Experimental Investigations on Loading Capacity and Reactive Power Compensation of Star Configured Three Phase Self Excited Induction Generator for Distribution Power Generation

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Abstract

Self excited induction generator (SEIG) is gaining popularity for off-grid power generation due to the inherent advantages. This paper presents a primary experimental investigative study on the performance of three-phase star configured SEIG (Y-SEIG). The aim of the experimental work is to identify a simple and cost-effective scheme of self-excitation and reactive power (VAR) compensation among the six possible operational configurations. From the investigated results, it is found that the capacitor excitation and VAR

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compensation in the delta connection scheme give the better performance. Experimental test procedure and obtained values of steady state analysis of SEIG for calculation of minimum excitation capacitance are also highlighted in this paper.

Keywords: Self excited induction generator (SEIG), minimum excitation capacitance, reactive power (VAR) compensation, distributed power generation, voltage regulation.

1 Introduction

Installation capacity of oil/coal-free power generating stations is increasing day by day across the India and as well as the World to reduce the global warming issues. In this context, the naturally available and harmless renewable energy sources (RES) are drawing more attention from energy sector to generate the electricity. Grid and off-grid/isolated systems are the two practice methods of utilization of electric energy. Transmission and Distribution (T&D) losses can be avoided through the deployment of small/micro energy systems by using the locally available RES [1–8].

The constant speed turbine sources, like small/micro-hydro and biomass and variable speed sources like wind energy systems need the generator solution to convert the mechanical energy into electric energy [9–19]. Induction generator (IG) is well suitable for constant speed applications. In generating mode, the slip of the IG should be negative, in other words, the speed of the rotor is maintained above the synchronous speed [20–25]. In isolated mode, the IG is not a self-started generator and needed the suitable rating of reactive power (VAR/VAr) for self-excitation and such a featured generator is termed as self-excitation induction generator (SEIG). The various methods have been reported in the literature for finding the excitation capacitance of SEIG [26–39].

The terminal voltage of the SEIG depends on the three factors; value of speed, connected rating of load, and core magnetization of the generator. By effectively managing these factors the voltage profile can be improved. Many researchers have been reported the power quality improved SEIG systems with power electronic interface [40–50]. Battery energy storage system (BESS) is useful for balancing the power in the system and SEIG based hybrid energy systems have been proposed in [18, 19, 45].

Generally, the nodal impedance, admittance methods are adapted for the computational analysis by using the per-phase equivalent circuit of three-phase SEIG. A simple method of improving the voltage regulation in SEIG is by proving an extra VAR compensation through the capacitor bank connection. The author [35] has investigated the performance of three-phase SEIG in shunt, short and long-shunt configurations and concluded that the short-shunt method of operation improves the voltage regulation adequately. For every value of the load of SEIG reaches to new steady state value, higher the load on the system leads to collapse the generation mode and needs the re-excitation process [30, 31].

MATLAB/Simulation based SEIG systems are reported in literature to verify the performance under various load conditions and improved the voltage regulation with and without power electronics and BESS systems. The general-purpose induction machines of drive applications can be operated in star or delta configuration. In the same way the SEIG too operate in star and delta mode. For special applications, like where the two ranges of voltages i.e., line and phase voltages are required, then the SEIG should be operated in star mode with three-phase 4-wire system. In this context, the performance of the Y SEIG is needed to be verified before the commencement of deployment of the small-scale system to restrict the load rating on the generator. On the other hand, the capacitors for self-excitation can also be connected in Y or Δ. In this paper, the performance of the star configured SEIG (Y SEIG) under resistance load is experimentally verified to investigate a simple, economical, and efficient configuration of capacitor for self-excitation and VAR compensation. The schematics of proposed comparative study of SEIG system, steady state analysis, calculation of minimum excitation capacitance is highlighted in this study.

The organization of the paper is as follows; in Section 2, the schematics of different possible configurations of excitation and reactive power compensation methods of Y SEIG feeding Y loads and the tests involved in steady state analysis is discussed. In Section 3, the best practices of capacitor connections and methods of self-excitation calculation are determined. Section 4 illustrates the experimental verification of self-excitation phenomena for voltage build-up under no load and performance of three-phase, 4-wire Y SEIG with balanced Y resistance load is investigated for identification of best voltage regulation scheme. Finally, the conclusion of the experimental study is given in Section 5.

2 Schematics of Different Possible Topologies of Star-Configured SEIG and Steady-state Analysis

This section covers the proposed study of different possible configurations of three-phase 4-wire Y SEIG system with minimum excitation capacitors and extra capacitors for self start of generator operation and VAR compensation, respectively. Steady state analysis and tests involved in it is also discussed in this section. The selection procedure of capacitor size and the respective numerical calculations for both the delta and star connected excitation schemes are given in detail bellow.

2.1 Schematics of the Proposed Study on Three-phase 4-wire Y SEIG System

In this work, the performance of three-phase 4-wire Y SEIG with both the Δ and Y mode excitations are studied under a balanced Y-connected resistive load. The experiment investigations are carried out for voltage regulation with the additional VAR supplement capacitance banks in Δ, Y and line to line (L-L) connection. The possible combinations of workable schemes and schematic diagram of proposed comprehensive connection of three-phase 4-wire Y SEIG supplying Y loads is presented in Figures 1 and 2, respectively.

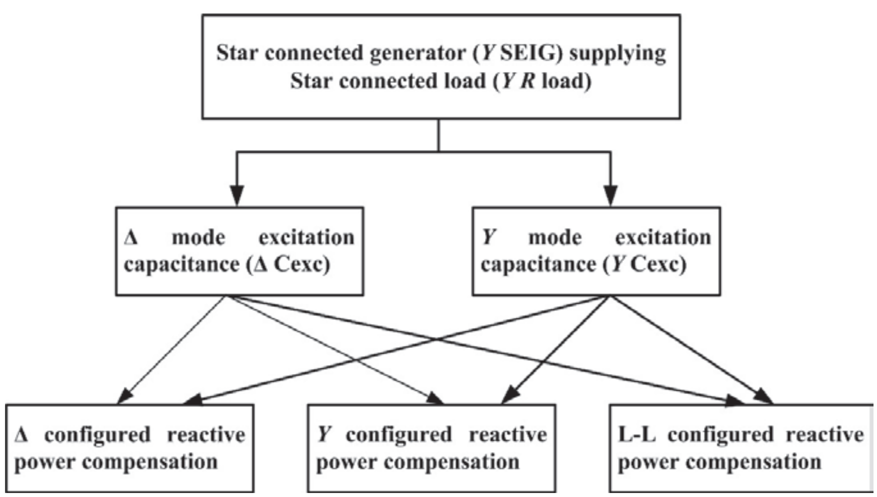

Figure 1 Possible combinations of workable schemes of three-phase star configured SEIG.

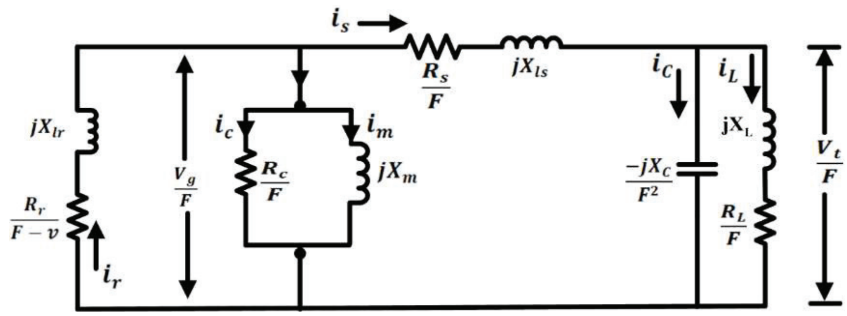

Figure 2 Per-phase equivalent circuit of three-phase SEIG including excitation capacitor.

2.2 Steady State Analysis of SEIG

The steady state analysis of SEIG is an important study to predict the performance, machine parameters and minimum excitation capacitance value for the supplement of required reactive power. The per-phase equivalent circuit of three-phase SEIG system is shown in Figure 2. All the equivalent values of circuit quantities are referred to stator side and the reactance values are referred to the base frequency (F).

The following three tests are needed to be conducted to find out the equivalent circuit parameters of the generator: (i) DC test for stator resistance (R_s), (ii) blocked rotor test for rotor resistance (R_r) and leakage reactance (X_l), and (iii) synchronous impedance test for magnetizing reactance (X_m) [3, 4, 6, 36–38]. The experimental procedure of the above three tests are given in bellow.

A. DC Test

The DC test is performing on induction motor (IM) to calculate the stator resistance (R_s). While conducting this test, the rotor should be at a stand-still or zero speed position and a minimal amount of DC voltage is applied to any of the two stator terminals of the IM to give a noticeable voltage drop. The experiment must be repeat for the two or three sets of voltages and the corresponding current readings. Note that the DC current, which make to flow through the terminals, should be less than the rated current of the test IM. The circuit arrangement for the DC test conduct on IM is shown in Figure 3. The DC resistance value is given by Equation (1).

$$R_{DC} = \frac{\sum_{n=1}^{N} \frac{V_{DCn}}{I_{DCn}}}{N} \tag{1}$$

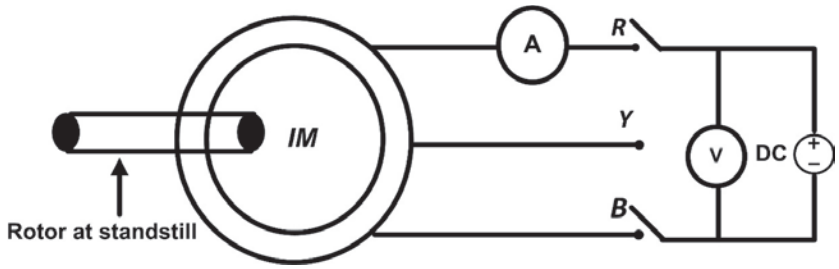

Figure 3 Circuit diagram representation of DC test conduct on Induction Machine (IM).

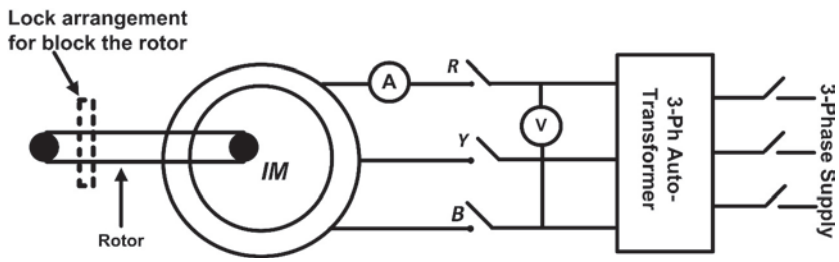

Figure 4 Circuit diagram representation of blocked rotor test conduct of IM.

In (1), V_{DCn} and I_{DCn} are the stator DC voltage and current respectively, and *N* is the number of sample sets of the readings.

B. Blocked-rotor Test

The blocked-rotor test conduct on IM is shown in Figure 4. To conduct this test, the rotor of the test IM should be blocked or locked by using some external force/lock and then slowly apply the voltage supply to the stator terminals through an auto- transformer until the rated current of the IM is reached. The input voltage, current and power readings are holds for some other parameter findings, which are given by Equations from (2) to (9).

$$I_{bkdph} = \frac{I_{bkdl\_l}}{\sqrt{3}} \tag{2}$$

$$V_{bkdl\_l} = V_{bkdph} \tag{3}$$

$$P_{bkd/ph} = \frac{P_{bkd}}{3} \tag{4}$$

$$R_{bkdr} = \frac{P_{bkdp}}{{I_{bkdl\_l}}^2} \tag{5}$$

$$Z_{bkdr} = \frac{V_{bkdph}}{I_{bkdph}} \tag{6}$$

$$X_{bkdr} = \sqrt{{Z_{bkdr}}^2 - {R_{bkdr}}^2} \tag{7}$$

$$X_{bkdr} = X_s + X_r \quad \text{(since, } X_s = X_r\text{)} \tag{8}$$

In blocked rotor test expressions of (3)–(8), the *r* is stands for rotor, V_{bkdl_l} is the line-line voltage, V_{bkdph} is the phase voltage, I_{bkdl} is the line-line current, I_{bkdph} is the input phase current, R_{bkdr} is the blocked rotor resistance, Z_{bkdr} is the impedance, X_{bkdr} is the reactance, P_{bkd} is the input power, $P_{bkd/ph}$ is the input per-phase power.

C. Synchronous Impedance Test

A schematic diagram of synchronous impedance test conduct on *IM* is shown in Figure 5, and which is used to find the relationship between the air-gap voltage ratio ($\frac{V_g}{F}$) and magnetic reactance (X_m). The $\frac{V_g}{F}$ depends on the magnetic flux (ϕ) and hence on the magnetizing reactance (X_m). To perform this test on *IM*, the rotor should be rotate at synchronous speed by using of an external controlled rotational energy source. Next, a three-phase voltage is applied across the stator windings of the *IM* through a three-phase auto transformer and the input voltage (V) value, current value (I), and power (W) values are needed to be noted.

Some of the derived formulas from the synchronous impedance test is given bellow.

$$\text{Apparent power, } S = \sqrt{3}VI \tag{9}$$

$$\text{Reactive power, } Q = \sqrt{S^2 - P^2} \tag{10}$$

$$\text{Air-gap voltage, } V_g = |V_1 - I_1(cos\varphi - jsin\varphi)(R_1 + jX_1)| \tag{11}$$

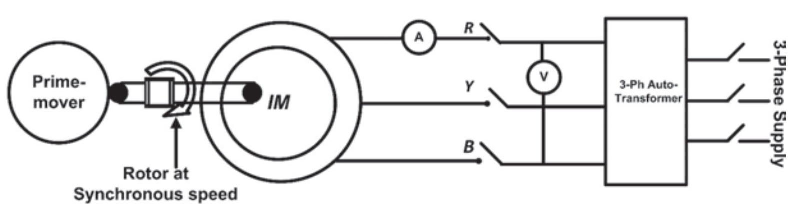

Figure 5 Circuit diagram representation of synchronous impedance test conduct of IM.

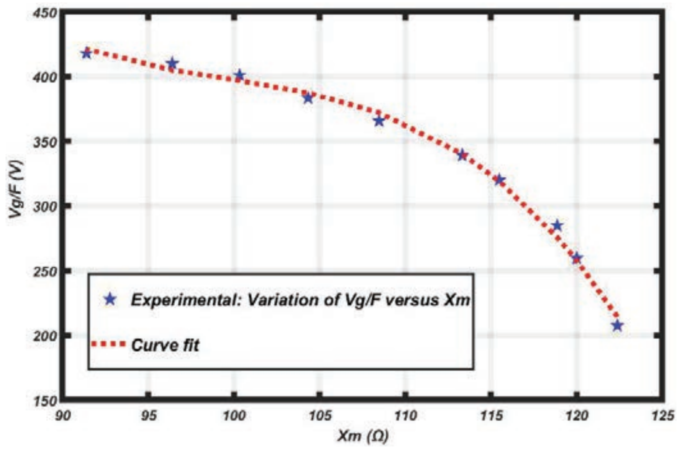

Figure 6 Variation of $\frac{V_g}{F}$ versus X_m in Y SEIG (real-time data of synchronous impedance test).

In the above Equation (11), V_1 and I_1 are the line voltage and line currents, respectively.

$$\text{Core-loss component, } R_c = \frac{V_g^2}{(P - 3I_1^2 R_1)} \tag{12}$$

$$X_m = \frac{V_g^2}{(Q - 3I_1^2 X_1)} \tag{13}$$

In the steady-state analysis, $\frac{V_g}{F}$ is expressed by the nth order polynomial of X_m in the normal operating region of the induction machine and which is given by (14)

$$\frac{V_g}{F} = k_1 + k_2 X_m + k_3 X_m^2 + k_4 X_m^3 \tag{14}$$

Here in Equation (14), the k_1, k_2,k_3 and k_4 are the coefficients and these can be calculated by incorporate the values of $\frac{V_g}{F}$ and X_m in the MATLAB routine "polyfit". The relation, $\frac{V_g}{F}$ vs. X_m is given in Figure 6. The equivalent circuit parameters determined from the above three experimental tests and machine parameters are tabulated in Table 1.

The minimum excitation capacitor (C_{min}) value is given by the relation (15) [9–11, 48, 49].

$$C_{min} = \frac{1}{[\omega n^2 (x_{ls} + x_{s\ max})]} \tag{15}$$

Table 1 Ratings of the test machine

Sl. No	Name of the Parameter	Specification of the Parameter
1.	Power, P (W)	1.1 kW
2.	Number of Poles, p	6
3.	Frequency (F)	50 Hz
4.	Line voltage (Vl)	415 V
5.	Line current (Il)	2.8 A
6.	Stator resistance (R_s)	7.2 Ω/ph
7.	Leakage inductance of stator (L_{ls})	35.25 mH
8.	Machine efficiency (η_m)	78.12%
9.	Power factor (p.f)	0.69

In (15), the value of $x_{s\ max}$ is considered as 91.05 from the Figure 6 for Y SEIG. The per phase minimum excitation capacitor in delta manner of Y SEIG ($Y\ SEIGC_{min\_\Delta ph}$) from the (16) is

$$Y\ SEIGC_{min\_\Delta ph} = \frac{1}{3[2\times\pi \times 50 \times 1^2(11.08 + 91.05)]} = 10.35 \approx 10.5\ \mu\text{F/ph} \tag{16}$$

The per phase minimum excitation capacitor in star manner of Y SEIG ($Y\ SEIGC_{min\_\mathrm{Y}ph}$) is given as (17)

$$Y\ SEIGC_{min\_\mathrm{Y}ph} = 3 \times Y\ SEIGC_{min\_\Delta ph}$$
$$Y\ SEIGC_{min\_\mathrm{Y}ph} = 3 \times 10.5 \approx 31.5\ \mu\text{F/ph} \tag{17}$$

The capacitor values of 10.50 μF/ph in delta connection and 31.50 μF/ph in star connection are selected for the self-excitation of three-phase Y SEIG. The capacitor connection in delta mode is an economical in such a way that as it needs 1/3 rating of the capacitors to supply the same required reactive power for the self-excitation process.

3 Experimental Verification of Self-excitation Phenomena of Three-phase SEIG

As discussed in the previous sections, the SEIG is not a self-started generator. Even though having a small amount of residual magnetism in the core itself cannot build the rated voltage and frequency under no-load and as well as in loading condition. The SEIG should obey two conditions for the successful operation of self-excitation process, those are (i) the stator terminals equipped with suitable rating of pre-charged capacitor bank and (ii) the speed of the rotor is above the synchronous speed.

In the present experimental work, the prime mover of the SEIG is a voltage/frequency-controlled fed induction motor (IM) of constant speed drive, which is an emulation of micro/pico hydro turbine. The shaft of the IM is coupled to the three-phase test machine to make them rotate at a same speed throughout the operation. Since having the v/f controlling drive, the mechanical speed of the prime mover is maintained at a desired constant speed. In this work, an instrument, Kusam made power analyzer is used for the experimental waveform recordings and another instrument called Meco made digital power analyzer is used for digital recordings during the operation of the SEIG.

The experimental setup of star configured SEIG system is shown in Figure 7. At stand still of rotor, the generated voltage is recorded as zero and it is 8 V under the running condition of above synchronous speed. The voltage generation with only the residual magnetism of core is shown in Figure 8.

It is well known that the capacitors are the reactive power sources and widely available. A pre-charged capacitors are used in this experimental study to provide the reactive power to the three-phase SEIG. Note that, the tolerance of the capacitors used for the self-excitation and reactive power compensation in the experimental study is $\pm 05\%$. After adding the calculated value of 10.50 μF/phase of excitation capacitance in delta manner, the SEIG

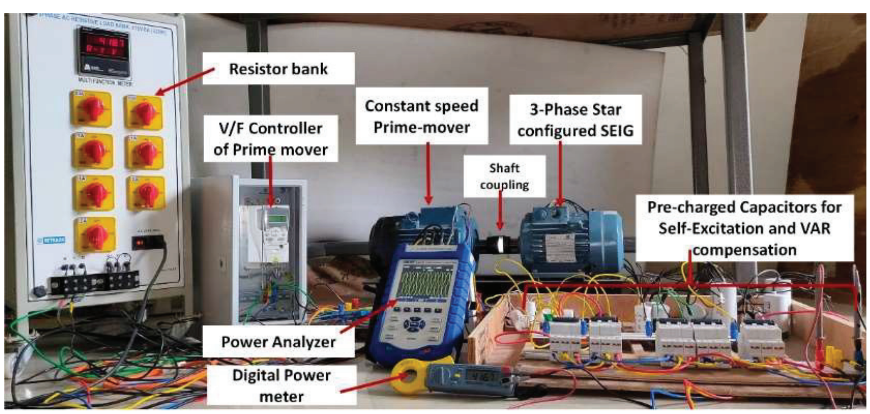

Figure 7 Experimental setup of star configured SEIG system.

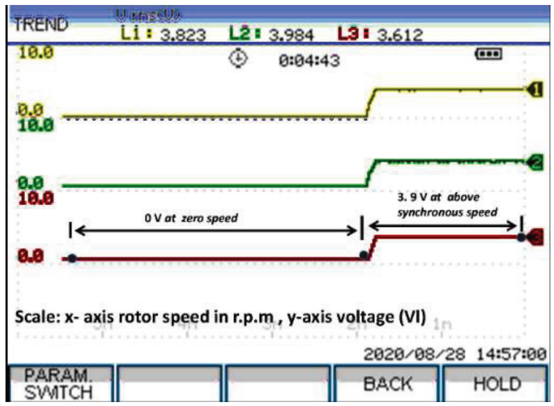

Figure 8 Output voltage of IG at above synchronous speed without self-excitation capacitors (Voltage due to residual magnetism).

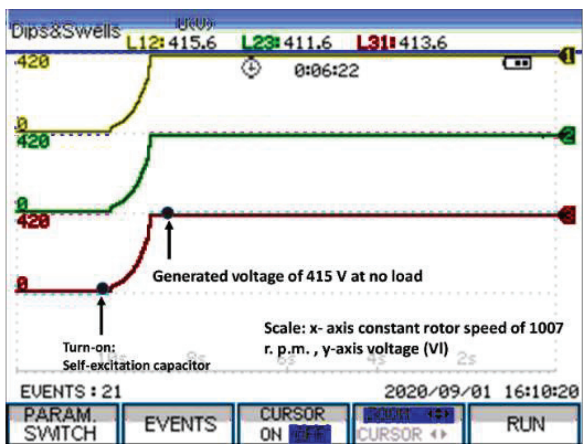

Figure 9 Generated voltage (415 V) of Y SEIG with self-excitation.

starts generating the rated voltage of 415 V and frequency of 50 Hz. The experimental screenshots of self-excitation process, the generated sinusoidal waveform and the voltage vector of 120^0 phase displacements are shown in Figures 9, 10, and 11, respectively.

Under the no load, the Y SEIG required the capacitance of 10.5 μF/phase in delta or 31.50 μF/phase of excitation at 1007 r.p.m, which is the value of more than the synchronous speed of the test SEIG to generate line voltage (Vl) of 415 or phase voltage (Vph) of 240 V at 50 Hz.

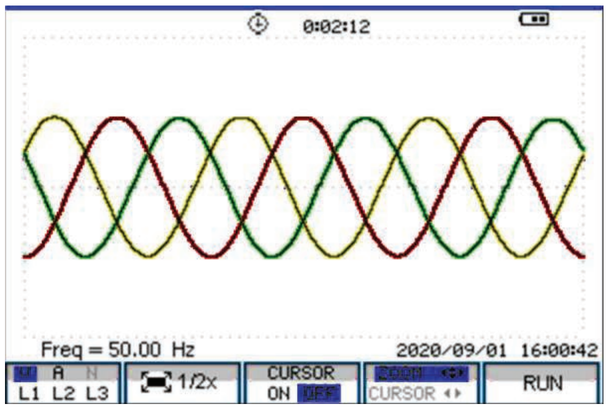

Figure 10 Generated sinewave of Y SEIG.

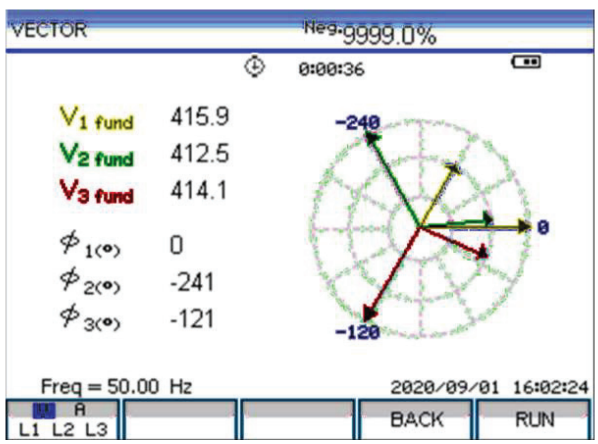

Figure 11 Voltage vector of Y SEIG.

4 Performance Study on Three-phase Configured SEIG Under Loading Condition

As said above, the constant speed prime mover is coupled with the Y SEIG and which is maintained at a constant speed throughout the experimentation. As shown in Figure 7, the generator can be loaded slowly by using the resistor (R) load bank. The Y SEIG is gradually loaded and the voltage profile with Δ configured excitation capacitance (Δ Cexc) is shown in Figure 12. It is recorded that the line voltage is dropped to 200 V without any VAR compensation at the rated load.

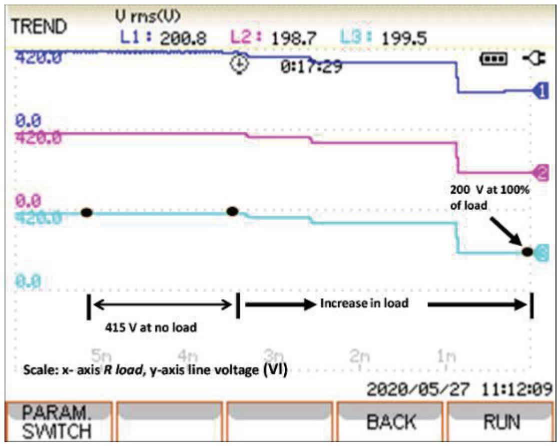

Figure 12 Voltage profile of Y SEIG under rated load without VAR compensation.

To address the poor voltage regulation of SEIG under the loading condition, an excess VAR through capacitors is needed. In this paper, a comparative study is proposed by conduct the experiment on Y SEIG excited by minimum excitation capacitance in star (Y Cexc) and delta (Δ Cexc) connections with three additional capacitors in star (Y), delta (Δ), and line-line (L-L) for the compensation of reactive power under star configured resistance load.

The experiment is conducted on the following six configurations to identify an economical, simple, and best scheme of VAR compensation. The lower allowable line voltage and frequency values are set to 391 V and 49.5 Hz, respectively under the load condition in all possible configurations of Y SEIG.

i. Y SEIG-Y Cexc-Y Load with Δ configured VAR compensation.
ii. Y SEIG-Y Cexc-Y Load with Y configured VAR compensation.
iii. Y SEIG-Y Cexc-Y Load with L-L configured VAR compensation.
iv. Y SEIG-Δ Cexc-Y Load with Δ configured VAR compensation.
v. Y SEIG-Δ Cexc-Y Load with Y configured VAR compensation.
vi. Y SEIG-Δ Cexc-Y Load with L-L configured VAR compensation.

4.1 Performance of Y SEIG-Y Cexc-Y Load Topology with VAR Compensation

As derived in the Section 2.2, the 31.50 μF/phase Y manner (Y Cexc) self-excitation capacitance, and it is almost 3 times of the Δ Cexc is required to generate the 415 V at 50 Hz. The voltage regulation performance of the Y

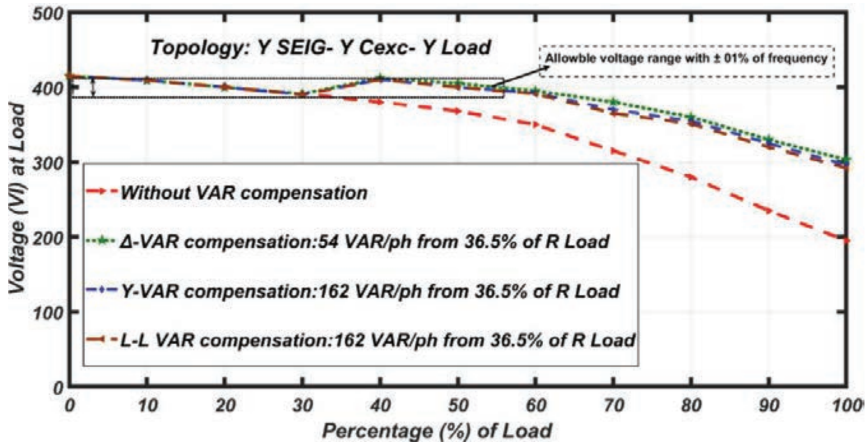

Figure 13 Experimental performance comparison of voltage regulating schemes of *Y* SEIG-*Y* Cexc –*Y* Load topology.

SEIG under R is load experimentally investigated for three VAR compensation schemes termed as (i) Δ, (ii) Y and, (iii) L-L (capacitor connection between R-Y and Y-B) configurations. From the experimental results, it is noticed that this topology can withstand up to 36.5% of load without any additional VAR requirement. After this loading point, Δ, Y and L-L compensation schemes are implemented by adding the 54, 162 and 162 VAR/ph, and enhanced the performance up to 58, 57 and 56.5%, respectively. The perforce of the topology with and without these three VAR compensation schemes are given in Figure 13. It is recorded that the rating of Δ VAR compensation is only 1/3 times of the Y and L-L configurations schemes.

4.2 Performance of Y SEIG-Δ Cexc – Y Load Topology with VAR Compensation

In this section, the *Y* SEIG is excited by using 10.50 μF/phase delta excitation capacitor (Δ Cexc) and investigated the voltage regulation under *R* load as like the previous section. From the experimental results, it is found that this topology can withstand up to 38% of load, which is slightly higher than the *Y* SEIG – *Y Cexc* – *Y* Load topology without any additional VAR requirement. Beyond this load, the VAR compensation schemes are implemented by adding the 28 VAR/ph in Δ connection and, 84 VAR/ph in *Y* and L-L configurations. The performance of this topology with three approaches are given in Figure 14. The rating of the *Y* and L-L VAR/ph compensation is

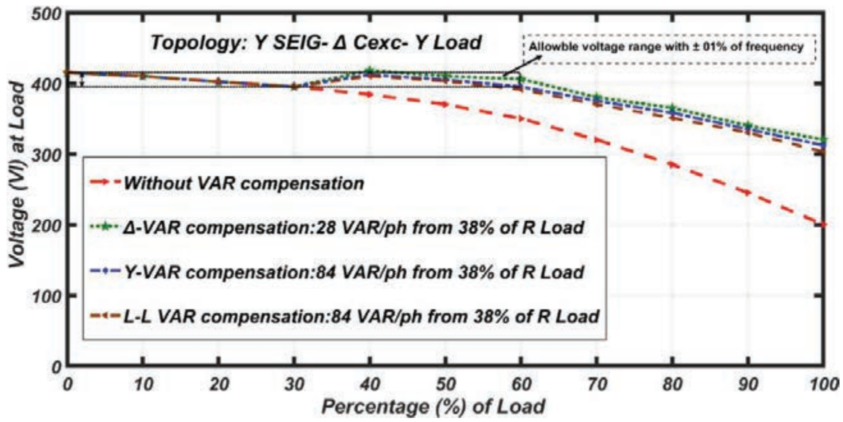

Figure 14 Experimental performance comparison of voltage regulating schemes on *Y* SEIG-Δ Cexc –*Y* Load.

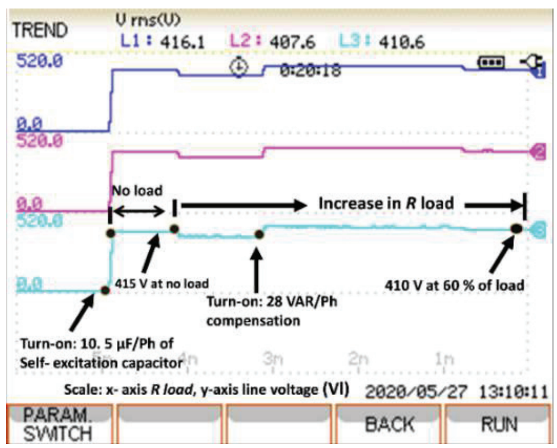

Figure 15 Voltage trend wave form of *Y* SEIG- Δ Cexc-*Y* Load with Δ configured VAR compensation.

three times to the Δ. By implementing Δ connected VAR compensation, the operation the system can be extended up to 60% with less rating capacitors of 24 VAR/ph compensation, while the other two performs up to 58.5% of load.

From the comparison study on the six possible configurations, the *Y* SEIG- Δ*Cexc* – *Y* Load topology with Δ VAR compensation schemes performs the better operation with less rating of VAR for self-excitation and compensation.

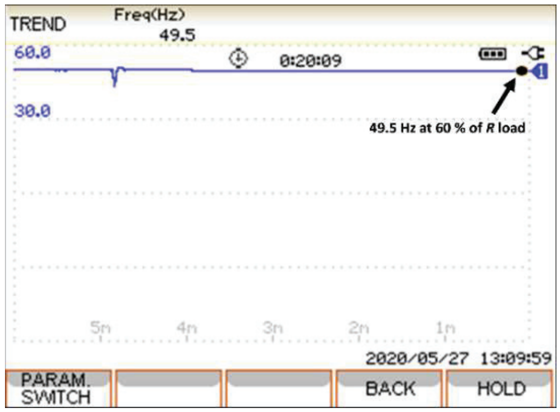

Figure 16 Frequency of Y SEIG- Δ Cexc-Y Load with Δ configured VAR compensation at 60% of load.

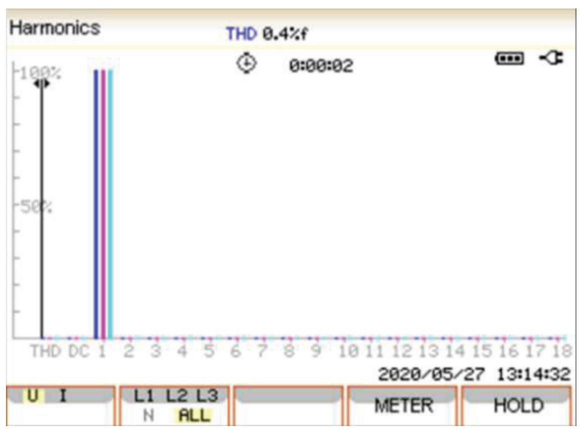

Figure 17 Voltage THD of Y SEIG- Δ Cexc-Y Load with Δ configured VAR compensation at 60% of load.

The voltage profile, frequency, and voltage THD of the best configuration among the six configurations of (i–vi), i.e., Y SEIG- Δ Cexc-Y Load with Δ configured VAR compensation, is recorded as 410 V, 49.5 Hz and 0.4, respectively at 60% of load. The test Y SEIG is suggested to restrict the loading capacity is up to 60% only. Under this load, the voltage trend wave form, frequency, and voltage THD responses are shown in Figures 15, 16 and 17. The voltage regulation comparison with allowable variation of 50 $\pm$ 01% Hz among all the six configurations are given Table 2.

Table 2 Voltage regulation of *Y* SEIG

Compensation Scheme	%Voltage Regulation of *Y* SEIG – *Y* Cexc – *Y* Load	% Voltage Regulation of *Y* SEIG – Δ Cexc – *Y* Load
Without VAR compensation	6.00 (at 36.5 % of Load)	5.80 (at 38% of Load)
i. Δ configured VAR compensation	1. 80 (at 58% of Load)	1.20 (at 60% of Load)
ii. Y configured VAR compensation	3.30 (at 57 % of Load)	2.80 (at 58.5% of Load)
iii. Line to line (L–L) configured VAR compensation.	3.90 (at 56 % of Load)	3.10 (at 58.5% of Load)

5 Conclusion

In this paper, the experimental results of proposed comparative study of six possible configurations of three-phase star configured SEIG is presented for identification of the simple, and best practice method for self-excitation and reactive power compensation. The proposed topologies offer both the line and phase voltages, and which can be used for rural/remote electrification systems. From the performance study of six possible configurations, the *Y* SEIG – Δ Cexc – *Y* load with Δ VAR compensation is the best and cost-effective method for self-excitation and as well as for voltage regulation. Further, in this study the good frequency profile is maintained by the constant speed operation of prime mover. Since the SEIG systems are dedicated for isolated application, the load ratings must be restricted to bellow the generation rating. It is cleared from the experimental results of the test SEIG system offer two levels of voltage feature and can withstand up to the 60% of load while maintaining the 1.20% of voltage regulation at 50 ±01% Hz of frequency with the simple Δ VAR compensation connection. Hence this work has aimed at developing a micro/pico-hydro driven isolated SEIG system without use of power electronics to reduce the complexity and investment by knowing the rated loading capacity.

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