A Zig-zag Transformer based Hybrid Power Filter with Cascaded Three level Multilevel Inverter to Enhance Power Quality in Three-Phase Four-wire Distribution Power System

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Abstract—In distribution power systems, due to nonlinear loads, harmonic currents are induced. These harmonic currents increase the losses in the distribution transformer which in turn reduce the efficiency. The Unbalance loading also results in neutral line current, which is undesirable. In worst case of the loading, the neutral current is twice the rated current which it can melt the neutral conductor of the distribution transformer. Different types of filters with different configurations are used to reduce the Total Harmonic Distortion (THD) and neutral line current. But the drawbacks of the existing filters will result in high THD, high DC link voltage and high filter currents. In this paper, A zig-zag transformer based Hybrid power filter with Cascaded three level multilevel inverter is used to reduce the neutral conductor current, harmonic currents, DC link voltage across capacitor and filter currents. The validity of the model is verified using MATLAB simulation results.

Keywords—Harmonic currents, THD, zig-zag transformer, multilevel inverter, DC link voltage.

I. Introduction

DISTRIBUTION power systems are widely used to supply power to the 3-phase and 1-phase loads. Due to nonlinear loads, such as Adjustable speed drives, Traction, Rectifiers, Arc furnaces, Start of large motors, etc. inject harmonic currents into the power system. All the nonlinear loads are harmonic current sources. The harmonic currents have the multiple of the fundamental frequency. The Unbalance loading results in huge amount of neutral line current, which is undesirable. Therefore in distribution power systems, the serious problems are harmonic currents and high neutral line current. Different types of power filters are used to eliminate the harmonic and neutral line currents.

Passive power filters are used to eliminate harmonic currents but they have the following drawbacks.

1. Less accurate.
2. Tuning problems.
3. Series and parallel resonance problems due to source impedance.
4. Large in size.

Shunt active power filters [1]-[6] can attenuate harmonic currents accurately but they have the following drawbacks.

1. High filter currents.
2. High DC link voltage.
3. Cost is high.

Hybrid power filters [7]-[14] are the combination of both passive and active power filters. The passive power filter is tuned to the most dominant harmonic frequency, generally 3rd harmonic frequency, thereby reducing the filter currents. Also, the DC link voltage is less compared to shunt active power filters. But, still, the filter currents are high in magnitude.

II. ZIG-ZAG TRANSFORMER

A zig-zag transformer is a special connection of three 1-phase transformers [15]. The circuit connection is shown in Fig .1.

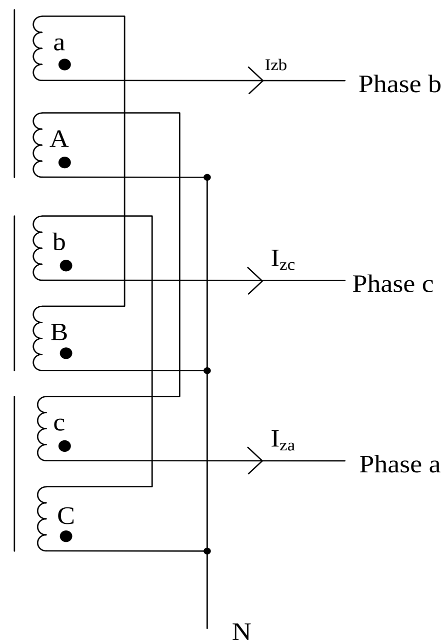

Fig. 1. Zig-zag transformer

The Turns ratio of each transformer is 1:1. The Secondary end windings of each transformer are connected to phase b, c and a conductors of utility and other remaining end windings are connected as shown in fig. 1.Clearly, from fig. 1, I_{za}=I_{zb}=Izc (since all the transformers have 1:1 turns ratio). Also $I_{za}+I_{zb}+I_{zc}$ is not equal to zero. Therefore the currents flowing in all the windings are equal and sum of all the currents is not equal to zero. It indicates that the currents are only zero sequence currents. In this way zig-zag transformer works.

A. Analysis

A zig-zag transformer is connected between source and load, it is shown in fig. 2. Its zero sequence equivalent circuit is shown in fig. 3. In fig. 3, Z_s, Z_{sn} and Z_{zt} are the source, neutral conductor and zig-zag transformer zero sequence impedances respectively. Let V_{sa}, V_{sb} and V_{sc} are the utility phase rms voltages and I_{La}, I_{Lb} and I_{Lc} are the load currents. Zero sequence voltage and current are given by eq. (1) and (2) respectively.

$$V_{s0} = \frac{1}{3}(V_{sa}+V_{sb}+V_{sc}) \quad (1)$$

$$I_{L0} = \frac{1}{3}(I_{La}+I_{Lb}+I_{Lc}) \quad (2)$$

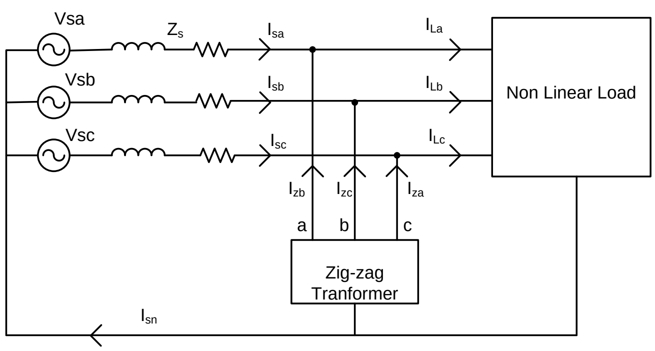

Fig. 2. Zig-zag transformer connected between source and load.

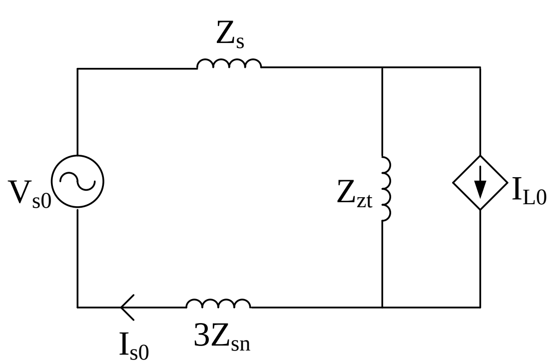

Fig. 3. Zero sequence circuit of fig. 2.

From fig. 3, the zero sequence current flowing through the utility is given by eq. (3)

$$I_{s0} = \frac{Z_{zt}}{Z_s+3Z_{sn}+Z_{zt}} I_{L0} + \frac{1}{Z_s+3Z_{sn}+Z_{zt}} V_{s0} \quad (3)$$

From eq (3), it is clear that the zero sequence current flowing through the source depends on the impedances of source and neutral conductor. Therefore Z_s should be greater than Z_{zt}. The zig-zag transformer performance is affected by the utility impedance. If the zig-zag transformer zero sequence impedance is greater than or equal to source impedance then the current flowing in the zero sequence transformer is less, which is undesirable [16]. But if an inverter is used along with it, its performance will be improved in eliminating zero sequence harmonic currents even its impedance is more than the utility impedance. The circuit diagram is shown in fig. 4. One end of a step down transformer is connected to a rectifier and the other end is connected between the two lines of the utility as shown in fig. 4. The rectifier is used to supply the power loss in the IGBTs. IGBT resistance is very small. Therefore the power required for rectifier is also very small.

The equivalent circuit of fig. 4 is shown in fig. 5. The output voltage of the power converter is given by eq. (4)

$$V_{con} = maV_{dc} \quad (4)$$

Where ma, modulation index=$\frac{i_{sn}}{v_{tri}}$

V_{dc} – DC link voltage

$V_{con} = \frac{i_{sn}}{v_{tri}} V_{dc}$

$V_{con} = k_1 i_{sn}$, where $k_1 = \frac{V_{dc}}{v_{tri}}$, gain of the amplifier.

If the load is balanced, $i_{sn} = 3i_{s0}$. Therefore $V_{con} = 3k_1 i_{s0}$.

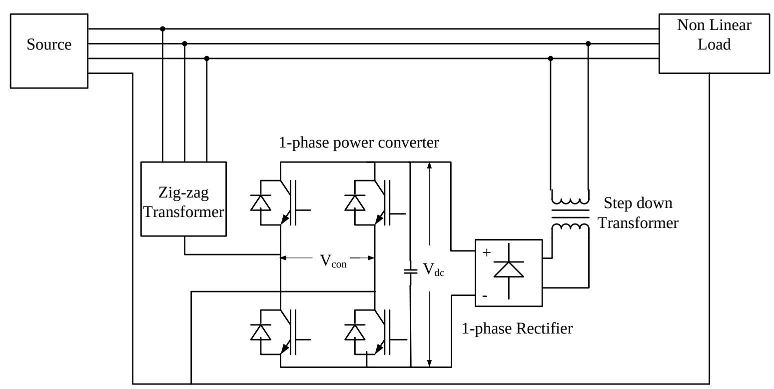

Fig. 4 inverter based zig-zag transformer

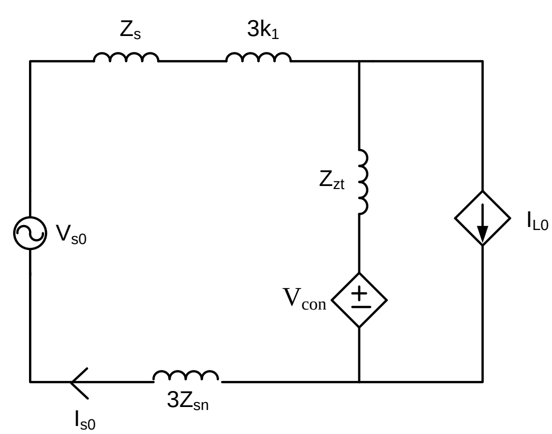

Fig. 5. Zero sequence equivalent circuit of fig. 2

The zero sequence current flowing through the utility is given by eq. (5)

$$I_{s0}=\frac{Z_{zt}}{Z_s+z_{zt}+3z_{sn}+3k_1}\ I_{L0}+\frac{V_{s0}}{Z_s+z_{zt}+3z_{sn}+3k_1} \quad (5)$$

In eq. (5), the term, $3k_1$ is added in the denominator and represents the impedance. Therefore it reduces the current flowing through the utility.

III. MULTILEVEL INVERTERS

The term, multilevel inverter was introduced by Nabae et al. [18]. If the number of levels in the inverter output voltage increase, then the output voltage will have less THD. There are three different topologies of multilevel inverters, namely, diode clamped multilevel inverter [4], flying capacitor multilevel inverter [17], [19], [20] and cascaded multilevel inverter with different DC voltage sources [17], [21] – [23].

A patent appeared in 1975 on cascaded multilevel inverter [23]. After so many modifications of cascaded multilevel inverter, diode clamped multilevel inverter was developed [24]. Many applications come in 1980 based on diode clamped multilevel inverter [25]. Although the cascaded multilevel inverter was first invented, its applications came after 1990. Many patents filed on cascaded multilevel inverters. Multilevel inverters are extensively used in high power applications with medium voltage levels. Multilevel inverters are used in mills, conveyors, fans, pumps etc.

IV. INVERTER TOPOLOGIES

A. *Diode Clamped Multilevel Inverter*

A three level diode clamped (Neutral Point Clamped) multilevel inverter is shown in fig. 6.

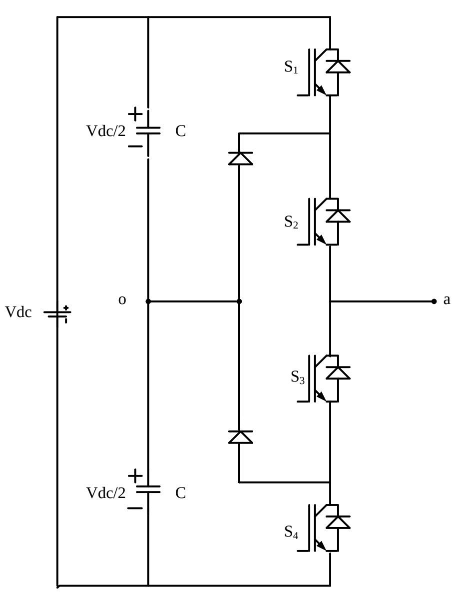

Fig. 6. Three level diode clamped multilevel inverter.

The output voltage, Vao, has three states, $\frac{V_{dc}}{2}$, 0 and $-\frac{V_{dc}}{2}$. If switches S_1 and S_2 are turned ON, then the output voltage Vao= $\frac{V_{dc}}{2}$. If switches S_2 and S_3 are turned ON, then the output voltage Vao=0. If switches S_3 and S_4 are turned ON, then the output voltage Vao= $-\frac{V_{dc}}{2}$.

B. *Flying Capacitor Multilevel Inverter*

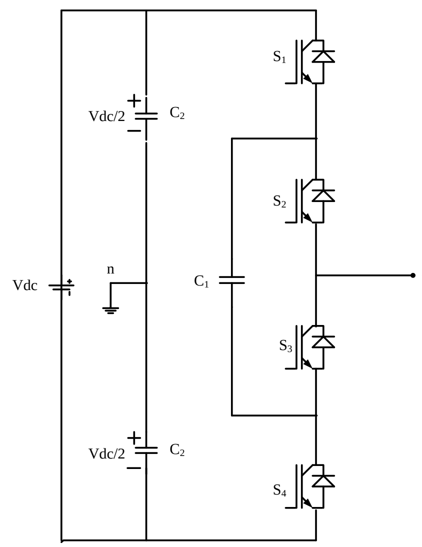

Fig. 7. Three level flying capacitor multilevel inverter

A three level flying capacitor multilevel inverter is shown in fig. 7 [17], [19], and [20]. The output voltage has three levels, $\frac{V_{dcc}}{2}$, 0 and $-\frac{V_{dcc}}{2}$. To get Van=$\frac{V_{dcc}}{2}$, the switches S_1 and S_2 need to be turned ON. To get Van=$-\frac{V_{dcc}}{2}$, the switches S_3 and S_4 need to be turned ON. To get Van=0, either the switches S_1 and S_3 or S_2 and S_4 have to be turned ON.

C. *Cascaded Multilevel Inverter*

Fig. 8 represents the three level cascaded multilevel inverter. It uses separate DC voltage sources. The output voltage V_{AO} has three levels, V_{dc}, 0 and $-V_{dc}$. To get V_{dc}, the switches S_{a1} and S_{a4} have to be turned ON. To get V_{AO}=0, the switches S_{a2} and S_{a4} have to be turned ON. To get $V_{AO}=-V_{dc}$, the switches S_{a2} and S_{a3} have to be turned ON.

If the output voltage level is more than 3, then the cascaded and NPC will have same number of separate DC voltage sources [25], [27]. Also, both will work perfectly for harmonic elimination and reactive power compensation [28], [29] and [30]. Flying capacitor multilevel inverter is not suitable for harmonic elimination, since it does not have voltage balance [31].

The first UPFC (Unified Power Flow Controller) was developed with three level diode clamped multilevel inverter

[32]. Among all topologies, the best topology is cascaded multilevel inverter for harmonic currents elimination/ reactive power compensation and other utility applications [26], [29] and [30]. Therefore, in this paper, three level cascaded multilevel inverter is used along with zig-zag transformer and passive power filter to eliminate harmonic currents and neutral line current in 3-phase, 4-wire distribution power system.

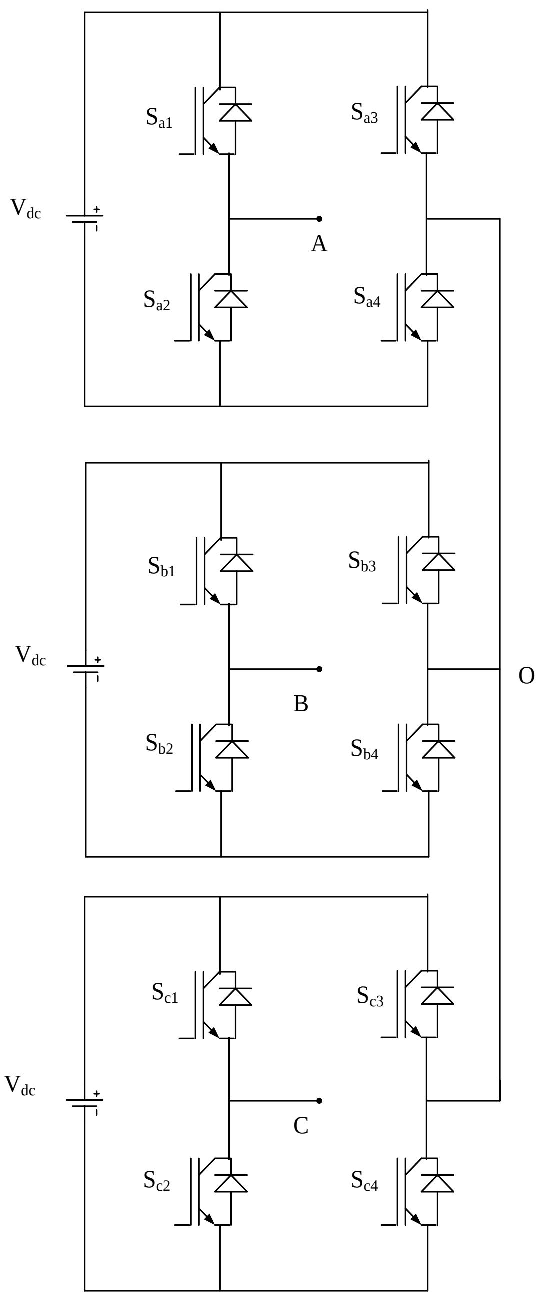

Fig. 8. Three level cascaded multilevel inverter

V. THREE PHASE FOUR WIRE HYBRID POWER CONDITIONER WITH MULTILEVEL INVERTER

It is shown in fig .9. It consists of a neutral current suppressor and hybrid power filter with a neutral point clamped three level multilevel inverter. The neutral current suppressor consists of a zig zigzag transformer [15]-[16], diode bridge rectifier and 1-phase power converter. The one end of the 1-phase step-down transformer is connected between the two lines of 3-phase utility and the other end is connected to the diode bridge rectifier. When the converter switches are conducting, results in power loss. This power loss is very small and it is supplied by diode bridge rectifier. Feed forward control is used to control the 1-phase converter. First, the neutral conductor current is detected with the help of a current detector. It is compared with a high-frequency carrier signal and the error is sent to the PI controller. The PI controller gives pulses to power electronic switches. The output voltage of the 1-phase converter is given by eq.(6)

$$V_{con}=K_{con}I_{sn} \tag{6}$$

The hybrid power filter consists of a passive power filter and 3-phase three level cascaded multilevel inverter. As the tuned frequency increases, the size and the cost of passive power filter reduces. The passive power filter is tuned to the 5th harmonic frequency. Therefore the size and cost reduces. Most of the utility voltage fall on the passive power filter. Therefore the DC link voltage reduces. All the zero sequence currents are attenuated by the neutral current suppressor and the 5th harmonic current is attenuated by the passive power filter, therefore the remaining harmonic currents magnitudes are less. Therefore the 3-phase power filter currents are less in magnitude.

VI. ANALYSIS OF HYBRID POWER CONDITIONER

The Analysis of Hybrid power conditioner can be done with the help of zero and nonzero sequence networks.

1) Zero Sequence Network

The zero sequence network of the Hybrid power conditioner is shown in fig .10.The 3-phase power converter carries nonzero sequence currents. Therefore the 3-phase power converter does not appear in the zero sequence network. Also, the inductor of the tuned power filter does not carry any zero sequence current but the capacitor carries. Therefore the capacitor presents in the zero sequence network and the inductor is absent. In fig. 10, two sources, the voltage source and current source, are presented and are given by eq (7) and (8), respectively.

$$V_{s0}=\frac{1}{3}(V_{an}+V_{bn}+V_{cn}) \tag{7}$$

$$I_{L0}=\frac{1}{3}(I_{La}+I_{Lb}+I_{Lc}) \tag{8}$$

Where V_{an}, V_{bn} and V_{cn} are the utility rms phase voltages and I_{La}; I_{Lb} and I_{Lc} are the rms load currents.

In fig .10, Z_s, Z_{sn}, Z_z and Z_c are the utility, neutral conductor, zigzag transformer and tuned power filter capacitor impedances respectively. The dependent voltage source is given by eq. (9)

$$V_{con} = 3K_{con}I_{sn} \tag{9}$$

In eq.(9), the term, $3K_{con}$ represents impedance. The modified zero sequence network is shown in fig. 11. The zero sequence current flowing through the utility is given by eq. (10)

$$I_{s0}=\frac{Z_c+Z_z}{Z_c+Z_z+Z_s+3Z_{sn}+3K_{con}}I_{L0}+\frac{1}{Z_c+Z_z+Z_s+3Z_{sn}+3K_{con}}V_{s0} \tag{10}$$

In equation (10), $3K_{con}$ is added in the denominator. Therefore it reduces I_{s0}. The neutral current $I_{sn} = 3I_{s0}$. In this way, the neutral current is reduced.

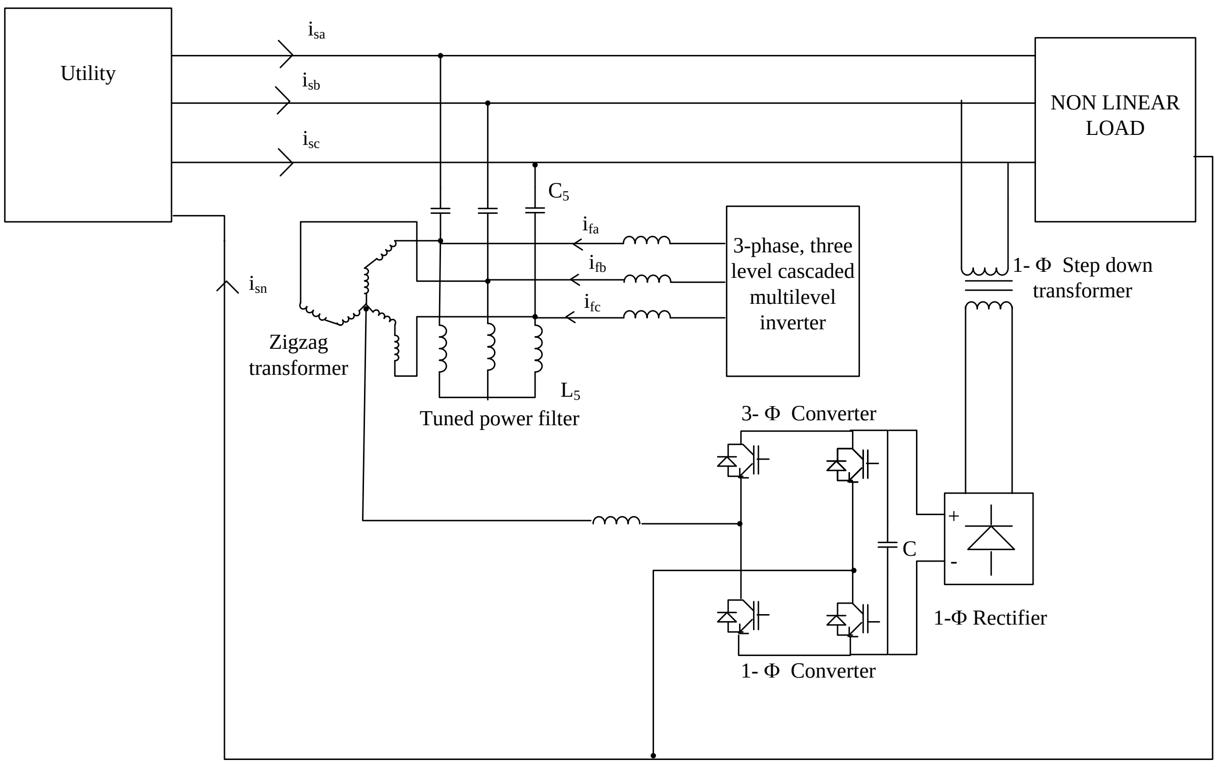

Fig. 9. Hybrid power conditioner with three level cascaded multilevel inverter.

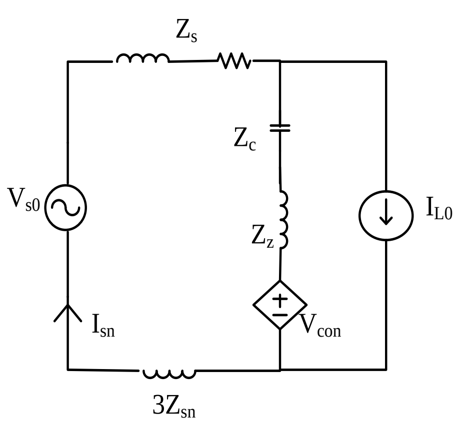

Fig. 10. Zero sequence network of fig. 1.

2) Nonzero sequence network

The nonzero sequence network is shown in fig. 12. In the nonzero sequence network, the zigzag transformer is not presented because it does not carry any harmonic currents other than the zero sequence currents. It consists of two harmonic sources, $I_{Lh(nz)}$ and $V_{sh(nz)}$. The voltage source, $V_{sh(nz)}$ represents the nonzero sequence voltage source and the current source, $I_{Lh(nz)}$ represents the nonzero sequence current source due to nonlinear load. In fig. 12, Z_{sh}, Z_{ch} and Z_{Lh} are the harmonic impedances of the utility, passive power filter capacitor and inductor respectively at specified harmonic frequency.

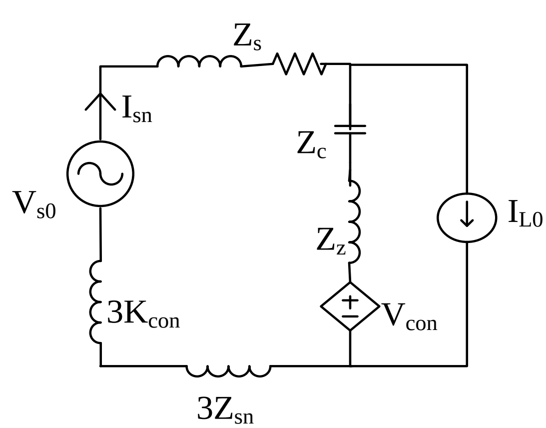

Fig. 11. Modified circuit of fig (2).

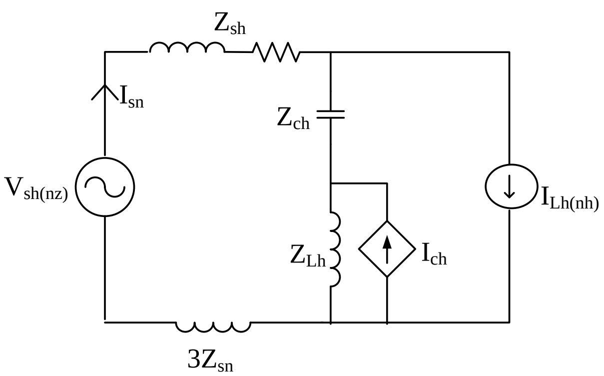

Fig. 12. Nonzero sequence network of fig. 9.

VII. CONTROL CIRCUIT BLOCK DIAGRAM

The compensating currents can be written as

$$I_{ca}=k_1I_{sah}+k_2V_{sa1} \quad (11)$$

$$I_{cb}=k_1I_{sbh}+k_2V_{sb1} \quad (12)$$

$$I_{cc}=k_1I_{sch}+k_2V_{sc1} \quad (13)$$

Where I_{sah},I_{sbh} and I_{sch} are the harmonic currents of utility and V_{sa1}, V_{sb1} and V_{sc1} are the fundamental utility rms phase voltages. From the above three equations (6), (7) and (8), first, the utility currents are detected with the help of current detectors. After that, the harmonic currents are extracted from the detected utility currents with the help of band stop filters. Similarly, the fundamental voltages are obtained with the help of voltage detectors. The compensating currents can be obtained by adding the harmonic currents and voltages, it is shown in fig. 13. The compensating currents are compared with the filter currents and the error signal is sent to PI controller. The PI controller minimizes the error and the output of the PI controller is sent to the PWM circuits to generate pulses. The PWM circuit generates pulses and sends to the 3-phase power converter.

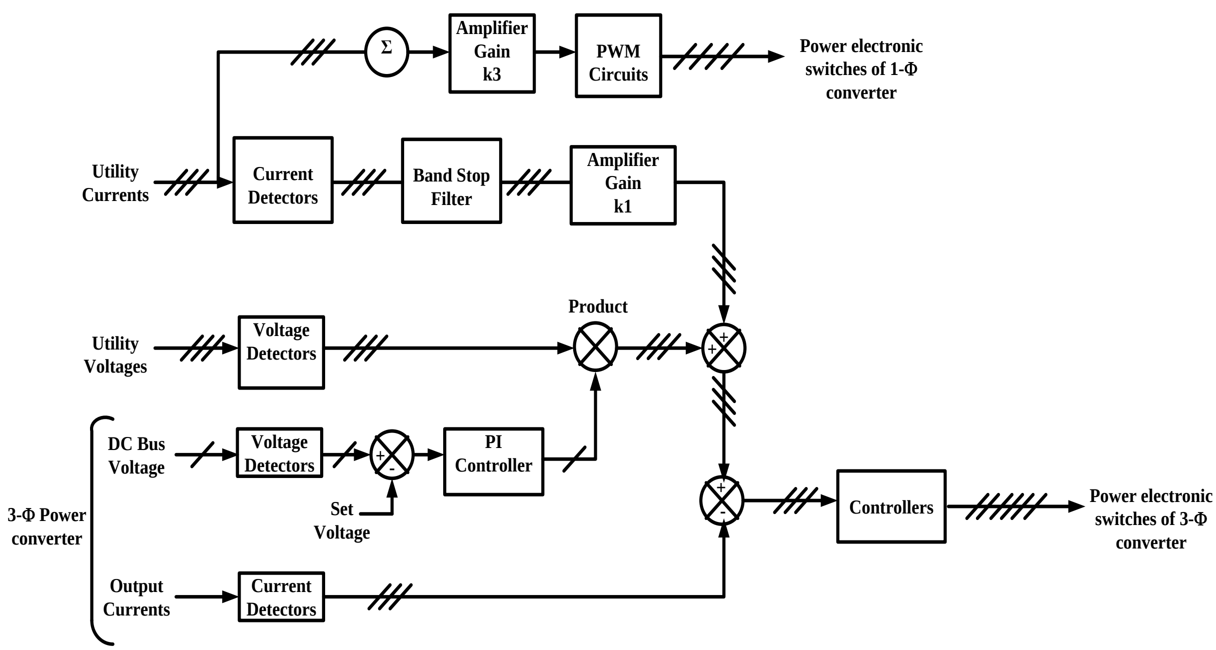

Fig. 13. Control circuit block diagram

VIII. SIMULATION RESULTS

A. Balance loading

1) Balanced Load without Hybrid Power Conditioner: Fig .14 represents the simulation results of the utility and neutral line currents without hybrid power conditioner under the balanced load. In this case, three balanced diode bridge rectifiers are connected to the utility. The utility rms currents are approximately equal. The utility currents rms values are equal to 9A.The rms value of neutral line current is 10A. It is very high. The THD values of utility currents, phases a,b and c are 40.31%, 40.36%, and 40.45% respectively, which are very high. It is shown in fig. 15.

2) *Balanced Load with Hybrid Power Conditioner:* Fig. 16 represents the simulation results of the utility and neutral line currents with hybrid power conditioner under the balanced load. Clearly, the utility currents are approximately sinusoidal and the neutral line current is 0.28 A (rms), which is very low. The THDs of the utility currents, phases a, b and c are 1.78%, 1.95%, and 1.81% respectively, and it is shown in fig. 17. Clearly, the THDs of the utility currents are very low.

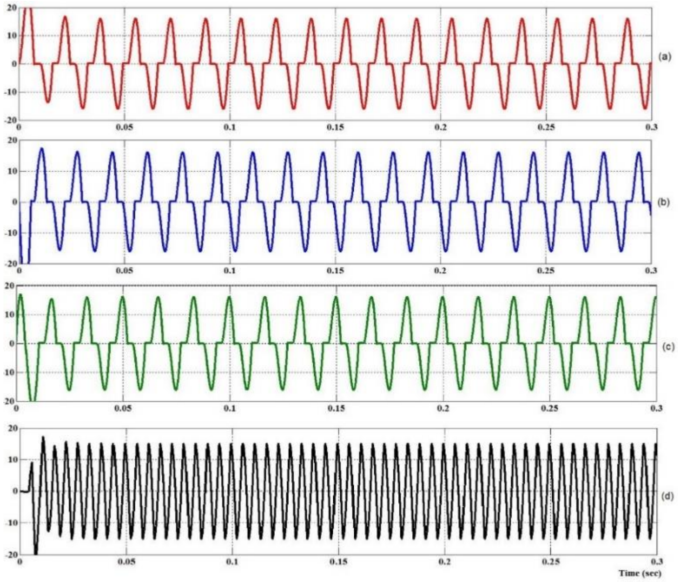

Fig. 14. Simulation results of the utility and neutral line currents under the balanced load without hybrid power conditioner: (a) phase a utility current, (b) phase b utility current, (c) phase c utility current and (d) neutral conductor current.

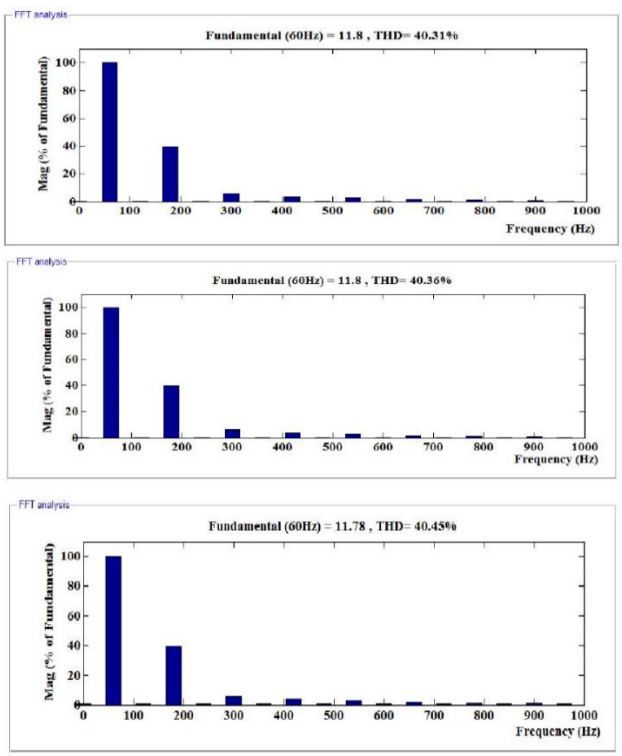

Fig. 15. Simulation results of the utility currents harmonic spectrum without hybrid power conditioner under the balanced load. (a) Phase a utility current harmonic spectrum, (b) Phase b utility current harmonic spectrum and (c) Phase c utility current harmonic spectrum.

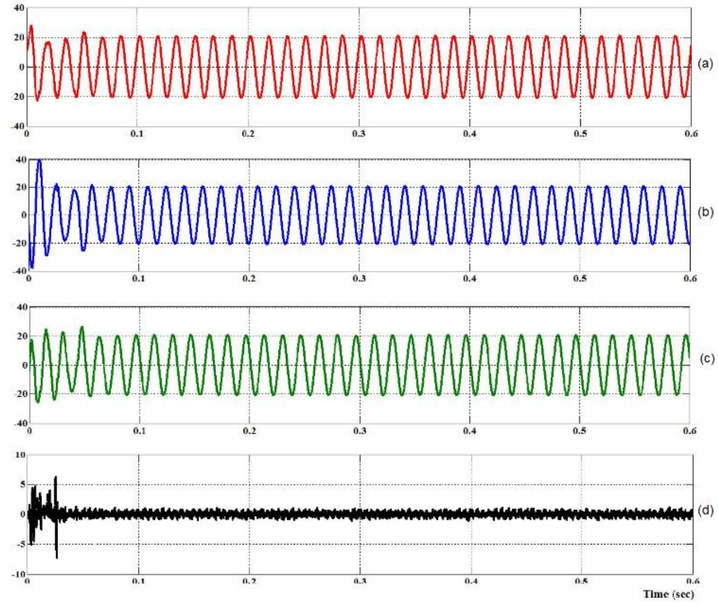

Fig. 16. Simulation results of the utility and neutral currents with hybrid power conditioner under the balanced load. (a) Phase a utility current, (b) phase b utility current, (c) phase c utility current and (d) neutral

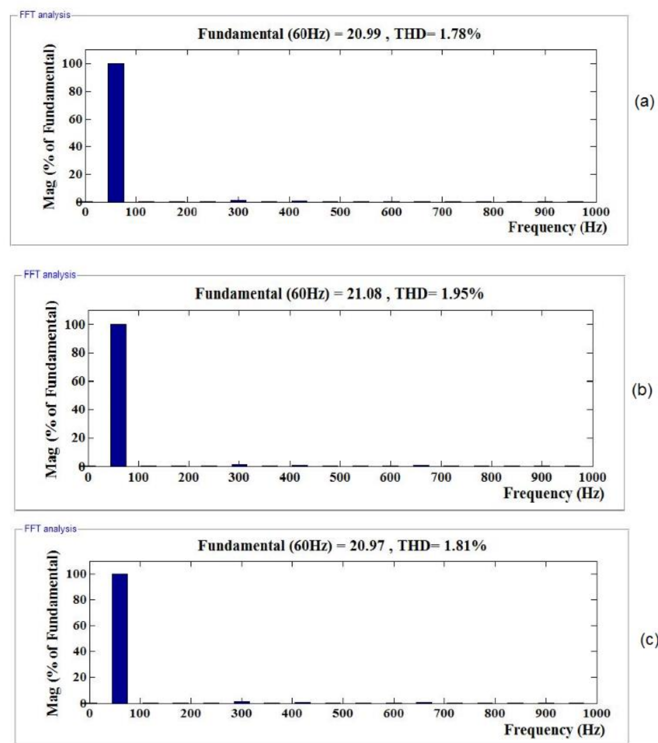

Fig. 17. Simulation results of the Harmonic spectrums of the utility currents with hybrid power conditioner under the balanced load. (a) Phase a utility current harmonic spectrum, (b) phase b utility current harmonic spectrum and (c) phase c utility current harmonic spectrum.

Fig. 18 represents the filter currents and DC link voltage across the capacitor of the 3-phase power converter. The zero sequence currents are attenuated by neutral current suppressor and the 5th harmonic current is attenuated by the passive power filter. Therefore the rest of the harmonic currents magnitudes are less. That's why the filter currents magnitudes are less. The rms values of the filter currents, phase a, phase b, and phase c, are approximately equal to 2.3 A, which is very less when compared to shunt active power filter.

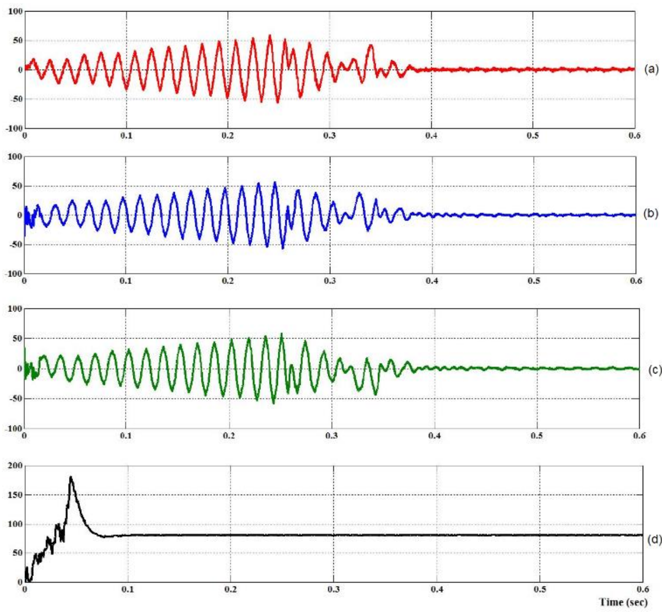

Fig. 18. Simulation results of the filter currents under the balanced load with hybrid power conditioner. (a) Phase a filter current, (b) phase b filter current, (c) phase c filter current and (d) DC link voltage across the capacitor of the 3-phase power converter.

B. Unbalance Loading

1) Unbalance Loading without Hybrid Power Conditioner: In this case, all the three phases of the utility are connected to the unbalanced diode bridge rectifiers. Fig. 19 represents the simulation results of the utility and neutral line currents without hybrid power conditioner under the unbalanced load. The neutral line current is 7 A (rms). The THDs of the utility currents, phases a, b and c, are 45.78%, 24.55%, and 44.61%, respectively. It is shown in fig. 20.

2) *Unbalance loading with Hybrid Power Conditioner*: Fig. 21 represents the simulation results of the utility and neutral line currents with hybrid power conditioner under the unbalanced load. It is clear that, the utility currents are nearly sinusoidal and the THDs of phase a, phase b, and phase c of the utility currents are 3.28%, 4.51% and 3.83% respectively. It is shown in fig. 22. Also, the neutral line rms current is 0.86 A. Fig. 23 represents the simulation results of the filter currents and DC link voltage across 3-phase power converter. The rms values of the filter currents, phase a, phase b and phase c are 3.24 A, 2.97 A and 3 A respectively.

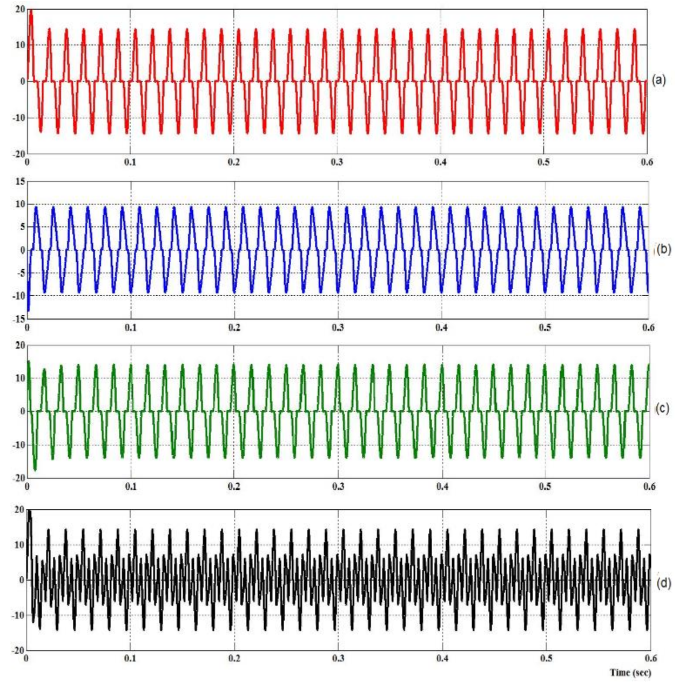

Fig. 19. Simulation results of the utility and neutral currents without hybrid power conditioner under the unbalanced load. (a) phase a utility current, (b) phase b utility current, (c) phase c utility current and (d) neutral line current.

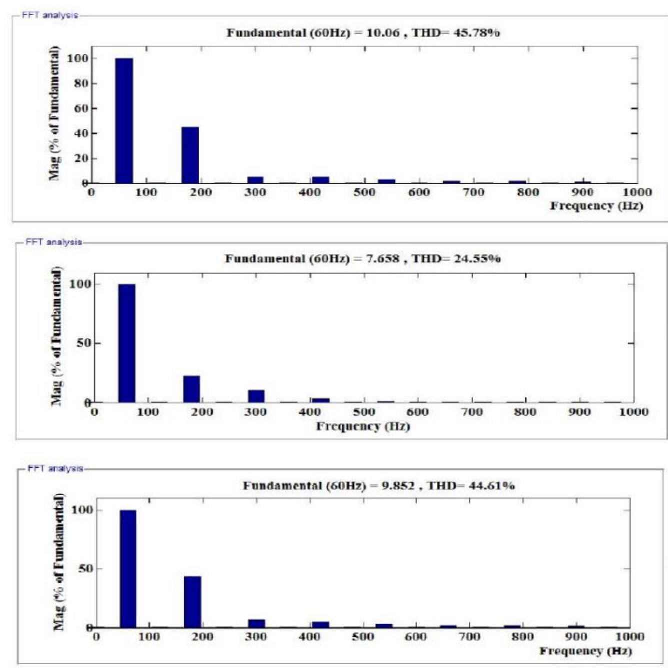

Fig. 20. Simulation results of the harmonic spectrums of the utility currents without hybrid power conditioner under the unbalanced load. (a) phase a utility current harmonic spectrum, (b) phase b utility current harmonic spectrum, (c) phase c utility current harmonic spectrum.

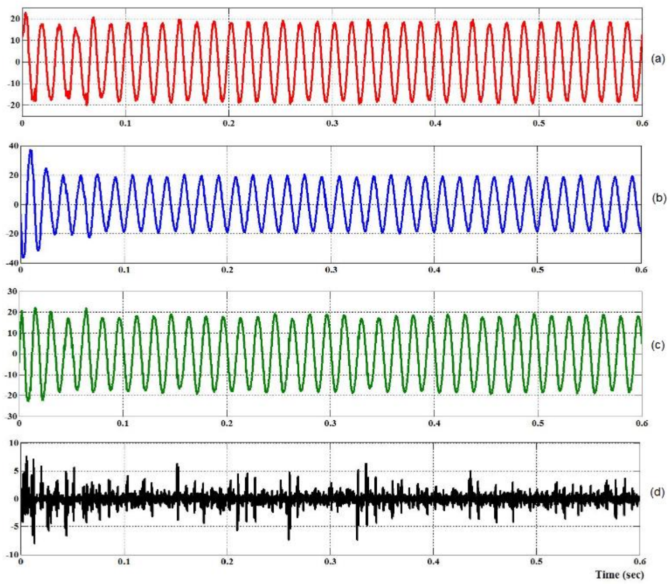

Fig. 21. Simulation results of the utility and neutral currents with hybrid power conditioner under the unbalanced load. (a) Phase a utility current, (b) phase b utility current, (c) phase c utility current and (d) neutral line current.

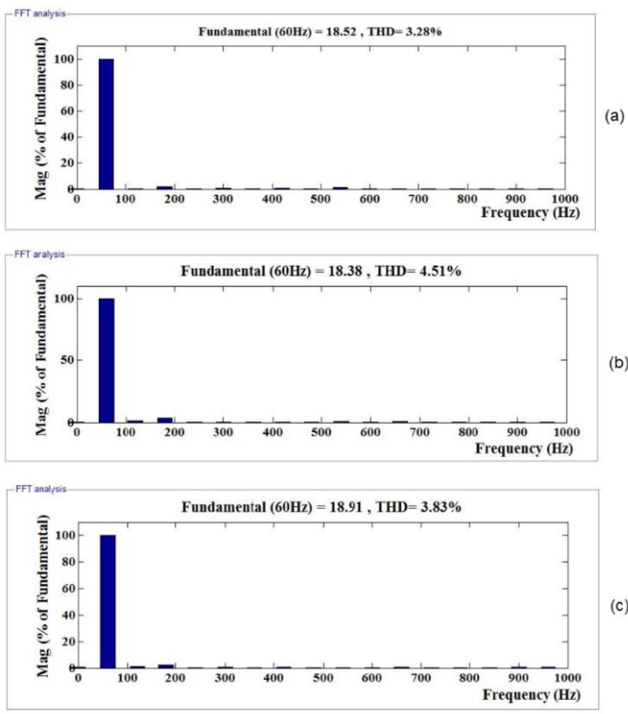

Fig. 22. Simulation results of the harmonic spectrums of the utility currents with hybrid power conditioner under the unbalanced load. (a) Phase a utility current harmonic spectrum, (b) phase b utility current harmonic spectrum and (c) phase c utility current harmonic spectrum.

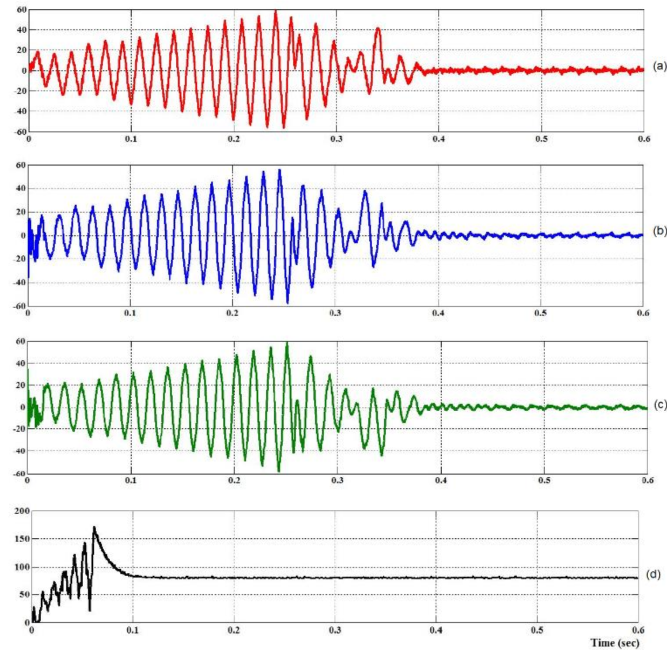

Fig. 23. Simulation results of the filter currents with hybrid power conditioner under the unbalanced load. (a) Phase a filter current, (b) phase b filter current, (c) phase c filter current and (d) DC link voltage across capacitor of a 3-phase power converter.

C. Worst case of Loading

1) *Without Hybrid Power Conditioner*: This is also called the unbalance loading but the difference is only one phase of the utility is loaded. This is called the worst of loading. In this case, only phase a of the utility is connected to the 1-phase diode bridge rectifier and the rest of the phases of the utility are not connected to any load. In this case, the utility and neutral currents are equal. The neutral line rms current is 9A which is equal to utility current, which is undesirable. Fig. 24 represents the simulation results of the utility and neutral line currents without hybrid power conditioner under the worst case of load. The THD of utility phase a current is 40.31% and is shown in fig. 25.

2) *With Hybrid power conditioner:* Fig. 26 represents the simulation results of the utility and neutral line currents with hybrid power conditioner under only phase a of the utility is connected to the load. It is clear that all the utility currents are approximately sinusoidal and neutral line current rms value is 0.88 A, which is very low. The THDs of the utility currents, phase a, phase b and phase c are 6.18%, 6.71%, and 4.14% respectively. It is shown in fig. 27. Fig. 28 represents the simulation results of the filter currents and DC link voltage across the capacitor of a 3-phase multilevel inverter. The rms values of phase a, phase b and phase c filter currents are 1.2 A, 0.69 A and 0.75 A respectively. The filter currents are very low.

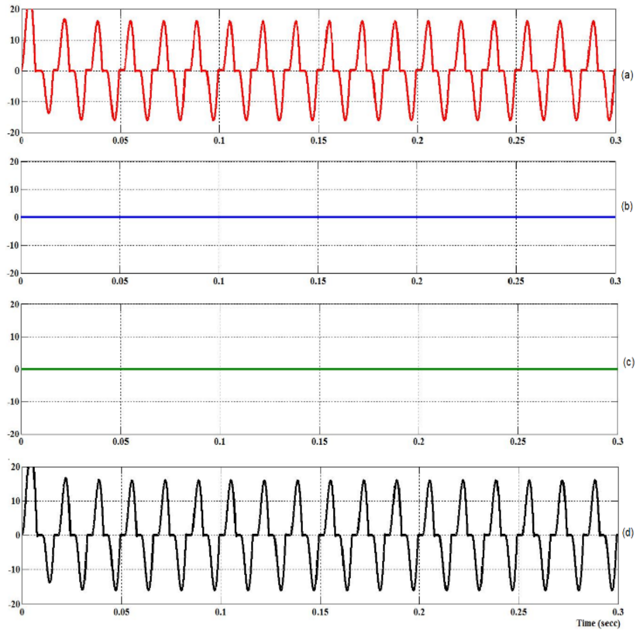

Fig. 24. Simulation results of the utility and neutral line currents without hybrid power conditioner under the worst case of load.

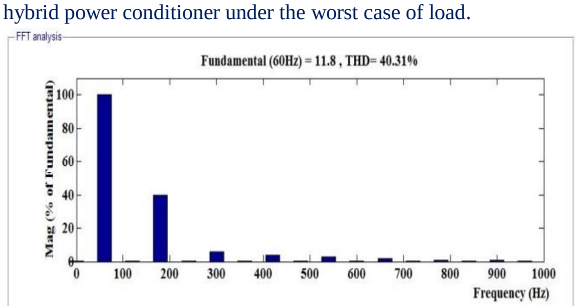

Fig. 25 Simulation results of the utility phase a current harmonic spectrum without Hybrid power conditioner under the worst case of loading.

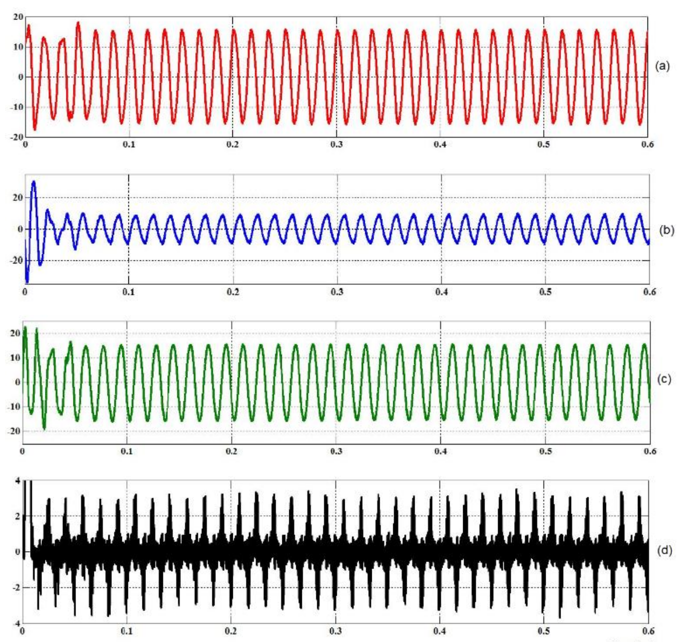

Fig. 26. Simulation results of the utility and neutral line currents with hybrid power conditioner under the worst case of loading.

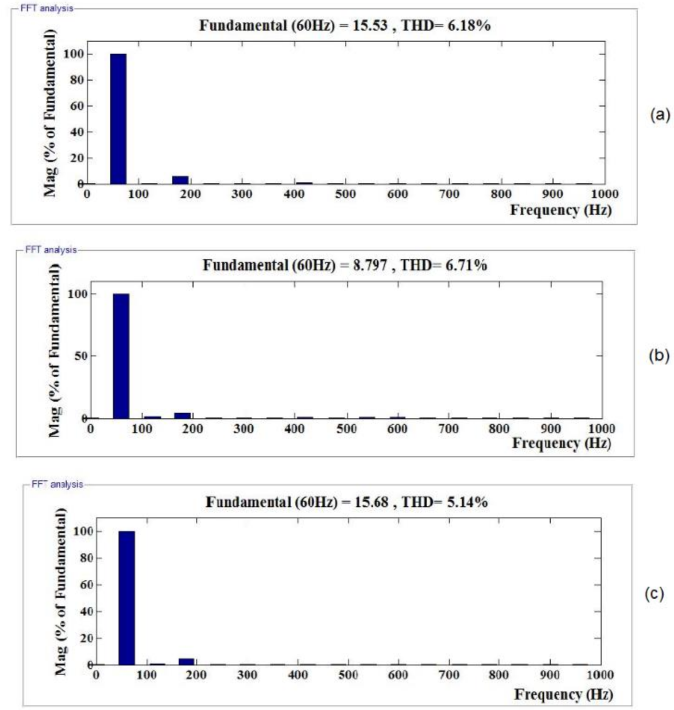

Fig. 27. Simulation results of the harmonic spectrums of the utility currents with hybrid power conditioner under the worst case of loading. (a) Phase a utility current harmonic spectrum, (b) phase b utility current harmonic spectrum and (c) phase c utility current harmonic spectrum.

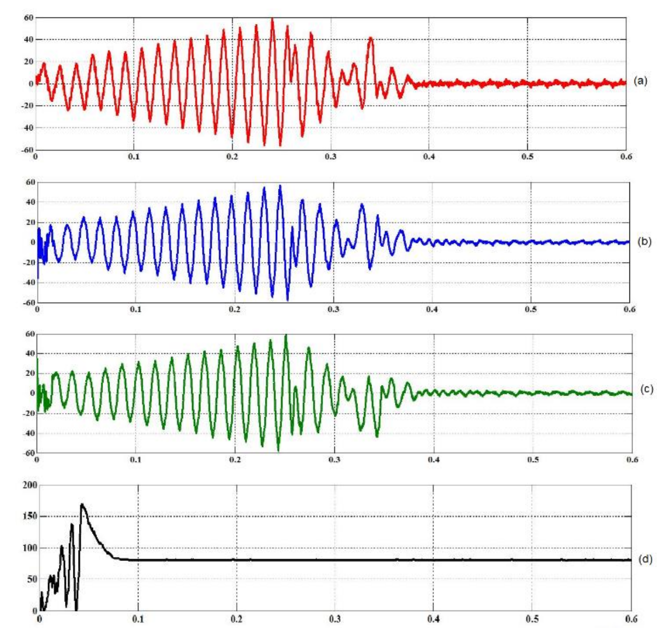

Fig. 28. Simulation results of the filter currents with hybrid power conditioner under the worst case of loading. (a) Phase a filter current, (b) phase b filter current, (c) phase c filter current and (d) DC link voltage across the capacitor of the 3-phase power converter

IX. CONCLUSION

Three phase four wire distribution power systems are used to supply the power to 1-phase and 3-phase loads. But the nonlinear loads and unbalance loading result in harmonic currents and large neutral current which are undesirable. The hybrid power filter with zig-zag transformer can effectively attenuate these currents. Hence it is an effective solution to eliminate harmonic currents and neutral line current. Also, the power rating of the 3-phase power converter is smaller than the conventional hybrid power filter. The zig-zag transformer power rating is also small. Therefore overall power rating of the proposed conditioner is small.

TABLE I

SYSTEM PARAMETERS

Phase voltage (rms)	220 V
Frequency	60Hz
Impedance/phase	1+j3.76

TABLE II

HYBRID POWER CONDITIONER WITH 3-LEVEL CASCADED MULTILEVEL INVERTER

3-Ø, 3-level Cascaded multilevel inverter			
Switching frequency	2KHz	DC link voltage	80 V
Inductor	2mH	Capacitors, C1 and C2	1100µF
Tuned power filter			
Inductor	2mH	Capacitor	130µF
1-Ø power converter			
Switching frequency	2KHz	DC link voltage	80 V
Inductor	2mH	Capacitor	2200µF

TABLE III

LOAD PARAMETERS (THREE 1-Ø DIODE BRIDGE RECTIFIERS WITH PARALLEL R AND C AS LOAD)

Balanced load		
Phase a	R=25Ω	C=300µF
Phase b	R=25Ω	C=300µF
Phase c	R=25Ω	C=300µF
Unbalanced load		
Phase a	R=25Ω	C=200µF
Phase b	R=25Ω	C=50µF
Phase c	R=25Ω	C=300µF
Worst case of loading		
Phase a	R=25Ω	C=150µF
Phase b	No load	
Phase c	No load	

References

[1] B Singh and J .Solanki "An implementation of an adaptive control algorithm for a three-phase shunt active filter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 2811–2820, Aug. 2009.

[2] O. Vodyakho and C. C. Mi, "Three-level inverter-based shunt active power filter in three-phase three-wire and four-wire systems," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1350–1363, May 2009.

[3] P. Salmeron and S. P. Litran, "Improvement of the electric power quality using series active and shunt passive filters," *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 1058–1067, Apr. 2010.

[4] M. Aredes, J. Hafner, and K. Heumann, "Three-phase four-wire shunt active filter control strategies," IEEE Transactions on Power Electronics, vol. 12, no. 2, pp. 311-318, Mar. 1997.

[5] L. Gyugyi and E. C. Strycula, "Active ac power filters," in Proc. IEEE/lAS Annu. Meeting, 1976, p. 529.

[6] H. Akagi, Y. Kanazawa, and A. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuits," in Proc. JIEE IPEC-Tokyo, 1983, p. 1375.

[7] P. Salmeron and S. P. Litrán, "A control strategy for hybrid power filter to compensate four-wires three-phase systems," *IEEE Trans. Power Electron.*, vol. 25, no. 7, pp. 1923–1931, Jul. 2010.

[8] S. P. Litrán and P. Salmeron, "Analysis and design of different control strategies of hybrid active power filter based on the state model," *IET Power Electron.*, vol. 5, no. 8, pp. 1341–1350, 2012.

[9] S. Rahmani, A. Hamadi, N. Mendalek, K. Al-Haddad, and K. , " A new control technique for three-phase shunt hybrid power filter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 2904–2915, Aug. 2009.

[10] H. Akagi and T. Hatada, "Voltage balancing control for a three-level diode-clamped converter in a medium-voltage transformer less hybrid active filter," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 571–579, Mar. 2009.

[11] H. L. Jou,K.D.Wu, J. C.Wu, C. H. Li, and M. S. Huang, "Novel power converter topology for three-phase four-wire hybrid power filter," *IET Power Electron.*, vol. 1, no. 1, pp. 164–173, Mar. 2008.

[12] S. H. Hosseini, T. Nouri, and M. Sabahi, "A novel hybrid active filter for power quality improvement and neutral current cancellation," in *Proc. Int. Conf. Elect. Electron. Eng.*, 2009, pp. I-244–I-248.

[13] L. Asiminoaei, W. Wiechowski, F. Blaabjerg, T. Krzeszowiak, and B. Kedra, "A new control structure for hybrid power filter to reduce the inverter power rating," in *Proc. IEEE IECON*, 2006, pp. 2712–2717.

[14] A. Hamadi, S. Rahmani, W. Santana, and K. Al-Haddad, "Study on a novel hybrid active power filter applied to a high-voltage grid," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 2344–2352, Oct. 2009.

[15] H.-L. Jou, J.-C. Wu, K.-D. Wu, W.-J. Chiang, and Y.-H. Chen, "Analysis of zig-zag transformer applying in the three-phase four-wire distribution power system," *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 1168–1173, Apr. 2005.

[16] J. C. Wu, H. L. Jou, K. D. Wu and S. T. Xiao, "Single-phase inverter-based neutral-current suppressor for attenuating neutral current of three-phase four-wire distribution power system," in *IET Generation, Transmission & Distribution*, vol. 6, no. 6, pp. 577-583,June 2012.

[17] J. S. Lai and F. Z. Peng, "Multilevel converters–A new breed of power converters," *IEEE Trans. Ind. Applicat.* vol. 32, pp. 509–517, May/June 1996.

[18] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral-point clamped PWM inverter," *IEEE Trans. Ind. Applicat.*, vol. IA-17, pp. 518–523, Sept./Oct. 1981. [4]

[19] T. A. Meynard and H. Foch, "Multi-level choppers for high voltage applications," *Eur. Power Electron. Drives J.*, vol. 2, no. 1, p. 41, Mar. 1992. [5]

[20] C. Hochgraf, R. Lasseter, D. Divan, and T. A. Lipo, “Comparison of multilevel inverters for static var compensation,” in *Conf. Rec. IEEE-IAS Annu. Meeting*, Oct. 1994, pp. 921–928. [6]

[21] P. Hammond, “A new approach to enhance power quality for medium voltage ac drives,” *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 202–208, Jan./Feb. 1997. [7]

[22] E. Cengelci, S. U. Sulistijo, B. O. Woom, P. Enjeti, R. Teodorescu, and F. Blaabjerge, “A new medium voltage PWM inverter topology for adjustable speed drives,” in *Conf. Rec. IEEE-IAS Annu. Meeting*, St. Louis, MO, Oct. 1998, pp. 1416–1423.[8]

[23] R. H. Baker and L. H. Bannister, “Electric power converter,” U.S. Patent3 867 643, Feb. 1975.[9]

[24] R. H. Baker, “Switching circuit,” U.S. Patent 4 210 826, July 1980. [10]

[25] ---- , “Bridge converter circuit,” U.S. Patent 4 270 163, May 1981. [11]

[26] F. Z. Peng and J. S. Lai, “Multilevel cascade voltage-source inverter with separate DC sources,” U.S. Patent 5 642 275, June 24, 1997. [13]

[27] M. P. Steimer and J. K. Steinke, “Five level GTO inverters for large induction motor drives,” in *Conf. Rec. IEEE-IAS Annu. Meeting*, Oct. 1993, pp. 595–601.[57]

[28] F. Z. Peng and J. S. Lai, “A static var generator using a staircase waveform multilevel voltage-source converter,” in *Proc. Seventh Int. Power Quality Conf.*, Dallas, TX, Sept. 1994, pp. 58–66.[55]

[29] F. Z. Peng, J. W. McKeever, and D. J. Adams, “A power line conditioner using cascade multilevel inverters for distribution systems,” in *Conf. Rec. IEEE-IAS Annu. Meeting*, New Orleans, LA, Oct. 1997, pp. 1316–1321.[62]

[30] ----,“Cascade multilevel inverters for utility applications,” in *Proc. IEEE IECON’97*, New Orleans, LA, Nov. 1997, pp. 437–442. [63]

[31] X. Yuan, H. Stemmler, and I. Barbi, “Investigation on the clamping voltage self-balancing of the three-level capacitor clamping inverter,” in *Proc. IEEE PESC’99*, 1999, pp. 1059–1064.[61].

[32] B. A. Renz *et al.*, “AEP unified power flow controller performance,” presented at the IEEE/PES Winter Meeting, Tampa, FL, 1998, Paper PE-042-PWRD-0-12.[73]

[33] P. P. Khera, “Application of zigzag transformers for reducing harmonics in the neutral conductor of low voltage distribution system,” in *Proc. IEEE IAS Conf. Rec*, pp. 1092–1990.

[34] H.-L. Jou, J.-C. Wu, K.-D. Wu, W.-J. Chiang, and Y.-H. Chen, “Analysis of zig-zag transformer applying in the three-phase four-wire distribution power system,” *IEEE Trans. Power Del.*, vol. 20, no. 2, pp. 1168–1173, Apr. 2005.

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