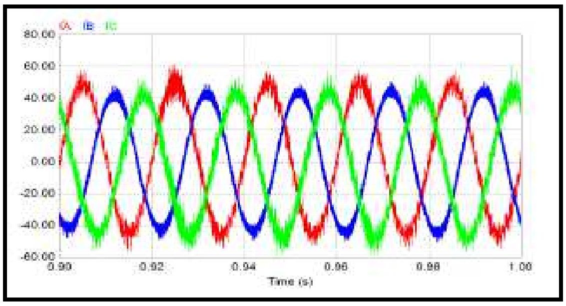
Fig 7 is the simulation current waveforms comparison before and after three-phase negative sequence current compensation at 220kV side when locomotive load is under A power arm. **Fig 7(a)** is the three-phase current waveform diagram before the compensation at the 220kV side, it can be seen that the current of B power arm IB is zero, so A and C phase current IA, IC have the same amplitude but have 180° phase difference. Meanwhile negative-sequence component of three-phase current is great content. **Fig 7(b)** is a simple RPC compensation only transferring half active power, it can be seen that B phase current amplitude equal to A phase. At the same time the negative-sequence current is decreased greatly after compensation, but still exists. **Fig 7(c)** is the three-phase current waveform after the proposed compensation system is used to transfer half active power. Meanwhile the filters and reactors are made to play the role of adjusting power factor angle of the A, B power arm to 30°. At this point, three-phase currents have same amplitude and have 120° phase angle difference. So negative-sequence components are almost zero. From comparison in **Fig 7,** it can be seen that the new power quality compensation system has many advantages, including transferring active power, compensating the negative sequence current by filter and reactor. Negative-sequence current can be fully compensated under the premise of the decreasing of active power capacity of RPC. The cost of the entire system is reduced.



(a) Three-phase current waveform before Compensation



(b) Three-phase current waveform after switching RPC on only and transferring half of active power



(c) Three-phase current waveform after a new power compensation system is switched on (30 degree for power factor angle of A, B power arm)

Figure 7: Comparison waveforms when the negative sequence of three-phase current is fully compensated

Fig 8 shows the waveform and spectrum of the locomotive load current and two power arms' current when the locomotive load is under A power arm In **Fig 8,** I_a represent the total current of A power arm. I_{La} is load current. From the waveform, it can be learned that the waveforms of total current A power arm become smooth and the burr is greatly reduced after the new power quality compensation system is run. From the frequency spectrum, it can be seen that the new power quality compensation system not only has a good performance at low-order harmonic suppression, but also has a good performance at high-order harmonic suppression. The THD of power arm current is reduced from 14% to 3%.

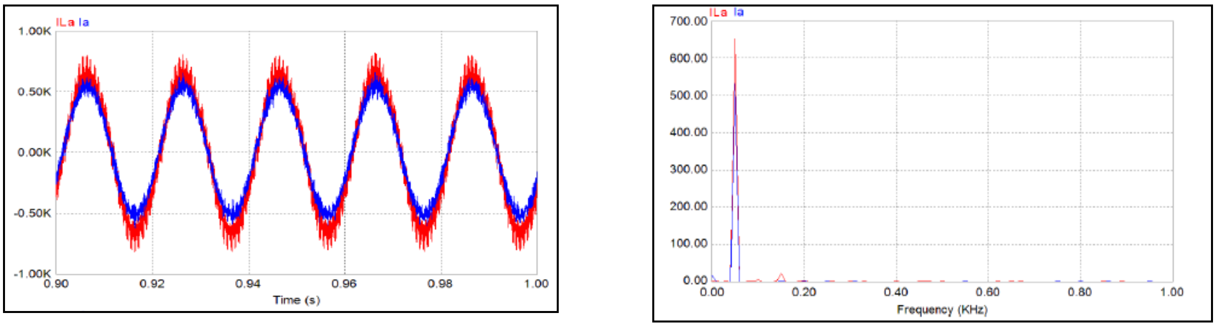


Fig 8: Current Waveforms and Spectrums of Load and Power Arm When the Locomotive Load is Under A Power Arm

The below **fig 9** shows the output waveform 'Vtr' before the subsystem runs (i.e. after the step down transformer and line impedance).

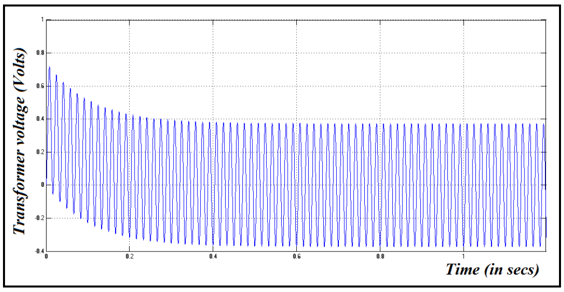


Fig 9: Vtr Output Waveform

Fig 10 shows the harmonic waveform 'Vinverter' occurs in the system (i.e. after the subsystem is run).

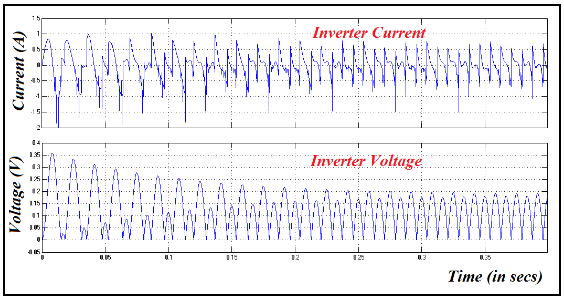


Fig 10: Vinverter Output Waveform

Fig 11 shows the pure sinusoidal waveform and overall output waveform 'Vload' after the filter is used.

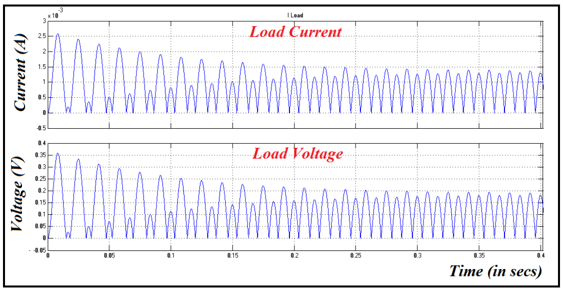


Fig 11: Vload Output Waveform

CONCLUSION

This paper proposes a new power quality compensation system which is composed of the railway power conditioner (RPC), two sets of thyristor-controlled reactor and 3rd thyristor control filter. The proposed system can be used to compensate negative-sequence current and suppress harmonic current in high-speed electrified railway. The uniform electric models in fundamental domain and harmonic domain are derived in this paper. The simulation results are shown that the proposed power quality compensator is effective. It can reduce the capacity of the active part and has a good performance at harmonic suppression and negative-sequence compensation.

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