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A Study on Excitation Requirement and Power Balance of Self Excitation Induction Generator for Off-grid Applications Through Experiment and Simulation

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Abstract

Research on induction machines gaining popularity for many decades as they can be used for both motoring and generating applications due to many advantages like, cheapest solution, rugged one, requires low maintenance, etc. Induction generators are being used for small-scale power generation in the grid and off-grid modes of operation. When it uses grid-connected applications, the operation is quite simple as it receives the required reactive power from the live-grid, but it may not happen in the case of off-grid applications because of the absence of reactive power to the core of the machine. For such off-grid conditions, the IG is must relate to a suitable minimum capacitor across its stator terminals, and such a generator is called a self-excitation induction generator (SEIG). This paper presents a simple method by using the name-plate details of the considered machine for finding the minimum value of excitation capacitor in a different manner for the successful operation of SEIG. The obtained values from the method are verified through an experimental setup and MATLAB/Simulink of three-phase SEIG. Another crucial challenge in the off-grid operation is the power imbalance of the system. To address the issue, an electronic circuit-based load power balance controller, which works on the principle of continuous sensing of the voltage of the SEIG is proposed and validated the performance of the SEIG system in this paper.

Keywords: Self-Excitation Induction Generator (SEIG), Constant Speed Turbine (CST), Excitation Capacitance, Load Power Balance.

1. Introduction

Global warming is one of the major issues in many countries around the world. Some of the major reasons are the burning of fossil fuel coal, oil, and gas for the generation of electric power and transportation. The above-stated issue is being slowly overcome by increasing the utilization of non-pollution emitting renewable energy sources (RES) like wind, hydro, biomass/biopower, and solar energy for the generation of power [1]-[6], [19].

The RES based systems need a suitable generator solution to convert the mechanical power into electric power except the solar energy [7]. Again, the sources can be broadly classified into variable and constant energy sources and power generation though these sources are reported in [8]-[12]. Induction generator is well suitable for the constant speed turbine (CST) sources, like small hydro and biomass/biopower [14]-[18], [19]. In [13], SS Murthy et. al have presented an article, which describes the the use of conventional induction motors as SEIG by using capacitor bank. Bhim Singh has presented the prospects of IG in [14]. A detailed application of IG for renewable energy applications is discussed in [14]-[17]. The theoretical aspects of self-excitation process of induction generator for autonomous operation are discussed in [18].

The combination of IG and CST offers a low-cost solution for power generation, eco-friendly, ease of operation, techno-friendly, less maintenance and long-life spam and all. The IG is one of the most preferable generators for isolated locations, like hilly areas and rural / remote areas. On the other hand, two primary requirements to fulfil the successful of IG for isolated load applications are ii) external excitation requirement, and ii) load balance. The authors [20-22] have reported the constant speed driven SEIG system for small scale off-grid applications. The methods of calculating the excitation and load balance phenomena are discussed.

As discussed earlier, the IG is not a self-started generator in the off-grid mode of operation. The operation of IG is not the same for all the modes of operation. The isolated systems don't have the grid-support, therefore the required reactive power should be supplied from the external side. To make the IG as a self-excitation generator in off-grid operation, a suitable rating of the capacitor bank is needed to be connected across the stator terminal of the machine while maintaining the slip value at negative [23]. A good number of papers have been reported in the literature to calculate the excitation capacitance value of the SEIG. One of the methods is steady-state analysis, which requires three tests, named as i) dc test, ii) synchronous impedance, and iii) blocked rotor test, and the data from these three tests are required to solve the equivalent circuit parameters [24]. Again, it involves the numerical solution methods like impendence [25], [25], [27] and/or admittance [28], [29], to solve. The second one is the solution through dynamic modeling of generator circuit, which involves the matrices form of circuit parameters to solve [30], [31], [32]-[37]. The

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understanding of the above two methods may be difficult for entry-level engineers at a rural or isolated location, where the techno-saviors are not available.

The diagrammatic representation of problem formulation of this paper is a constant speed turbine-driven SEIG-based isolated load system with a load balance circuit and which is shown in Fig. 1. In this paper, a simple method of calculation of excitation capacitance for the SEIG is theoretically analyzed and verified through the experimental setup and MATLAB/Simulink to address the calculation of excitation capacitance. The electricity demand in rural/remote areas is different from urban users as it is variable and has low capacity. The total power produced by the generating units always should be consumed by loads, so in this context, a load balancing unit is needed to share the total generating power [38]-[43]. In this paper, the study is extended to fix the system balance by means of design and controlling a power electric-based power balance controller. The primary goal in the isolated load applications is to maintain the ± 05% 240/415 V of voltage and ± 01% of 50 Hz frequency respectively at end-users. In this work, to maintain the basic criteria, the reactive power compensation of load value and prime-mover speed are maintained accordingly.

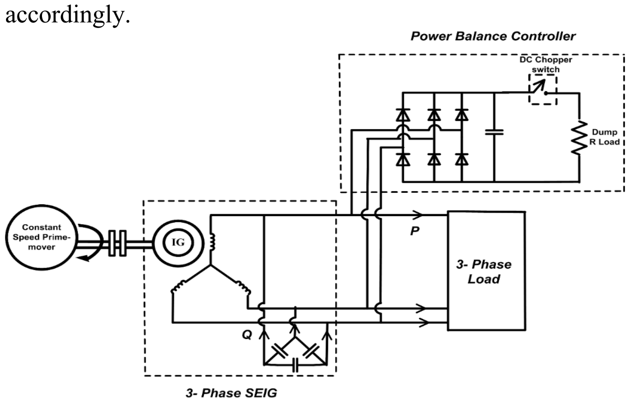

Fig. 1. Three Phase SEIG system with power balance controller.

This paper is organized as follows. Section II demonstrates the calculation and validation of excitation capacitance of SEIG. Design and Control of load balance controller for isolated loads is covered in section III. The conclusion of the paper is given in section IV.

2. Calculation and Validation of Excitation Capacitance of SEIG

This section covers the theoretical analysis of the calculation ofexcitation capacitance for the successful operation of the SEIG. The method didn't involve any complex mathematical calculations and other electrical testson the machine. The name plate details of the considered machine for bothexperimental and simulation are given in Tab. 1.

Table 1. Ratings of the test machine.

Name of the parameter	Rating of the parameter
Phase	3
Voltage, V	415 Volts
Current, I	2.8 Amps
Power, P	1100 Watts
Frequency, f	50 Hz
Power factor, (Cos ϕ)	0. 69
Efficiency, (η)	78%

2.1 Calculation of excitation capacitance (C_{exc})

The excitation capacitor per phase in delta manner ($C_{exc\_\Delta ph}$) is calculated by using following equation (1).

$$C_{exc\_\Delta ph} = \frac{Q_g}{3xV^2x2x\Pi xf} \quad (1)$$

In (1), the Q_g is the reactive power (in VAR or Var) consumed by the SEIG to build the rated voltage. The value of V is considered as 415V. To determine the required reactive power for the generator, let us find first the reactive power that the machine absorbs while operating as a motor using the below equation (2).

$$Q_m = \frac{P}{\eta} \tan(\cos^{-1}\varphi) \text{ VAr} \quad (2)$$

In (2), the P_n is the rated mechanical power; η_m is the efficiency, and $\varphi_m$is the power factor as a motor. One can obtain the Q_m value of (2) by substituting the machine parameters of Table 1.

$$Q_m = \frac{1100}{0.78} \times \tan\ (cos^{-1}0.69) \approx 1480 \text{ VAr}$$

The required reactive power for generator (Q_g) is calculated as

$$Q_g = \frac{Sin\ Q_g}{Sin\ Q_m} \times Q_m = \frac{0.84}{0.72} \times 1480 = 1727 \text{ VAr}$$

After getting the Q_g, one can easily convert the Qg value into capacitor value by using the (1).

$$C_{exc\ \_\Delta ph} = \frac{1700}{3\times 415^2 \times 2 \times \pi \times 50} \approx 10.6 = 10.5\ \mu F/\text{ph (selected)}$$

Now the excitation capacitance in star manner (C_{exc_Yph}) is given by (3)

$$C_{exc\_Yph} = 3xC_{exc\_\Delta ph} \quad (3)$$

$$C_{exc\ \_Yph} = 3 \times C_{exc\ \_\Delta ph} = 3 \times 10.5 = 31.50\ \mu F/\text{ph}$$

It is observed that the $C_{exc\ \_\Delta ph}$ value is only 1/3 value of the $C_{exc\ \_Yph}$ for generating the same voltage rating. The obtained values from this method are used for self - excitation phenomena through an experimental setup and MATLAB/Simulink in the next two subsequent sections.

2.2 Validation of Excitation Capacitance value of SEIG through Experimental Setup

An AC driver of voltage/frequency (V/F) control fed induction motor is used as a prime mover to the SEIG to validate the calculated excitation capacitance. The shaft of the IM is coupled to the rotor to the generator and the speed of the rotor is maintained at a constant speed value according to the requirement. The experimental setup of a constant speed prime mover driven (which is the emulation of micro hydro/biomass turbine) three phase SEIG system is shown in Fig. 2. The derived value of $C_{exc\ \_\Delta ph}$, 10.5 μF/ph is connected across the stator terminals while maintaining the speed of the rotor at above synchronous speed to generate the voltage of 415 V at 50 Hz. After the successful validation of self- excitation phenomena, the generated voltage trend waveform, sine waveform, and voltage vectors are shown in Figures 3 to 5, respectively.

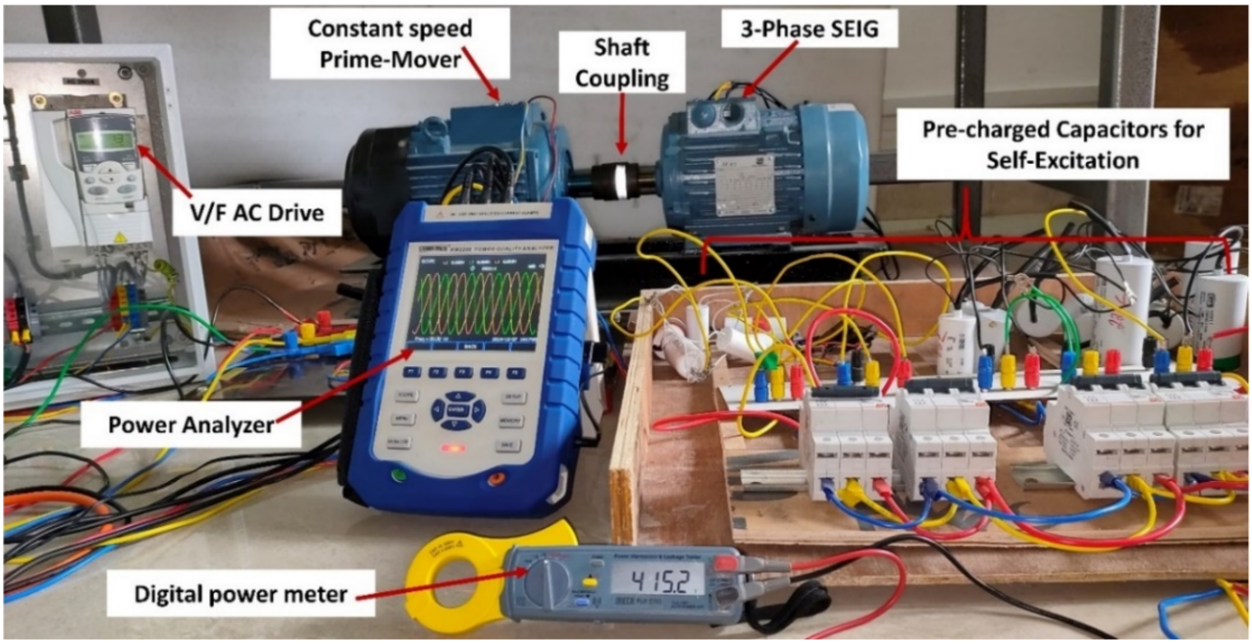

Fig. 2. Experimental setup of constant speed prime mover driven three phase SEIG system.

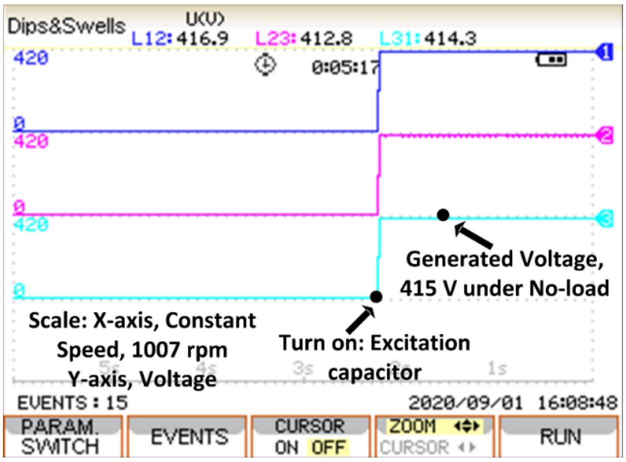

Fig. 3. Generated trend waveform voltage, 415V of SEIG with $C_{exc\ \_\Delta ph}$ of 10.5 µF/ph.

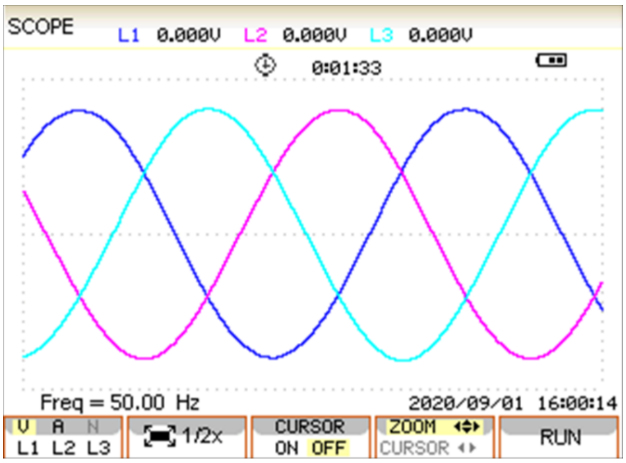

Fig. 4. Generated sinewave voltage waveform of SEIG.

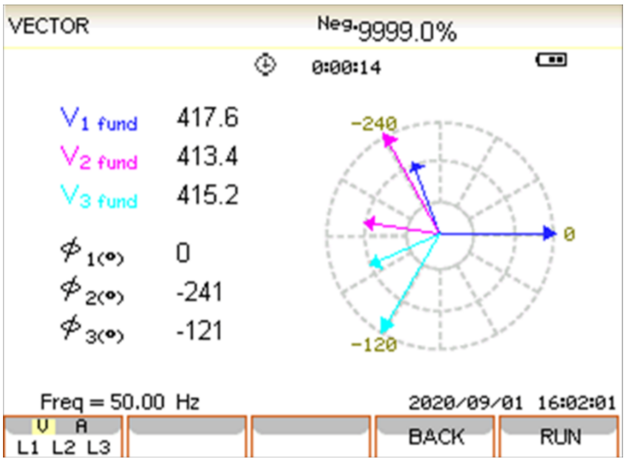

Fig. 5. Voltage vector of SEIG.

2.3. Validation of Excitation Capacitance value of SEIG through MATLAB/Simulink

In this work, the micro hydro/ biomass turbine characteristics of constant speed is emulated by a constant speed input to the induction machine block in MATLAB/Simulink. The shaft torque (T_{sh}) of prime mover is given by (4) [22].

$$T_{sh} = \frac{2J}{P} p\omega_r + T_e \tag{4}$$

In (4), T_e is the electromagnetic torque, J is the moment of inertia of the shaft and, P is the number of poles. One can write the simplified value of T_{sh} as

$$T_{sh} = k_1 - \omega_r k_2 \tag{5}$$

In (5), the ω_r is the rotor speed in r.p.s and the calculated values of k_1 and k_2 is 1088 and 9.80, respectively. The ω_r is maintained at a constant value of 108 r.p.s to generate the voltage of 415V at 50 Hz. The parameters of Table 1 are used for the simulation study too. As like experimental setup working procedure, capacitor bank of 10.5 µF/ph in the delta manner is connected across the stator terminals of the SEIG to generate the voltage of 415 V at 50.0 Hz. The MATLAB/Simulink based three phase SEIG system with masked blocks is shown in Fig. 6. The MATLAB/Simulink based results of the rotor speed, frequency, and generated voltage of SEIG are shown in Figures 7, 8, and 9, respectively.

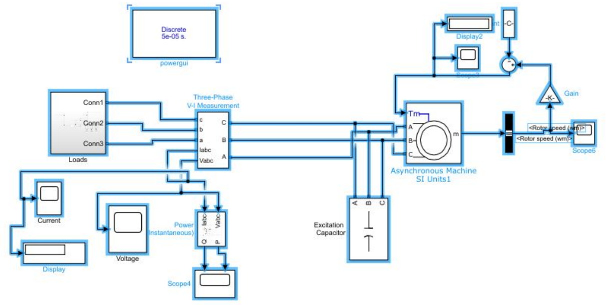

Fig. 6. MATLAB/Simulation based three phase SEIG system.

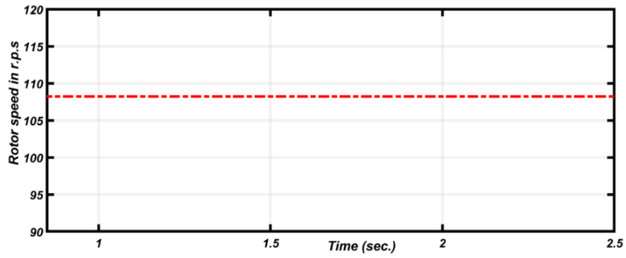

Fig. 7. MATLAB/Simulation based rotor speed of SEIG in r.p.s.

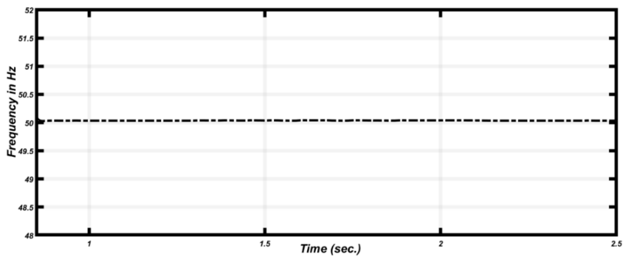

Fig. 8. MATLAB/Simulation based frequency of SEIG in Hz.

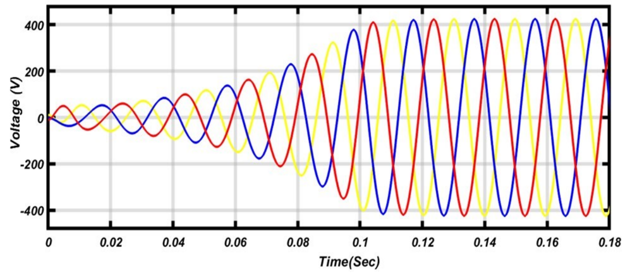

Fig. 9. MATLAB/Simulation based generated voltage (V) of SEIG.

3. Design and Simulation of Power Balance Controller for SEIG System

Power balance controller is a power electronic enabled circuit unit to balance the power between the generator and connected loads for the isolated load applications and which is quite simple and easy for practical implementation. The proposed power balance controller (PBC) of the SEIG operated system requires one 3-phase diode bridge rectifier and a single IGBT switch as chopper switch. The deployment of the PBC unit aims to divert the excess generated power and make it consumed by a dump/special purpose load.

3.1. Operation and Design of PBC

The slip of the IG increases with respect to an increase in load, then the terminal voltage drops due to a drop in internal impedance and demagnetization of the core. This phenomenon is used for the design of PBC, the IGBT chopper works based on this voltage droop characteristics. The logical turn on or turn-off ofthe DC chopper switch (IGBT switch) depends on a simple control function thatif the reference voltage is less than the actual voltage across load terminals,then the IGBT switch will turn ON to divert the surplus generated power in to the dump load to balance the system power. On the other hand, if the reference voltage is greater than the actual load voltage, then the IGBT will remain in the OFF position and do not allow the power flow to the dump load. The generationof gate pulses of the PBC is shown in Fig. 10. The logic involved in the PBC isgiven by Pseudocode 1 shown in table 2.

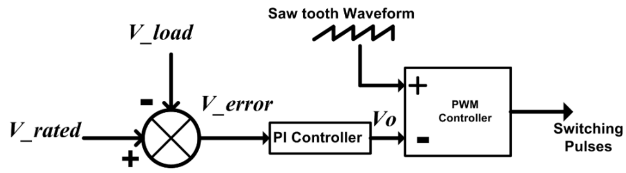

Fig. 10. Generation of gate pulse.

Table 2. Pseudocode 1. Logic of PBC

Step 1:	Read V_{rated}, P_{rated}, P_M, P_D.
Step 2:	Turn on: SEIG
tep 3:	Turn on: SEIG Main load
Step 4:	**while** (1) /* infinite loop*/
Step 5:	**if** ($P_{rated} < I_M$)
Step 6:	Turn ON P_D
Step 8:	**else-if** ($P_{rated} = P_M$)
Step 9:	Turn OFF P_D
Step 10:	**end-if**
Step 11:	**end-while**

Duty cycle (δ) value of the IGBT chopper switch to divert the generated power into the dump load is given by (6).

$$P_D = \frac{(\delta . V_{cap})^2}{R_D} \tag{6}$$

Here in (6), $V_{cap}$is the output voltage of diode bridge rectifier and R_D is the value of the dump resistance load. The value V_{cap} of bridge rectifier is given by (7).

$$V_{cap} = \frac{3\sqrt{2}}{\Pi} X V_{L-L} \tag{7}$$

$$V_{cap} = \frac{3\sqrt{2}}{\pi} \times 415 = 560 \text{ V}$$

The rated output line current of rectifier bridge decides the current rating of the is given by

$$I_S = \frac{P_{Rated}}{\sqrt{3} V_{L-L}} \tag{8}$$

$$I_s = \frac{1100}{\sqrt{3} \times 415} \cong 1.5 \text{ A}$$

The voltage and power ratings of the selected SEIG decides the values of the bridge rectifier and chopper. The dump resistance (R_D) is chosen in such a way that it should withstand for the full power capacity of the SEIG. The value of R_D is given by (9).

$$R_D = \frac{(V_{cap})^2}{P_{Rated}} \quad (9)$$

$$R_D = \frac{(560)^2}{1100} = 285\ \Omega$$

3.2. *Simulation Results and Discussion on SEIG Performance with PBC*

A capacitor bank of 10.50 μF/ph is connected in delta-manner to generate the voltage of 415 V at frequency of 50 Hz, and voltage regulation and frequency variations are restricted to ±05 and ± 01% respectively. The minimum excitation value is not enough to supply the required reactive power under loading condition. A total of 1350 VAr is supplied by adding the extra capacitors across the stator terminals of the SEIG to improve the voltage profile. The compensated voltage waveform is shown in Fig. 11. The rated power under rated load with VAR compensation is given in Fig. 12. As shown, the rated load is removed from the SEIG at 1 to 1.5 seconds of time, then power is approaching the zero value.

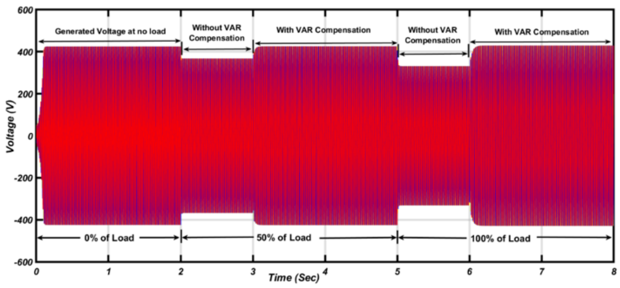

Fig. 11. Voltage waveform of SEIG under loading condition with and without reactive power compensation.

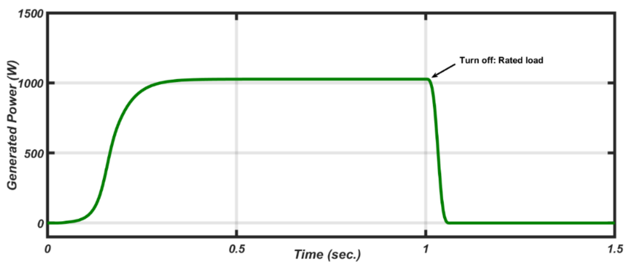

Fig. 12. Rated power, P_{rated} (W) of SEIG.

The PBC aims to balance the generated power as well as the load voltage. As the generator is driven by the constant speed source, then the connected loads should be at it's rated value to balance the generation unit power and voltage. Removal of any amount of rated load increases the SEIG voltage at the load terminal, which is an unnecessary action in the system.

The voltage profile under varying load conditions of SEIG without PBC is shown in Fig 13. The system is under the rated load from 0-1 and 3-10 seconds of simulation, the voltage is maintained at ±05% of 415 V, but at the instant of 1-3 sec of total time, an amount of load, say 40% is removed, then the rise in voltage reaches to around 520V. The excess amount of voltage creates the disturbance in the total system, and also which is far beyond the ±05% of acceptable voltage. The voltage profile of the SEIG under the same loading conditions with the designed PBC is shown in Fig. 13. As shown in Fig. 14, the excess voltage during the duration of 1-3 sec due to less rated load is now levelled by diverting the excess amount of energy to dump load and the voltage is maintained ±05% of 415 V.

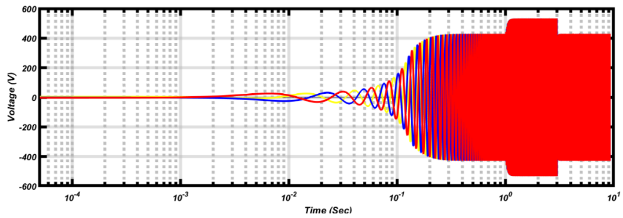

Fig. 13. Voltage profile of SEIG under varying load condition without PBC.

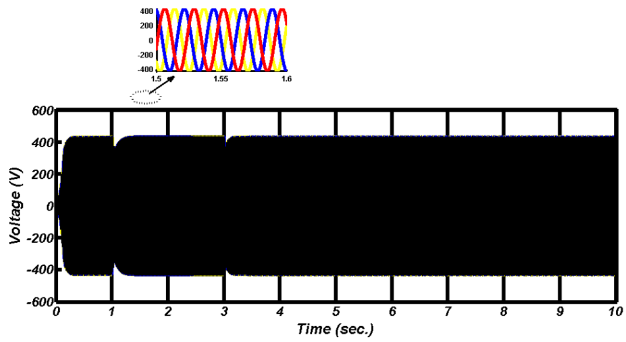

Fig. 14. Levelling of load voltage of SEIG with PBC.

The load and dump powers are shown in Fig.s15 and 16. Initially, the SEIG is started with the rated load to consume the 1100 W of power up to 1 sec of time. The load is decreased from the rated value between 1-3 secs, then the designed PBC is activated by sensing the excess voltage appearing across the load, and then the IGBT chopper switch is turned on to allow the excess power to be consumed by the dump load to balance the power and voltage as well.

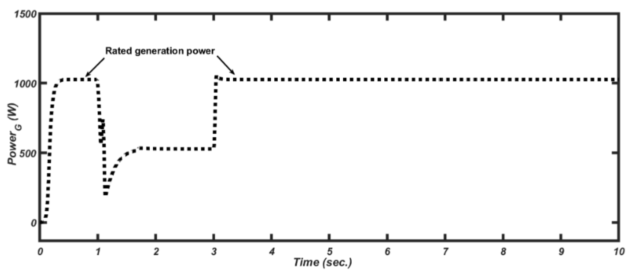

Fig. 15. Turn-on and Turn-off of rated power, P_{rated} (W).

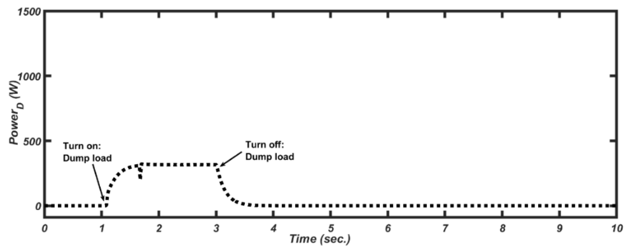

Fig. 16. Turn-on and Turn-off of dump power, P_D (W).

4. Conclusion

In this paper, two primary requirements for the successful operation of the SEIG system i.e., excitation requirement and load power balance are addressed through experimental and simulation studies. A simple method by using the name plate details of the considered induction machine for the calculation of excitation capacitance value is presented and validated to a constant speed turbine-driven SEIG system through the experimental setup and MATLAB/Simulink. The results of the paper show the usefulness of the method of approach to the deployment of SEIG system for rural/isolated location applications. Moreover, it didn't require any other tests, like DC, synchronous impedance and blocked rotor tests, and other complex mathematical techniques. The paper is also addressed the load balance by means of a power balance circuit. The operating principle and design process of PBC is discussed and simulated. The surplus/dump power can be utilized for heating load applications. The SEIG system with PBC helps the isolated/rural/remote communities where micro-hydro and biomass energy isimpressive.

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