IJAREEIE

e-ISSN: 2278-8875
p-ISSN: 2320-3765

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

Volume 13, Issue 6, June 2024

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 8.317

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 8.317|| A Monthly Peer Reviewed & Referred Journal |

||Volume 13, Issue 6, June 2024||

|DOI:10.15662/IJAREEIE.2024.1306001|

Performance Analysis of an Autonomous Hybrid Synchronous Reluctance Generator

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ABSTRACT: Hybrid synchronous reluctance generator is one of the emergent new configurations of synchronous reluctance machine with ultra-high output power capability with a view to coping with the ever increasing demand of electrical energy. Self-excitation of the hybrid synchronous reluctance generator is the subject of this study. The machine comprises a cylindrical rotor and salient-pole rotor machine elements that are mechanically coupled together. There are no windings in the rotor but the stator, however, has dual windings known as the main and auxiliary windings that are integrally wound for the same number of poles. The main winding is connected to the output terminals while the auxiliary winding terminals which are transposed between the machine elements are terminated across a variable capacitance bank; and by varying the capacitance bank the X_d/X_q ratio of the machine which is directly proportional to the output power is varied and unity power factor is achievable. It is shown using MATLAB that the hybrid machine has good self-excitation when capacitor values in the range of 30 μF – 38 μF are placed across the output terminals of the machine and from the stand point of stability the value of 36 μF gives the best result. Voltage regulation is good and in the range of 0.27% - 20.39%. Efficiency also improved with increase in load current.

KEYWORDS: Hybrid synchronous reluctance generator, Main winding, Auxiliary winding, X_d/X_q ratio, Self-excitation, Ultra-high output power capability.

I. INTRODUCTION

The demand for electric power is ever increasing because electrical power establishes the foundation of the current human civilization. All human activities have dependence on electrical power in one form or the other. This underscores the need for electrical generators of high output power. It is known that in some parts of the world especially in developing nations some areas are isolated from the national grid. These areas can have access to electrical power by means of autonomous generators.
Also, in conditions of possible natural disasters the centralized power supply can be broken. In this case in some isolated area generation of the electrical energy can be realized only by means of local autonomous system [1]. Again, self-excited generators are the most popular voltage sources installed onboard of modern ships [2]. These self-excited or autonomous generators must be good, robust and without much sophisticated technology for easy adaptation to rural areas. The self-excitation of induction and synchronous reluctance generators have been reported in literature [3,4,5,6]. However, these have setbacks which include the dependence of the output frequency and voltage on load and prime mover speed for self-excited induction generators and poor power factor as well as low output power for self-excited salient pole synchronous reluctance generators [7]. Therefore, there is need to develop a self-excited generator that will solve these problems.

The self-excited hybrid synchronous reluctance generator is a new machine with high output power, high power factor and very good efficiency. It is a machine that has a salient pole machine element and a round rotor machine element coupled together. The salient pole machine element has an anisotropic rotor made of ferromagnetic material which does not have excitation. The round rotor machine element has a round rotor that has no windings or conductors and therefore does not contribute any torque making it not participating in the energy conversion process. Each machine element has a stator that has two sets of poly-phase (three phase) stator windings. The windings of one set are transposed between the two sections of the machine. One set of the windings is known as the main winding while the other is known as auxiliary winding which is connected to a variable capacitor load bank which can be tuned or adjusted to vary the saliency ratio of the generator without altering rotor geometry. For self-excitation to occur, the main winding is connected to excitation capacitor bank which supplies the magnetizing current.
The self-excited hybrid synchronous reluctance generator is robust, generates high output power and has good voltage regulation.

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II. ANALYSIS OF THE HYBRID SYNCHRONOUS RELUCTANCE GENERATOR

The terminals of the main windings of the hybrid generator are connected to a properly sized excitation capacitor bank. The rotor is driven by a prime mover at the rated speed. The capacitor will supply magnetizing current to the winding. Like a synchronous generator with salient pole rotor, when the rotor rotates the residual magnetic flux in the rotor induces an emf in the stator conductors which causes current to flow in them and through the capacitor bank. This increases the magnetic flux of the stator which by reaction induces a current in the rotor thereby increasing its flux. This process continues resulting in a voltage build up in stator until magnetic saturation is reached in the rotor. The reactive power required for the load is supplied by a capacitor bank whereas the active power is supplied by the generator. The balanced capacitor load bank connected to the auxiliary winding can be tuned to achieve the desired saliency ratio and power output. The machine attains the steady-state condition with the particular terminal voltage and load current, if saturation is considered. This is obviously determined by the real and reactive power flow between the machine, excitation capacitance and connected load. The schematic diagram of the hybrid synchronous reluctance generator is shown in Figure 1 while the steady-state equivalent circuit which one of the authors of this paper had earlier derived in one of his publications [8] is shown in Figure 2.

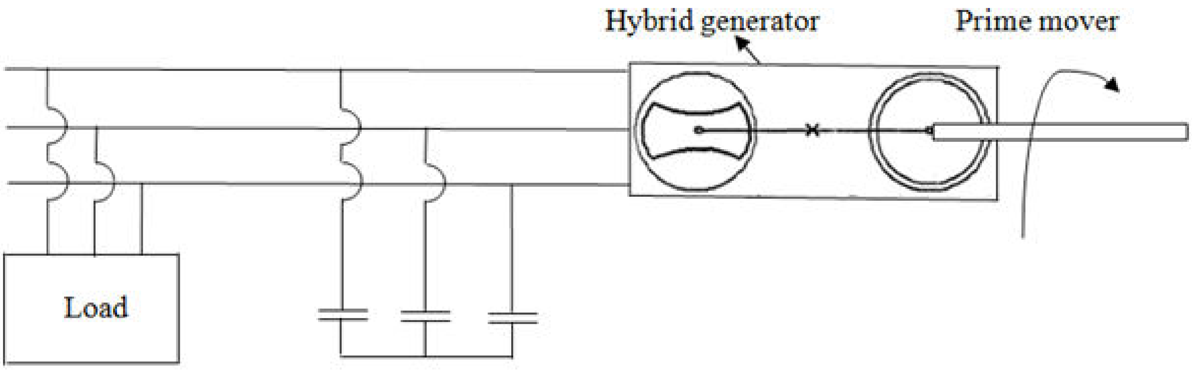

Figure 1: Schematic diagram of the hybrid synchronous reluctance generator.

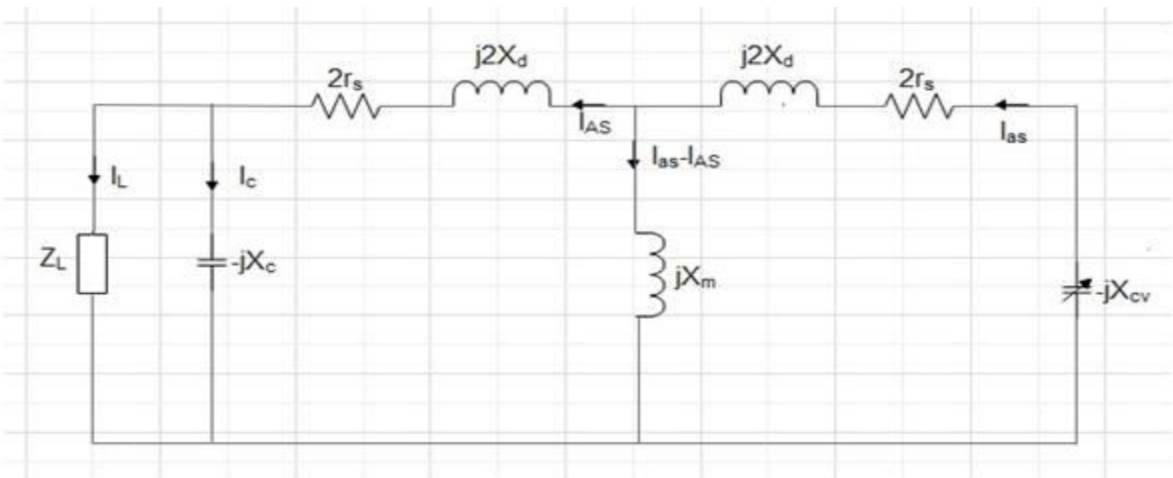

Figure 2: Per-phase steady-state equivalent circuit of the hybrid synchronous reluctance generator.

The analysis of the reluctance generator depends upon the Park's d-axis and q-axis steady-state model of synchronous machines [6]. Using that model, the vector diagram of the isolated (self-excited) hybrid synchronous reluctance generator with a bank of capacitors connected to its terminals can be shown to be of the form given in Figure 3.

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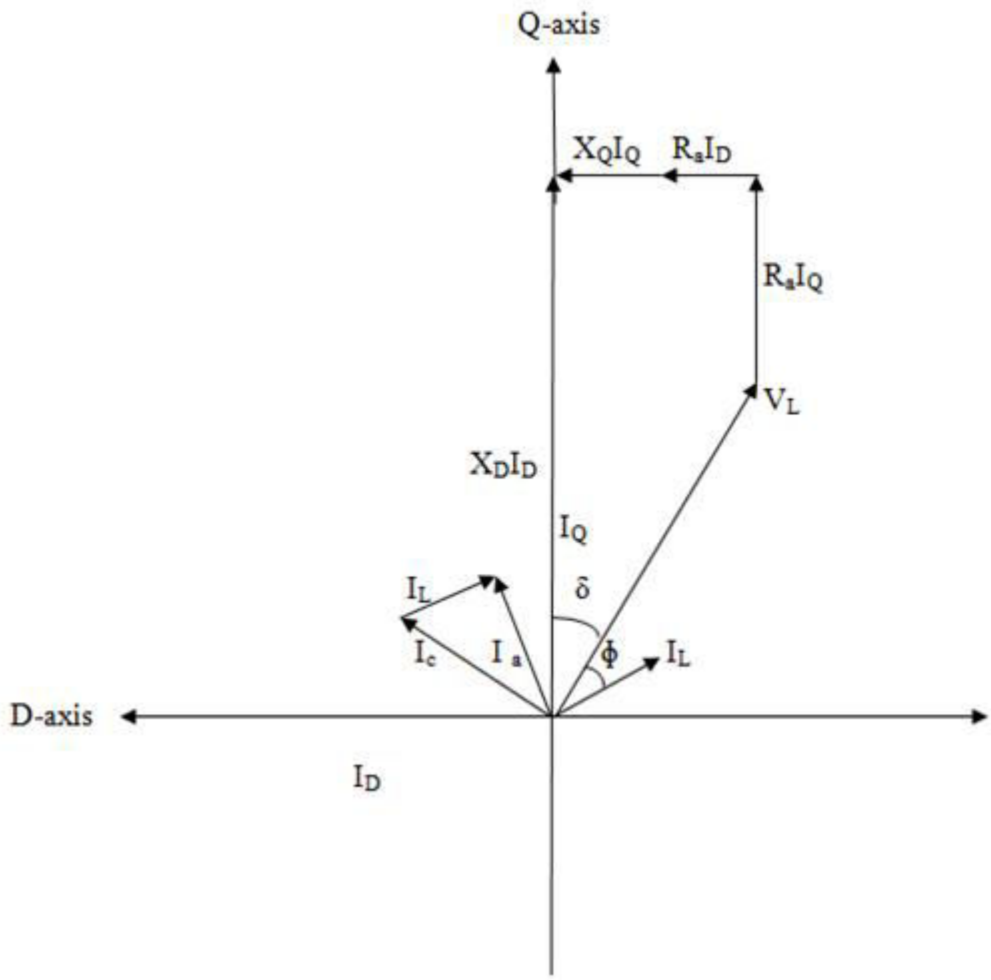

Figure 3: Phasor diagram of the loaded self-excited hybrid synchronous reluctance generator

III. MATHEMATICAL MODELING

Mathematical modeling and analysis are usually developed for the prediction of the behavior of a machine.
The transformed voltage equations of the generator in the D-Q reference frame are given below:

$$V_D = -[2r_s I_D + \omega_r \lambda_Q] \quad (1)$$

$$V_Q = -[2r_s I_Q - \omega_r \lambda_D] \quad (2)$$

$$V_{cvd} = -2r_s i_d - \omega_r \lambda_q \quad (3)$$

$$V_{cvq} = -2r_s i_q + \omega_r \lambda_d \quad (4)$$

Equations 1 and 2 are for the main windings while equation 3 and 4 are for the auxiliary windings. The voltage equation for the D-Q model in matrix form is given by:

$$\begin{bmatrix} V_D \\ V_Q \end{bmatrix} = -\begin{bmatrix} R_a & X_Q \\ -X_D & R_a \end{bmatrix} \begin{bmatrix} I_D \\ I_Q \end{bmatrix} \quad (5)$$

where,

$$\mathrm{Ra} = 2r_s \quad (6)$$

$$X_D = \omega_r L_D \quad (7)$$

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$$X_Q = \omega_r L_Q \quad (8)$$

$$X_Q = \omega_r L_Q \quad (9)$$

Using the phasor diagram shown in Figure 3, the steady-state operation of the hybrid synchronous reluctance generator at lagging power factor can be analyzed and simulated for both voltage and current in D- and Q-axes components by the proceeding equations. Therefore, the expressions of the load angle δ and the magnetizing reactance X_D will be obtained.

$$V_L sin\delta = R_a I_D + X_Q I_Q \quad (10)$$

$$V_L cos\delta = X_D I_D - R_a I_Q \quad (11)$$

$$I_D = I_C cos\delta - I_L \sin(\phi + \delta) \quad (12)$$

$$I_Q = I_C sin\delta + I_L \cos(\phi + \delta) \quad (13)$$

$$I_C = \frac{V_L}{X_C} \quad (14)$$

$$I_L = \frac{V_L}{Z_L} \quad (15)$$

Substituting equations 12, 13, 14, and 15 into equation 10 and doing some simplifications, the expression of the load angle δ can be readily shown as:

$$tan\delta = \frac{R_a Z_L - R_a X_C \sin\phi + X_Q X_C \cos\phi}{X_C Z_L + R_a X_C \cos\phi - X_Q Z_L + X_Q X_C \sin\phi} \quad (16)$$

Also, substituting equations 12, 13, 14, and 15 into equation 11 and doing some simplifications, the expression of the direct-axis reactance X_D can be shown to be as given by:

$$X_D = \frac{X_C Z_L + R_a Z_L tan\delta + R_a X_C \cos\phi - R_a X_C \sin\phi \tan\delta}{Z_L - X_C \sin\phi - X_C \cos\phi \tan\delta} \quad (17)$$

Also, substituting equations 14 and 15 into equation 12 and doing some simplifications, the expression of the terminal voltage can be shown to be as given by:

$$V_L = I_D \frac{Z_L}{\frac{Z_L}{X_C} cos\delta - \sin(\phi + \delta)} \quad (18)$$

Load impedance Z_L is given by:

$$Z_L = \sqrt{R_L^2 + X_L^2} \quad (20)$$

For the no-load condition, I_L is zero, then equations 16 and 17 reduce to:

$$tan\delta = \frac{R_a}{X_C - X_Q} \quad (21)$$

$$X_D = X_C + \frac{R_a^2}{X_C - X_Q} \quad (22)$$

From equation 12, I_C can be obtained as:

$$I_C = \frac{I_D}{cos\delta} \quad (23)$$

The no-load voltage is given by:

$$V_O = I_C X_C \quad (24)$$

X_C is excitation capacitive reactance.

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IV. RESULTING PERFORMANCE CHARACTERISTICS AND DISCUSSIONS

The hybrid synchronous reluctance generator is rated at 1.5 KW, 380/220 V, 4 poles and Y connected.
The parameters of the hybrid synchronous reluctance generator at 50 Hz are shown in table 1.

Table 1: Hybrid synchronous reluctance generator parameters at 50 Hz.

unsaturated d-axis reactance	68.3 ohms
q-axis reactance	3.41 ohms
stator winding resistance per-phase	10 ohms

The hybrid synchronous reluctance generator has auxiliary windings connected to a variable balanced capacitance load which has been tuned to obtain a saliency (X_d/X_q) ratio of 20 [8].
Using the machine D-axis magnetizing characteristics shown in Figure 4 [9], the value of the direct axis current I_D corresponding to each value of $X_D$can be determined and used to obtain the corresponding terminal voltage V_L on load and V_O on no-load.

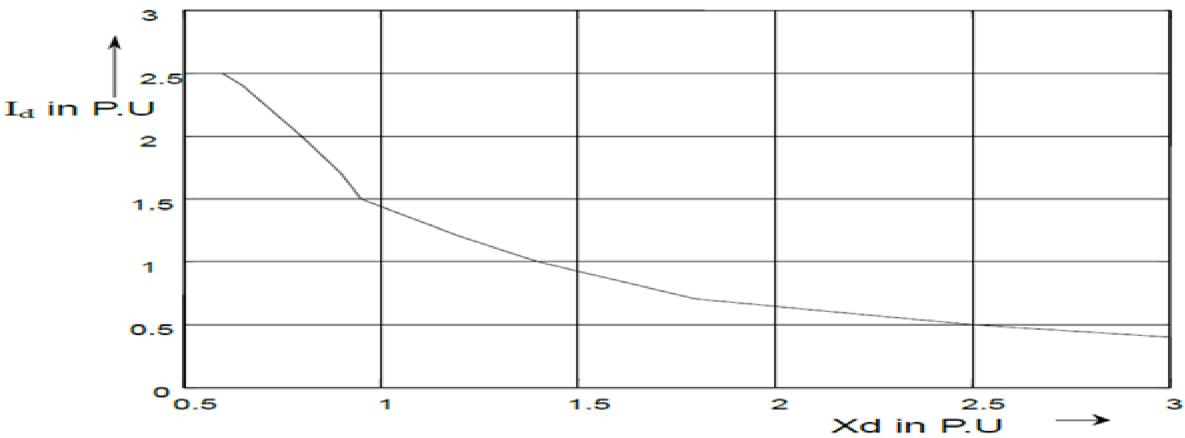

Figure 4: Direct axis magnetization curve for a reluctance generator.

A suitable curve fitting technique has been used to represent the d-axis magnetization curve giving I_D as a function of X_D. The function is given by:

$$I_D = 0.49\, X_D^2 - 2.6\, X_D + 3.8 \qquad (25)$$

A MATLAB code was developed with equations 13 to 20 and equation 25 and used to compute the value of terminal voltage, load current, capacitor current and output power at different excitation capacitance values. The relevant graphs have also been plotted using the same MATLAB code thereby determining the performance or behavior of the self-excited hybrid synchronous reluctance generator. It has been demonstrated and determined using the graphs plotted that the hybrid synchronous reluctance generator shows stable performance with excitation capacitance values ranging from 30 μF to 36 μF. However, the performance is best or optimum with excitation capacitance value of 36 μF. This is shown in Figure 5.

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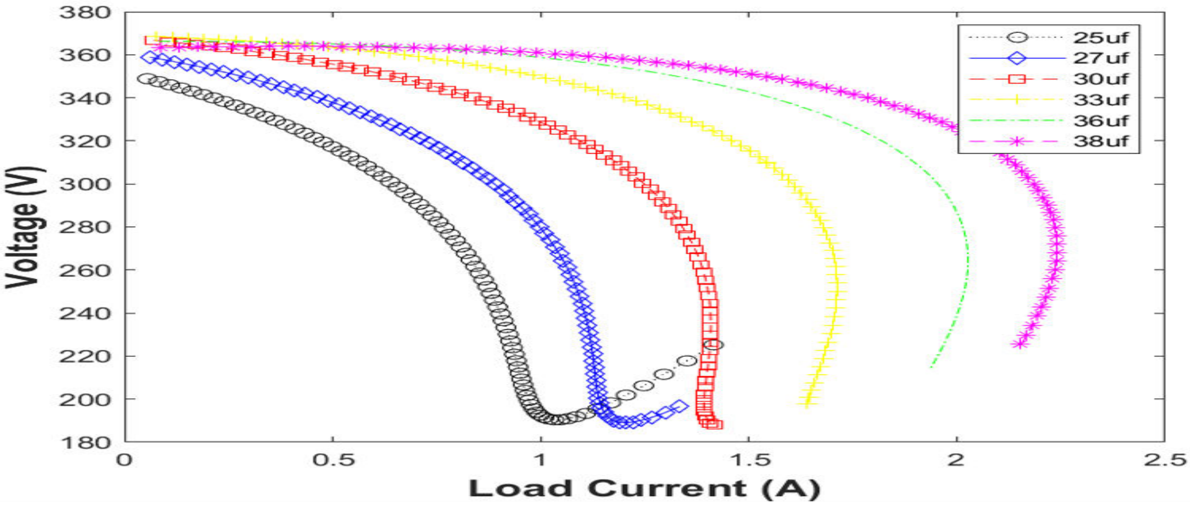

Figure 5: Variation of terminal voltage with load current.

No-load operation

The no-load capacitor current and terminal voltage at different excitation capacitance values have been computed using equations (23) and (24) respectively. The values are given in Table 2.

Table 2: No-Load capacitor current and terminal voltage.

Excitation capacitance (μF)	Capacitor current (A)	Terminal voltage (V)
30	3.48	369
31	3.57	366
32	3.74	371
33	3.85	371
34	3.94	368
35	4.03	366
36	4.15	366

It has been observed that increasing the excitation capacitance on no load increases the capacitor current with the terminal voltage remaining fairly constant.

Load operation

Figure 5 shows the variation of terminal voltage with load current at different excitation capacitance values. The load current increases as a result of increase in load. It has been found that the drop in terminal voltage as a result of increase in load is small over a large portion of the load current with excitation capacitance values from 30 μF to 36 μF. This shows that the generator has stable performance under increasing load condition. This also shows that the generator has good voltage regulation which is needed in stand-alone or autonomous generators. It has been observed that the voltage regulation of the hybrid generator improves with higher excitation capacitance values. This feature of the self-excited stand-alone generator is good and required for proper operation in isolated mode.

Figure 6 shows the variation of capacitor current with load current at different excitation capacitance values. It has been observed that the capacitor current at a particular excitation capacitance drops slightly as the load increases which implies good performance.

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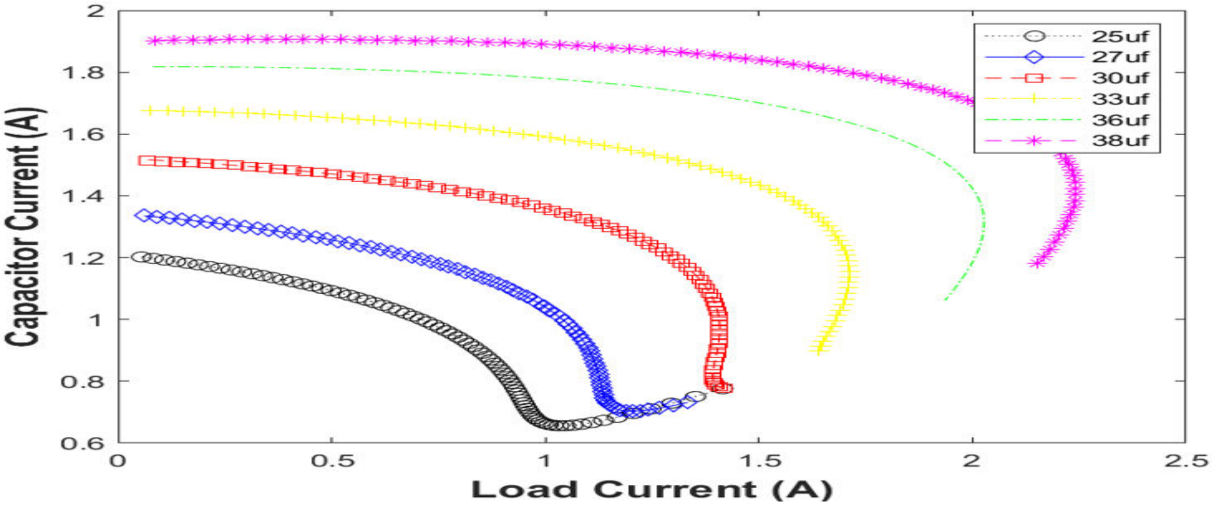

Figure 6: Variation of capacitor current with load current.

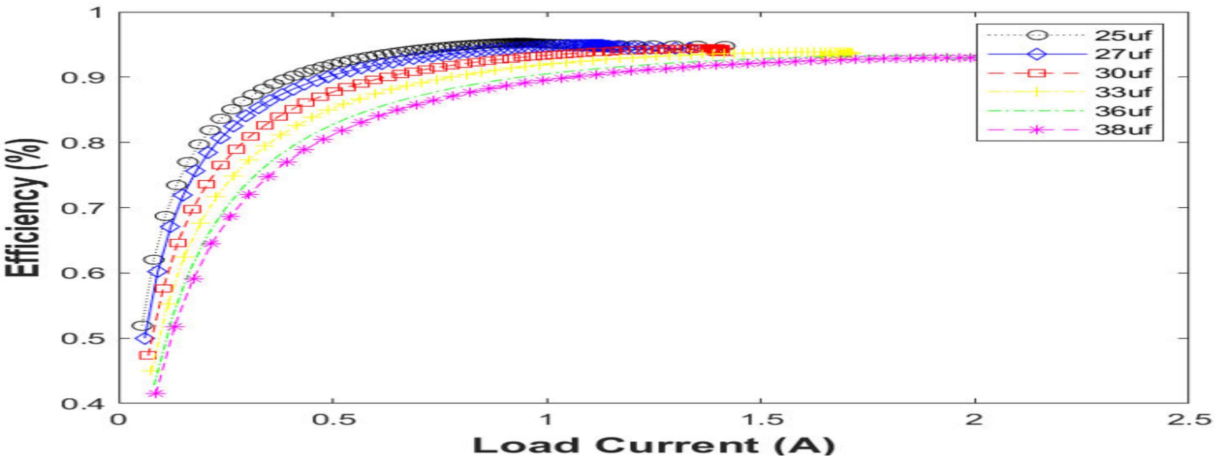

Figure 7: Variation of efficiency with load current.

Figure 7 shows how the efficiency of the generator varies with the load current at different excitation capacitance values. The efficiency increases as the load increases with the value approaching the peak value over a small portion of the load current. This shows that the generator is very efficient. However, efficiency is better with lower excitation capacitance values because the generator is able to carry lower loads with such excitation capacitance values and load current is small when compared with its value when the excitation capacitance value is higher.

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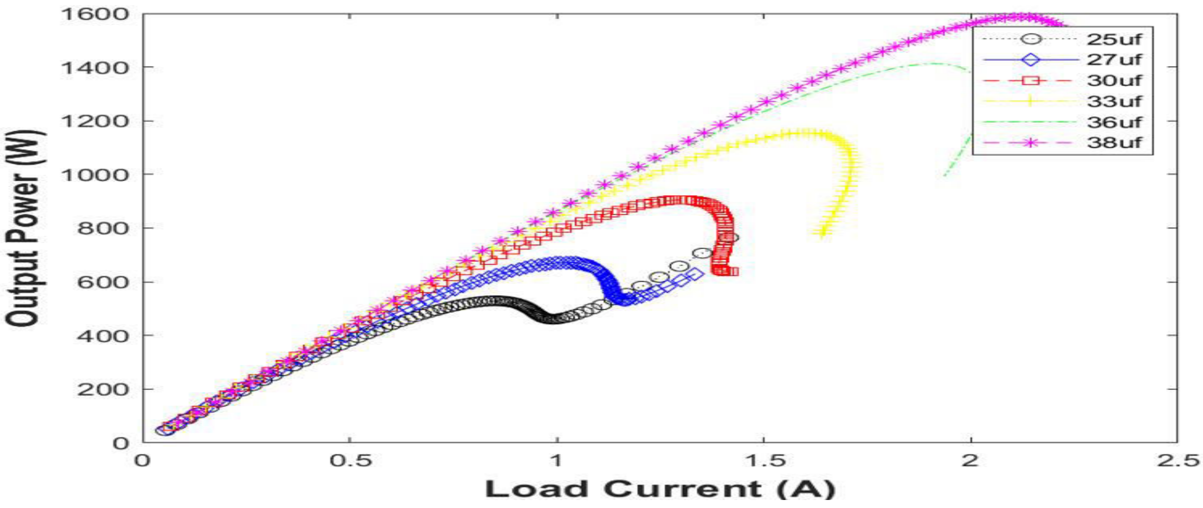

Figure 8: Variation of output power with load current.

Figure 8 shows the variation of output power with load current at different excitation capacitance values. From investigation of this figure, it can be seen that increasing the load increases the output power which is normal with all generators. It can also be seen that increasing the excitation capacitance increases the output power and therefore the load that the generator can carry. The performance of the hybrid synchronous reluctance generator is optimum with excitation capacitance value of 36 μF. The output power of this generator is over 1400 watts with this excitation capacitance value. This shows that the hybrid synchronous reluctance generator has high output power and can be called a generator with ultra-high output power. Also, the inherent maximum power factor of a synchronous reluctance machine depends on the saliency ratio. The power factor of a generator depends on its inherent power factor, output power and connected load. The hybrid generator with high saliency ratio and output power can attain a high power factor under any given load condition within the range of its capacity.

V. CONCLUSION

The performance of an autonomous (self-excited) hybrid synchronous reluctance generator has been presented. The generator has stable performance and generates high output power of over 1400 Watts. The power factor is also high which can be as high as unity. It also has good voltage regulation which can be up to 0.27% and high efficiency as high as 92%. The application of the hybrid synchronous reluctance generator especially in rural/remote areas will yield the needed service results of high output power, enhanced power factor, stable operation and reduced maintenance.

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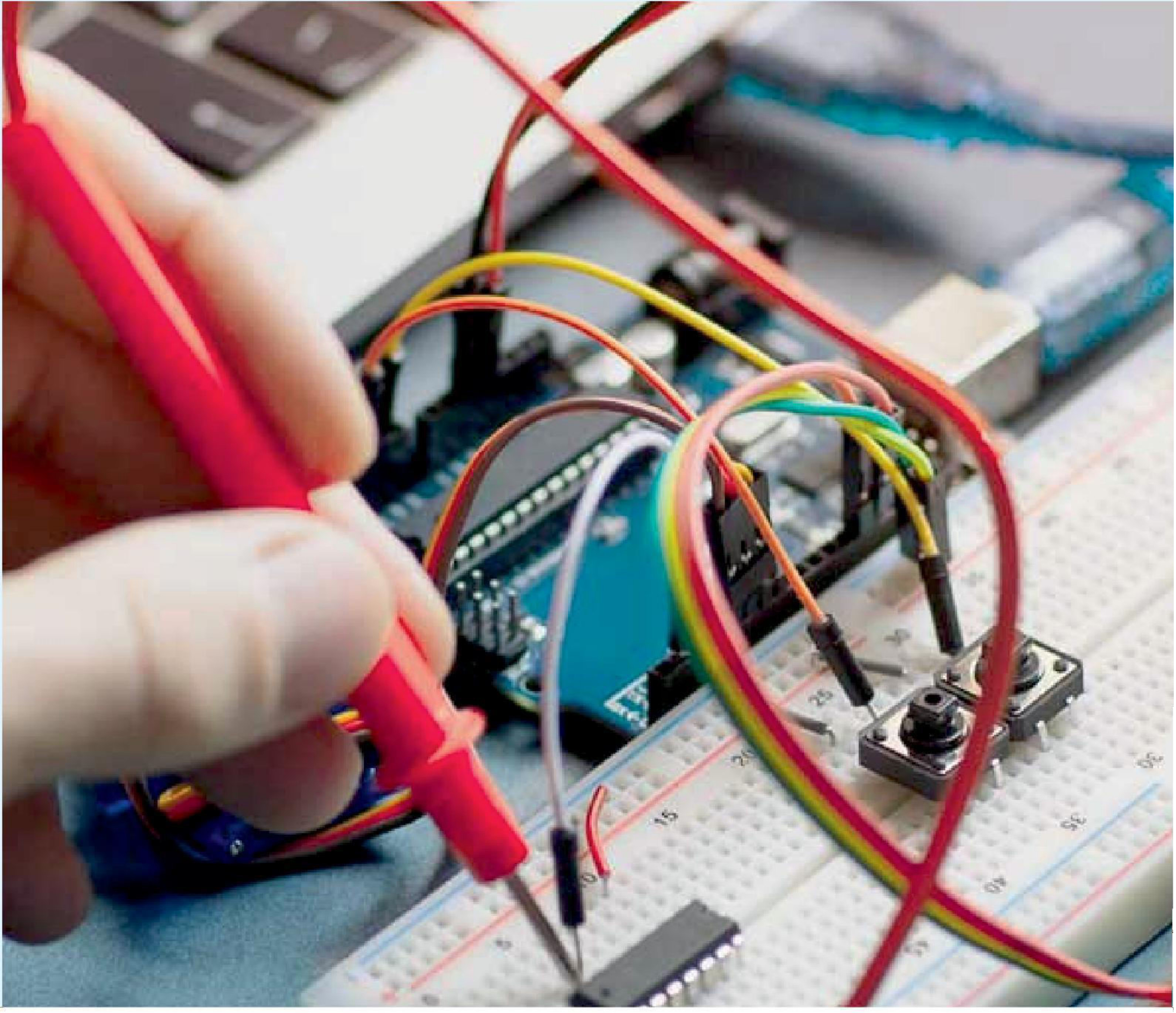

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