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](image_url)

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}=I_{zc} (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.

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

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

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

$$I_{s0} = \frac{2I_{L0}}{Z_s + 3Z_{sn} + Z_{zt}} \quad (3)$$

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 $m_a$, modulation index = $\frac{I_{sn}}{V_{tri}}$.

$$V_{dc} = DC \text{ link voltage}$$

$$V_{con} = \frac{I_{sn}V_{dc}}{V_{tri}}$$

$$V_{con} = k_1i_{sn}, \text{ where } k_1 = \frac{V_{dc}}{V_{tri}}, \text{ gain of the amplifier.}$$

If the load is balanced, $i_{sn} = 3i_{s0}$. Therefore $V_{con} = 3k_1i_{sn}$.

![Fig. 2. Zig-zag transformer connected between source and load.](image)

![Fig. 3. Zero sequence circuit of fig. 2.](image)

![Fig. 4 inverter based zig-zag transformer](image)

![Fig. 5. Zero sequence equivalent circuit of fig. 2](image)
The zero sequence current flowing through the utility is given by eq. (5)
\[
I_{o0}\frac{z_{st}}{z_{st}+2z_{st}+3z_{sn}+3k_1} I_{o0} = \frac{V_{ao}}{z_{st}+2z_{st}+3z_{sn}+3k_1}
\]  
(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.](image)

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

B. Flying Capacitor Multilevel Inverter

![Fig. 7. Three level flying capacitor multilevel inverter.](image)

A three level flying capacitor multilevel inverter is shown in fig. 7 [17], [19], and [20]. The output voltage has three levels, \(\frac{V_{dc}}{2}\), 0 and \(-\frac{V_{dc}}{2}\). To get \(V_{ao} = \frac{V_{dc}}{2}\), the switches \(S_1\) and \(S_2\) need to be turned ON. To get \(V_{ao} = 0\), the switches \(S_1\) and \(S_3\) need to be turned ON. To get \(V_{ao} = -\frac{V_{dc}}{2}\), the switches \(S_2\) 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 \(S_{a2}\) have to be turned ON. To get \(V_{ao} = 0\), the switches \(S_{a2}\) and \(S_{a3}\) have to be turned ON. To get \(V_{ao} = -V_{dc}\), the switches \(S_{a3}\) and \(S_{a4}\) 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.
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.

\[ V_{\text{dc}} = \frac{1}{3} (V_{\text{an}} + V_{\text{bn}} + V_{\text{cn}}) \]  

\[ I_{\text{L0}} = \frac{1}{3} (I_{\text{La}} + I_{\text{Lb}} + I_{\text{Lc}}) \]

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.

\[ V_{\text{si}} = \frac{1}{3} (V_{\text{an}} + V_{\text{bn}} + V_{\text{cn}}) \]  

\[ I_{\text{L0}} = \frac{1}{3} (I_{\text{La}} + I_{\text{Lb}} + I_{\text{Lc}}) \]

Where \( V_{\text{an}} \), \( V_{\text{bn}} \) and \( V_{\text{cn}} \) are the utility rms phase voltages and \( I_{\text{La}} \), \( I_{\text{Lb}} \) and \( I_{\text{Lc}} \) 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)

\[ V_{\text{con}} = 3K_{\text{con}}I_{\text{sn}} \]  

(9)

In eq. (9), the term, \(3K_{\text{con}}\) 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)

\[ I_{\text{s0}} = \frac{V_{\text{s0}}}{Z_s + Z_z + Z_c + Z_{\text{ch}} + Z_{\text{Lh}}} \]  

(10)

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

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, \(I_{\text{zh(nz)}}\) and \(V_{\text{sh(nz)}}\). The voltage source, \(V_{\text{sh(nz)}}\)

\[ I_{\text{zh(nz)}} = \frac{Z_c + Z_z + Z_{\text{ch}} + Z_{\text{Lh}} + 3K_{\text{con}}}{Z_c + Z_z + Z_{\text{ch}} + Z_{\text{Lh}} + 3Z_{\text{sn}} + 3K_{\text{con}}} V_{\text{zh}} \]  

(11)

represents the nonzero sequence voltage source and the current source, \(I_{\text{zh(nz)}}\) represents the nonzero sequence current source due to nonlinear load. In fig. 12, \(Z_{\text{zh}}, Z_{\text{ch}}\) and \(Z_{\text{Lh}}\) are the harmonic impedances of the utility, passive power filter capacitor and inductor respectively at specified harmonic frequency.
The compensating currents can be written as
\[ I_{ca} = k_1 I_{sa} + k_2 V_{sa1} \] (11)
\[ I_{cb} = k_1 I_{sb} + k_2 V_{sb1} \] (12)
\[ I_{cc} = k_1 I_{sc} + k_2 V_{sc1} \] (13)

Where \( I_{sa}, I_{sb}, \) and \( I_{sc} \) are the harmonic currents of utility and \( V_{sa1}, V_{sb1}, \) and \( V_{sc1} \) are the fundamental utility rms phase voltages.

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.

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.

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.

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.

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>
<thead>
<tr>
<th>TABLE I</th>
<th>SYSTEM PARAMETERS</th>
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<tr>
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<th>HYBRID POWER CONDITIONER WITH 3-LEVEL CASCADED MULTILEVEL INVERTER</th>
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<tr>
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<tr>
<td>Switching frequency</td>
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<tr>
<td>Capacitors, C1 and C2</td>
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<tr>
<td>Capacitor</td>
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<tr>
<td>1-Ø power converter</td>
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<td>Switching frequency</td>
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<td>Phase a</td>
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<tr>
<td>Phase b</td>
<td>R=25Ω C=300µF</td>
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<tr>
<td>Phase c</td>
<td>R=25Ω C=300µF</td>
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<td>Unbalanced load</td>
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<td>Phase c</td>
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<tr>
<td>Phase c</td>
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References

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