Turkish Online Journal of Qualitative Inquiry (TOJQI)
Volume 12, Issue 10, October 2021 :3156 - 3169

Research Article

Harmonics Analysis of Indian Rail Electric Locomotive Traction Drives Converters and their Mitigation Techniques

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Abstract

In the new era, the presence of harmonics in electrical traction used in Indian railways has become one of the major concerns in the last decade. The quality of power supply has deteriorated as the voltage and current signals are loaded with unwanted frequency components. The cause of harmonic distortion in these locomotives is due to the traction substations (TSS) of Indian Railways take two-phase power (132 or 66 kV) and convert it to single-phase 25 kV power using a step-down transformer (usually in the range of 21.6 MVA capacity). Typically, two transformers are used, with one transformer normally remaining in standby mode. One of the terminals of the secondary side of the transformer is earthed, while the other terminal feeds the substation equipment and also the overhead line. The TSS, more specifically its 25 kV supply, experiences a fluctuating traction load of 50 to 800 ampere. The power factor also varies and can reach a low value of 0.8 at higher loads. The reactive power compensation requirement for such a TSS can reach as high as 4.0 to 7.0 MVAr, depending on the minimum power factor limit set.

The second major problem of TSS is the high percentage of current harmonics, especially of lower order, and the associated total distortion Current Harmonic Distortion (I_{THD}) and total supply voltage distortion / Voltage Harmonic Distortion (V_{THD}). Due to the presence of a large number of rectifiers and thyristor converters in the electric traction, the current drawn from the 25 kV supply has a high percentage of lower order current harmonics (5, 7, 11, 13......) including the 3rd order current harmonics. Since the short circuit capacity (SCC) is limited at 25 kV, the voltage distortion increases. Both the current and voltage distortions need to be addressed as per the current / prevailing standard (IEEE 519 -2014). This is the problem that is considered and addressed in detail in this paper, considering both reliability and economics of the solution.

Index Terms— Traction substations, Current harmonic distortion, Voltage harmonic distortion, Short circuit capacity, Reliability.

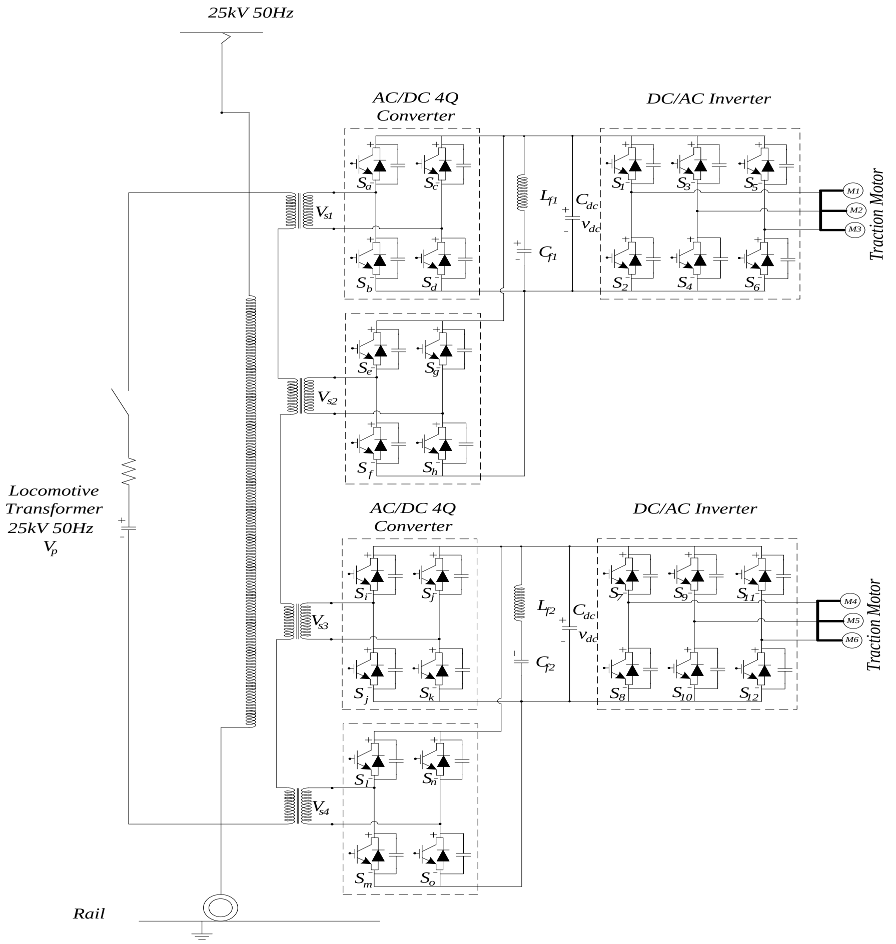

Fig. 1: Four-quadrant (4Q) converters used in AC locomotives in 25 kV 50 Hz rail network.

I. INTRODUCTION

The generation and transmission systems of supply authorities are 3-phase systems. The single-phase traction load causes unbalance in the supply system. This unbalance has undesirable effects on the-generators of the supply authorities and equipment of other consumers, if its value becomes excessive. TSS of Indian railways experiences a fluctuating load of 50 to 800 ampere. These problems pose a threat to the reliability and safety of the transportation system in many countries.

The traction power changes rapidly when the operating conditions of the locomotives change, so the traction currents of the locomotives fluctuate violently.

The harmonic currents generated by the locomotives are influenced by many factors, such as the condition of the railway line, the harmonic impedance of the power system, and the weather. But the influences of traction power are the most direct and significant among these factors. Pulse width modulated (PWM) control of traction converters with GTO or IGBT is an important development in high-speed railways. Many approaches have been proposed for modeling the 4-quadrant converters [1-4]. As the harmonic content generated by the PWM converter during PWM processes affects the power, torques generated in rotating devices minimize and become pulsating, audible noise from rotating and static devices increases, current and voltage levels increase due to resonance effects, communication interference due to inductive coupling between power and communication circuits [5-7]. However, from the overall system point of view, special attention should be paid to the harmonic behavior of the high-speed locomotives under different operating conditions. A harmonic model for PWM converter is proposed in, and the harmonic content is analyzed at rated power.

The objective of this paper is to investigate the occurrence of large frequency components in the traction system, i.e., larger harmonics, in the secondary supply system currents and to propose techniques to reduce the current harmonics in the supply system on which the tests were performed. Section II describe the different harmonic sources in 25kV, 50Hz in Indian railway systems. The simulated performance of electric traction systems is discussed in detail in Section III. The Harmonic Mitigation Technique are discussed in Section IV and Section V summarizes the work as a conclusion.

II. HARMONIC SOURCES IN 25 KV 50 HZ RAILWAY SYSTEMS

The distortion of voltage and current waveforms in AC traction systems is caused by many factors. The traction substation (TS) that supplies power to the railway catenary is not itself purely sinusoidal. The grid feeding the TS has a certain power quality and is affected by the number of nonlinear devices present in the grid and the unbalanced conditions of the power system [8-9]. The PQ issues, such as harmonic, unbalance, low-frequency voltage fluctuation, have drawn more and more attention due to their adverse effects on both traction electrical devices and utility power systems [1,2]. Four-quadrant (4Q) locomotive traction converters, based on pulse width modulation (PWM) control is also the source of generating high-frequency harmonic current components flowing into the overhead contact line (OCL). A common 4QC power electronics system widely used in 25 kV; 50 Hz locomotives is shown in Fig. 1.

In addition, auxiliary converters, along with electronic devices with nonlinear characteristics within the locomotive, are all sources of distortion for incoming AC. The inrush current of a locomotive transformer is another source of harmonics in AC traction systems. The locomotive engine must pass through several neutral sections of the power system. During this time, the supply to the main transformer in the locomotive is interrupted for a few seconds. The magnetizing current of the transformer generates low-order current harmonics with frequencies up to 300 Hz.

Arcing events due to pantograph bounce also generate low to medium frequency harmonic components that alter the overall frequency spectrum of the signals perceived at the pantograph. Rapid changes in train load and regenerative braking processes also increase the harmonics in the system. [10-12]

III. SIMULATED PERFORMANCE OF ELECTRIC TRACTION SYSTEM

The train is furnished with ac power through the catenaries line. The electrical converter provides a three-phase variable frequency and voltage supply to asynchronous motor [7]. The parameters of traction locomotives used in Indian Railways are shown in Table 1.

TABLE-I : PARAMETERS OF WAP$_7$ TRACTION LOCOMOTIVE

System Parameters	Value
Input voltage	25 kV, 50 Hz, 1 phase (AC)
Frequency	50 Hz + 3%
Transformer secondary voltage	4 x 1269 V at 25 kV line voltage
DC link voltage	2800 V nominal
Aux. Converter winding	1000V, 334 kVA, 334 A
Filter winding	1154 V, 400 kVA, 347 A
No Load current	0.5A at 22.5 kV
Inverter output voltage	415 V, 50 Hz, 3 phase (AC)

The AC traction drive system consists of PWM converters, DC link and electrical converter. The control schematic of four quadrant converter is depicted in Fig. 2 initiates with DC link voltage sensing V_{dc} and its comparison with a constant reference voltage V_{dc_ref} to generate voltage error signal is multiplied by the phase angle signal by the PI controller to produce the line current setpoint I_{s_ref}. The rectifier line current I_s is compared with the target line current I_{s_ref} and controlled by the AC current controller. An additional feed forward regulator compensates the influence of the line voltage and the voltage drop across the leakage inductance. Its output is the required inverter input voltage 4Q converter, which divided by the actual DC -link voltage V_{dc} gives the duty cycle D at switching frequency of 250 Hz.

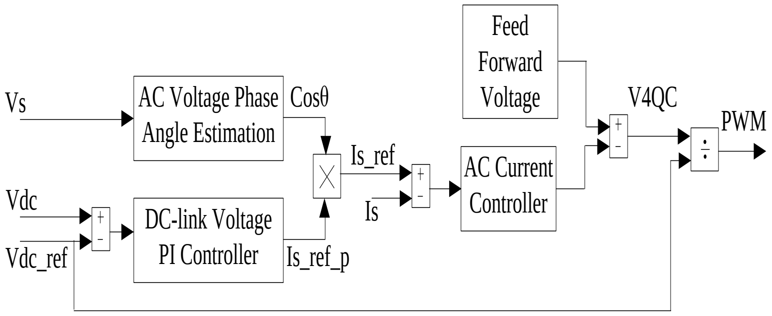

Fig. 2: Control principle of four-quadrant converter

The simulated performance of IGBT-based electric traction drive system is shown in Figs. 3 and 4 which indicates the secondary voltage, converter PWM voltage and transformer secondary current.

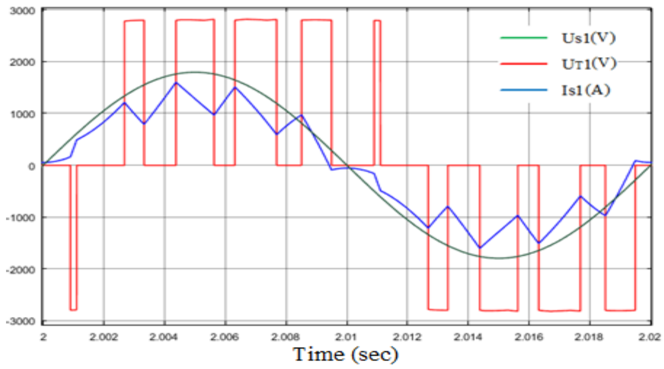

Fig. 3: Transformer secondary U_{S1}, PWM voltage U_{T1} and transformer secondary current I_{S1} of simulation results

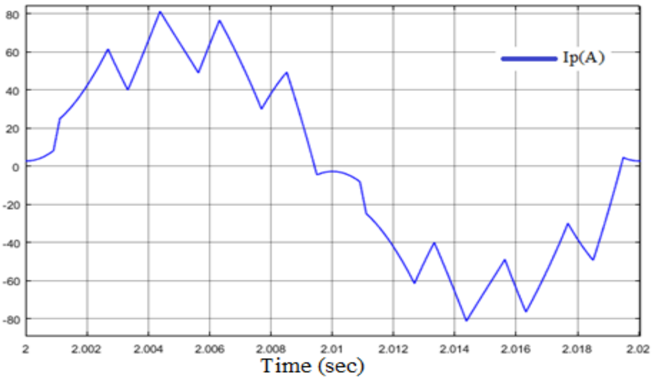

Fig. 4: Transformer primary line current

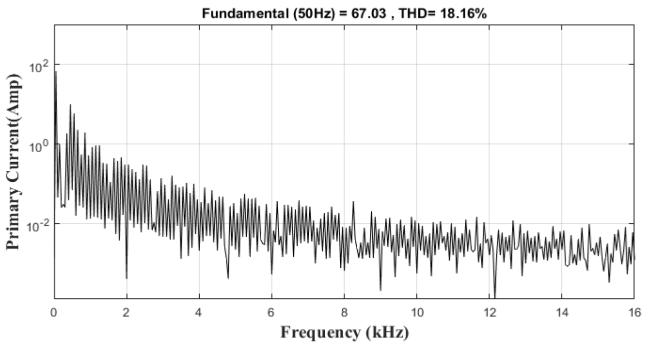

Fig. 5: Source current harmonic spectrum

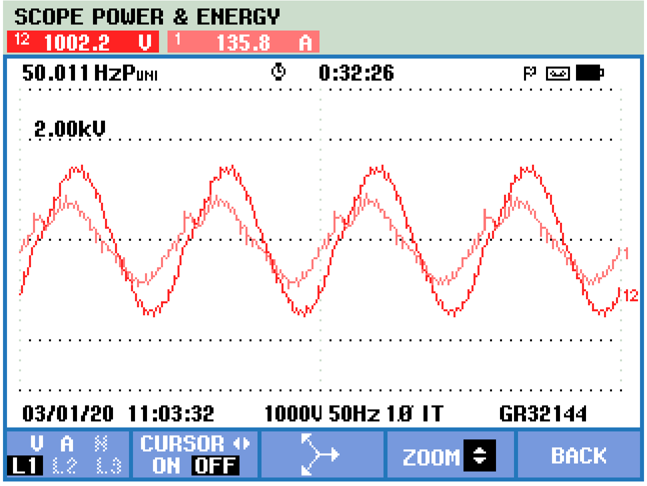

Fig. 6 : Source voltage and current

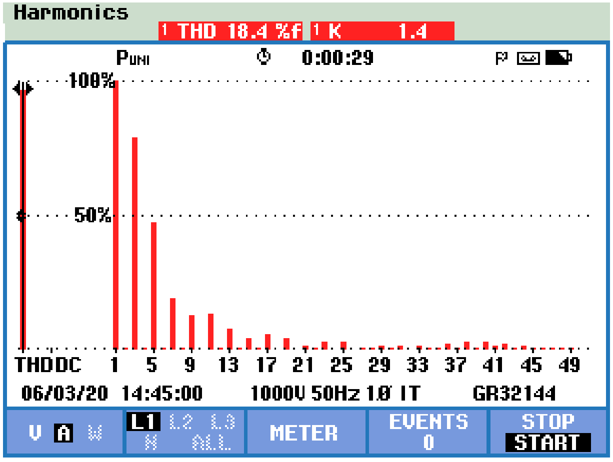

Fig. 7 Harmonic spectrum at source current

Fig. 5 shows the FFT analysis of the current which is drawn by traction system. The FFT analysis indicates that the magnitude of harmonics present in the signal is quite large which can create problems in traction system.

IV. HARMONIC MITIGATION TECHNIQUE

A. Double tuned filter circuit

Large unbalanced currents and harmonic distortion may cause considerable negative currents to impact the electrical devices in utility power system. Therefore, in order to minimize the harmonic distortion of the current, a double-tuned passive filter designed to remove both the 5th and 7th harmonic components. The connection diagram of the double tuned filter is shown in Fig. 3. A double tuned filter is a combination of two individual single tuned filters. The major advantage of a double tuned filter over a single tuned filter is that the power dissipation is less and only one inductor is subjected to the full surge voltage [10]. To determine the parameter values of the doubly tuned passive filter [10], the following expressions are used.

$$\Theta_c = \varsigma[tan\, tan\, (\alpha_1) - \ tan\, tan\, (\alpha_2)] \qquad (1)$$

Where Θ_c is the compensated reactive power, ς is the active power delivered to the load and α_1 and α_2 are the actual and set values of the phase angle. The capacitive reactance at the filter can be obtained by (2)

$$\chi_c = \frac{V^2}{\Theta_c} \qquad (2)$$

$$C_1 = C_2 = \frac{1}{2\pi f_o \chi_c} \qquad (3)$$

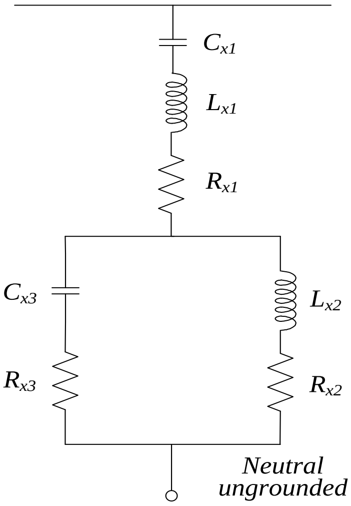

Fig. 8 Circuit diagram of double-tuned passive filter

where $C_1\ and\ C_2$ are the values of two single tuned passive filters by which double-tuned passive filter values are calculated. Now the capacitor value C1 can be obtained by (4)

Where $C_1\ and\ C_2$ are the values of two single-tuned passive filters, which are used to calculate the values of double-tuned passive filters. The capacitor value C_x can now be obtained by

$$C_x = C_1 + C_2 \qquad (4)$$

Now,

$$R_1 = \left[\frac{\left(\frac{1}{2\pi f_{r1} C_1}\right)}{\left(\frac{\sqrt{\frac{L}{C}}}{R}\right)} \right] \qquad (5)$$

$$R_2 = \left[\frac{\left(\frac{1}{2\pi f_{r2} C_2}\right)}{\left(\frac{\sqrt{\frac{L}{C}}}{R}\right)} \right] \qquad (6)$$

Furthermore, the values of the inducers for single-tuned filters converted to double-tuned filters are expressed in (7)

$$L_1 = \left(\frac{\sqrt{\frac{L}{C}}}{R}\right)^2 \left(\frac{\left(\frac{1}{2\pi f_{r1} C_1}\right)}{\left(\frac{\sqrt{\frac{L}{C}}}{R}\right)}\right)^2 \left(\frac{1}{2\pi f_o \chi_c}\right)$$

and

$$L_2 = \left(\frac{\sqrt{\frac{L}{C}}}{R}\right)^2 \left(\frac{\left(\frac{1}{2\pi f_{r2} C_2}\right)}{\left(\frac{\sqrt{\frac{L}{C}}}{R}\right)}\right)^2 \left(\frac{1}{2\pi f_o \chi_c}\right)$$

(7)

Finally, the parameters of double-tuned passive filters are expressed by (8), (9), (10), (11).

$$L_{x1} = \frac{L_1 L_2}{L_1 + L_2}$$

and

$$L_{x2} = \left[\frac{(L_1C_1 - L_2C_2)^2}{(C_1+C_2)^2(L_1+L_2)}\right] \qquad (8)$$

$$C_{x2} = \frac{C_1C_2(C_1+C_2)(L_1+L_2)^2}{(L_1C_1-L_2C_2)^2} \qquad (9)$$

$$R_{x2} = R_1\left[\frac{q^2(1-p^2)}{(1+p^2)(1+q)^2}\right] - R_2\left[\frac{(1-p^2)}{(1+p^2)(1+q)^2}\right] \qquad (10)$$

$$R_{x3} = -R_1\left[\frac{q^2p^4(1-p^2)}{(1+p^2)(1+qp^2)^2}\right] + R_2\left[\frac{(1-p^2)}{(1+p^2)(1+qp^2)^2}\right] \qquad (11)$$

where

$p = \sqrt{\frac{L_2C_2}{L_1C_1}}$ and $q = \frac{C_1}{C_2}$

(12)

Usually, R_{x1} is neglected since Inductor L_{x1} has some resistance. Despite various advantages of double-tuned filter it has some disadvantages which are

- It has higher losses as compared to single tuned filter.
- Design is complex since it has many components.
- Reactors are required for accurate tuning at fundamental frequency.

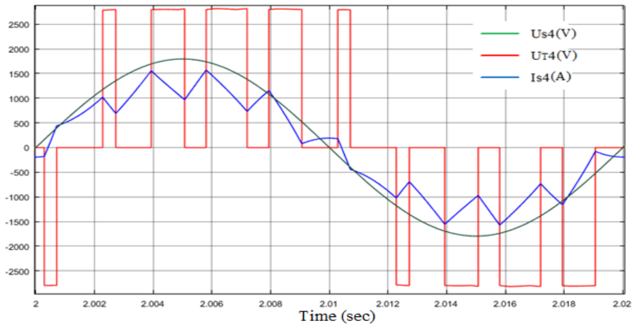

Fig. 9 : Transformer secondary U_{S1}, PWM voltage U_{T1} and transformer secondary current I_{S1} of simulation results

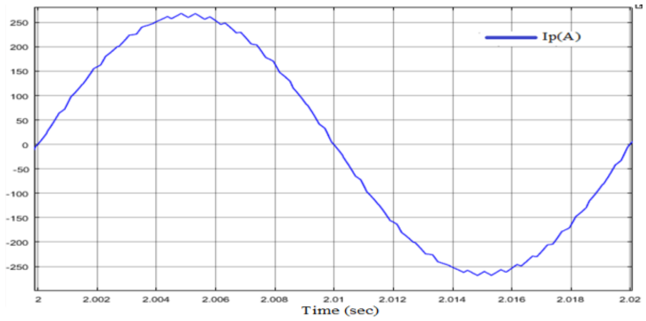

Fig. 10 : Transformer primary line current

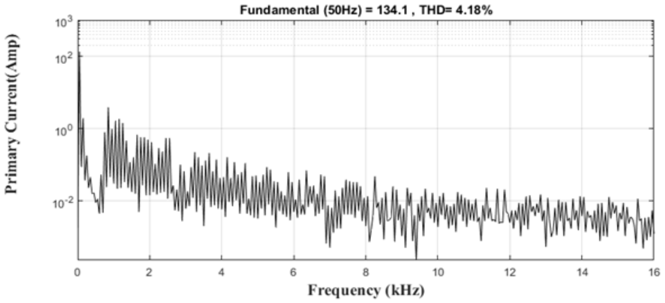

Fig. 11: Source current harmonic spectrum

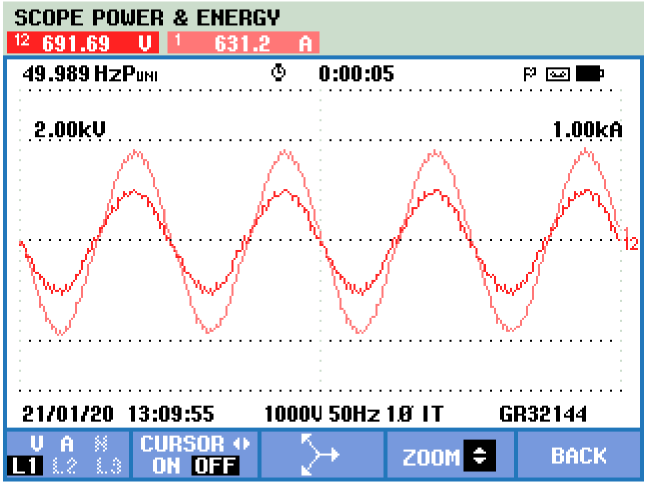

Fig. 12 : Source voltage and current

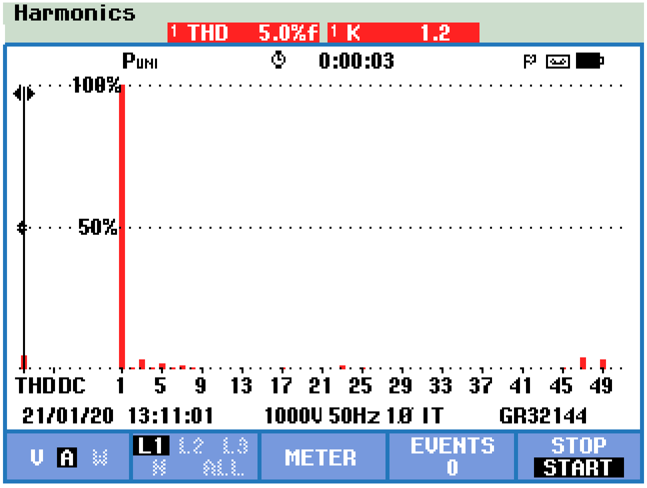

Fig. 13 Harmonic spectrum at source current

B. *Steinmetz circuit*

Locomotives are single-phase loads with high power requirements. Steinmetz compensation circuit (SCC) is used to balance the load in three phases [13].

Fig. 14 shows the configuration of the SCC. The SCC is composed of the power factor correction circuit and the balancing circuit. The variable capacitor connected in parallel in the load phase is used to compensate the reactive power. The compensation circuit consists of the variable reactance and the capacitor. With respect to the voltage of the load, the leading phase must connect the variable reactance in parallel, while the lagging phase must connect the variable capacitor in parallel. In fig. 14, the capacity of each phase is shown in eq. 13 to implement full compensation, while the total capacity is shown in eq. 14.

$$S_1 = S_L \sin \sin \alpha , S_2 = S_3 = \frac{1}{\sqrt{3}} S_L \cos \cos \alpha$$

(13)

$$S_E = (\sin \sin \alpha \ + \frac{2}{\sqrt{3}} \cos \cos \alpha \ ) S_L$$

(14)

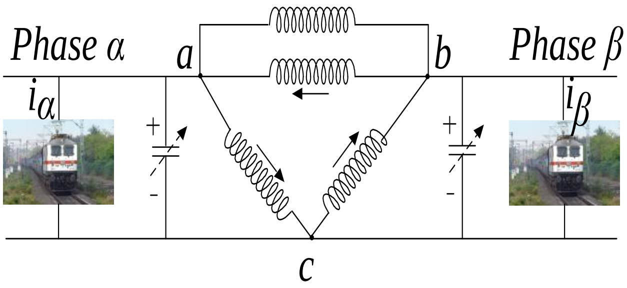

Fig. 14 : Configuration of steinmetz compensation circuit

C. *Phase shifting of switching pulses*

The second LSC on the grid side is connected to traction winding no.2 is connected to the common DC link. The pulses of the line side converters are staggered to obtain minimum harmonic content in the 25KV line. The LSC pulses are staggered in the order 0°, 90°, 45° and 135°. This will ensure that in case of one boogie operation still the staggering is at its best values. An external fixed staggering obtained from converter can be added for all the converters with respect to the synchronizing signal to obtain proper staggering of signals in case of multiple locomotive operation. A random offset can be further added to all the converters in a locomotive which could ensure minimization of harmonics in the traction network where many trains operate.

i. *Results of ripple current when there is no carrier wave shifting*

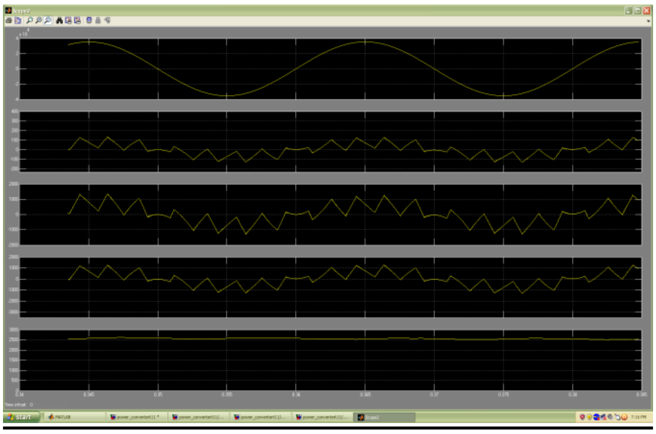

Fig. 15: Results of ripple current when there is no carrier wave shifting

ii. *Bogie System [0˚]*

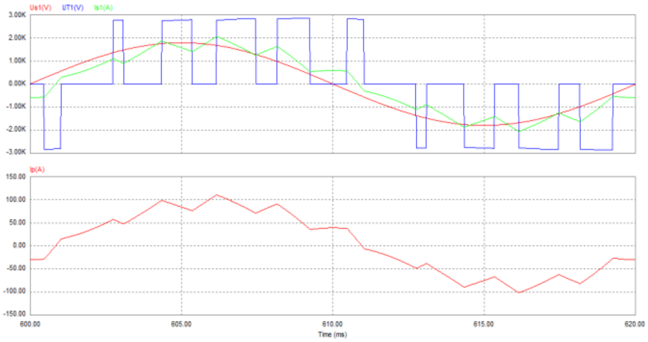

Fig.15 0.5 Bogie System

b. *1 Bogie System [0˚, 90˚]*

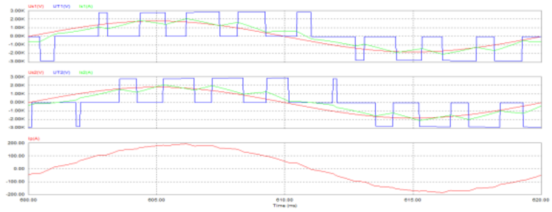

Fig. 16 1 Bogie System

c. 1.5 Bogie System [0˚ , 60˚ , 120˚]

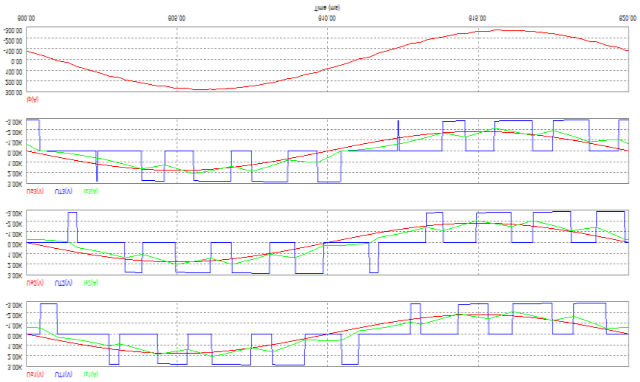

Fig. 17 1.5 Bogie System

d. 1.5 Bogie System [0˚ , 90˚ , 45˚]

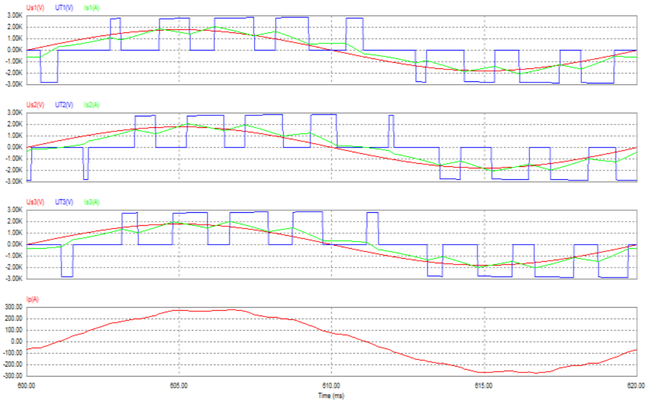

Fig. 18 1.5 Bogie System

e. 2 Bogie System [0˚ , 90˚ , 45˚ , 135˚]

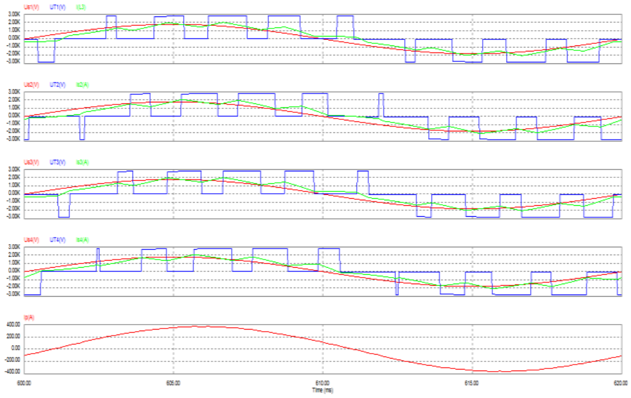

Fig. 19 2 Bogie System

f. 2 Bogie System [0˚ , 90˚ , 22.5˚ , 112.5˚]

g.

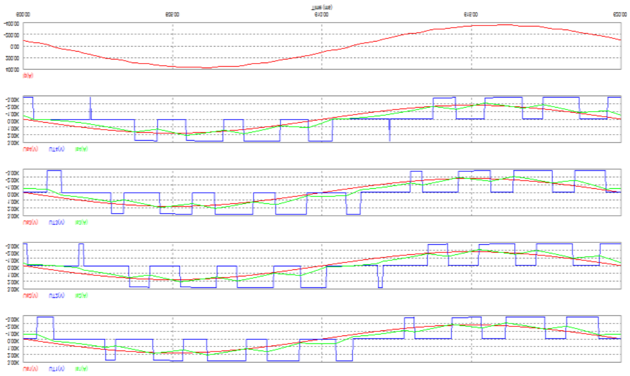

Fig. 20 2 Bogie System

where

Ip – Transformer Line Current (A)
Us1 – Transformer Secondary 1 Voltage (V)
Is1 - Transformer Secondary 1 Current (A)
Us2 – Transformer Secondary 2 Voltage (V)
Is2 - Transformer Secondary 2 Current (A)
Us3 – Transformer Secondary 3 Voltage (V)
Is3 - Transformer Secondary 3 Current (A)
Us4 – Transformer Secondary 4 Voltage (V)
Is4 - Transformer Secondary 4 Current (A)

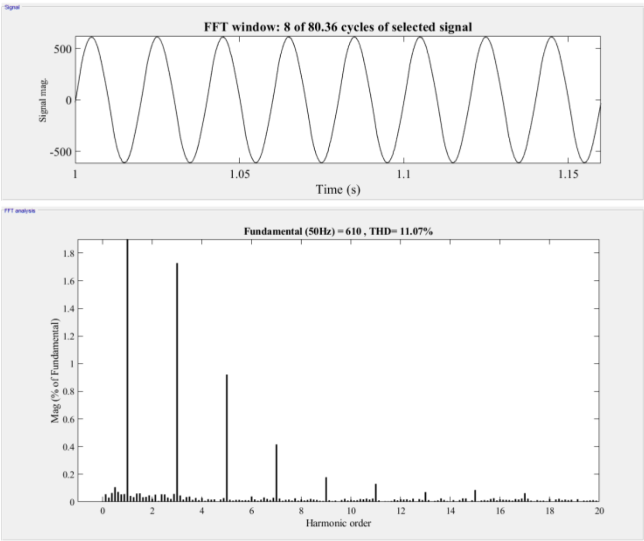

Fig. 21: Harmonic spectrum at source current

V. CONCLUSION

In this paper, in order to make detail harmonic analysis of the input current in traction converter, performance has been simulated and validated which calculate the harmonic characteristic of input current in single-phase voltage source PWM converter. Modeling techniques are adapted to simulate power quality aspects with improved computational efficiency. In this paper, discussion on the various power quality problems and also on the co-phase traction supply system using various traction transformers is made. The behavior of the system under active, reactive and harmonic compensation is studied in this paper, employing at traction transformers.

It has been observed that, the drives extract various nonfundamental frequency components which can be reduced using double-tuned passive filter. This presented method will provide appreciably credible and highly recommended solution for harmonic suppression of the input current in traction converter. The Total Harmonic Distortion is measured in each case to evaluate the harmonic contents. From the tests we observe that the Total Harmonic Distortion of load current is reduced from 18.16% to 4.18%.

The Steinmetz compensation circuit (SCC) and the balancing circuit of the SCC are independent of the structure and the control. This mode of operation is easy to implement in practice. Regardless of how the load and power factor change, the SCC can theoretically achieve an ideal compensation effect. The current ripple is reduced drastically when phase shifting is employed.

Various compensation schemes have been proposed to improve the harmonic and reactive power problems. This paper compares their performances in suppressing harmonics and reactive power.

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