The Third Harmonic Model for Salient Pole Synchronous Generator Under Balanced Load

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***Abstract*—The third harmonic current produced by salient pole synchronous generator has always been associated with high neutral current causing problem to neutral earthing resistor, telecommunication system, and earthfault protection. In this paper, the third harmonic model for salient pole synchronous generator in symmetrical component domain is proposed that comprise of generator parameter and generated voltage. The new computational technique in determining the third harmonic zero-sequence synchronous impedance is introduced. In completing the model, the method to characterize generated third harmonic zero-sequence voltage under balanced combine resistive and inductive load is described. In order to study the third harmonic current flowing in the network, the propagation model is also established. The third harmonic synchronous generator parameters are measured and comparatively validated with laboratory experiment results. In addition to that, the third harmonic generated voltage is characterized and validated experimentally.**

***Index Terms*—Generated third harmonic zero-sequence voltage, symmetrical component domain, third harmonic, third harmonic zero-sequence synchronous impedance.**

I. Introduction

IN power quality, the neutral of synchronous generator is exposed to the risk of overloading or elevated voltage due to triplen harmonic. The characteristic of triplen harmonic current being zero sequence in nature that adds up at neutral is the major contributor to these problems. In fundamental frequency, the zero-sequence current can exist in the neutral during earthfault or unbalanced load condition. Salient pole synchronous generator has been recognized as triplen harmonic source and the third harmonic being the largest component. Salient pole shape and concentrated field winding of synchronous generator have caused the third harmonic voltage generation at no load. Field current and salient pole shape, direct-axis armature reactance and quadrature-axis armature reactance are the components of the third harmonic voltage generation at balanced load [1].

It has been reported earlier that continuous third harmonic currents flow through synchronous generator neutral earthing resistor which originated from the generator itself [2]. Higher third harmonic currents have been reported during synchronous generator interconnection to utility grid due to lower zero-sequence impedance of the network provided by zigzag transformer at utility end.

Circulating third harmonic current under various synchronous generator earthing methods have been calculated based on the model of the third harmonic driving voltage connected to zero-sequence network. Synchronous generator third harmonic voltage source at full-load and no-load are assumed to be some percentage of rated fundamental frequency phase voltage or based on typical manufacturer data. The synchronous generator third harmonic reactance is assumed as three times larger than the fundamental frequency zero-sequence reactance [3].

In [4], the fundamental frequency zero-sequence reactance formula expression for salient pole synchronous generator has been derived to represent the third harmonic flux. Zero-sequence slot and leakage reactance are influenced by winding pitch being as a minimum when synchronous generator having 2/3 pitch. Fundamental frequency zero-sequence reactance is very small in the region of 15%–60% of direct axis subtransient reactance due to no armature reactance MMF that resulted from zero-sequence current [5].

The third harmonic voltage measurement is being used in the earthfault protection for synchronous generator stator winding and neutral for better coverage and reliability. The load fundamental frequency real power influences on the third harmonic voltage appear at synchronous generator terminal whereas its reactive power has an insignificant effect [6]. Many harmonic load flow methods introduced earlier are either entirely in time domain [7], or within harmonic domain [8], or hybrid of time and harmonic domain [9].

The triplen harmonic has been documented in the literatures to cause interference in communication line due to induction from earth return current of directly supplied synchronous generator [10], [11]. Furthermore, the significant problem of elevated neutral to earth voltage due to triplen harmonic has been demonstrated by Maitra *et al.* and Collins and Jiang [12], [13].

A solution to mitigate the high triplen harmonic currents in neutral due to resonance condition by unearthing the wye connected capacitor bank is proposed in [14]. Zigzag transformer has been proven effective in mitigating the high impact of triplen harmonic current in three-phase four wires distribution system [15], [16].

Synchronous generator connected directly to a medium voltage system is commonly found in oil and gas platforms or isolated distribution network. However, not many studies on third harmonic in this type of network configuration were published. Hence, the objective of this research is to propose the

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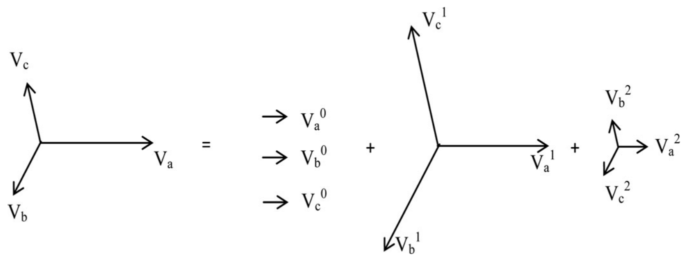

Fig. 1. Symmetrical component analysis.

third harmonic model for salient pole synchronous generator under balanced load in medium voltage system using symmetrical component domain.

II. Methodology

In this paper, the third harmonic model for synchronous generator in symmetrical component domain is first established. The new computational technique in determining third harmonic zero-sequence synchronous impedance is presented and validated. The generated third harmonic zero-sequence voltage is characterized for various synchronous generator connections to a combined resistive and inductive balanced load. Thus, the phenomenon of the third harmonic current which is not necessary flow to the load is emulated and validated via experiment.

A. Third Harmonic Model for Synchronous Generator in Symmetrical Component Domain

Symmetrical component analysis is used to solve unbalanced condition due to faults or load variation. According to Fortescue's theorem, unbalanced three-phase system can be represented as summation of three separate systems of balanced and symmetrical voltages or currents known as zero sequence, positive sequence, and negative sequence as shown in Fig. 1. Since the direction of third harmonic current depends on ground connection, symmetrical component analysis can offer a directional solution.

Subsequently, the relationship between the sequence and phase quantities are derived and shown in the following equation:

$$\begin{bmatrix} \mathrm{V}_a^0 \\ \mathrm{V}_a^1 \\ \mathrm{V}_a^2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} \mathrm{V}_a \\ \mathrm{V}_b \\ \mathrm{V}_c \end{bmatrix} \text{ where a } = 1\angle 120^\circ. \quad (1)$$

Let V_{3a} be the generated third harmonic voltage in phase "a". Under balanced and symmetrical condition, the generated third harmonic voltages are derived as

$$\begin{bmatrix} \mathrm{V}_{3a} \\ \mathrm{V}_{3b} \\ \mathrm{V}_{3c} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \mathrm{V}_{3a}. \quad (2)$$

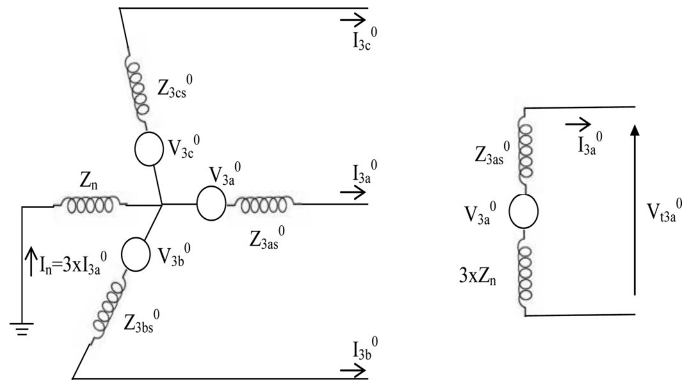

Fig. 2. Synchronous generator third harmonic sequence networks.

Substituting (2) into (1) gives the sequence quantities as follows:

$$\begin{bmatrix} \mathrm{V}_{3a}^0 \\ \mathrm{V}_{3a}^1 \\ \mathrm{V}_{3a}^2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \mathrm{V}_{3a} = \begin{bmatrix} \mathrm{V}_{3a} \\ 0 \\ 0 \end{bmatrix}. \quad (3)$$

Equation (3) indicates that only zero-sequence network has third harmonic voltage source which resulted to the sequence network for the synchronous generator as depicted in Fig. 2. Therefore, mathematically, under balanced and symmetrical condition, the synchronous generator third harmonic can be modeled using zero-sequence network alone.

In real-world application, the terminal fundamental frequency voltage of synchronous generator is always maintained at fixed value regardless of load current variation by means of automatic voltage regulator. Therefore, the action of synchronous generator excitation system to maintain a constant terminal fundamental frequency voltage construed that the generated voltage is a variable parameter due to the voltage drop at fixed value of synchronous impedance.

Subsequently, it is expected that, the generated third harmonic zero-sequence voltage will vary under various balanced load conditions. The synchronous generator neutral impedance is modeled as three times larger to its value due to the returning third harmonic neutral current that is three times larger than the third harmonic zero-sequence phase current. In this model, the critical issues are to determine accurately the third harmonic zero-sequence synchronous impedance and variable generated voltage that influence the third harmonic voltage and current characteristics in the network. In arriving to that, inevitably, the fundamental frequency positive-sequence synchronous impedance needs to be ascertained. It is important to mention that this paper deal with instantaneous steady-state measurement of the third harmonic when synchronous generator is operating within its normal rated capacity.

1) Synchronous Generator Parameters: The established method of determining the fundamental frequency positive-sequence synchronous impedance (Z_{as}^1) is by conducting the open-circuit and short-circuit tests. The fundamental frequency synchronous impedance is computed by applying (4). It applies the corresponding fundamental frequency positive-sequence voltage of open-circuit test $(V_{\rm oc}^1)$ and current of short-circuit test $(I_{\rm sc}^1)$ at the rated field current. The fundamental frequency armature resistance $(R_{\rm a})$ is measured using the dc method with the assumption that dc armature resistance is approximately equal to the ac value (slightly higher due to skin effect). The fundamental frequency positive-sequence synchronous reactance $(X_{\rm as}^1)$ is then calculated using (5):

$$Z_{\rm as}^1 = \frac{V_{\rm oc}^1}{I_{\rm sc}^1} \tag{4}$$

$$X_{\rm as}^1 = \sqrt{(Z_{\rm as}^1)^2 - R_a^2}. \tag{5}$$

All the aforementioned measurements are instantaneous and scalar quantities. The proposed new computational technique in determining the third harmonic zero-sequence synchronous impedance begins with the computing of the complex value for fundamental frequency positive-sequence synchronous impedances using (4). It is expected that these fixed magnitude complex value impedances would revolve since the measurement of open-circuit and short-circuit tests are made at a different time interval. The fundamental frequency armature resistance is assumed the same as its dc measurement. The fundamental frequency positive-sequence synchronous impedance angle $(\Phi_{\rm as})$ is calculated using (6) which will be applied to determine the fundamental frequency positive-sequence impedance.

The third harmonic zero-sequence synchronous impedances $(Z_{\rm 3as}^0)$ are determined using correspondingly the third harmonic zero-sequence voltages of open-circuit test $(V_{\rm 3oc}^0)$ and currents of short-circuit test $(I_{\rm 3sc}^0)$ by applying (7). Since fundamental frequency and the third harmonic measurements are done simultaneously, it is assumed that fundamental frequency positive-sequence synchronous impedance angle $(\Phi_{\rm as})$ is the same as the third harmonic zero-sequence impedance angle $(\Phi_{\rm 3as})$. This angle is used to determine the third harmonic zero-sequence armature resistance $(R_{\rm 3a}^0)$ and reactance $(X_{\rm 3as}^0)$ using (8) and (9). In this model, the third harmonic zero-sequence synchronous impedance is assumed to be a constant:

$$\Phi_{\rm as} = \arccos\left(\frac{R_a}{Z_{\rm as}^1}\right) = \Phi_{3as} \tag{6}$$

$$Z_{3as}^0 = \frac{V_{3oc}^0}{I_{3sc}^0} \tag{7}$$

$$X_{3as}^0 = Z_{3as}^0 \sin(\Phi_{3as}) \tag{8}$$

$$R_{3a}^0 = Z_{3as}^0 \cos(\Phi_{3as}). \tag{9}$$

2) Generated Voltage: The generated third harmonic zero-sequence $(V_{\rm 3a}^0)$ voltage is derived and is given as

$$V_{3a}^0 = V_{t3a}^0 + I_{3a}^0 Z_{3as}^0. \tag{10}$$

Thus, from (10), the generated third harmonic zero-sequence voltage is computed from its corresponding terminal voltage $(V_{\rm t3a}^0)$ by referring to its equivalent circuit as depicted in Fig. 3.

It has been validated that, the third harmonic current flows through the zero-sequence network of the power system [2]. Therefore, the third harmonic real and calculated reactive power will be applied to correlate them with the generated third harmonic zero-sequence real and imaginary voltages, respectively.

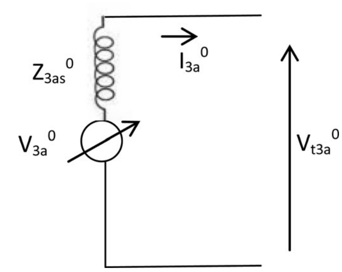

Fig. 3. Third harmonic zero-sequence equivalent circuits.

In order to cover the whole spectrum of generated third harmonic zero-sequence voltages, measurement should be done for various synchronous generator to load connection. The reference connection is when the synchronous generator is in the island operating mode. The connection is directly to the wye connected load without neutral earthing impedance to allow larger current for better accuracy. There is a need to consider the generated third harmonic zero-sequence voltage when transformers of all possible winding configurations are connected between the synchronous generator and the load. Subsequently, the generated third harmonic zero-sequence voltage, when synchronous generator is in parallel with the grid, needs to be characterized for the case of synchronous generator feeding both of grid and load.

B. Third Harmonic Propagation Model

Fundamental frequency power flow is about determining bus voltage and its phase angle by utilizing the network equation (11) and bus power equation (12) iteratively using the Newton Raphson or the Gauss Seidel method:

$$l_i = \sum_{n=1}^{N} Y_{\rm in} V_n \tag{11}$$

where, i = bus i and N = total bus number:

$$P_i + Q_i = V_i I_i^*. \tag{12}$$

Most harmonic power flow uses Newton's method based on fundamental frequency power flow equation but customizing to time or harmonic or hybrid domains. Therefore, the harmonic voltage and current depend on load quantum and load flow direction. Investigation by Abdullah *et al.* [2] revealed that the third harmonic current originated from synchronous generator flow in reversal to the fundamental frequency load flow direction. In order to explain the phenomenon that the third harmonic current do not necessarily flow to the load, only (11) is used in calculating the third harmonic current.

The third harmonic propagation is modeled by connecting the synchronous generator third harmonic sequence network to the zero-sequence network of the power system as shown in Fig. 4.

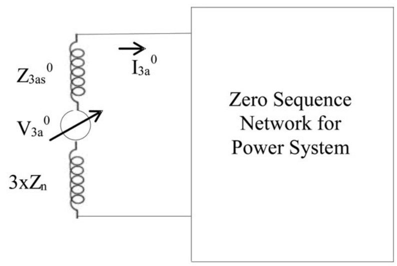

Fig. 4. Third harmonic propagation model.

TABLE I
LABORATORY EQUIPMENT

Equipment	Ratings/specifications
Synchronous generator	Lab-Volt 415 V; 0.17 A; 0.2 kW; 1500 rpm; salient pole
PQ Analyzer	Fluke 435; 5 A current clamps; 1000 V voltage probes
Resistive& inductive Load (constant impedance angle)	Lab-Volt 415 V/252 W/252 VAR; 960 W + j2.2 H (960+j660 W - 35^0); 1600 W + j3.8 H (1600+j1200 W - 37^0); 2400 W + j 5.1 H (2400+j1600 W - 34^0); 3600 W + j7.6 H (3600+j2400 W - 34^0); 4800 W + j 11.4 H (4800+j3580 W - 37^0)
Resistive& inductive Load (increasing load impedance angle)	Lab-Volt 415 V/252 W/252 VAR; 4800 W + j2.18 H (4800+j686 W - 8^0); 1200 W + j2.18 H (1200+j686 W - 30^0); 686 W + j 2.18 H (686+j686 W - 45^0); 686 W + j3.8 H (686+j1200 W - 60^0); 686 W + j 15.3 H (686+j4800 W - 82^0)
Transformer	Lab-Volt 415 V/252 W; Input voltage (425/240 V); Output voltage (240 V)

C. Parameterization Experiment

Laboratory experiments are conducted to demonstrate the applicability of new computational technique in determining synchronous impedance and characterizing generated third harmonic zero-sequence voltage. Table I outlines the synchronous generator, power quality analyzer, load and transformer details that are used in the experiment.

1) Synchronous Generator Parameters: The fundamental frequency and third harmonic phase voltages from open-circuit test and phase currents from short-circuit test measurements at corresponding field current are transformed to their sequence quantities. The fundamental frequency positive-sequence synchronous impedance is then calculated and their average envelope is plotted in *R*–*X* plane. The armature dc resistance is measured using a multimeter.

The fundamental frequency positive-sequence synchronous impedance angle is determined using average fundamental frequency positive-sequence synchronous impedances and armature resistances. This angle is later to be used to determine the fundamental frequency positive-sequence synchronous reactance. Similarly, the same procedure is carried out to determine the third harmonic zero-sequence synchronous resistance and reactance.

2) Generated Voltage: The synchronous generator terminal third harmonic phase voltage and current are measured for synchronous generator connected directly and through transformer [wye–delta (TXSD), wye–wye (TXSS), delta–wye (TXDS), and

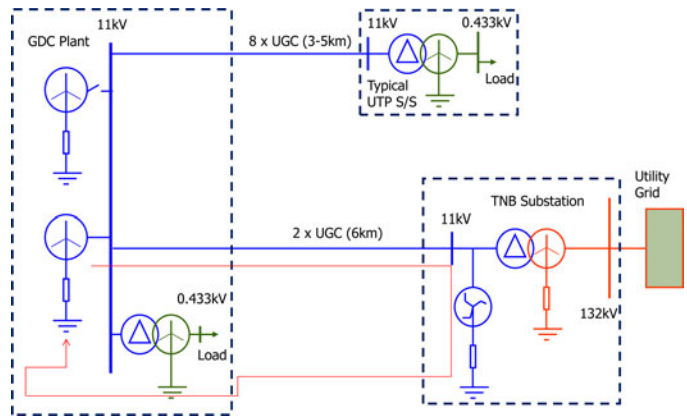

Fig. 5. Synchronous generator in parallel with utility grid.

delta–delta (TXDD)] to wye connected load experiments. Generator in parallel with grid experiment is also carried out for the case of generator feeding the grid and load.

These voltage and current are then transformed to the third harmonic zero-sequence voltage and current. The generated third harmonic zero-sequence voltages are calculated once the third harmonic zero-sequence synchronous impedances have been determined.

The characteristics of generated and terminal voltages for third harmonic zero sequence during direct load connection are observed as the reference. Then, the relationship of the generated third harmonic zero-sequence real and imaginary voltages against the third harmonic real and calculated reactive power, respectively, is formulated.

D. Model Validation

It is not the intention of this paper to validate the model using electrical machine basic theory but validation is performed using experiment data with justification and assumption. The new computational technique in determining fundamental frequency positive-sequence synchronous impedance is first validated with the existing established method. Then the value of the third harmonic zero-sequence synchronous impedance is validated comparatively with justification. The next step involves the comparison of generated third harmonic zero-sequence voltage for combined resistive and inductive load with increasing load impedance angle from 8° to 82° in island operation.

To validate that the model agrees with the real situation, experiment to simulate pairing of the synchronous generator with utility grid as detailed in [2] and as shown in Fig. 5 is conducted. Neglecting the small third harmonic current that flow through cable capacitance, the zero-sequence network for this power system is interpreted as shown in Fig. 6. Table II describes the zero-sequence impedances for the whole system.

The flow of the third harmonic current is indicated by the arrow direction and only those parameters in the loop have influence on its magnitude. It is worth to mention that the third harmonic current contribution from both the grid and load are blocked by delta winding of utility power transformer and load transformer, respectively. All measurement at 11-kV system will

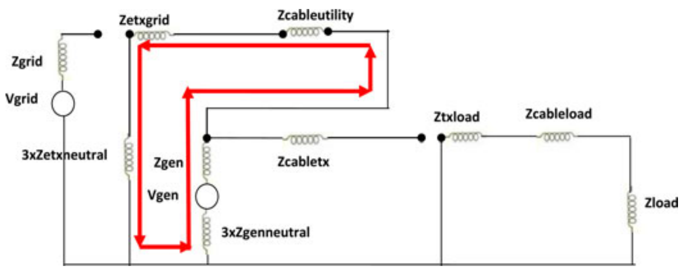

Fig. 6. Zero-sequence network for system in Fig. 5.

TABLE II
ZERO-SEQUENCE IMPEDANCES DESCRIPTION

Legend	Description
Vgen	Generated third harmonic voltage
Vgrid	Grid third harmonic voltage
Zgen	Third harmonic zero sequence synchronous impedance
Zgenneutral	Generator neutral earthing impedance
Zcableutility	Underground cable zero sequence impedance from generator to utility substation
Zetxgrid	Earthing transformer zero sequence impedance at utility substation
Zetxneutral	Earthing transformer neutral earthing impedance at utility substation
Zgrid	Grid zero sequence impedance
Zcabletx	Underground cable zero sequence impedance from generator to load transformer
Ztxload	Load transformer zero sequence impedance
Zcableload	Underground cable zero sequence impedance from load transformer to load
Zload	Load zero sequence impedance

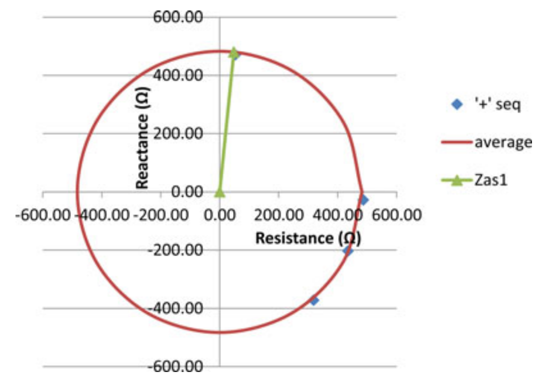

Fig. 7. Fundamental frequency positive-sequence synchronous impedance.

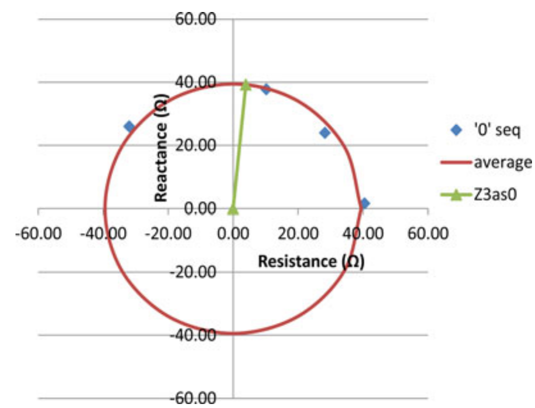

Fig. 8. Third harmonic zero-sequence synchronous impedance.

always be balanced since the unbalanced at 0.433 kV load side will circulate in delta winding of load transformer.

Due to small laboratory synchronous generator size, this experiment is conducted without cables (Zcableutility, Zcabletx, Zcableload) and neutral earthing impedance (Zgenneutral and Zetxneutral) to allow larger third harmonic current to flow for better accuracy. The grid and zigzag transformers are replaced by a wye–delta transformer that serves the same function.

The zero-sequence network for this experiment setup is almost similar to island operation with wye–delta configuration of load transformer. Hence, comparison on generated third harmonic zero-sequence voltage is to be validated. The third harmonic real-power direction is mapped for synchronous generator supplying the load and grid to further validating that the third harmonic current does not necessarily flowing to the load during parallel operation with grid.

III. Results and Discussion

The third harmonic zero-sequence synchronous generator parameters, generated voltage characteristics, and parallel operation results are presented here and they are validated either quantitatively or qualitatively.

A. Synchronous Generator Parameters

The fundamental frequency positive-sequence synchronous impedances are shown in Fig. 7. It is obvious that fundamental frequency positive-sequence synchronous impedances are constant magnitudes that revolve around their average value. The average fundamental frequency positive-sequence synchronous impedance is 482.85 Ω while armature resistance is 48 Ω. The fundamental frequency positive-sequence synchronous impedance angle is 84.3°. Hence, the fundamental frequency positive-sequence synchronous impedance is 48 + j480.45 Ω.

Applying established method, the average fundamental frequency positive-sequence synchronous impedance calculated using (4) is also 482.85 Ω and reactance calculated using (5) is 480.46 Ω. Hence, the new computational and established methods give the same value of fundamental frequency positive-sequence synchronous impedance.

The third harmonic zero-sequence synchronous impedances are shown in Fig. 8. Expectedly, the third harmonic zero-sequence synchronous impedances are constant magnitudes that revolve around its average value. The average third harmonic zero-sequence synchronous impedance is 39.45 Ω. Using the third harmonic zero-sequence synchronous impedance angle 84.3°, the third harmonic zero-sequence synchronous impedance is 3.92 + j39.26 Ω.

The average third harmonic zero-sequence synchronous impedance calculated using (4) is 39.51 Ω. However, the third harmonic synchronous reactance could not be calculated using (5) if the third harmonic armature resistance is assumed as 48 Ω. Hence, the calculation for the third harmonic zero-sequence

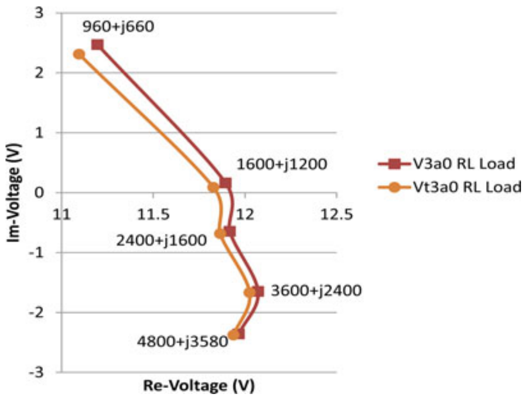

Fig. 9. Generated and terminal third harmonic zero-sequence voltage under direct resistive and inductive load.

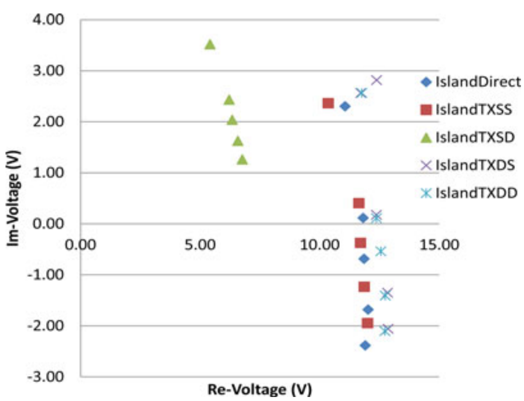

Fig. 10. Generated third harmonic zero-sequence voltage under direct and through various transformer winding configuration in island operation.

synchronous impedance is only feasible using the proposed new computational technique.

B. Generated Voltage

The generated and terminal third harmonic zero-sequence voltages under direct balanced resistive and inductive load are as shown in Fig. 9. The magnitude of generated third harmonic zero-sequence voltages increases quadratically as the load impedances are increased. However, the action of excitation system in keeping the terminal fundamental frequency positive-sequence voltage fixed all the times could not maintain the terminal third harmonic zero sequence at a constant value.

The generated third harmonic zero-sequence voltages under direct and through various transformer winding configuration connected to a balanced resistive and inductive load in island operation are shown in Fig. 10.

The generated third harmonic zero-sequence real and imaginary voltages against the third harmonic real and reactive power for various load impedances are plotted as shown in Fig. 11.

The best curve with highest coefficient of determination (R-squared) that represents the generated third harmonic zero-sequence real ($V_{3\text{real}}$) and imaginary ($V_{3\text{imaginary}}$) voltages for corresponding third harmonic real (P_3) and reactive (Q_3) power

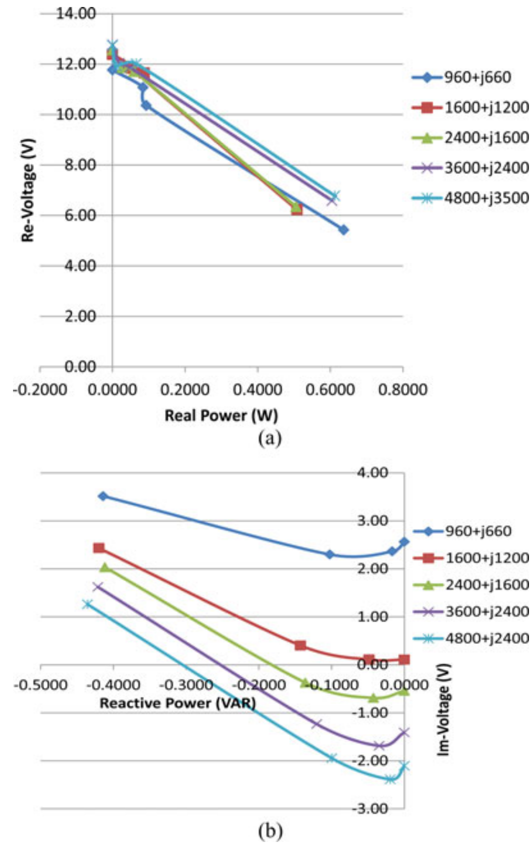

Fig. 11. (a) Generated third harmonic zero-sequence real voltage versus the third harmonic real power and (b) generated third harmonic zero-sequence imaginary voltage versus the third harmonic reactive power.

are shown in Fig. 12. Their relationships are given as follows:

$$V_{3\text{real}} = -8.0512\, P_3^2 - 7.9493\, P_3 + 12.35 \quad (13)$$

$$V_{3\text{imaginary}} = 12.574\, Q_3^2 - 0.2928\, Q_3 + 0.0925. \quad (14)$$

C. Model Validation

The proposed new computational technique is very accurate to determine the fundamental frequency positive-sequence synchronous impedance. The third harmonic zero-sequence synchronous impedance is 8.17% of fundamental frequency positive-sequence synchronous impedance magnitude. The small values of the third harmonic armature resistance and reactance obtained are somewhat agrees to the known fact that even fundamental frequency zero-sequence impedance or transient or subtransient reactance is small and often contain no resistive component.

Reliability of the proposed new computational technique is further strengthened with the fact that the fundamental frequency and the third harmonic measurement used in the calculation are extracted from the same synchronous generator open-circuit and short-circuit tests, simultaneously.

The percentage difference between the generated third harmonic zero-sequence voltage calculated using (13) and (14) and experimental result for resistive and inductive (increasing load

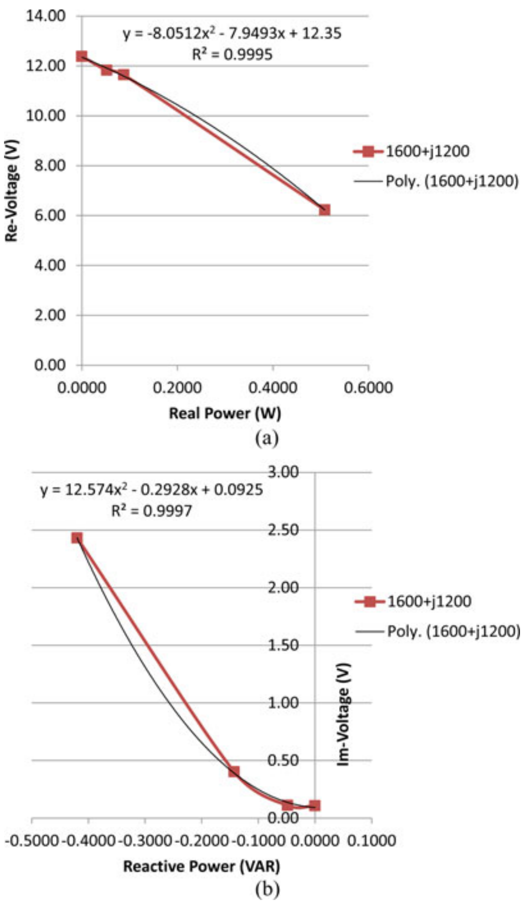

Fig. 12. (a) Average generated third harmonic zero-sequence real voltage versus the third harmonic real power and (b) generated third harmonic zero-sequence imaginary voltage versus the third harmonic reactive power.

TABLE III
PERCENTAGE DIFFERENCE OF GENERATED THIRD HARMONIC ZERO-SEQUENCE VOLTAGE FOR BALANCED RESISTIVE AND INDUCTIVE LOAD (INCREASING LOAD IMPEDANCE ANGLE)

Load Impedance		% Difference			
R	X	Vlreal	Vlimag	Absolute	Angle
4800	686	3%	-108%	3%	-108%
1200	686	8%	-91%	6%	-91%
686	686	1%	-85%	-1%	-85%
686	1200	-11%	-128%	-11%	-131%
686	4800	-2%	-104%	-6%	-104%
Average		0%	-103%	-2%	-104%

impedance angle) load are shown in Table III. The percentage difference for generated third harmonic zero-sequence real voltage is between 8% and −11% and the average is 0%. The generated third harmonic zero-sequence imaginary voltage fluctuates within −85% and −128% differences and the average is −108%. The expected large difference in the generated third harmonic zero-sequence imaginary voltage is due to the deviation from the best fitted referenced curve as shown in Fig. 11(b). In terms of their absolute magnitude of generated third harmonic zero-sequence voltage, the percentage difference is between 6% and −11% with the average of −2%.

During synchronous generator parallel with the grid, it is interesting to note that generated third harmonic zero-sequence

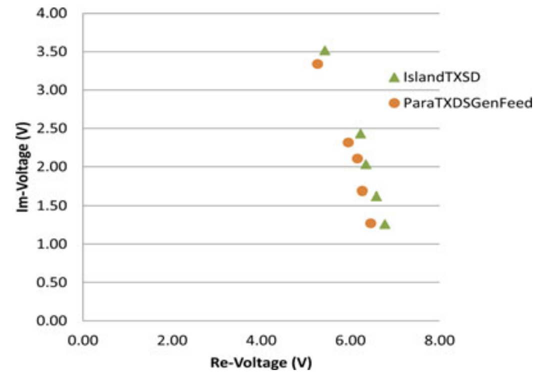

Fig. 13. Generated third harmonic zero-sequence voltage for island operation (wye–delta load transformer) and parallel with grid.

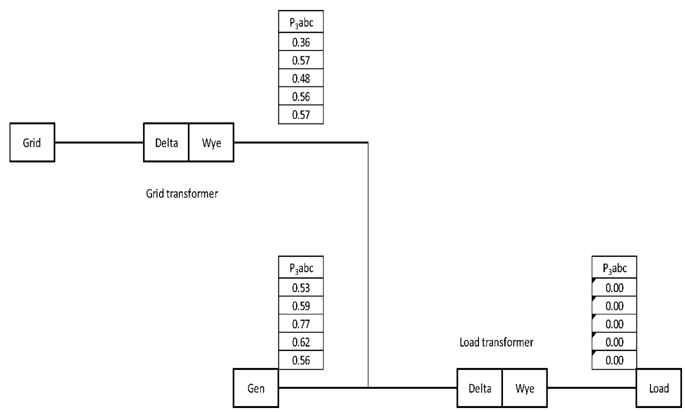

Fig. 14. Third harmonic real-power flow during parallel with grid.

voltage show almost the same characteristic with island operation in wye–delta transformer connection as shown in Fig. 13. This is because the zero-sequence impedance is almost the same for both conditions.

When synchronous generator is pairing with the grid, the third harmonic real-power flows to the grid or its zero-sequence network and not to the load as shown in Fig. 14.

IV. CONCLUSION

In developing the third harmonic model for salient pole synchronous generator in symmetrical component domain, the new computational technique in determining the third harmonic zero-sequence synchronous impedance is derived, experimentally measured and comparatively validated. Prior to completing the model, the method to determine the generated third harmonic zero-sequence voltage is suggested. The proposed propagation model of the third harmonic produced by salient pole synchronous generator is addressing both island and parallel operation with the grid. The finding in the research would help in better understanding of the third harmonic propagation in medium voltage of the electrical network and possibly contribute to mitigating measures in reducing their impact.

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