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The Study of Triplen Harmonics Currents Produced by Salient Pole Synchronous Generator

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Abstract— **Triplen harmonics study for harmonics produced by salient pole synchronous generator is very important because their presence have caused communication line interference, damage to neutral earthing resistor etc. The purpose of this paper is to study the characteristics of triplen harmonics under balanced/unbalanced resistive/inductive loads, different generator neutral earthing resistor values and various transformer winding configurations. Lab scale salient pole synchronous generator is used for the experiment and third harmonic currents are recorded for analysis to represent triplen harmonics currents characteristics. Under balanced load, third harmonic current is inversely proportional to load impedance and neutral current is three times the phase current. During unbalanced load condition, the neutral current is lower than arithmetic sum of phase current due to different phase current magnitude and angle. The phase and neutral third harmonic currents magnitude is inversely proportional to generator NER resistance under balanced load. Transformer winding configurations under balanced load permit third harmonic current flowing through them in accordance to zero sequence network for the transformer apart from higher transformer reactive impedance at third harmonic. This study provides a very important input to mitigation method in reducing triplen harmonics currents propagation in the network.**

Keywords— **Salient pole synchronous generator, triplen harmonics currents, neutral earthing resistor.**

I. INTRODUCTION

Triplen harmonics currents and voltages are the odd multiples of third harmonics (3^{rd}, 9^{th}, 15^{th} etc.). Balanced triplen harmonics are zero sequence in nature because their phase quantity having same magnitude and phase angle. Hence, triplen harmonics currents add at neutral resulting in magnitude three times the phase value.

The source of triplen harmonics are switched electronics device (e.g. static power converter) and non-linear device/load (e.g. iron-core reactor) [1]. Synchronous generator also produced triplen harmonics depending on its winding design in terms of pitch factor, distribution factor and slot skew. Third harmonics studies for triplen harmonics currents propagation is adequate since higher triplen harmonics frequencies are opposed by higher impedance [2].

Salient pole shape and concentrated field winding of synchronous generator have caused third harmonic voltage at no-load. Salient pole shape and concentrated field winding, direct-axis armature reactance and quadrature-axis armature reactance contribute to third harmonic voltage at balanced load. Resultant of addition the effect of backward field mmf to salient pole shape and concentrated field winding, direct-axis armature reactance and quadrature-axis armature reactance yield third harmonic voltage at unbalanced load [3].

The design formula for calculating harmonics content in generated voltage produced by synchronous generator under balanced three phase load is detailed in [4]. The experiment verification of the formula in [4] is proven in [5] with minor inaccuracies due to saturation, manufacturing tolerances, departures of load currents etc.

Noise interference in telephone lines due to triplen harmonics voltages induction produced by synchronous generator is reported in [6]. High temperature of neutral earthing resistor (NER) for generator due to triplen harmonics currents conduction has been investigated in [7]. Triplen harmonics currents have been found to raise the neutral to earth voltage and increase the magnetic field in the vicinity of the lines [8]. The presence of triplen harmonics voltages lead to multiple zero crossings in phase to neutral voltage waveform causing the voltage zero crossing based detection lighting control system to malfunction [9].

The objective of this paper is to study the characteristics of triplen harmonics currents produced by salient pole synchronous generator under various load conditions, different value of generator NER and common transformer winding configurations. Lab experiment methodology is described in section II. Experimental results and discussion are detailed in section III. The conclusion and recommendation of the study are summarized in section IV. The salient pole synchronous generator will be termed as generator throughout the remaining of this paper.

II. METHODOLOGY

Triplen harmonics voltages are present at the output terminals of generator even when it is not connected to a load.

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However, triplen harmonics currents only exist when generator begin to supply a load.

There are many factors that influence triplen harmonics currents produced by generator as simulated in [10]. In order to study the characteristics of these triplen harmonics currents, a low voltage generator is used for a laboratory scale experiment. Table I shows the laboratory equipment ratings for generator, transformer and loads.

Table I
Laboratory equipment rating

Equipment	Ratings
Generator	415 V; 0.35 A; 175 W
Transformer	415 V / 240 V; 250 VA
Resistive load	240 V; 252 W
Inductive load	240 V; 252 Var

The experiments are conducted in three parts to cover the full spectrum of simulations in [10] except for cable related parameters such as cable size, length etc.

A. Load variation

Balanced and unbalanced load conditions are studied for resistive and inductive loads. Table II, Table III and Table IV show the value for each phase under unbalanced resistive, inductive and their combination load impedances, respectively. Loads are connected in wye with neutral wire connected to generator neutral. The generator is connected directly to the load and the harmonics currents are measured at the load terminals.

Table II
Unbalanced resistive load impedance

Case study	Phase 'a' (Ω)	Phase 'b' (Ω)	Phase 'c' (Ω)
Case1	686	800	1200
Case2	1600	2400	4800
Case3	800	1600	2400
Case4	1200	2400	4800
Case5	800	1200	1600
Case6	1600	2400	4800

Table III
Unbalanced inductive load impedance

Case study	Phase 'a' (H)	Phase 'b' (H)	Phase 'c' (H)
Case1	3	4	5
Case2	4	5	8
Case3	5	8	2
Case4	10	11	15
Case5	3	4	8
Case6	2	3	4

Table IV
Unbalanced resistive and inductive load impedance

Case study	Phase 'a' (Ω+H)	Phase 'b' (Ω+H)	Phase 'c' (Ω+H)
Case1	686+2.5	800+3.8	1200+5.1
Case2	1600+3.8	2400+5.1	4800+7.6
Case3	800+5.1	1600+7.6	2400+2.1
Case4	1200+2.5	2400+3.8	4800+5.1
Case study	Phase 'a' (Ω+H)	Phase 'b' (Ω+H)	Phase 'c' (Ω+H)
Case5	800+2.5	1200+3.8	1600+7.6
Case6	1600+2.1	2400+2.5	4800+3.8

B. Generator NER

The NER value for generator is varied during which an identical balanced resistive load is directly connected to it. Loads are connected in wye with neutral wire connected to generator neutral. The harmonics currents are measured at the generator terminals.

C. Transformer winding configurations

There are four possible transformer winding configurations namely delta-delta, delta-wye, wye-delta and wye-wye. The generator is connected directly to the primary winding of the transformer and the step-down secondary winding is directly connected to an identical balanced resistive load. Loads are connected in wye with neutral wire connected to transformer (applicable to wye winding only) and generator neutral points. The harmonics currents are measured at the generator terminals, primary and secondary sides of the transformer and load end.

III. Experimental Results And Discussion

In the study of triplen harmonics currents produced by generator, third harmonic current is of concern and significant. Therefore, the measurement for third harmonic current is studied and presented here to characterize the general behaviour of triplen harmonics currents.

A. Load variation

The third harmonic current for balanced resistive, inductive and their combination load are shown in Fig. 1 to Fig. 3, respectively. Fig. 4 to Fig. 6 shows the third harmonic current for unbalanced resistive, inductive and their combination load correspondingly.

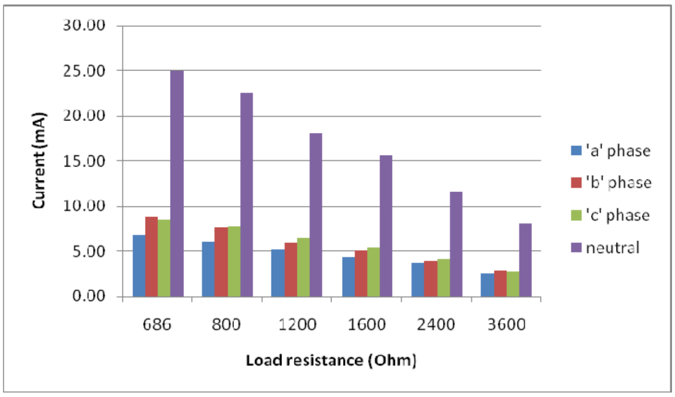

Fig. 1 Third harmonic current vs balanced resistive load impedance

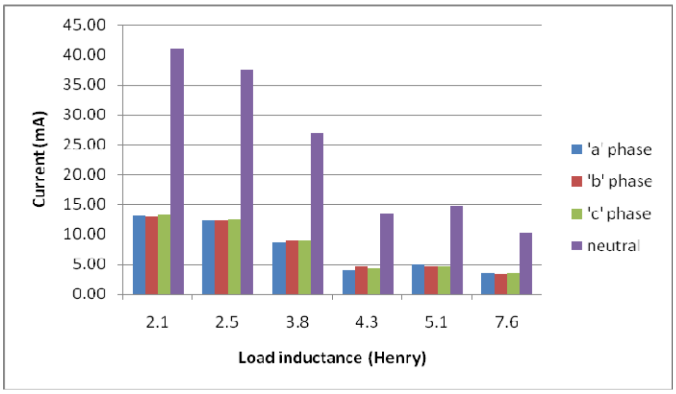

Fig. 2 Third harmonic current vs balanced inductive load impedance

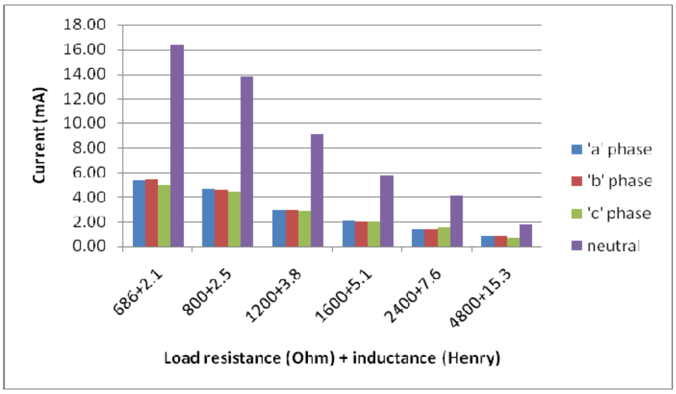

Fig. 3 Third harmonic current vs combination balanced resistive and inductive load impedance

Under balanced load, all phase currents magnitude almost equal. The phase and neutral third harmonic currents magnitude are inversely proportional to balanced resistive, inductive and their combination load impedance. The third harmonic current in the neutral is three times the phase current.

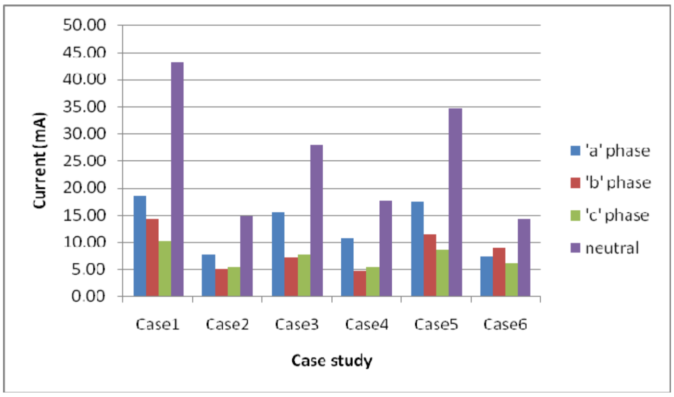

Fig. 4 Third harmonic current vs unbalanced resistive load impedance

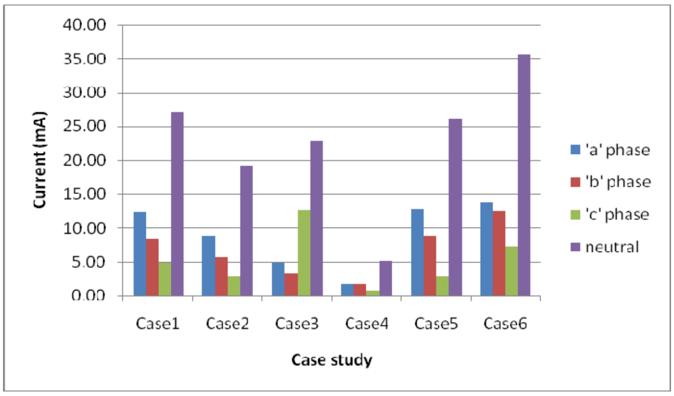

Fig. 5 Third harmonic current vs unbalanced inductive load impedance

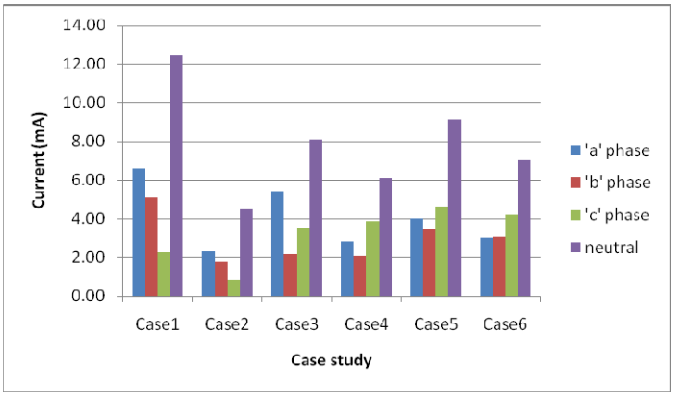

Fig. 6 Third harmonic current vs combination unbalanced resistive and inductive load impedance

All phases have different current magnitude due to unbalanced resistive, inductive and their combination load impedance. The third harmonic current in the neutral is slightly lower than the arithmetic sum of all phase currents due to different magnitude and angle.

B. *Generator NER*

The relationship between third harmonic current and generator NER value is shown in Fig. 7.

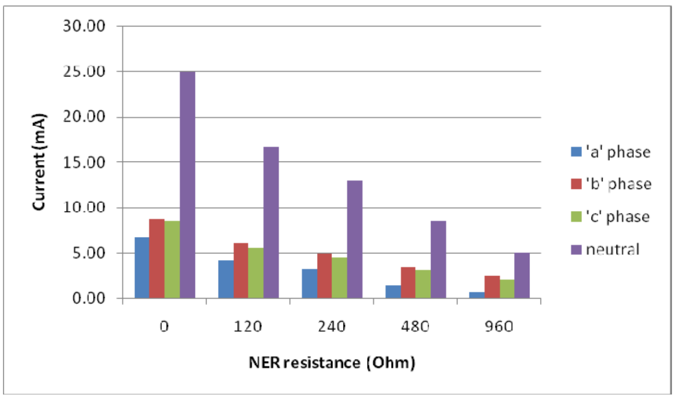

Fig. 7 Third harmonic current vs generator NER value

The phase and neutral third harmonic currents magnitude are inversely proportional to generator NER resistance. On average the reduction in phase and neutral third harmonic currents are 32% against 100% increased in NER resistance.

C. Transformer winding configurations

The phase and neutral (applicable to wye winding only) third harmonic currents at the generator terminals, primary and secondary sides of the transformer and load end for different transformer winding configurations are shown in Fig. 8 to Fig. 11.

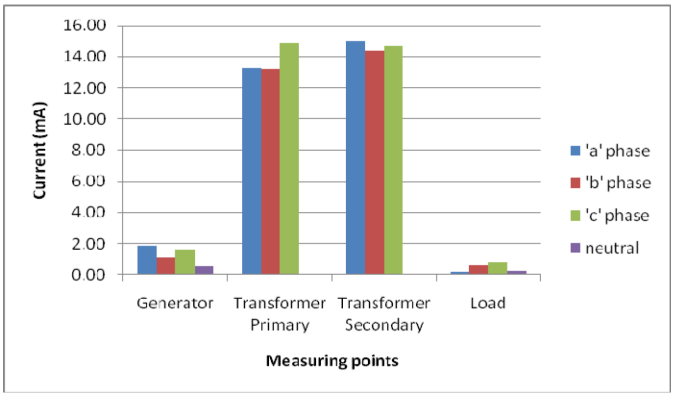

Fig. 8 Third harmonic current for delta-delta TX configuration

In delta-delta transformer configuration, the circulating third harmonic current in ‘b’ phase of delta primary winding is 1190% higher than its line third harmonic current.

On the same phase, the corresponding third harmonic current on the delta secondary winding stand at 1300% higher. Third harmonic current is trapped in delta primary and secondary windings. No third harmonic current flows in the load.

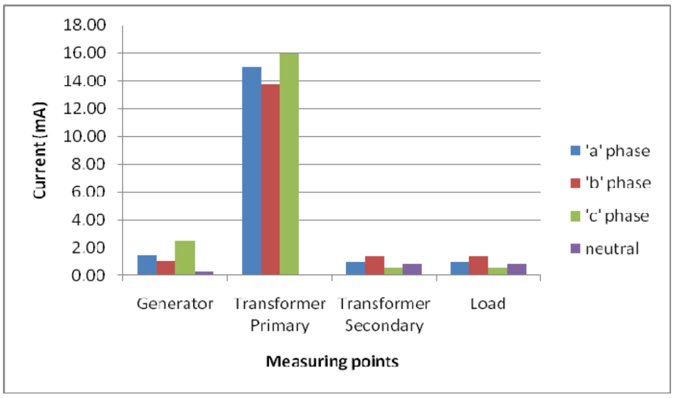

Fig. 9 Third harmonic current for delta-wye TX configuration

The third harmonic current in ‘b’ phase of delta primary winding for delta-wye transformer configuration is 1298% higher than its line third harmonic current. The third harmonic current is trapped in delta primary winding. Very small third harmonic current flows in the load probably due to slight transformer unbalance impedance as noticed in the phase current magnitude and angle.

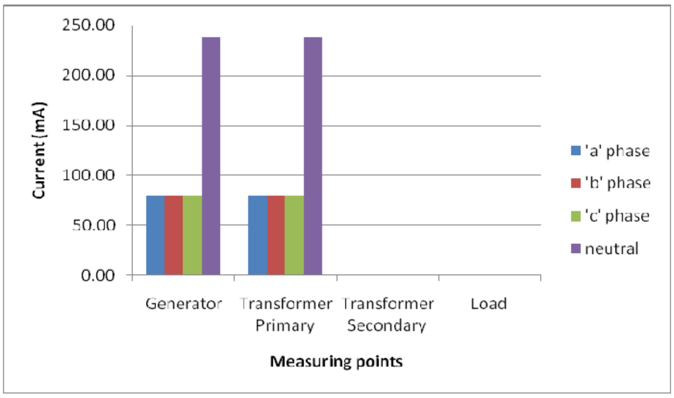

Fig. 10 Third harmonic current for wye-delta TX configuration

The highest phase and neutral third harmonic currents occur in the wye-delta transformer configuration since wye primary winding provides the lowest zero sequence impedance or a shunt path to neutral. No third harmonic currents circulating in the delta secondary winding and load.

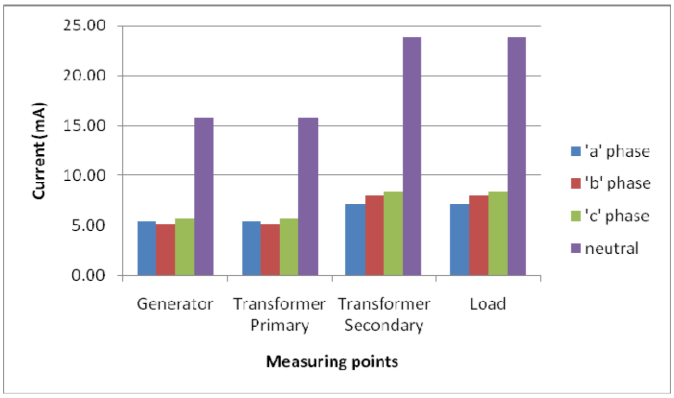

Fig. 11 Third harmonic current for wye-wye TX configuration

In the wye-wye transformer configuration, third harmonic current flows through the transformer similar to fundamental harmonic currents except that transformer exhibit higher reactive impedance to third harmonic. This is evident when the ratio of phase third harmonic current on the wye secondary winding to wye primary winding is 1.44 times, whereas, the corresponding fundamental harmonic ratio is 1.73 times.

IV. CONCLUSIONS

Triplen harmonics currents produced by salient pole synchronous generator are influenced by load impedance, generator NER value and transformer winding configurations.

In general, higher load impedance result in lower triplen harmonics currents. Unbalanced load can cause triplen harmonics currents not identical in magnitude and phase angle.

Generator NER function is to reduce earth fault current and from the experiment it also reduce the magnitude of triplen harmonics currents. Under balanced load, generator NER value exhibit zero sequence quantity where their value are three times thus reducing the current to one third.

Triplen harmonics currents are zero sequence in nature under balanced load. Thus, zero sequence network for any transformer winding configurations would determine the triplen harmonics currents flowing through them.

The outcome of this study can be used to further research on method to reduce triplen harmonics currents flowing in the network. Special attention must be given to address unbalanced triplen harmonics currents due to unbalanced network impedance.

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