The Influence of Cable Capacitance, Generator Neutral Grounding and Zig-zag Transformer to Third Harmonic Produced by Synchronous Generator

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Abstract—**Salient pole synchronous generator is one of harmonic sources that causes various power system harmonic problem especially related to neutral. This paper aims to study the characteristics of third harmonic voltage and current from generator when connected to balanced load via cable, generator load connection with different generator neutral grounding resistor and generator load connection shunted by zig-zag transformer. Lab scale experiments have been conducted to vary all parameters related to cable capacitor and generator neutral grounding resistor under various combined resistive and inductive load. Cable capacitance which depends on cable length, size and number of parallel cable, combined with load impedance determines the third harmonic current magnitude. The presence of cable capacitance that interact with generator inductance resulted to series harmonic resonance at 9th and 15th harmonic order that causes high 9th and 15th harmonic current flowing between generator and cable capacitor. Generator neutral grounding resistor can effectively reduce the third harmonic in the phase and neutral. However care should be taken not to use very high generator neutral grounding resistor that can also restrict earth fault current that may pose problem to the sensitivity of earth fault protection system. Zig-zag transformer efficiently divert third harmonic current from generator to enter the load but high circulating third harmonic current between generator and zig-zag transformer may pose heating problem to the equipments.**

Keywords-Third harmonic voltage; third harmonic current; synchronous generator; cable capacitance; grounding

I. INTRODUCTION

Harmonic becomes important when their presence in power system can cause problem to equipment functionality. Some of these problems related to harmonic voltage and the other to harmonic current or both. The advancement of electronic industry resulted in devices that are sensitive to the voltage and current inputs.

Generally, harmonic study does not go beyond 50th harmonic since above that level their existence is negligible due to high impedance posed by the power system network at that frequency. Third harmonic is the first harmonic number of triplen harmonic which are 3rd, 9th, 15th, etc. series.

Large round rotor synchronous generator in a thermal power plant has been reported to produce harmonic even under no load condition [1]. Experiment carried out by [2] revealed that under various load condition, voltage regulation of synchronous generator related to harmonic distortion level produced by load. Parallel resonance contributed by network capacitance in cable, inverter, and household with inductance in transformer and cable has resulted higher voltage distortion. While series resonance would cause higher current distortion when large number of power inverters are connected in the system [3].

Electrical parameters of the subsea cable such as cable capacitance affect the frequency response characteristics for the same length of different types of subsea cables, although its influence is not as large as the cable length [4]. The influence of subsea cable shunt capacitance on harmonic distortion due to parallel resonance is investigated in detail by [5].

Triplen harmonic current from synchronous generator return to its neutral via cable capacitance and has caused the neutral grounding resistor to experience high temperature when connected to distribution grid [6]. Various transformer winding configuration of distributed generation interconnection transformer and neutral grounding reactor sizing have positive or negative impact on the triplen harmonic current [7]. Triplen harmonic current is one of the causes contributed to neutral grounding resistor failure apart from lightning, storms, earthquakes, extreme temperature changes, vibration etc. [8]. Simulation conducted by [9] has shown that zig-zag transformer is very effective to reduce triplen harmonic current from utility entering the load.

The objective of this paper is to study the influence of cable capacitance, generator neutral grounding resistor and zig-zag transformer on third harmonic voltage and current produced by low voltage synchronous generator directly connected to balanced load. In varying the parameters, lab experiment was conducted and the methodology is described in section II. The experimental results is presented and discussed in Section III. Finally the conclusion and recommendation is tabled in section IV. The term generator will be used to represent salient pole synchronous generator in the remaining text of this paper.

II. METHODOLOGY

The simulated results on the influence of cable length, number of parallel cable, cable size and neutral grounding resistor size on the magnitude of third harmonic current have been reported by [10]. Lab scale experiment are conducted in three parts namely, generator directly connected to balanced load via cable, generator directly connected to balanced load

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with different value of generator neutral grounding resistor and generator directly connected to balanced load shunted by zig-zag transformer. Due to generator's reactive power limitation, the cable is only represented by its capacitance without resistance and inductance. All the experiments will be using a three-phase 415 V, 50 Hz, 0.2 kW generator as harmonic source.

A. Generator Connected to Load Via Cable

Generator and load are connected in star with no neutral impedance. Cable capacitor is connected between the generator and load. Common neutral connection is made for generator, cable capacitor and load. Different combined resistive and inductive load are varied with different values of cable capacitances in the experiment. Third harmonic phase/neutral currents and voltages measurements are taken at generator, cable capacitor and load terminals.

B. Generator Neutral Grounding Resistor

Different value of generator neutral grounding resistor is applied to generator and load that are connected in star. Common neutral connection is made for generator with neutral grounding resistor and load. Combined resistive and inductive loads are varied for every generator grounding resistor value. Third harmonic phase/neutral currents and voltages are measured at generator and load terminals.

C. Generator Shunted by Zig-zag Transformer

In this experiment, generator and load are connected in star with no neutral impedance. Zig-zag transformer is connected between the generator and load. Common neutral connection is made for generator, zig-zag transformer and load. Combined resistive and inductive loads are varied throughout the experiment. Third harmonic phase/neutral currents and voltages measurements are taken at generator, zig-zag transformer and load terminals.

III. Results

Recorded experimental third harmonic voltage and current are phase measurement. 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, 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 Connected to Load Via Cable

The first part of the experiment is to vary the cable capacitance for different fixed loads. The third harmonic voltage magnitude at generator, cable capacitor and load terminals decrease when the cable capacitance increase regardless of load impedance phase angle magnitude as shown in Fig. 1 for combined resistive and inductive load of 686+j686 Ω.

The third harmonic current magnitude at generator terminal is the vector sum of third harmonic current flowing through cable capacitor and load. Therefore, the magnitude of third harmonic current at generator terminal depends on combined impedance of cable capacitor and load. Regardless of load impedance phase angle magnitude, the magnitude of third harmonic current at cable capacitor terminal always increase with increase in cable capacitance. Fig. 2 shows the third harmonic current magnitude at generator, cable capacitor and load terminals for combined resistive and inductive load of 686+j686 Ω.

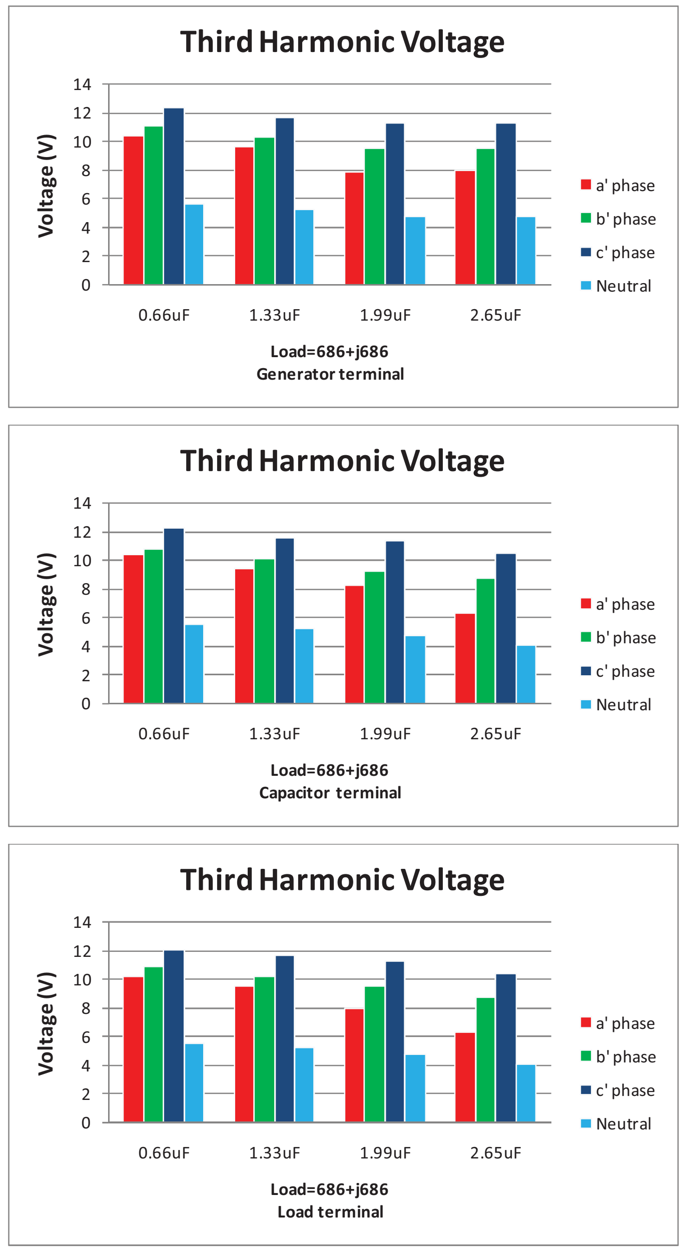


Fig. 1. Third harmonic voltage at generator, cable capacitor and load terminals for combined resistive and inductive load 686+j686 Ω

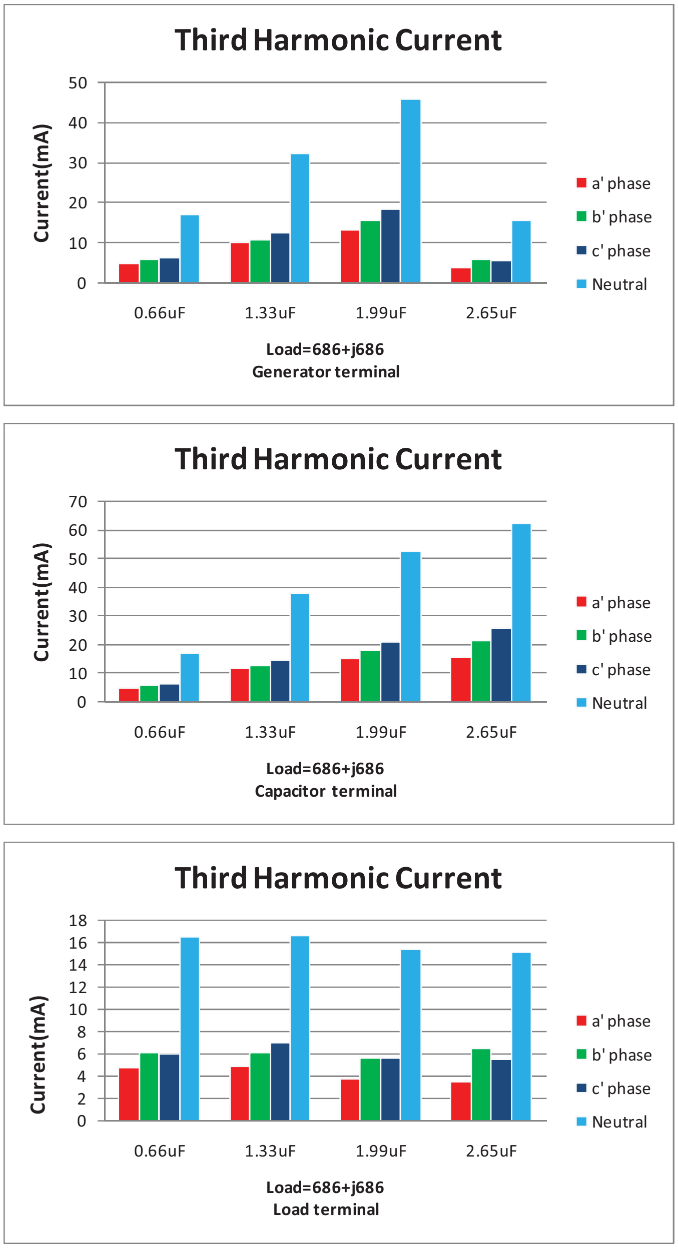


Fig. 2. Third harmonic current at generator, cable capacitor and load terminals for combined resistive and inductive load 686+j686 Ω

The combined resistive and inductive load is varied for different fixed capacitance value in the second part of the experiment. The third harmonic voltage magnitude at generator, cable capacitor and load terminals are proportional to the load impedance phase angle magnitude as shown in Fig. 3 for 1.99µF cable capacitance. The bigger the load impedance phase angle magnitude, the bigger the voltage magnitude.

The third harmonic current magnitude at generator terminal is the vector sum of third harmonic current flowing through cable capacitor and load. Therefore, the magnitude of third harmonic current at generator terminal depends on combined impedance of cable capacitor and load. Regardless of cable capacitance values, the magnitude of third harmonic current at cable capacitor terminal is proportional to the load impedance phase angle magnitude. Fig. 4 shows the third harmonic current magnitude at generator, cable capacitor and load terminals for 1.99µF cable capacitance.

The harmonic current spectrum when generator directly connected to a combined resistive and inductive load show that almost no current at other harmonic number except third harmonic. Harmonic series resonance is observed at 9^{th} and 15^{th} harmonic number and the highest harmonic current of both harmonic numbers at resonance is shown in Fig. 5. Resonance at 9^{th} harmonic number occurred at higher capacitor value while resonance at 15^{th} harmonic number detected at lower capacitor value.

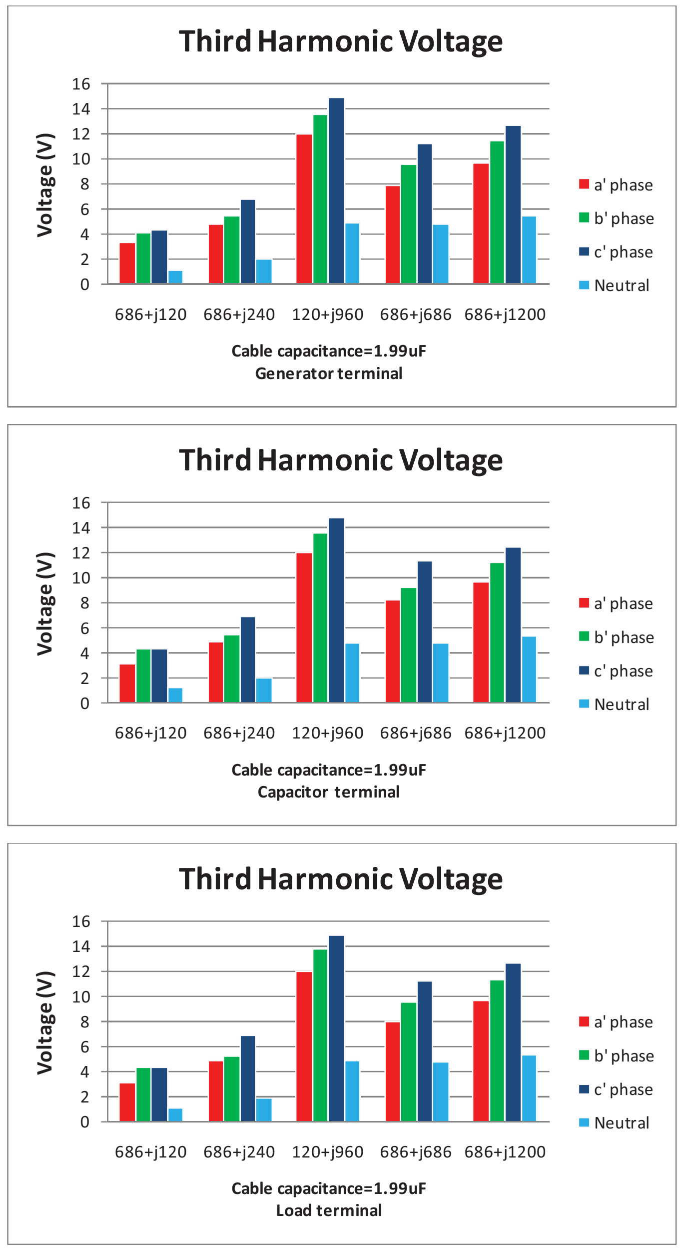


Fig. 3. Third harmonic voltage at generator, cable capacitor and load terminals for 1.99µF cable capacitance

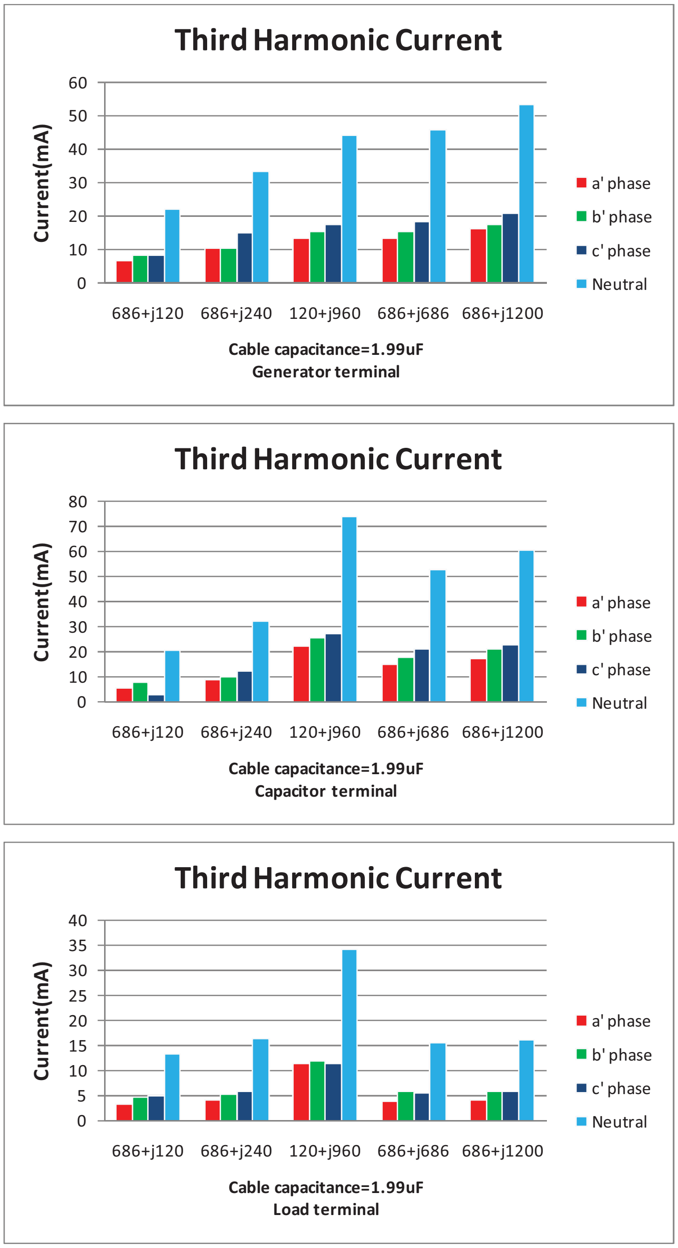
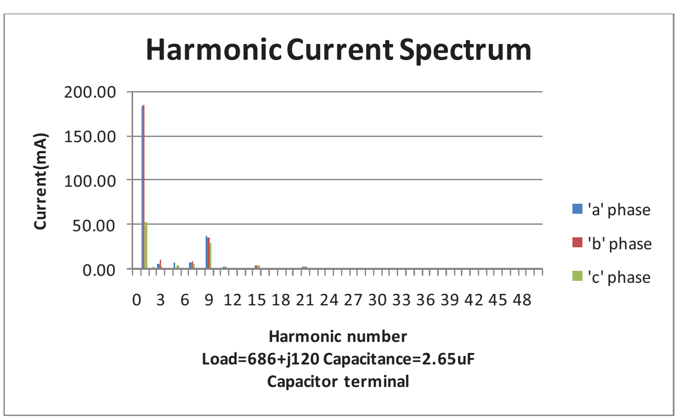


Fig. 4. Third harmonic current at generator, cable capacitor and load terminals for 1.99μF cable capacitance



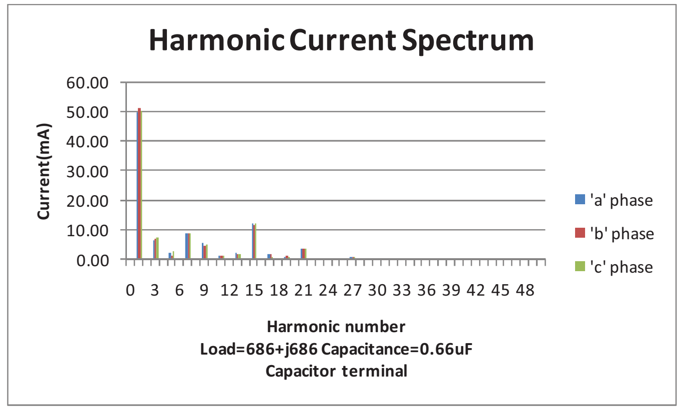
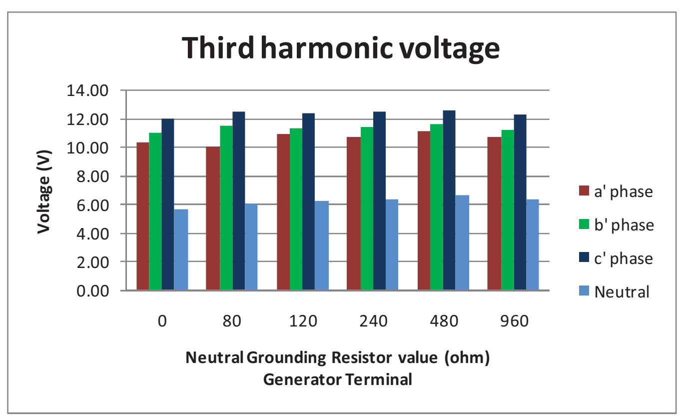


Fig. 5. Harmonic current spectrum for 9th and 15th harmonic resonance

B. Generator Neutral Grounding Resistor

The generator neutral grounding resistor is varied for various combined resistive and inductive load. The third harmonic voltage at generator terminal is almost constant for all generator neutral grounding resistor values. However, at load terminal, the third harmonic voltage decrease as the neutral grounding resistor values increase as shown in Fig. 6 for combined resistive and inductive load of 686+j686 Ω. This is due to voltage drop at neutral grounding resistor since the third harmonic current is present in the neutral. The magnitude reduction of third harmonic voltage is influenced by the neutral grounding resistance because the neutral third harmonic current is small.

The phase and neutral third harmonic current at generator and load terminals decrease as the neutral grounding resistor values increase as shown in Fig. 7. Almost zero sequence in nature, the phase neutral current sum at neutral hence resulting neutral current almost three times phase current magnitude. The net series impedance of neutral grounding resistor value and combined resistive and inductive load value determine the phase/neutral third harmonic current magnitude.



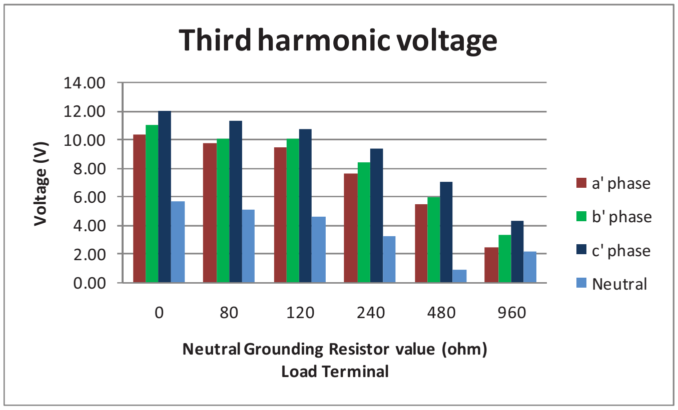


Fig. 6. Third harmonic voltage at generator and load terminals for combined resistive and inductive load 686+j686 Ω

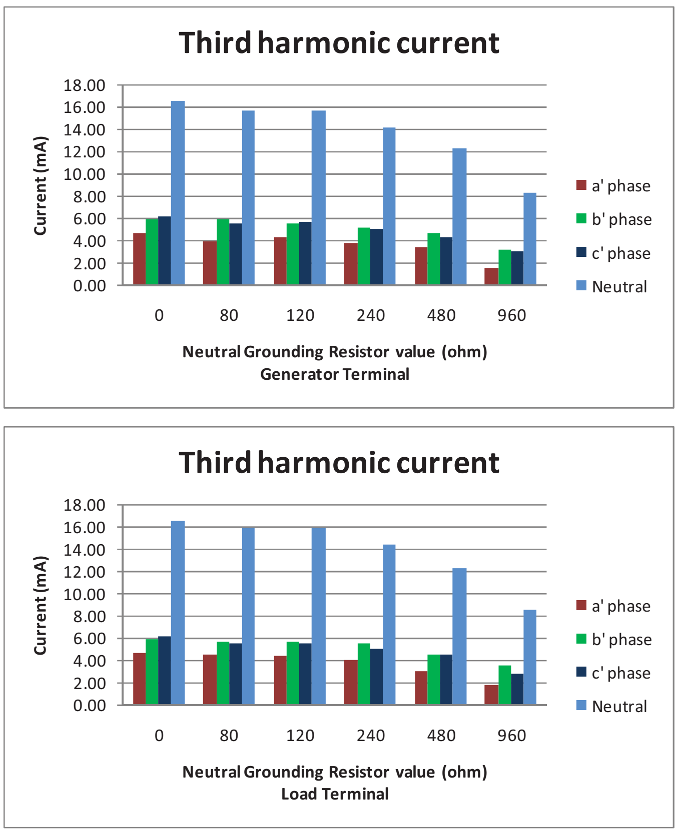


Fig. 7. Third harmonic current at generator and load terminals for combined resistive and inductive load 686+j686 Ω

C. Generator Shunted by Zig-zag Transformer

The third harmonic voltage at generator, zig-zag transformer and load terminals are quite constant for every combined resistive and inductive load as shown in Fig. 8. Higher load impedance phase angle magnitude yield higher voltage magnitude at generator, zig-zag transformer and load terminals.

Almost zero sequence in nature, the phase neutral current sum at neutral hence resulting neutral current almost three times phase current magnitude. In Fig. 9, almost all third harmonic current for phase and neutral from generator flow through zig-zag transformer and very small amount flow to the load for all combined resistive and inductive load. This is because zig-zag transformer provides the least impedance to ground as compared to combined resistive and inductive load for third harmonic current to flow.

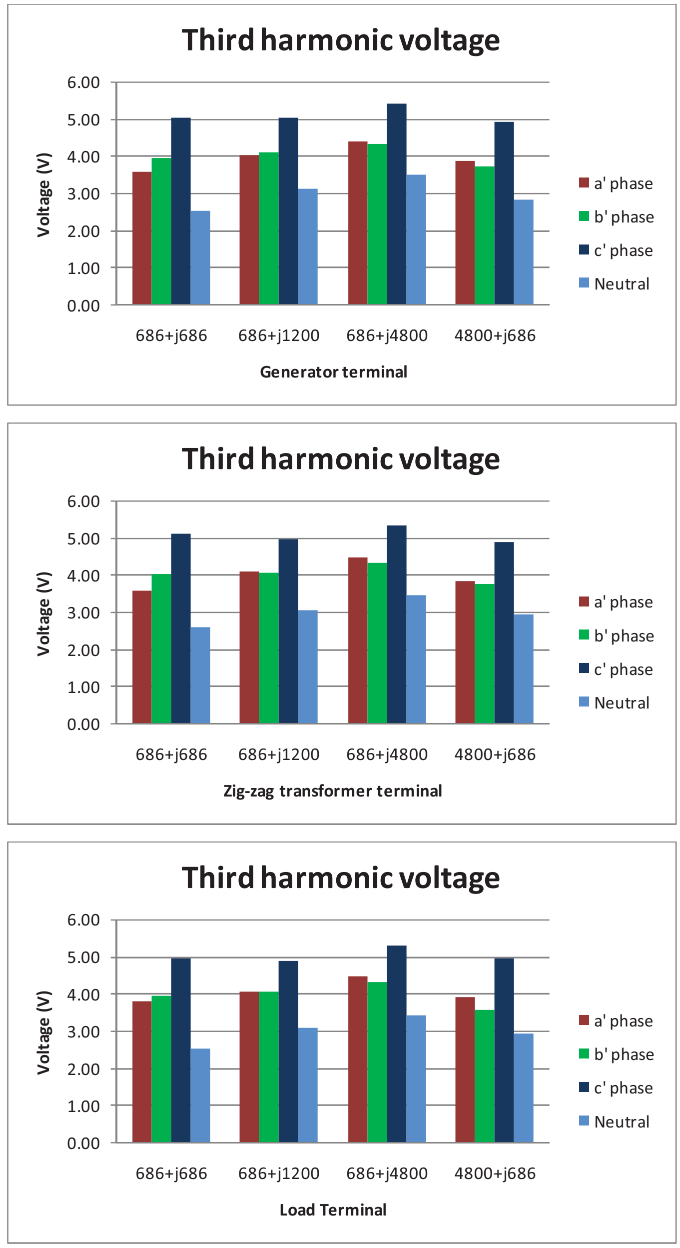


Fig. 8. Third harmonic voltage at generator, zig-zag transformer and load terminals for combined resistive and inductive load

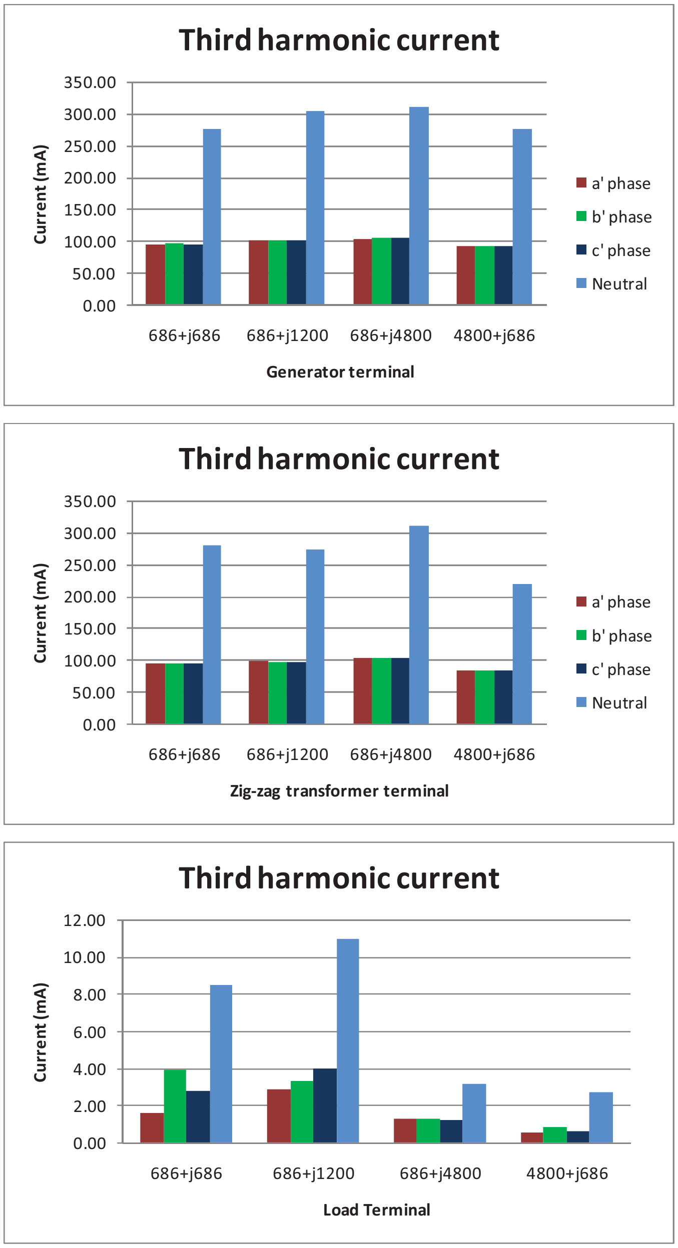


Fig. 9. Third harmonic current at generator, zig-zag transformer and load terminals for combined resistive and inductive load

IV. Conclusion

The cable capacitor provides the earth path for third harmonic current to return to generator neutral. Since cable capacitance is in parallel connection with combined resistive and inductive load, their net impedance decides the magnitude of third harmonic current. The presence of cable capacitance and generator inductance creates series resonance at 9th and 15th harmonic number. In practice the cable capacitance value represents cable length, size and number of cable in parallel.

Generator neutral grounding resistor provides additional impedance in the neutral and their resultant impedance with combined resistive and inductive load determines the magnitude of third harmonic current. Practically, generator neutral grounding resistor can be used to reduce third harmonic current from generator.

Zig-zag transformer exhibits low impedance earth path for third harmonic current to return to generator neutral. It diverts the generator third harmonic current from flowing to the load but very high third harmonic current circulating between generator and zig-zag transformer. This may pose heating problem to generator, zig-zag transformer and generator neutral grounding resistor.

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