Ain Shams Engineering Journal (2015) xxx, xxx–xxx

Ain Shams University

Ain Shams Engineering Journal

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ELECTRICAL ENGINEERING

Harmonic analysis on various traction transformers in co-phase traction system

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Received 30 November 2014; revised 4 May 2015; accepted 1 June 2015

KEYWORDS

Power quality;
Railway power conditioning;
Harmonics;
Co-phase traction;
Traction transformer

Abstract Traction loads are subjected to significant load changes and frequent voltage change of about 5%, which is usually unacceptable to the public electricity supply. This paper presents a comparative study of traction transformers such as Scott, YNvd, Leblanc and Impedance Matching Transformer for reducing the total harmonic distortion and thereby improving the power quality in a co-phase traction system. A dual converter with a compensator is employed together with special traction balanced transformers to reduce the harmonics, voltage unbalance, negative sequence current and reactive power problems. This scheme is implemented by using Matlab/Simulink R2009a software. The simulation results show that the performance of the Impedance Matching Transformer is better compared to other special traction transformers.

1. Introduction

In the present scenario, electric traction system is the most economical and efficient channel for both personnel and material transmission. The first railway use of three-phase supply and induction motors was on the Lugarno tramway in 1896, on which Brown installed a system using 40 Hz supply [1]. The research and development in electric traction system is progressing dramatically over the past 100 years. The study commenced in 1930s, when McGee and Harder discussed the characteristics of the traction supply system with available ac systems (two wire system, three wire system without and with transmission system) [2]. Price also produced a paper emphasizing the need of a commercial frequency power supply for railway electrification in 1957 [3].

The ac traction system consumes 25 kV, 50 Hz ac supply from 220/132/110/66 kV Extra High Voltage 3-phase grid system through a traction substation, in which step-down transformers are employed. The transformer feeds the electric locomotive through contact line system. The contact line system consists of the contact wire, suspension wire and return wire. Fig. 1 shows the basic components of the ac traction supply system. To facilitate easy load sharing, each transformer feeds to a distance of 30 km to one side. Electric locomotives are connected single phase loads in our power system. They create power quality problems due to their dynamic speed

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Peer review under responsibility of Ain Shams University.

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http://dx.doi.org/10.1016/j.asej.2015.06.004
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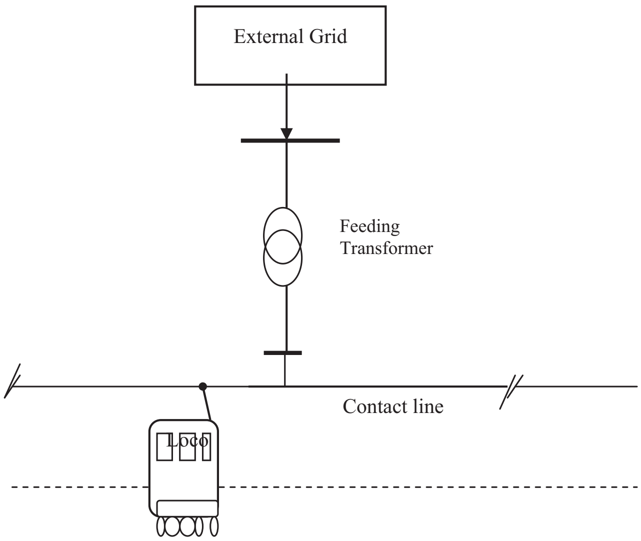

Figure 1 The schematic of electric traction supply system.

and load conditions. The new high capacity swift-flying trains require good quality power. So the transformers are designed so as to increase the power quality of system.

Power quality problem refers to a set of disturbances or conditions that produce undesirable results for equipment, system or a facility [4]. The major power quality problems in traction are voltage distortion, harmonics, negative sequence currents, power unbalance, reactive power problems, power factor problems, impulse current, flicker, etc. These problems initiate vibrations and torque reduction in machines, overheating, extraline losses in transformers and lines, interference problems with neighboring communication lines and also malfunctioning of relays. So power quality studies are given key importance in traction system.

The degree of the problem depends on the feeding electric railway traction loads, including train movement, tractive profile of electric locomotives, and power-supply scheme [5]. The current harmonics and power quality aspects are very complicated because of the frequent and strong transient regimes. Several papers discuss about the major solutions for the power quality problems in traction systems. Consequently, some standards and recommendations have been established in order to avoid the potential problems caused.

The most used standard for harmonic pollution limits is IEEE 519-1992. Harmonic suppression can be done either by rectifying the source or by implementing harmonic filtering circuits. Due to the expense in source modeling, harmonic filters are used to limit the harmonic currents flowing into the upstream network and to decrease the resonance effect causing current amplification along the 25 kV supply line. Among passive, active and hybrid filters, passive filters are most economic, but they cannot give dynamic compensation.

The negative sequence current suppression can be done with either using transformer with specific connection to balance load current or feeding from high voltage. The voltage unbalance problems caused by the unbalanced current can be resolved by using the following solutions: distribution of different power supply position, distribution of different phases to balance the load, by feeding high voltage power supply or by implementing balanced devices/equipments.

In 1984, Duncan Glover et al. have done train voltage analysis for modeling of supply system and discussed the use of booster transformers and autotransformers in traction system [6]. In 1985, Kneschke summarized the theory regarding unbalance problems [7]. He initiated the discussions on the use of special winding three phase to two phase transformers such as Scott connected, modified Woodbridge-connected, and Le Blanc connected transformers in traction systems to reduce unbalance which include the typical arrangement for rotary balancing equipment, such as synchronous condensers or induction motors, to remove the negative sequence currents from the three-phase system.

In 1993, Fumi et al. proposed a Static Power Conditioner (SPC) using self-commutated inverters in order to solve the problems of AC electrified railway [8]. This paper concluded that the SPC connected at phase A and phase B of a modified Woodbridge connected transformer installed at Substations can control active power, reactive power and harmonic currents. Simplified models of electric railway power-supply substations for three-phase power flow studies have been developed and are introduced by Chen in 1994 [9].

In 1999, Olofsson and Thunberg proposed an Energy Management System (EMS) function for optimal starting and stopping of converter units. The focus was on calculating train positions and power demands [10]. They also proposed the idea of introducing SCADA in traction systems. At the same time Bhargava concluded the electrical configuration of a traction system depends on the rail system, train load, clearance requirement, technology availability, etc. [11]. Hence the power requirements for different traction systems are different and should be such that it is cost effective economical. It provides reliable and efficient operating system without adverting other power company consumers. The paper summarized the different systems of rails, their power requirements and the main power quality problems in U.S., Sweden and Germany.

Active Filters and Harmonic Compensators were introduced for active, reactive power and harmonic compensation, flicker, voltage distortions, etc. [12–15]. Also a signal processing system for extraction of harmonics and reactive current of single-phase systems, static voltage fluctuation compensator, Multi-mode Active Power Quality Conditioner for Series Voltage Compensation and STATCOM were implemented to improve line conditions. Table 1 shows the comparison of various filters and static VAR compensators [16].

In order to avoid the disadvantage of two phase power supply system, co-phase traction system was implemented.

Table 1 Comparison of filters and static VAR comp.

Compensators	Compensations against		
	Harmonics	Passive power	Negative sequence current
Passive Power Filter	Y	Y	Y
Active Power Filter	Y	Y	N
Synchronous condenser	N	Y	N
Static VAR generator	N	Y	Y
Static VAR compensator	N	Y	Y

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Implementation of FACTS devices in traction system and co-phase system is the highlight [17–26] of this technological era. For the detailed study on co-phase traction system, a co-phase traction power supply test system was proposed [26]. Researchers now focus on reducing the power losses and initial cost by Hybrid Railway Power Conditioning Circuit (HRPC) using an LC branch provided with ac–dc–ac compensator [24,27].

In this paper, the same modeling technique of Co-phase Traction Power System (CTPS) with YNvd transformer and Active Power Compensator (APC) [21] is taken and the system was implemented in Matlab/Simulink R2009a software. Fig. 2 shows the block diagram of the proposed work. The power quality problems are addressed with the different traction transformers such as Scott, Le Blanc and Impedance Matching Transformers and a dual converter to study the reduction in the harmonics and power quality problems.

2. Cophase traction system

The two distribution lines between two adjacent substations can transfer power in same phase and can be connected together in co-phase traction system to overcome the limitations of two phase system [18–25]. Fig. 3 shows the schematic diagram of a co-phase traction system. Cophase system will also allow reducing the length of PTFE (polytetrafluoroethylene) layer (neutral section), reducing cost and increasing efficiency of system. Transients in traction system are unacceptable to the public electricity supply. However the consequence of allowing the voltage to remain at a low level, affects vehicle performance and excessive system power loss. Therefore low system voltage is an important power quality issue to traction power system than voltage fluctuation.

Transformer is the only device that acts as the adapter between the three-phase source and the single-phase load in this system. Fig. 4 shows the winding diagram of different traction transformers [12,19,27,29]. The variation in speed and load condition in electric locomotives results in unbalanced feeding current. To avoid such problems, a balanced transformer along with a dual converter as compensator is employed. In this work, we have compared THD of the following transformers: YNvd, Scott, Le-Blanc and Impedance Matching Transformers.

The special connected traction transformers take supply from the three phase external grid and convert it to two phases. One phase is connected to load and power from the other

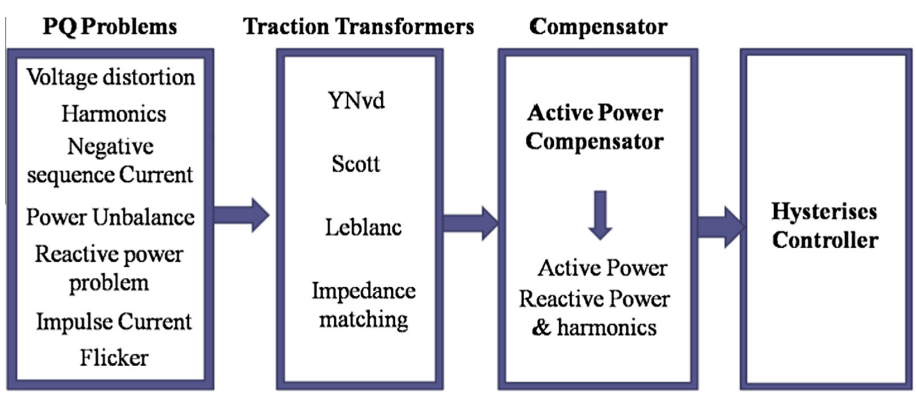

Figure 2 Schematic block diagram.

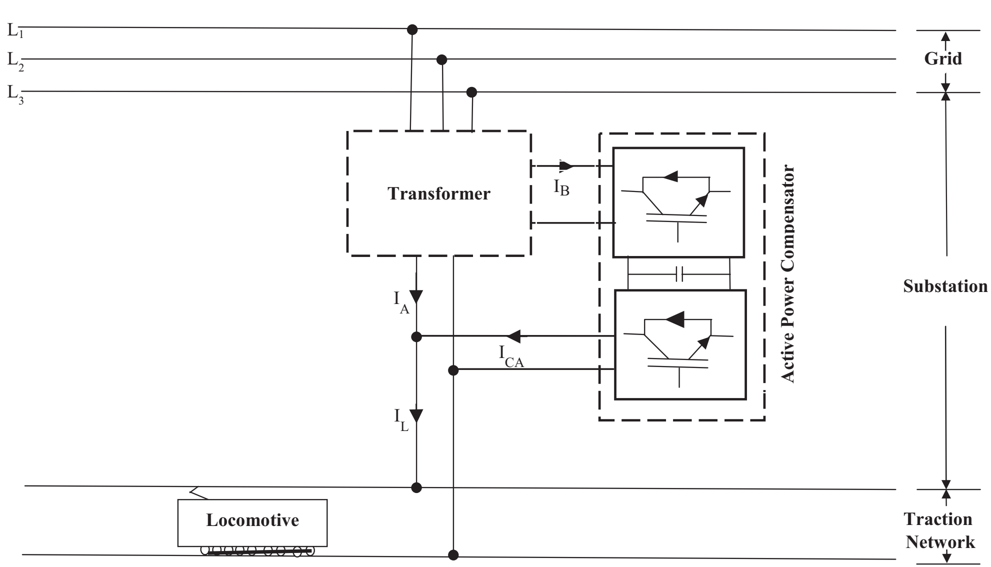

Figure 3 Schematic diagram of CTPS.

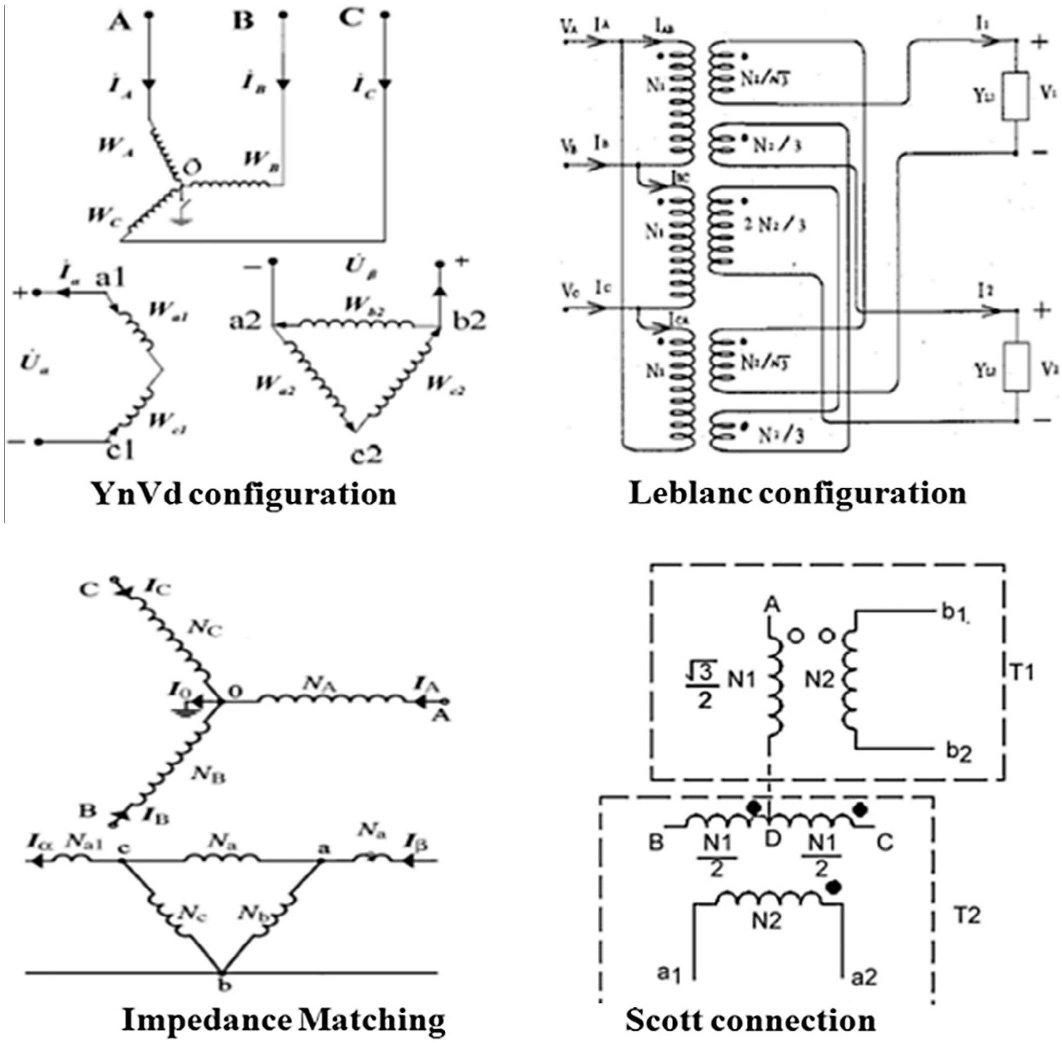

Figure 4 Special traction transformers [12,19,28,29].

phase is taken and used for providing Active compensation through the compensator. Compensator is an ac–dc–ac converter. The compensation is achieved by control circuit, in which p.u. value of voltage is multiplied with load current to find out the fundamental power component.

The load current, $i_L = i_A + i_{CA}$ (1)

where i_{CA} = compensation current
i_A = transformer phase A current

Let Input voltage, $V_A(t) = V_A \sin \omega t$ (2)

The distorted phase A current,

$$\text{Load current, } I_L(t) = \sum_{n=1}^{\alpha} I_n \sin(n\omega t + \varphi_n) \quad (3)$$

$$= I_p \sin(\omega t) + I_q \cos(\omega t) + \sum_{n=2}^{\alpha} I_n \sin(n\omega t + \varphi_n)$$

$$= I_p(t) + I_q(t) + I_h$$

where I_p is the active power component of current
I_q is the reactive power component of current
I_h is the nth harmonic current
ω is angular velocity, rad/s
φ is the phase shift in radians.

Let $V_A = 1\ p.u.$

Power, $P(t) = I_L(t) \times V_A(t)$ (4)

$$= \frac{I_p V_A}{2}[1 - \cos 2\omega t] + \frac{I_q V_A}{2} \sin 2\omega t + \sum_{n=2}^{\alpha} \left[\frac{I_n V_A}{2} [\sin\{(n-1)\omega t + \varphi_n\} + \sin\{(n+1)\omega t + \varphi_n\}]\right]$$

Active power is compensated to dc and 2ω component and the reactive power is also transferred to 2ω component. The nth harmonics is transferred to $(n \pm 1)$th ac quantities. Thus a low pass filter can easily filter the fundamental components, P_f. Thus the three phase grid currents will be balanced and undistorted. Fig. 5 shows the control circuit of scheme, in which the load current is analyzed and active component is separated. This active component is transferred to dc by filtering through a low pass filter. The filtered dc power is injected

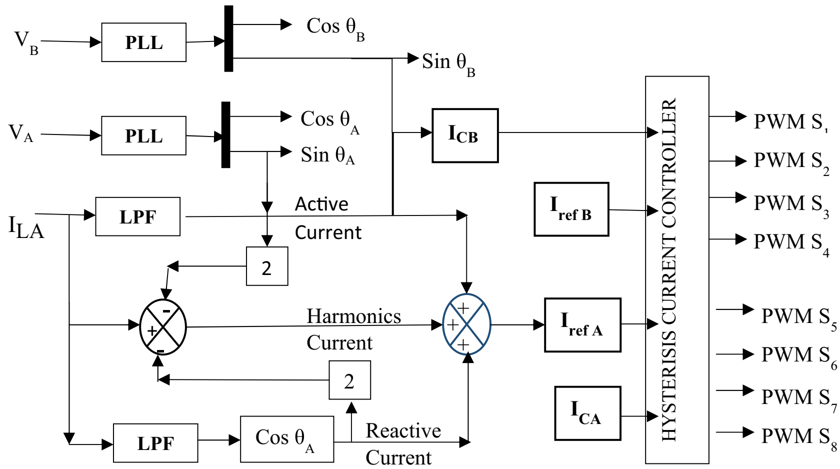

Figure 5 Block diagram of control circuit.

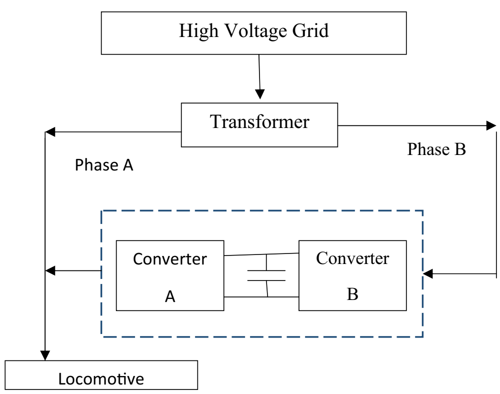

Figure 6 Schematic of power flow of RPC.

to the circuit as compensating current after making it in phase with B phase. The detailed analysis of waveforms for active, reactive and harmonics is made possible in all combinations in the same circuit.

The maximum energy that is exchanged between the load and Active Power Filter (APF), W is calculated using Eq. (5) as follows:

$$W = \frac{I_p V_A}{2\omega} + \sum_{m=1}^{\alpha} \frac{2m+1}{2m(m+1)} \frac{V_A I_{2m+1}}{2\omega} \tag{5}$$

And also the capacity of the DC link is determined using Eq. (6) as follows:

$$C = \frac{W}{2\delta V_{dc2}} \tag{6}$$

Where $\delta = \frac{(V_{dc\,max} - V_{dc\,min})}{2V_{dc}}$, fluctuating ratio

Hysteresis control, also called tolerance-band or dead-band control is employed in this work since this controller type recognizes the voltage source converters in seven different output voltages. This leads naturally to a limit-cycle oscillation in the line current vector, which by the controller is kept inside a small area of some shape in the current vector space. The advantage is small deviation from the current reference, but the switching pattern is more or less random, making it hard to predict converter losses. Fig. 6 shows the outline of power transfer in co-phase traction system.

3. Modeling of cophase traction system

The traction system is modeled in Matlab/Simulink with the following traction transformers. Table 2 shows the comparison of different traction transformers employed.

(1) Scott Transformer
The Scott connection is a special connection made in transformers to eliminate the asymmetry in the power supply line, especially on railway lines with high traffic density. So it is used near major railway junctions or on the main railway lines [28]. The Scott connection is made in system using 2 methods: using a multiwinding transformer and

Table 2 Comparison of different traction transformers.

Name	YNvd	Scott	Impedance Matching balance	Leblanc
Neutral ground in primary side	Yes	No	Yes	No
Delta connection of secondary windings	Yes	No	Yes	Yes
Electrical link of secondary windings	No	No	Yes	No
Supply of three phase A.C source for substation	Simple	Complex	Simple	Simple
Balance transformer	Yes	Yes	Yes	Yes
Making technology	Simple	Medium	Complex	Simple
Price	Low	Medium	High	Low

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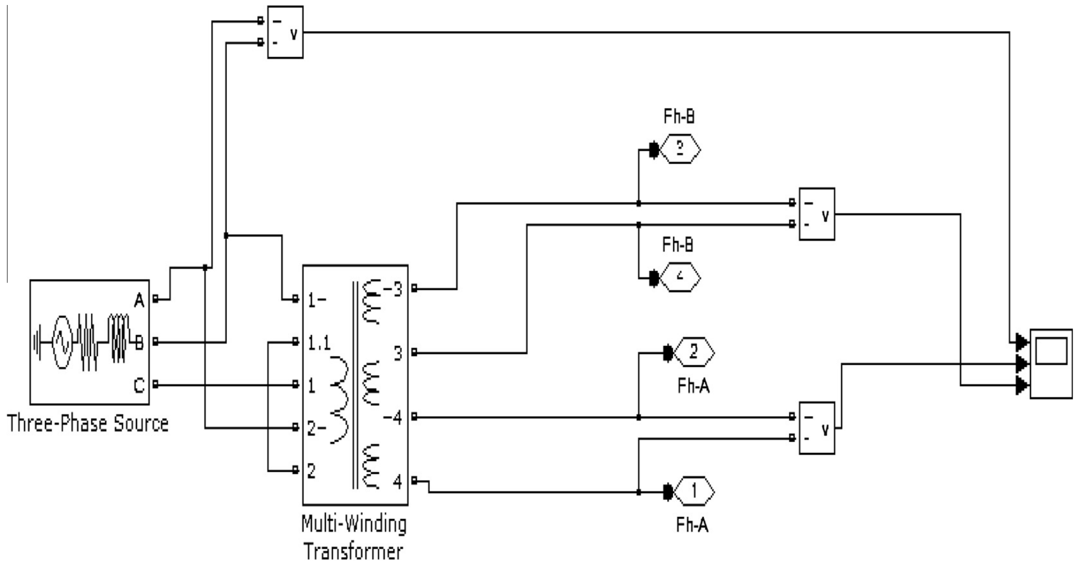

Figure 7 Model of Scott connected Transformer.

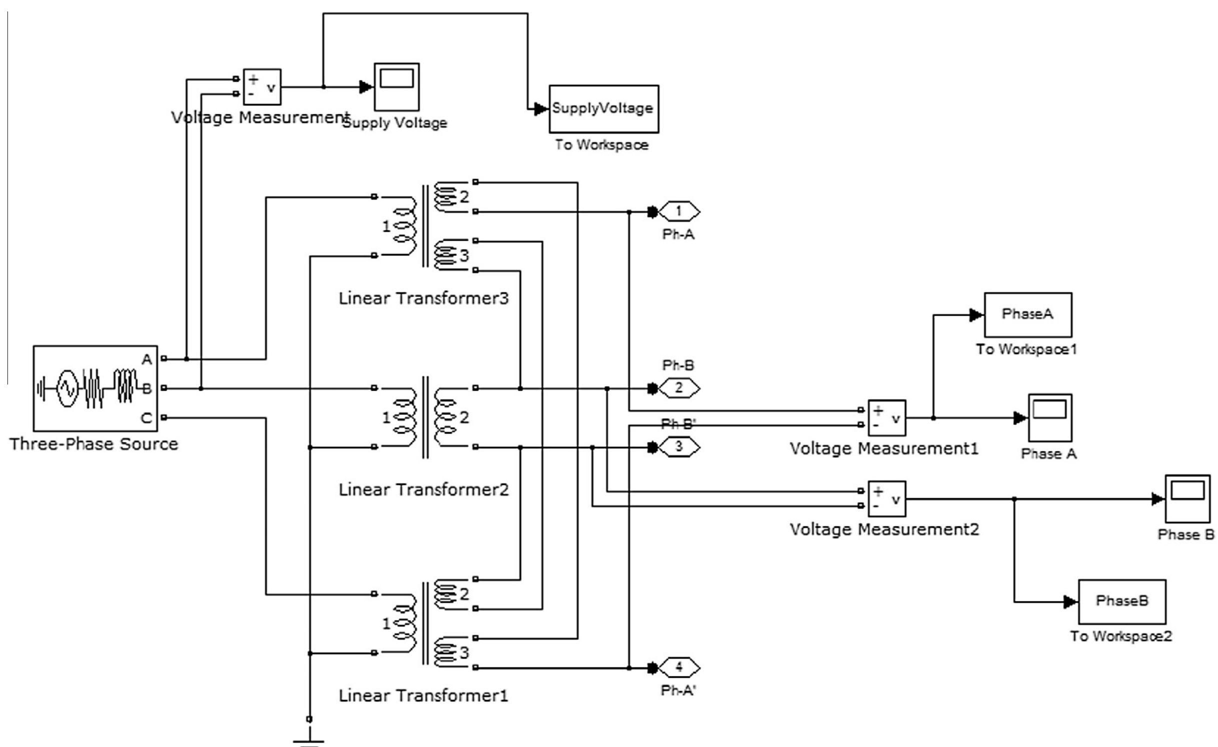

Figure 8 Model of YNvd transformer.

by using a combination of linear and multiwinding transformer. Fig. 7 shows the model of Scott transformer with multiwinding transformer.

(2) YNvd Transformer

The transformer is of YNvd configuration in which Y winding in the primary with a neutral point that can be grounded directly, as in Fig. 8. The secondary consists of a V winding and a delta winding which form a two phase 90° apart in time so that the adverse effects are reduced in the system [19].

(3) Impedance Matching Transformer

Among balanced transformers, the material utilization factor for Impedance Matching (IM) Transformer is 91.95%. Fig. 9 shows the model of Impedance Matching Transformer. This transformer can produce symmetrical two phase voltages with a 90° phase displacement. The neutral point of primary is grounded. The IM transformer reduces the impact of negative sequence current, thereby reducing unbalance problems in traction power supply. Though it has a very good overload capacity and

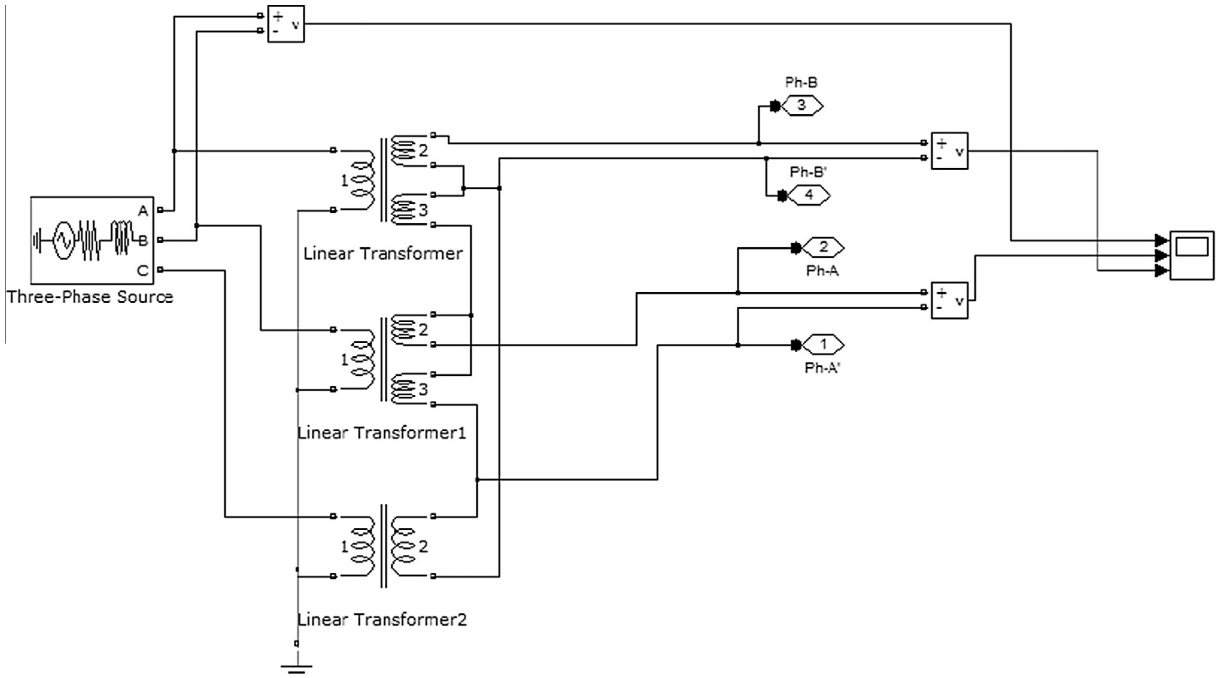

Figure 9 Model of Impedance Matching Transformer.

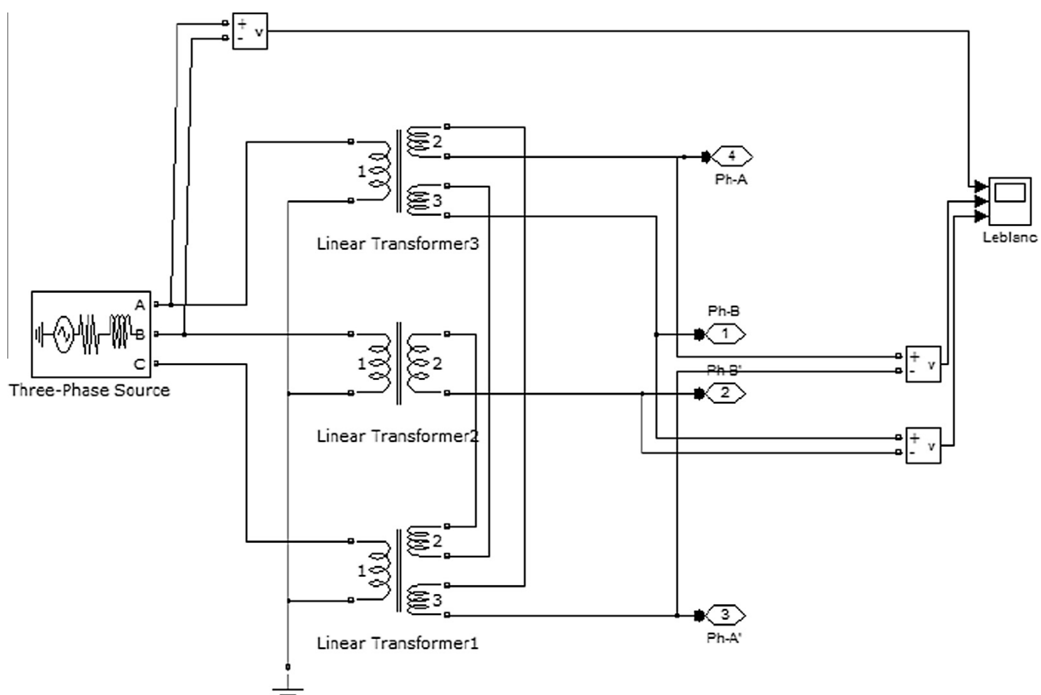

Figure 10 Model of Leblanc transformer in MATLAB.

utilization, the designing is complicated with expensive manufacturing process [29].

(4) Leblanc transformer

The Leblanc transformer is also a type of balanced transformer used in traction system to convert three phase supply system to two phase supply systems. Fig. 10 shows the model of Leblanc transformer in which the primary is star connected and there are two secondaries: a V connected winding and an open delta. The two output voltages are of equal magnitudes and have a 90° phase shift. The harmonic content in this transformer is more [30].

The traction load is modeled as a rectifier unit with RL load. Active power compensator absorbs half of the active

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power and a corresponding compensation current is injected to the load. The active power compensator is also modeled in Simulink. Fig. 11 shows the model of dual converter as active power compensator. The switching of the converter is from the control circuit. Hysteresis current controller is employed in the simulation.

4. Results and discussion

Models of different traction transformer schemes such as YNvd, Scott, Le-Blanc and Impedance Matching Transformers are analyzed in MATLAB. The model of each transformer is verified by plotting the voltage waveforms. The two output phases were found orthogonal, as in Fig. 12. The rectifier load and compensator are modeled and analyzed in MATLAB. The result is verified by plotting the waveforms. The load current is analyzed in this paper, by splitting into active, reactive and harmonic components. Figs. 13–16 show total, active, reactive and harmonic components of uncompensated load current expressed in milli seconds.

The total harmonic distortion for each case is also plotted to analyze the compensation of CTPS using different traction transformers. The FFT analysis result is taken for all cases. The FFT analysis result infers that the THD of distorted

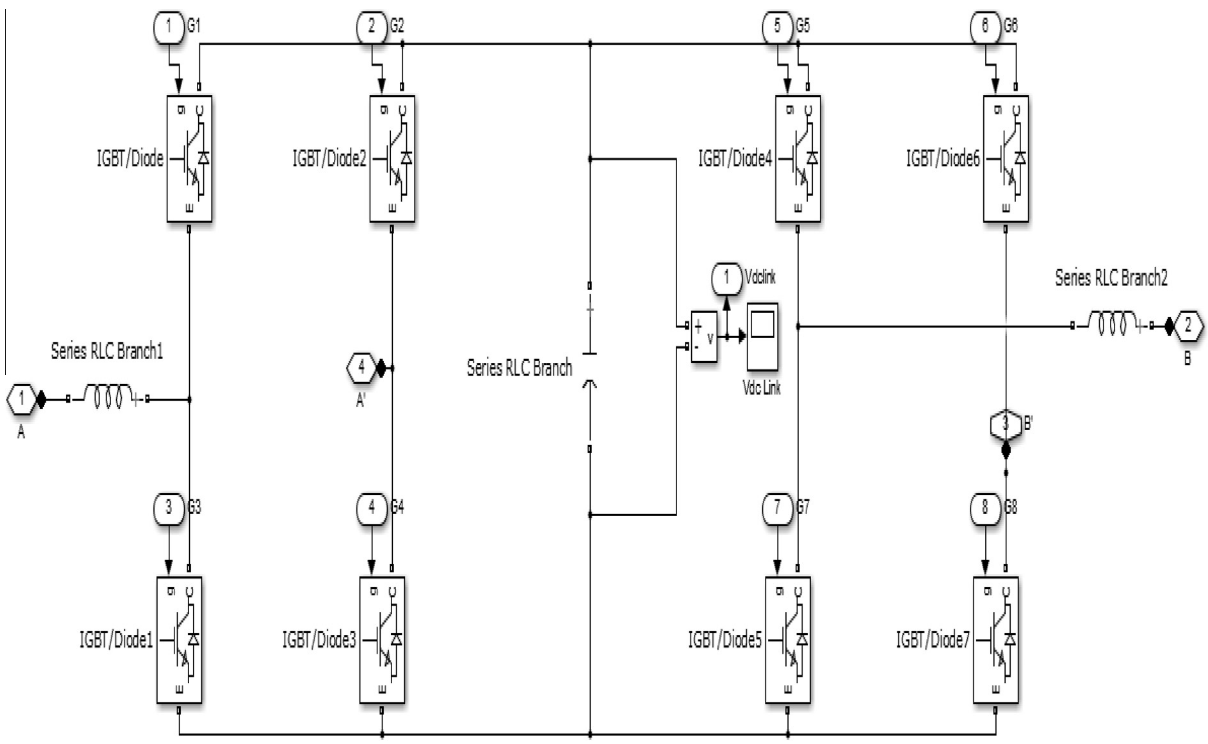

Figure 11 Model of RPC in MATLAB.

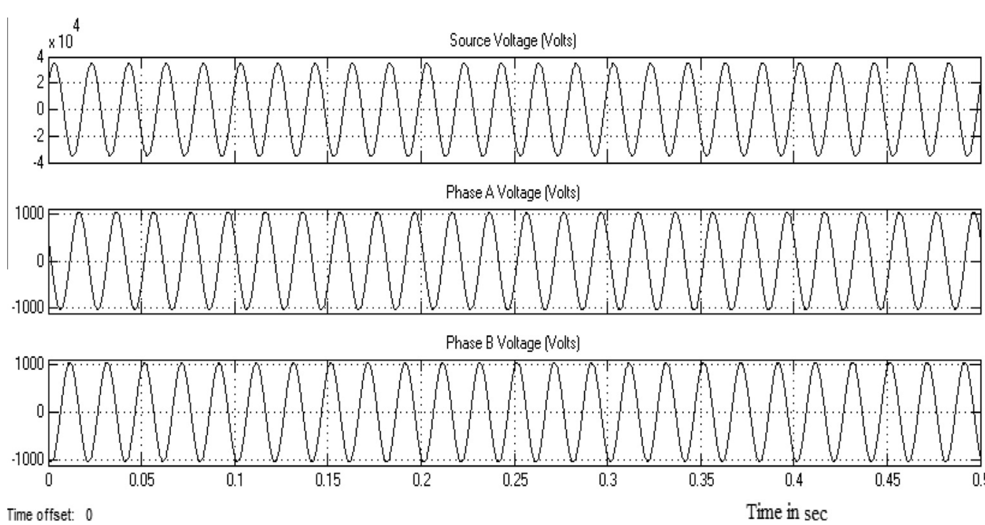

Figure 12 Voltage waveforms of YNvd transformer.

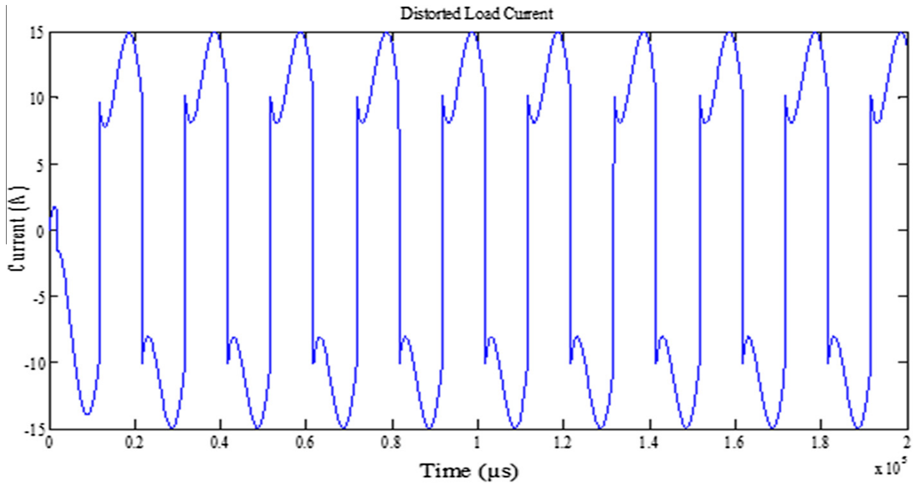

Figure 13 Waveform of uncompensated load current.

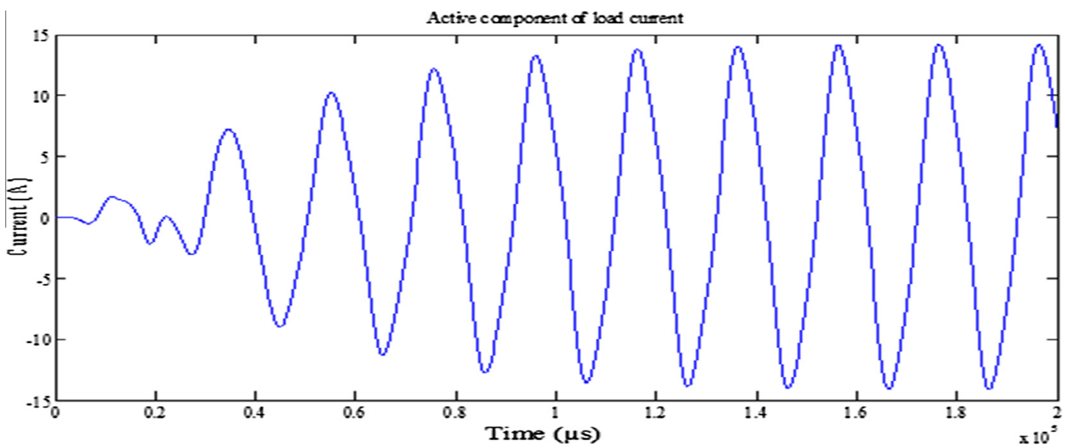

Figure 14 Waveform of active component in uncompensated load current.

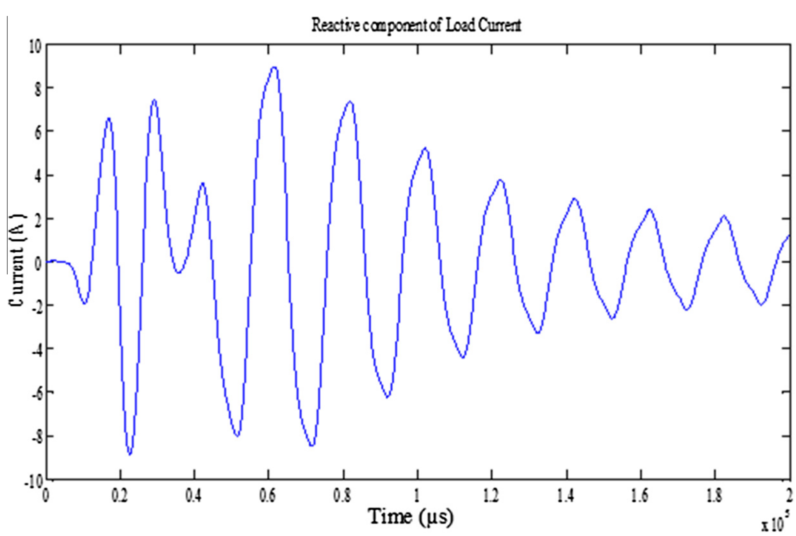

Figure 15 Waveform of reactive component in uncompensated load current.

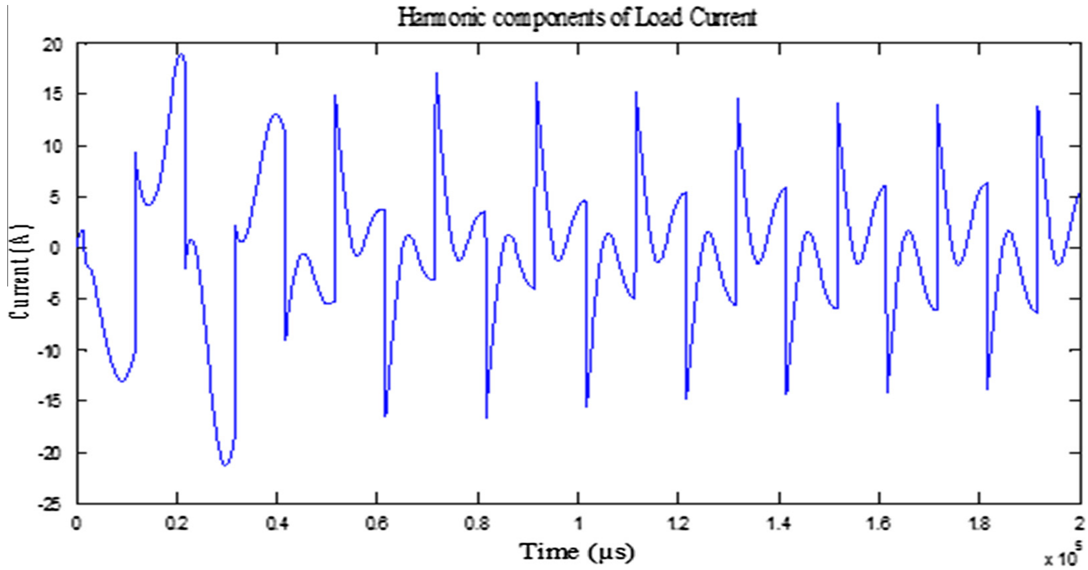

Figure 16 Waveform of harmonics in uncompensated load current.

Table 3 THD values in % found using different transformer connections.

Transformer Connection		Simulation result of THD in %	Reduction in THD (%)
YNvd		15.74	22.59
Scott transformer	Multiwinding Transformer	14.05	24.28
	Linear & multiwinding Transformer	15.24	23.09
Impedance Matching		4.73	33.6
Leblanc		15.72	22.6

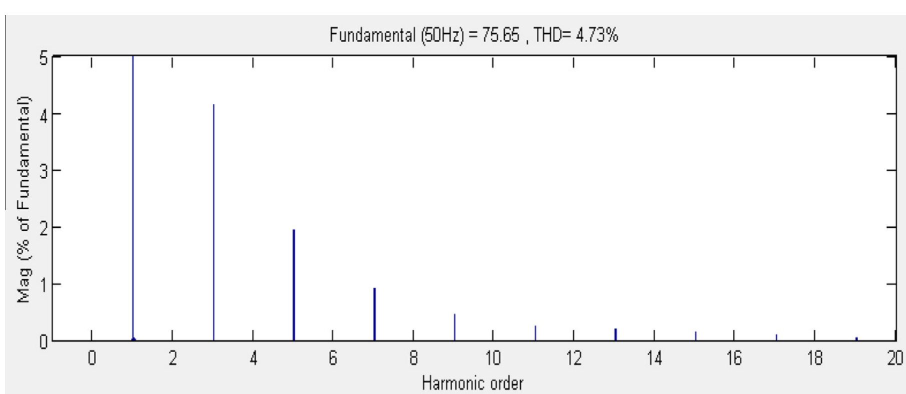

Figure 17 Harmonic analysis of IM transformer.

Table 4 Harmonic content in different transformer in THD (%).

Transformer type	3rd	5th	7th	9th	11th	13th	15th	17th
Uncompensated load	25.74	15.82	11.4	8.96	7.39	6.25	5.39	4.73
YNvd	13.15	6.98	4.02	2.32	1.34	0.85	0.66	0.57
Scott multiwinding	11.34	6.44	4.04	2.61	1.68	1.08	0.72	0.53
Multiwinding + linear Scott	12.31	7.05	4.16	2.51	1.62	1.22	1.06	0.90
Impedance Matching	4.15	1.95	0.95	0.46	0.27	0.22	0.17	0.12
Leblanc	13.15	6.98	4.02	2.32	1.34	0.85	0.66	0.57

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Table 5 FFT analysis of uncompensated load current.

Sampling time = 9.99996e-007 s

Samples per cycle = 20000.1

DC component = 0.3614

Fundamental = 13.76 peak (9.727 rms)

Total Harmonic Distortion (THD) = 38.33%

Frequency (Hz)	Harmonic order	THD (%)	Phase shift (°)
0	DC	2.63	90.0
50	Fundamental	100.00	139.0
100	h2	15.85	0.0
150	h3	19.72	139.9
200	h4	14.69	225.8
250	h5	5.82	75.0
300	h6	11.47	189.1
350	h7	4.14	0.0
400	h8	7.5	154.5
450	h9	6.81	224.7

current is 38.33%, as shown in Table 5 and that of compensated current is shown in Table 3. After the compensation the currents at the phases A and B seem to be same in amplitude and orthogonal in phase since they contain only active power. Fig. 17 shows the THD obtained for IM transformer. Third harmonics component constitutes the major harmonics. As the order of harmonics increases, the harmonic content decreases. From Table 3, it is observed that the performance of Impedance Matching Transformer is superior to other traction transformers in co-phase traction system (see Table 4).

5. Conclusions

Most of the literature looks at improving techniques to assess the power quality of a railway system. 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 different traction transformers. Traction transformers and rectifier load are modeled and analyzed in MATLAB environment. The various transformer schemes are also discussed in the above sections. The Total Harmonic Distortion is measured in each case to evaluate the harmonic contents (Table 3). From the tests we observe that the Total Harmonic Distortion of load current is reduced from 38.33% (uncompensated) to 4.73% by employing suitable balanced IM transformer and an ac–dc–ac compensator in cophase traction system. After the compensation, the currents at the phases A and B seem to be same in amplitude and orthogonal in phase since they contain only active power.

Acknowledgments

The authors acknowledge the support rendered by VIT University, Tamil Nadu, for carrying out this work. The authors also sincerely thank them for their technical support throughout the period of their study.

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