Characteristic of Third Harmonic From Synchronous Generator Passing Through Transformer and Rectifier

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Abstract—**The third harmonic has caused much power quality problem in the neutral of distribution system. Salient pole synchronous generator has been recognized as one of the triplen/third harmonic sources. This research is aimed at studying the characteristic of third harmonic from generator flowing through the load directly, via transformer and shunt connection to rectifier. Lab scale experiments have been conducted to vary load impedance and transformer winding configuration. When generator is connected directly to a combined resistive and inductive load, the third harmonic current and voltage depend on the load impedance magnitude and phase angle. Since the third harmonic voltage produced by generator are in phase or zero sequence in nature, the third harmonic current depend on transformer winding configuration, the load impedance magnitude and phase angle. When full-wave bridge rectifier is shunt connected between generator and load, the third harmonic current at both rectifier and load are actually coming from generator that depend on load impedance magnitude and phase angle. It is recommended that the study on third harmonic voltage and current propagation from generator should be done by performing harmonic measurement and analysis at all parts of the network. Third harmonic voltage and current magnitude alone may not give correct indication to their severity because they are vector quantity and rely on zero sequence network, load impedance magnitude and phase angle.**

Keywords-Third harmonic voltage; third harmonic current; synchronous generator; transformer; rectifier

I. INTRODUCTION

Harmonic in power system has existed since the discovery of alternating current (AC) system way back in 1980s when first alternator was built. The imperfect sinusoidal voltage produce by AC generator or distorted voltage/current resulted from non-linear load contain various harmonic levels when analyzed using Fourier series/transform. Prior to the electronic era, harmonic has been recognized to cause various problems in AC power system and equipment mainly due to generator produced harmonic. During electronic era until today, non-linear load such as rectifier becomes major contributor to harmonic problem in terms of quantity.

Triplen harmonic for a balance and half wave symmetry three phase system are the odd multiples of third harmonic namely 3rd, 9th, 15th, etc. Synchronous generator has been reported to cause telephone interference [1-2] as the result of induced triplen harmonic voltage into telephone circuitry. Test by [3] has shown that triplen harmonic is dominant as compared to unbalance in raising the neutral to earth voltage (NEV). The phenomena of high circulating triplen harmonic current during uninterruptible power supply (UPS) bypass operation when paralleling with generator is documented in [4].

Investigation by [5] has shown that generator neutral earthing resistor (NER) became hot when synchronous generator operated in parallel with distribution grid. It has been revealed that continuous triplen harmonic current flowing through generator NER originated from the synchronous generator itself. This triplen harmonic current that return to generator NER has caused it to experience high temperature in direct proportional quantity. During synchronous generator operated in parallel with distribution grid, higher triplen harmonic current flowing through generator NER but in reversed direction to the load flow direction.

Harmonic propagation studies are carried out either in time domain [6], harmonic domain [7] or time/harmonic (hybrid) domain [8]. Most of these studies focus on non-linear load being the source of harmonic. Not many detail study on harmonic propagation from synchronous generator through low or medium voltage distribution system.

Journal published by [9] has stated that in real distribution system, harmonic order such as 2nd, 3rd, 4th, etc. are not corresponding to negative, zero, positive, etc. sequence due to unbalance and wave distortion. Therefore assumption that triplen harmonic is zero sequence in nature (same magnitude and phase angle) no longer hold and three phase harmonic measurement should be taken and analyzed.

The objective of this paper is to study the characteristic of third harmonic voltage and current produced by low voltage synchronous generator directly connected to load, via transformer and shunt connected to full-wave bridge rectifier. Lab experiment was conducted and the procedure is described in section II. Section III presents the experimental results and discussion. Finally, section IV provides the conclusion and recommendation of the study. The term generator will be used to represent salient pole synchronous generator throughout this paper.

II. METHODOLOGY

The characteristics of triplen harmonic currents produced by generator have been reported by [10] but the study presented only third harmonic current magnitude. The complete third harmonic studies should encompass three phase/neutral currents and their corresponding voltages.

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Lab scale experiment was conducted in three parts namely generator directly connected to load, generator connected to load via transformer of various winding configuration and generator connected to load with shunt connection of three phase full-wave bridge rectifier. A three-phase 415 V, 50 Hz, 0.2 kW generator, 415/415 V & 415/240 V transformers and full-wave bridge rectifier are used in the experiment.

A. Generator Load Direct Connection

This experiment serves as the base data of generator voltage and current characteristic under balanced combined resistive and inductive load. Generator and load are connected in star with common neutral connection but no neutral impedance. Third harmonic phase/neutral currents and voltages measurement at generator terminal is deemed the same as load terminal since negligible impedance between them.

B. Generator Load Via Transformer Connection

In this experiment, transformer is used to connect the generator and load. Generator and load are connected in star with no neutral impedance. Common neutral connection is made for generator, transformer (only at star side) and load. The transformer winding configurations are varied for star-star, star-delta, delta-delta and delta-star. Third harmonic phase/neutral currents and voltages measurements are taken at generator, transformer primary, transformer secondary and load terminals.

C. Generator Load With Rectifier Connection

Non linear load interaction with third harmonic produced by generator is studied by using full-wave bridge rectifier shunt connected to load. Generator and load are connected in star with no neutral impedance. Common neutral connection is made for generator, rectifier and load. Third harmonic phase/neutral currents and voltages are measured at generator, rectifier and load terminals.

III. RESULTS

All third harmonic voltage and current measurement are phase values. Mathematically, symmetrical and balanced three phase harmonic voltages produced by generator are:

$$V_a=V_1e^{jwt}+V_2e^{j2wt}+V_3e^{j3wt}+\ldots\ldots. \quad (1)$$

$$V_b=a^2V_1e^{jwt}+aV_2e^{j2wt}+V_3e^{j3wt}+\ldots\ldots. \quad (2)$$

$$V_c=aV_1e^{jwt}+a^2V_2e^{j2wt}+V_3e^{j3wt}+\ldots\ldots. \quad (3)$$

where, $a=e^{j\frac{2\pi}{3}}$

Therefore, three phase third harmonic voltage:

$$V_a=V_3e^{j3wt} \quad (4)$$

$$V_b=V_3e^{j3wt} \quad (5)$$

$$V_c=V_3e^{j3wt} \quad (6)$$

A. Generator Load Direct Connection

The third harmonic voltage magnitude increase when the resistive or inductive components of the impedance increase as shown in Fig. 1. However, third harmonic current magnitude decrease when the resistive or inductive components of the impedance increase as shown in Fig. 2. All third harmonic voltages are in phase and all third harmonic currents are almost in phase as shown in Fig. 3 and Fig. 4 respectively.

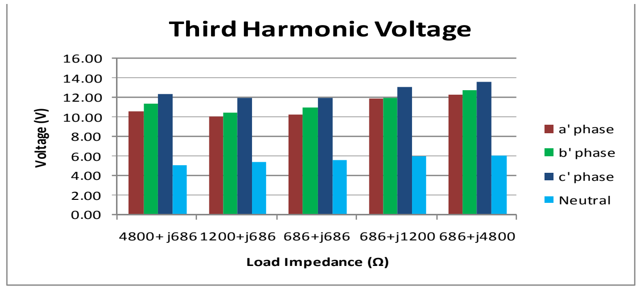


Fig. 1. Generator connected directly to combined resistive and inductive load

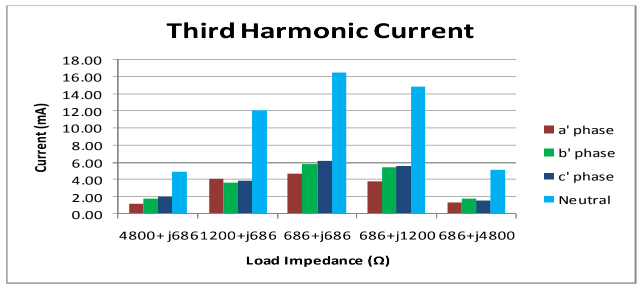


Fig. 2. Generator connected directly to combined resistive and inductive load

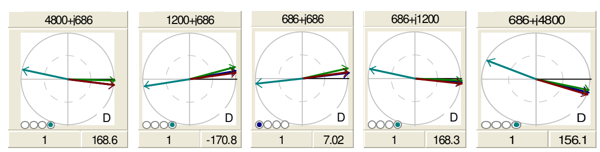


Fig. 3. Voltage phase angle for generator connected directly to combined resistive and inductive load

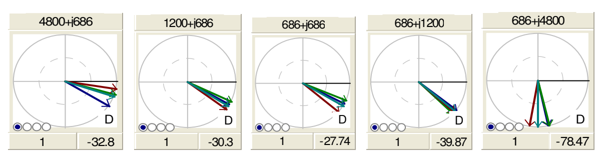


Fig. 4. Current phase angle for generator connected directly to combined resistive and inductive load

Being in phase, third harmonic current added at neutral causing neutral current almost three times the phase current. The third harmonic current lag the third harmonic voltage similar to current lag voltage at fundamental frequency for combined resistive and inductive load. However, the lagging angle is more than fundamental frequency impedance phase angle due to the influence of resistive and inductive component of the impedance seen by third harmonic voltage.

B. Generator Load Via Transformer Connection

Only result for 686+j686 Ω load is presented here but overall characteristic is deduced taking into account all load impedance used in experiment for section III (A).

1) Star-star

The third harmonic voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic current magnitude decrease when the resistive or inductive components of the impedance increase. Slightly decrease in the third harmonic voltage magnitude from generator to load as shown in Fig. 5. The third harmonic current magnitude at transformer secondary/load reduced from the transformer primary/generator as shown in Fig. 6. All the third harmonic voltages and currents are almost in phase as shown in Fig. 7 and Fig. 8.

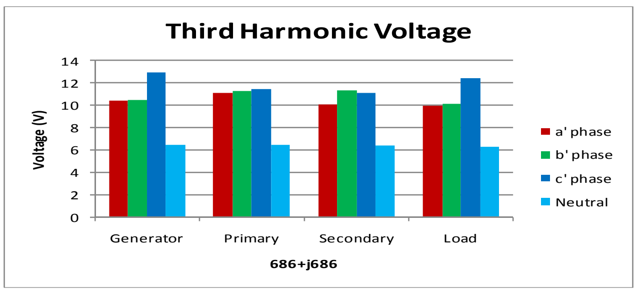


Fig. 5. Star-star transformer winding configuration

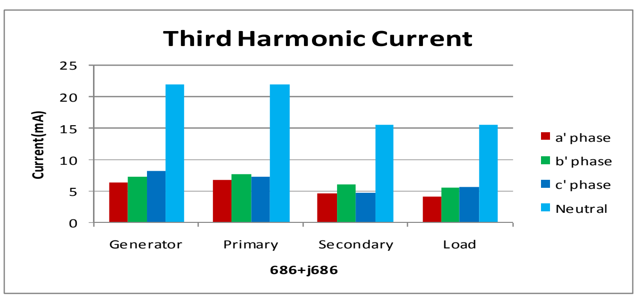
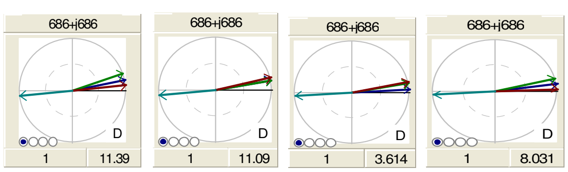
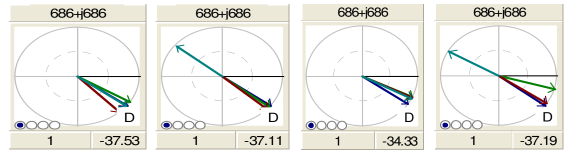


Fig. 6. Star-star transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 7. Voltage phase angle for star-star transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 8. Current phase angle for star-star transformer winding configuration

The third harmonic voltage and current magnitude decrease slightly due to transformer impedance. The third harmonic current from the generator circulates around transformer primary as shown by the opposite direction of neutral current. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around load as shown by the opposite direction of neutral current.

2) Star-delta

The third harmonic voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic current magnitude decrease when the resistive or inductive components of the impedance increase. The third harmonic voltage magnitude at generator almost equal to transformer primary. Low third harmonic voltage magnitude at transformer secondary but highest at load as shown in Fig. 9. The third harmonic current magnitude at transformer primary almost equal to generator. Small third harmonic current magnitude at transformer secondary and none at load as shown in Fig. 10. The third harmonic voltages are almost in phase at generator, transformer primary and load but not in phase at transformer secondary as shown in Fig. 11. The third harmonic currents are almost in phase at generator, transformer primary and transformer secondary but not in phase at load as shown in Fig. 12.

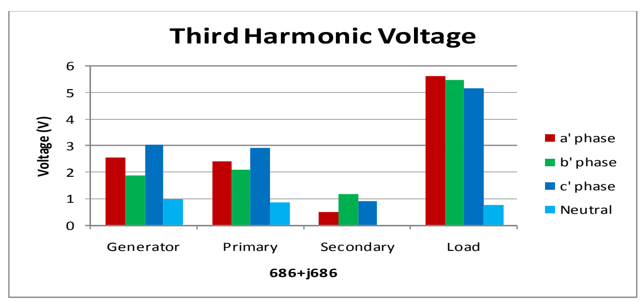


Fig. 9. Star-delta transformer winding configuration

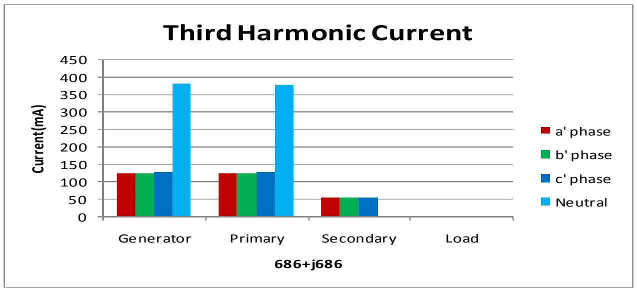
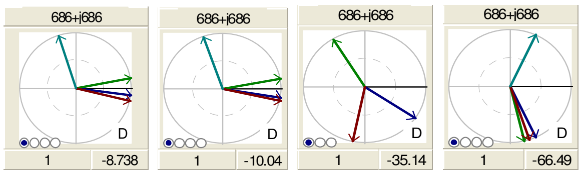
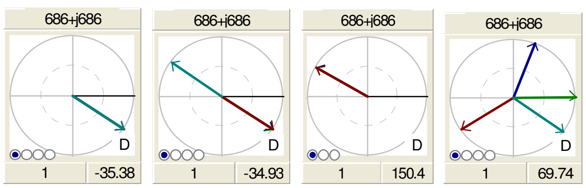


Fig. 10. Star-delta transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 11. Voltage phase angle for star-delta transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 12. Current phase angle for star-delta transformer winding configuration

The third harmonic current from the generator circulates around transformer primary as shown by the opposite direction of neutral current. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around delta winding preventing it from entering the load.

3) Delta-delta

The third harmonic voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic current magnitude decrease when the resistive or inductive components of the impedance increase. Small third harmonic voltage magnitude at transformer primary that almost equal to transformer secondary. Higher third harmonic voltage magnitude at generator as compared to load as shown in Fig. 13. The third harmonic current magnitude at transformer primary almost equal to transformer secondary. Small third harmonic current magnitude at generator and almost zero at load as shown in Fig. 14. The third harmonic voltages are almost in phase at generator and load but not in phase at transformer primary and secondary as shown in Fig. 15. The third harmonic currents are almost in phase at transformer primary and secondary but not in phase at generator and load as shown in Fig. 16.

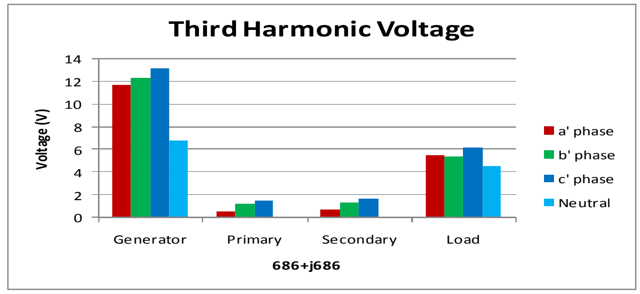


Fig. 13. Delta-delta transformer winding configuration

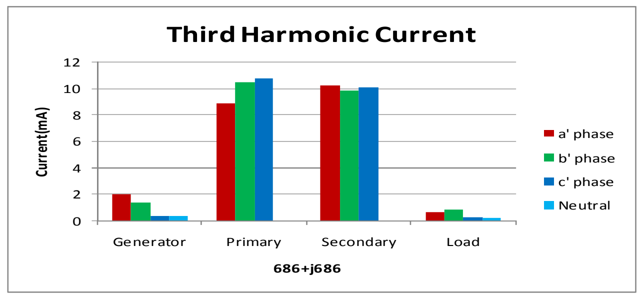
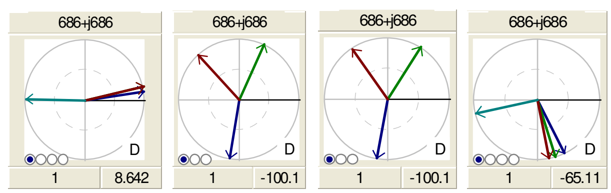
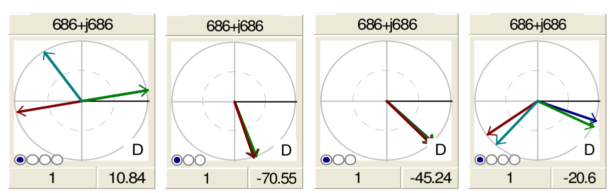


Fig. 14. Delta-delta transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 15. Voltage phase angle for delta-delta transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 16. Current phase angle for delta-delta transformer winding configuration

The third harmonic current from generator circulate around transformer primary and secondary delta windings preventing them from entering the load.

4) Delta-star

The third harmonic voltage magnitude increase when the resistive or inductive components of the impedance increase. The third harmonic current magnitude decrease when the resistive or inductive components of the impedance increase. The third harmonic voltage magnitude at transformer secondary almost equal to load. Low third harmonic voltage magnitude at transformer primary but highest at generator as shown in Fig. 17. The third harmonic current magnitude at transformer secondary almost equal to load. Small third harmonic current magnitude at generator but highest at transformer primary as shown in Fig. 18. The third harmonic voltages are almost in phase at generator but not in phase at transformer primary, secondary and load as shown in Fig. 19. The third harmonic currents are almost in phase at transformer primary, secondary and load but not in phase at generator as shown in Fig. 20.

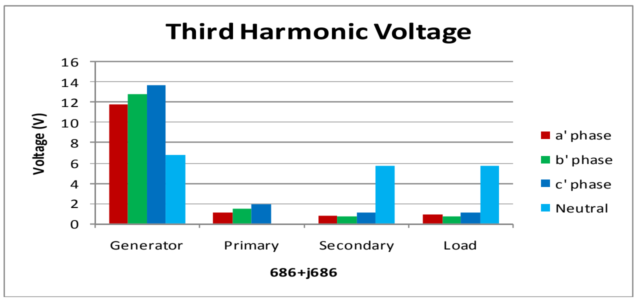


Fig. 17. Delta-star transformer winding configuration

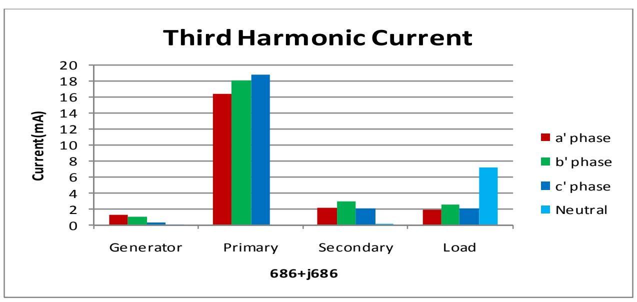
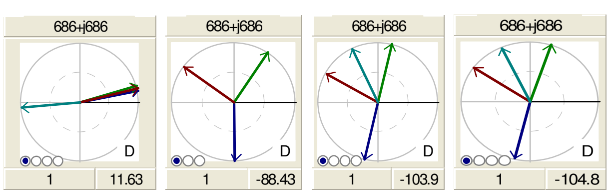
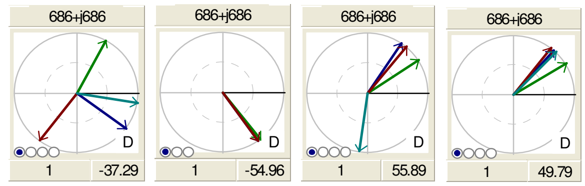


Fig. 18. Delta-star transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 19. Voltage phase angle for delta-star transformer winding configuration



Generator TX Primary TX Secondary Load

Fig. 20. Current phase angle for delta-star transformer winding configuration

The third harmonic current from the generator circulates around transformer primary. The third harmonic voltage induced at transformer secondary causes the third harmonic current circulates around load.

C. Generator Load With Rectifier Connection

Similar to section III(B), only result for 686+j686 Ω load is presented here but overall characteristic is deduced taking into account all load impedance used in experiment for section III (A).

The third harmonic voltage magnitude at generator, rectifier and load are almost equal as shown in Fig. 21. The third harmonic current magnitude at rectifier and load are almost equal but lower at generator as shown in Fig. 22. All the third harmonic voltages are almost in phase as shown in Fig. 23. Almost all third harmonic current are in phase as shown in Fig. 24.

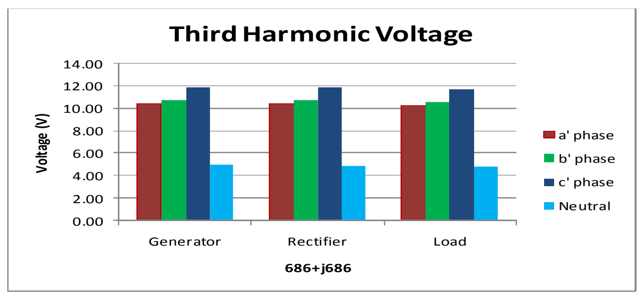


Fig. 21. Generator load with rectifier connection

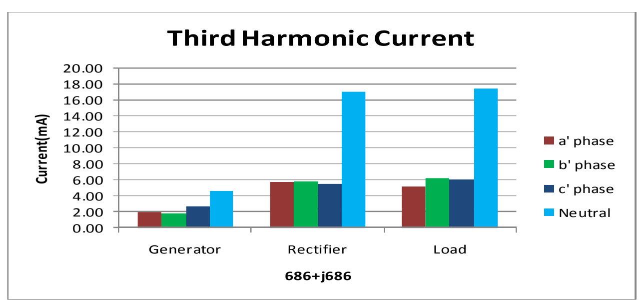
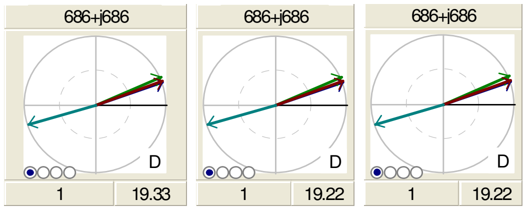
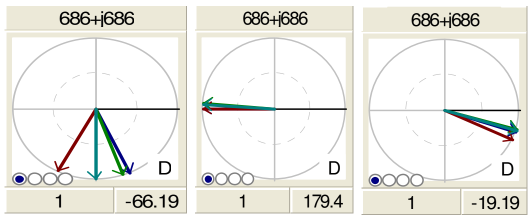


Fig. 22. Generator load with rectifier connection



Generator Rectifier Load

Fig. 23. Voltage phase angle for generator load with rectifier connection



Generator Rectifier Load

Fig. 24. Current phase angle for generator load with rectifier connection

The third harmonic current at both rectifier and load appear to be larger in magnitude than generator. However, the generator third harmonic current is actually the vector sum both rectifier and load third harmonic currents. Therefore, third harmonic current from the generator flows through both rectifier and load.

IV. CONCLUSION

When generator is connected directly to a combined resistive and inductive load, the third harmonic current and voltage depend on load impedance magnitude and phase angle. Inductive component of the impedance has higher magnitude impact on the third harmonic voltage and current as compared to resistive component for identical impedance magnitude.

Since the third harmonic voltage produced by generator is in phase or zero sequence in nature, the transformer star winding provide the return path for third harmonic current. Transformer delta winding trap or provide path for third harmonic current to circulate in them. This is similar to zero sequence circuit for transformer used in symmetrical component analysis. Apart from transformer winding type, the load impedance magnitude and phase angle also influenced the third harmonic current and voltage.

When full-wave bridge rectifier is shunt connected between generator and load, no additional third harmonic current being produced by non-linear load. The third harmonic current at both rectifier and load are actually coming from generator that depend on load impedance magnitude and phase angle.

In general, the study on third harmonic voltage and current propagation from generator should be done by performing harmonic measurement and analysis at all parts of the network. Third harmonic voltage and current magnitude alone may not give correct indication to their severity because they are vector quantity and rely on zero sequence network, load impedance magnitude and phase angle.

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