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A Three-Phase Three-Level T-Type Converter for Three-Phase Four-Wire (3P4W) Active Power Filter

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***Abstract*—Three-phase four-wire system is commonly used in residential, commercial and educational centers. However, the three-phase four-wire system has suffered from harmonic, reactive, excessive neutral current and imbalanced loads. In the proposed control, a modified sensitivity function based RC controller was investigated for a three-phase three-level T-type converter to mitigate harmonics, reactive and neutral current caused by the ever-increasing nonlinear loads. The results were analyzed and presented in collaboration with the MATLAB/Simulink environment and the TMS320F28335 board. The proposed control achieved a harmonic compensation, reactive power correction, reduction of neutral current and balancing loads. Therefore, the three-phase three-level T-type converter active power filter can be taken as a good candidate for load harmonics, reactive, and neutral current compensation.**

Keywords*— Three-level; T-type converter; Active power filters; power quality.

I. INTRODUCTION

Three-phase four-wire (3P4W) distribution feeders have been used for low voltage systems. The power feeder is taken from the secondary side of the $\Delta - \mathrm{Y}$ distribution transformer to deliver power for residential, commercial, manufacturing-offices and educational centers of single/ three-phase loads. In the present day, single-phase nonlinear loads have been increasing into the low voltage distribution systems. This is due to the attractive features of the appliances from the customer's point of view for the ever-increasing requirements of information technology [1] and electric traction [2], [3] [4]. The nonlinear and traction loads have known with an imbalance in the grids. In the case of non-sinusoidal source or unbalanced nonlinear load, the neutral current problem will be serious in the three-phase four-wire system. In the three-phase four-wire distribution cases, the third harmonic current contributed by each single-phase nonlinear load will add up together and results in three times the zero-sequence components of phase current. Moreover, the three-phase four-wire system is exposed to unbalanced loads due to single-phasing and abnormal phase change in the industry.

The distribution engineers are tried to distribute loads at the design stage equally among the phases to maintained low neutral-line current and better efficiency. However, this is not possible for large loads moreover single-phase loads switched on/off from the system in an unpredicted manner. Moreover, even the balanced single-phase nonlinear loads contribute a significant neutral current. Therefore, in today's three-phase four-wire distribution systems excess neutral current, load unbalances and high total harmonic distortion (THD) is a challenging practice.

The harmonic currents on the three-phase four-wire system have negative effects on phase line(s), Δ/Y distribution transformer and neutral conductor. The harmonic effects on the phase line(s) increase harmonic distortion and power losses. Similarly, harmonic increases the circulation of zero sequences harmonic current on the neutral line and delta winding of distribution transformer. The neutral current depends upon the type and condition of the load in the system. In many cases, the neutral-line current exceeds the phase line-current. An excessive neutral-line current causes overloading of distribution transformer and feeder, rise common mode noise, flat topping voltage waveform. The excessive neutral-line current may raise the potential of the neutral line to cause an accident. It's flat-topping voltage waveform also affects the normal function of precision devices.

Different researchers have investigated different configurations using the passive filter, star-delta transformer, zigzag-transformer, single/three-phase active power filter, and a combination of the above [5],[6],[7],[8],[9]. The passive filter has been proposed in [FBD] with resonance LC filter branches for dominant positive/negative sequence and zero sequences. The passive filter has low cost and simple to implement with the system. However, the passive filter might losses its tuning performance to the target frequency due to component aging, and creates a series/parallel resonance with the system inductance [10]. The Zigzag transformer is a low cost, high-reliability option to create a low-impedance path for zero-sequence current and open circuit for positive-sequence or negative-sequence current. However, the zig-zag transformer may not be a good option for a system with an unbalanced utility voltage. Because its low-impedance path for zero-sequence source voltage may aggravate the problem of neutral current and even may burn-down the Zig-Zag transformer, the neutral conductor and the distribution power transformer [11]. Moreover, its neutral line current attenuation level determined by the source side to the zig-zag transformer impedance ratio [8, 12]. The D–Y transformer connected in series with a reduced switched three-phase active has been proposed in [12] to achieve a reduction of neutral current. However delta-star transformer is expensive and its filtering performance depends upon its installation location.

The multilevel pulse-width-modulation has advantages on its higher efficiency up to medium switching frequency range,

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better harmonic characteristics and smaller output voltage steps as compared to the two-level VSIs [13, 14]. Among the multilevel converter, the T-type topology is much preferred for its reduced number of switching semiconductors than neutral point clamped (NPC). Thus the T-type converter has lower power losses as compared to the NPC [15]. The authors proposed a sensitivity function based repetitive controller (RC) for a three-phase three-level T-type converter [16] to mitigate dominant load harmonic frequency, reactive power, and reduced neutral current. Therefore, the research has significant importance for harmonic and reactive compensation in low voltage applications to improve power quality. In many works of literature, the repetitive controller (RC) is preferred for the active power filter controller due to its good tracking ability and high gain for the desired frequencies [17]. The instability of the RC control is limited by applying a modified squaring sensitivity function [18], [19]. This provides a wide and deep notch at the selected frequencies. The rest of the paper is organized as follows: Section 2 describes a three-phase four-wire three-level T-type converter configuration, section 3 explains the repetitive controller for inner controller section 4 presents simulation and experimental results, and finally, the conclusion is drowned in section 5.

II. MODEL OF THE SYSTEM

Fig.1 presents the three-phase four-wire three-level T-type converter with the mixed linear and nonlinear load. The converter has two mono-directional switches (Tx1, Tx2) and one bidirectional switch (Tx3) per phase. Three-phase four-wire active filter is applied to guarantee a unity power factor and to set a balanced three-phase current in the network. The PI controllers are used to regulate the dc-bus voltage variation and the voltage difference between the capacitor. The RC controller is used to compensate for the harmonics and reactive power for the nonlinear loads. The main objective of this controller is to achieve a unity power factor using the proper operation of two power switches and one ac power switch in each leg of the active power filter. The switching states in each leg to generate a unipolar voltage pattern are given as :

$$T_{x1} + T_{x2} + T_{x3} = 1 \tag{1}$$

Where $T_{xi} = 1$ if switch T_{xi} is switched on and $T_{xi} = 0$ if switch T_{xi} is switched off and i = 1, 2, 3 stands for the upper, bottom and inner legs respectively. Similarly, $x = a, b, c$ stands for the three-phase. The power switch T_{x1} is turned on to generate a positive ac-side voltage, v_{x0} which is equal to, $\frac{V_{dc}}{2}$. This effect reduces the compensation phase current, i_{cx} as the boost inductor voltage is negative, $L\frac{di_{cx}}{dt} = v_{sx} - v_{xo}$. If the compensation current i_{cx} needs to be increased T_{x2} is switched on. As a result of this, the boost inductor voltage is positive $L\frac{di_{cx}}{dt} = v_{sx} - v_{xo}$ and the ac side voltage v_{x0} is changed to $-\frac{V_{dc}}{2}$. On the other hand, zero voltage on the ac side is achieved with switching on T_{x3}. Following this switching effect, the compensation current increases for positive phase voltage and decrease for negative phase voltage, v_{sx}. As a result of this switching effect on any phase, a unipolar voltage is obtained on the respective phase of the ac side of the T-type converter. The state-space model of the T-type converter is defined as [16]:

$$\begin{aligned} \frac{di_{cx}}{dt} &= -\frac{r_x}{L} i_{cx} + \frac{V_{sx} - V_{invxo}}{L} \\ \frac{dv_{C1}}{dt} &= \frac{i_p}{C1} - \frac{v_{C1} + v_{C2}}{RC1} \\ \frac{dv_{C2}}{dt} &= -\frac{i_n}{C1} - \frac{v_{C1} + v_{C2}}{RC2} \end{aligned} \tag{2}$$

Where the converter output voltage, $v_{invxO} = T_{x1}v_{C1} - T_{x2}v_{C2}$, converter current, $i_p = T_{a1}i_{ca} + T_{b1}i_{cb} + T_{c1}i_{cc}$ and $i_n = T_{a2}i_{ca} + T_{b2}i_{cb} + T_{c2}i_{cc}$, and the capacitor voltage v_1 and v_2 respectively. The neutral load current, $i_o = T_{a3}i_{ca} + T_{b3}i_{cb} + T_{c3}i_{cc}$.

III. REPETITIVE CONTROLLER FOR INNER CURRENT LOOPS.

The dynamic of the inner current controller $G_I(s)$ is design using the transfer function as:

$$G_I(s) = \frac{i_{cx}(s)}{V(s)} = \frac{-1/r}{sL/r + 1}$$

The inner controller is discretized with the zero-order hold (ZOH) discretization method. The source voltages are defined as:

$$\begin{aligned} v_{s,a} &= V_s\sqrt{2}\,\sin(\omega_r + 0) \\ v_{s,b} &= V_s\sqrt{2}\,\sin(\omega_r - \frac{2\pi}{3}) \\ v_{s,c} &= V_s\sqrt{2}\,\sin(\omega_r - \frac{4\pi}{3}) \end{aligned} \tag{3}$$

In the Fourier series, the steady-state load current of the three-phase four-wire system is usually a periodic signal with only odd harmonics. The current in each phase can be written as:

$$\begin{aligned} i_{l,x} = \sum_n a_{n.x} \sin(\omega_r(2n+1)t + \emptyset_x) \\ + b_{n.x} \cos(\omega_r(2n+1)t + \emptyset_x) \end{aligned} \tag{4}$$

where $a_{n.x}, a_{n.x} \in R$ is the real Fourier series coefficients of the x-phase current. The load currents of the three-phase nonlinear loads are composed of the fundamental active current, fundamental reactive current, and harmonic current.

$$i_{l,x} = i_{l,x,p}(t) + i_{l,x,q}(t) + i_{l,x,h}(t) \tag{5}$$

The active nonlinear load current and the active current of the converter are supplied by the ac source:

$$i_{sx,p} = i_{c,x,p}(t) + i_{l,x,p}(t) \tag{6}$$

When the SAPF control meets its goal, the load can be seen as a resistive for the supply. Taking the I_m as the phase RMS current, the corresponding three-phase current can be written as:

$$\begin{aligned} I_a &= \sqrt{2}\ I_m \cos(\omega t) \\ I_b &= \sqrt{2}\ I_m \cos(\omega t - \frac{2}{3}\pi) \\ I_c &= \sqrt{2}\ I_m \cos(\omega t + \frac{2}{3}\pi) \end{aligned} \tag{7}$$

The asymmetrical linear and/or nonlinear harmonic in symmetrical nonlinear load causes the imbalance phase current. The imbalance phase current in any phase causes the

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neutral-point current and further aggravates the neutral-point imbalance.

The system reference and disturbance signals are usually an odd harmonic frequency of the power system. Therefore, the repetitive control is the best choice to introduce an infinite gain at a submultiple of these harmonics below the half of the sampling frequency, i.e. π/T_s. The basic block is formed from the feedback a delay of $N \in \mathbb{N}$ sampling periods, where $N = T/T_s$, T is the period of the signal to be tracked or rejected, and T_s is the sampling period.

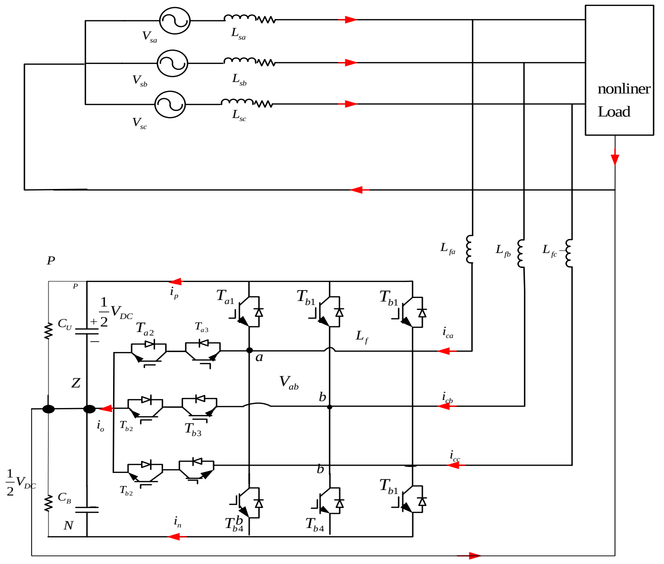

Fig. 1. Three-phase four-wire active power filter with a three-phase three-level T-type converter.

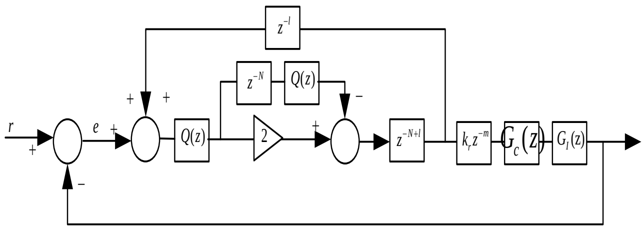

Fig. 2. Robust modified RC structure.

The inner controller is designed for a phase margin of 74.7 degrees and bandwidth of 6280 rad/sec as depicted in Fig. 3. The closed-loop system without the repetitive controller Go(z) is stable, where (8):

$$G_O = \frac{G_c(z)G_I(z)}{1 + G_c(z)G_I(z)} \tag{8}$$

The sensitivity function of the closed-loop system with RC expressed as (9):

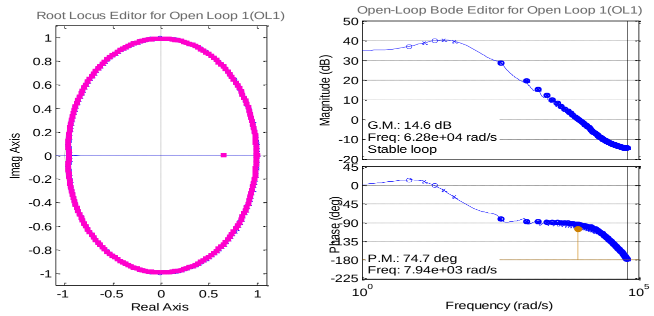

Fig. 3. Open-loop design for the RC controller.

$$S = S_O * S_{Mod\_rc} = \frac{1}{1 + G_c(z)G_I(z)} * \frac{1 - \sigma W(z)H(z)}{1 - \sigma W(z)H(z)(1 - G_x(z)G_o(z))} \tag{9}$$

Assuming that $G_x(z)G_x(z) \approx 1$, and $\sigma = -1$ for odd RC and $\sigma = 1$ for conventional RC controller, the modified RC sensitivity function can be written as (10):

$$S_{Mod\_rc} = \frac{1 - \sigma W(z)H(z)}{1 - \sigma W(z)H(z)(1 - G_x(z)G_o(z))} \approx \frac{1 - \sigma W(z)H(z)}{1 - \sigma W(z)H(z)} \tag{10}$$

Taking the square of the sensitivity function,

$$S^2_{Mod\_rc} \approx (1 - \sigma W(z)H(z))^2 \tag{11}$$

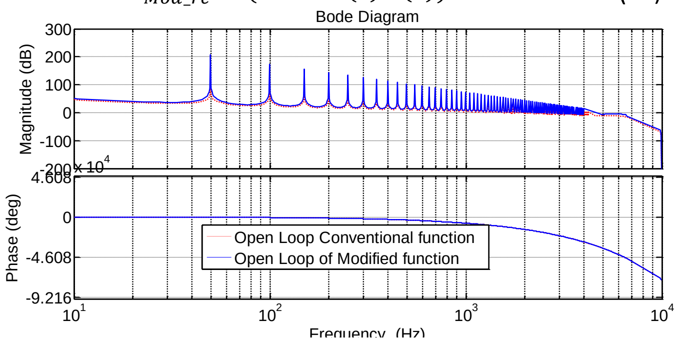

Fig. 4. Comparison of open-loop bode-plot for conventional and modified RC controller.

As one observed from Fig. 4. Comparison of open-loop bode-plot for conventional and modified RC controller and Fig. 5. Comparison of sensitivity function for convectional and modified function the modified sensitivity function based RC controller has higher open-loop gains and deep notches at targeted harmonic frequencies. This provides better performance for the RC controller as compared to the convention one [18].

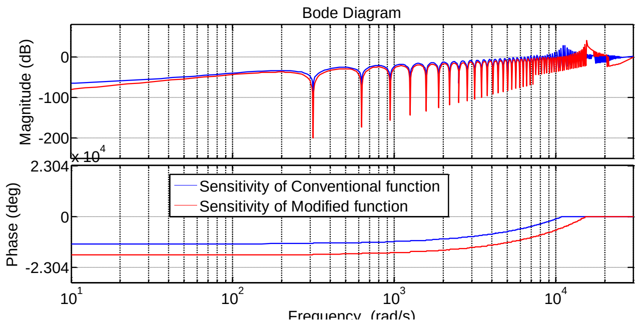

Fig. 5. Comparison of sensitivity function for convectional and modified function.

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IV. SIMULATION RESULTS AND DISCUSSION

The various MATLAB/Simulink toolboxes are used to simulate and design the proposed system of three-phase four-wire with three-level T-type inverter. The six outer IGBTs form the three-phase converter and the other six IGBT form the inner circuits. The simulation incorporates various balanced and unbalanced loads such as three-phase as well as single-phase non-linear loads. The investigation also includes unbalancing source voltage and unbalanced three-phase four-wire nonlinear load.

a) Balanced three-phase nonlinear loads

A balanced three-phase nonlinear RL load is applied to the system to evaluate the proposed controller against harmonic compensation. The system harmonic before and after compensation are presented in fig. 1 and 3 respectively.

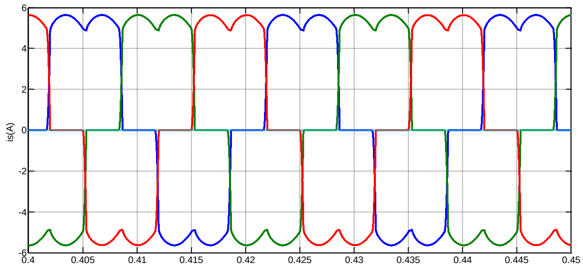

Fig. 6. Uncompensated source current waveform for balanced three-phase nonlinear load with rectifier RL loads of $R = 100\Omega$ and $L = 10$ mH.

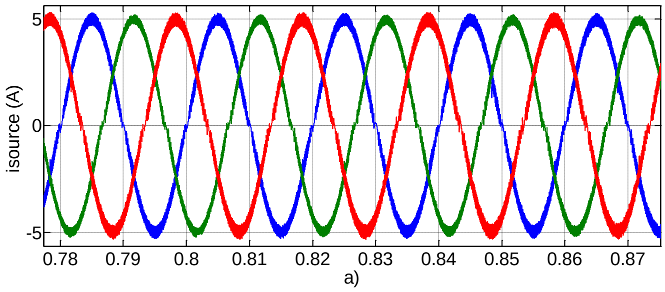

Fig. 7. Compensated source Current waveform for balanced three-phase nonlinear load with rectifier RL loads of $R = 100\Omega$ and $L = 10$ mH.

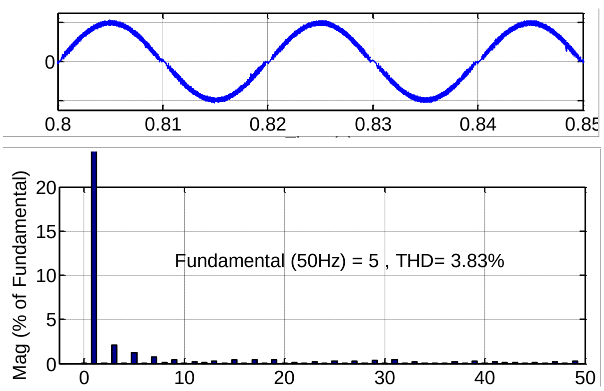

Fig. 8 . Phase current FFT after compensation for three-phase four-wire system rectifier with RL loads of $R = 100\Omega$ and $L = 10$ mH.

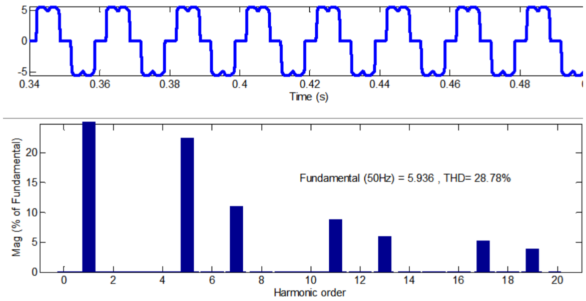

Fig. 9. The load current THD for uncompensated balanced three-phase nonlinear load with rectifier RL loads of $R = 100\Omega$ and $L = 10$ mH.

b) Unbalanced nonlinear loads

Three single-phase nonlinear loads with rectifier RC loads are connected to the system to evaluate its compensation for unbalanced nonlinear loads.

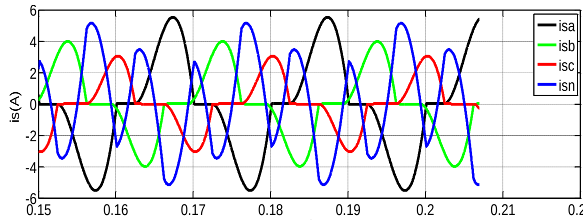

Fig. 10. Current waveform of the unbalanced three single-phase rectifier with RC loads of phase –A = 2 kW, phase –B = 1.2 kW, phase –C = 0.8 kW.

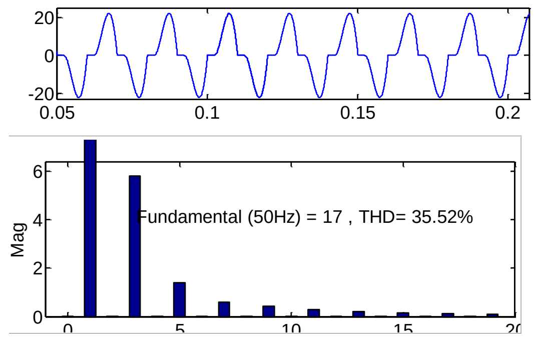

Fig. 11. The FFT analysis for phase –A.

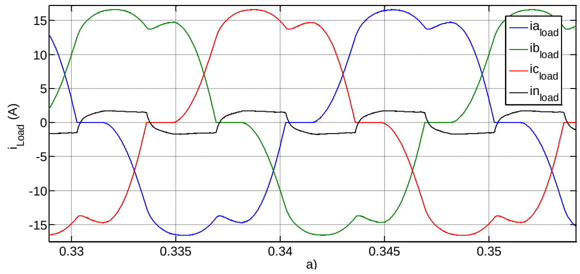

Fig. 12. Uncompensated load current.

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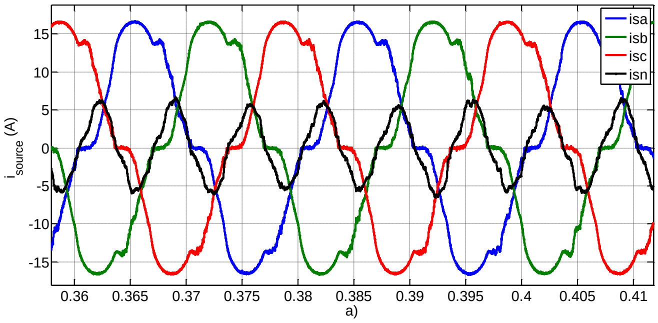

Fig. 13. The current waveforms for compensated source current for three-phase four-wire active power filter with repetitive control for three-level t-type converters.

TABLE I

HARMONIC SPECTRUM WITHOUT AND WITH PROPOSED ACTIVE FILTER

H. Order	Without filter	With APF	IEEE Standard	
	Source current THD %age	Source current THD %age	% age Indv THD	% age Indv THD
THD	16.66	4.84	8	
3	4.04	4.42	7	5
5	14.48	4.83	7	5
7	6.38	1.72	7	5
9	0.924	1.37	7	5
11	1.82	1.98	7	5
13	1.27	0.31	3.5	5
15	0.42	0.89	3.5	5
17	*0.79*	*0.66*	*3.5*	*5*

TABLE II

SPECIFICATION FOR PROPOSED ACTIVE FILTER

Parameters	**Units**
Source voltage, V_s	***380 V***
Source inductance, L_s	***0.1 mH***
Filter inductance, L_p	***3 mH***
DC-link capacitance, C_p	***2*3940 μF***
Dc voltage , V_{DC}	***580V***
Load inductance , L_d	***10 mH***
Load resistance , R_d	***100, 80,110 Ω,***
Load Capacitance , C_d	***1100 μF***

c) Unbalanced source voltage and balanced nonlinear loads

The system with an unbalanced source voltage of phase –A, $v_{sa} = 210 * \sqrt{2}\sin(\omega_r - 0)$ phase –B, $v_{s,b} = 220 * \sqrt{2}\sin(\omega_r - \frac{2\pi}{3})$ and phase –C, $v_{s,c} = 230 * \sqrt{2}\sin(\omega_r - \frac{4\pi}{3})$ are used to investigate its performance for unbalanced source voltage.

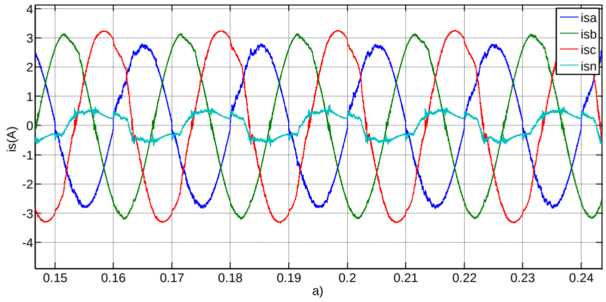

Fig. 14. Compensated source current for unbalanced source voltage of phase –A, $v_{sa} = 198 * \sqrt{2}\sin(\omega_r - 0)$ phase –B, $v_{s,b} = 220 * \sqrt{2}\sin(\omega_r - \frac{2\pi}{3})$ and phase –C, $v_{s,c} = 242 * \sqrt{2}\sin\left(\omega_r - \frac{4\pi}{3}\right)$ and balanced nonlinear load.

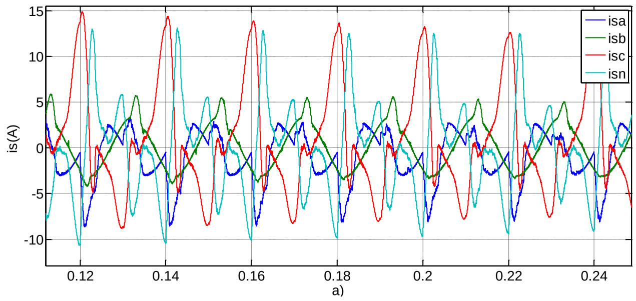

Fig. 15. Uncompensated source current for unbalanced source voltage of phase – A, $v_{sa} = 198 * \sqrt{2}\sin(\omega_r - 0)$ phase –B, $v_{s,b} = 220 * \sqrt{2}\sin(\omega_r - \frac{2\pi}{3})$ and phase –C, $v_{s,c} = 242 * \sqrt{2}\sin\left(\omega_r - \frac{4\pi}{3}\right)$ and balanced nonlinear load.

d) Unbalanced source voltage and nonlinear loads

The system with an unbalanced source voltage of phase –A, $v_{sa} = 210 * \sqrt{2}\sin(\omega_r - 0)$ phase –B, $v_{s,b} = 220 * \sqrt{2}\sin(\omega_r - \frac{2\pi}{3})$ and phase –C, $v_{s,c} = 230 * \sqrt{2}\sin(\omega_r - \frac{4\pi}{3})$ and unbalanced nonlinear loads are used to investigate its performance for unbalanced source voltage and unbalanced nonlinear loads.

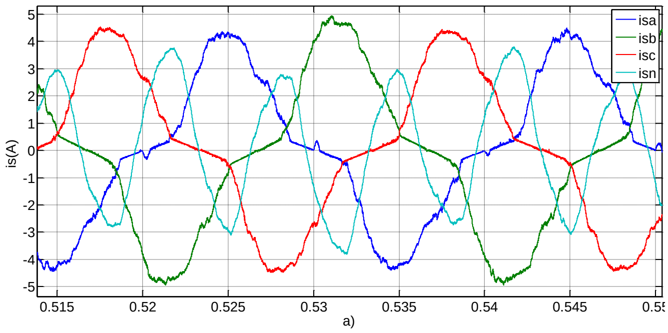

Fig. 16. Uncompensated unbalanced source and unbalanced nonlinear load source current.

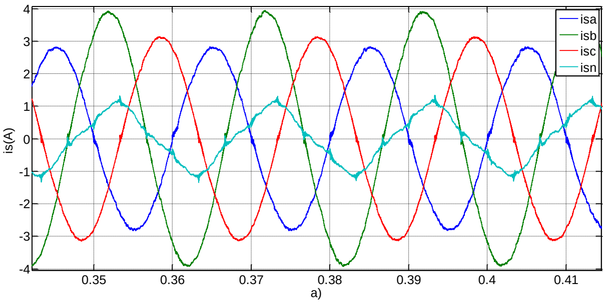

Fig. 17. Compensated unbalanced source and unbalanced nonlinear load source current

V. CONCLUSION

A three-phase four-wire active power filter based on three-level T-type converter topology was investigated to perform harmonics elimination, reactive power compensation, neutral line current reduction, and split dc capacitor voltages balance. The dc-link voltage and capacitor voltage differences are regulated with the PI controller. A repetitive controller is applied for the inner current loop controller. The loss current is applied for unit power factor regulation. The PWM strategy is applied for the converter. The adopted controller achieves for harmonic compensation, reactive power regulation and minimizes neutral current and unbalance in unbalanced nonlinear or linear loads. The three-phase three-level T-type converter has a potential advantage for low power applications.

VI. ACKNOWLEDGMENTS

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