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Steady-State Performance Analysis of Permanent Magnet Synchronous Generator with Capacitive Assistance

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Abstract
This paper presents the steady-state performance analysis of an electrical connection scheme that improves the power factor and output power of a three-phase interior-rotor permanent magnet generator (IPMSG). The inverse saliency ratio ranges from 1 to 6. A three-phase capacitor is connected across the stator winding, close to the generator load, for each ratio. Leading current from the capacitor was used to improve the lagging power factor of the machine, maintain the load voltage under varying load conditions, and enhance the output power conversion ability, which the inverse saliency ratio scheme could not do alone, and without the need for external power electronics control circuitry. The numerical solution of the study was implemented in MATLAB®. The proposed IPMSG performance curves were enhanced with the generator yielding an improved output power of about 11.1% when compared with the inverse saliency ratio scheme without capacitors.

Keywords: *Voltage Regulation, Interior Permanent Synchronous Generator, Inverse Saliency Ratio, Power Factor, Capacitive Assistance*

1.0 INTRODUCTION

The possibility to operate the permanent magnet synchronous machine has been known for years, particularly as a stand-alone generator. This is a result of the setback of self-excited inductions generators and synchronous reluctance generators. These include the dependence of the output frequency and voltage on load and prime-mover speed for self-excited induction generators [1-3]- and poor power factor as well as low output power for self-excited synchronous reluctance generators [4-6]. The weakness of synchronous reluctance generators (SynRG) in terms of poor power factor, has shifted the attention of researchers to the use of permanent magnet synchronous generators. Permanent magnet (PM) excitation is lossless as natural magnets are used for excitation instead of field windings. However, the excitation voltage cannot be adjusted to satisfy changing requirements as the machine terminal voltage or load variation. Research work on IPMSG has been reported in [7], where low-cost ceramic magnets were used for the design of the PMSG. Upon the discovery of natural magnets in recent times, high-energy materials such as neodymium-iron-boron (NdFeB) have dominated the use of PM and it is becoming more popular [8-10].

The use of PM to improve the performance of a salient-pole synchronous generator has been reported in [11] to overcome the problem of magnetic saturation in the iron cores which limits armature terminal voltage.

The authors in [12] did similar work on a salient-pole synchronous generator with an inserted magnet. They worked both on the PM assisting the normal synchronous generator by reducing the magnetic saturation in the rotor-pole bodies and direct flux linkage of the armature windings from the permanent magnet. The study revealed that the efficiency of the IPMSG was better than that of the normal synchronous generator. Fundamentally, more losses will be incurred in the regular synchronous generator due to the field winding of the machine [11, 12]. Other researchers' works were reported in [13] and [14].

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Despite many attractive features of the IPMSG in terms of reliability and robustness over the conventional synchronous generators, the self-excited PMSG has found limited practical application due to difficulties in adjusting or controlling the voltage on changing load conditions. Normally, the conventional IPMSG has poor voltage regulation characteristics due to the demagnetization of the armature reaction, as a result of the no-load induced voltage being constant. The voltage regulation value, therefore, becomes large as the load is increasing, because the magnetic field cannot be controlled.

Voltage regulation is very important in the operation of electric generators. A capacitor has earlier been suggested as a tool to achieve voltage regulation and improvement of load capability of induction and reluctance generators [15-20]. Capacitors have been used for the regulation of output voltage of self-excited induction generator as presented in [15] for which the exciting capacitor is connected in parallel to the load (shunt connection). A general analysis to determine the steady-state performance of an isolated self-excited induction generator feeding a balanced load has also been presented in [16]. The analysis included the machine core losses and their variations with air-gap flux, predictions of the minimum value of excitation capacitance under no-load, resistive and inductive load, as well as the capacitance value required to maintain a constant terminal voltage under varying load, power factor and speed. The authors also show a mathematical basis for the design of a static exciter that utilizes a Fixed Capacitor Thyristor-Controlled Reactor (FCTCR) to provide the variable excitation capacitance. The results depict that the capacitance requirement increases significantly with decreasing speed, load impedance and power factor for a lagging load.

Furthermore, the authors in [17] presented a controlled shunt capacitor self-excited induction generator, which is continuously adjusted to maintain a constant output voltage over a relatively wide range of load and rotor speed. The method employed Insulated Gate Bipolar Transistor (IGBT) switches connected back-to-back across the fixed excitation capacitors to achieve variable excitation. It was stated that the scheme can achieve a high level of voltage regulation for a wide range of loads. However, load conditions affect the frequency for the induction generators [18, 19], and poor power factor and low output voltage are limitations of the scheme with reluctance generators [20].

The authors in [21-25] also applied capacitors to regulate the terminal voltage of a stand-alone permanent magnet synchronous generator. The authors in [25] for instance used a Fixed Capacitor Thyristor-Controlled Reactor (FCTCR) and Static Volt-Ampere Reactive (VAR) compensator to regulate the terminal voltage of a stand-alone permanent magnet synchronous generator driven by a diesel engine. The objective of the controller was to maintain the load voltage and frequency under varying load conditions by controlling the thyristor ignition angle and fuel rate as system variables. The steady-state method was based on an equivalent circuit and phasor diagram of the generator. Their conclusive results show that the generator terminal voltage can be maintained at the rated value for a typical range of load variations using FCTCR and static VAR compensator. Capacitors were also used for voltage regulation as reported in [22-25], however, a large number of capacitors was said to be required; and this could make the whole system bulky.

An alternative solution is a configuration where the armature resistance and/or the prime-mover speed is reduced [26]. Although a change in armature resistance can affect the performance of a machine. However, since the resistance coefficient of temperature for copper windings is relatively low, optimal machine performance can still be achieved for temperatures below the maximum temperature limit [20]. It is also true that varying the prime-mover speed can call for the use of power electronics, which can be complicated sometimes [2]. A more efficient approach, which was to modify the rotor structure (inverse saliency ratio) has also been reported in [7] and [26]. It has been realized that even though the use of inverse saliency ratio gave a better voltage regulation, this method is less effective when the power factor is lagging [26]. Therefore, this study aims to enhance the generator performance by considering a fixed capacitor connected to the armature winding of an IPMSG with different inverse saliency ratios. This is done to mitigate the problem of a poor lagging power factor of the machine which was reported in [26] and improve the voltage regulation. The machine parameters used in this study were derived from [27].

2.0 METHODOLOGY

The connection diagram in Fig. 1 is used to describe the steady-state mathematical model of the IPMSG. The IPMSG and its subsystems are modelled by a set of nonlinear differential equations to a linearized model of the overall nonlinear system. The rotor windings of the generator were modified by introducing permanent magnets. The machine has 36 slots and 4 poles. The stator unit has a double layer distributed winding. The stator unit also has a balanced three-phase winding, including a balanced capacitor bank well arranged. The load unit included a variable resistive and inductive load connected across the capacitor. In this paper the following simplifying

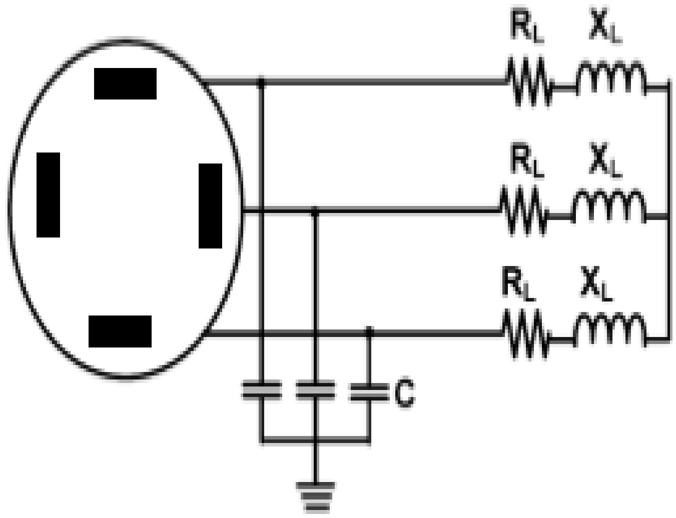

Figure 1: Conceptual connection diagram of the three-phase IPMSG [27]

assumptions have been made: Core losses, Eddy current and hysteresis effects are negligible.

The steady-state direct and quadrature voltage equations of the IPMSG were given as:

$$V_{qs} = E_o - X_{ds}I_{ds} - R_m I_{qs} \tag{1}$$

$$V_{ds} = X_{qs}I_{qs} - R_m I_{ds} \tag{2}$$

where E_0 - open-circuit voltage due to the permanent magnets. R_m - the per-phase equivalent stator resistance, I_{ds} - the steady state d-axis current. I_{qs} - the steady-state q-axis currents, X_{ds} - the steady state d-axis reactance, X_{qs} - the steady-state q-axis reactance. δ - the generator power load angle.

The steady-state direct and quadrature capacitor voltage equations are given as:

$$V_{qs} = V_g \cos\delta = V_L \cos\delta \tag{3}$$

$$V_{ds} = V_g \sin\delta = V_L \sin\delta \tag{4}$$

V_g and V_L are the per phase generator and load voltage respectively, where I_{cds} is the steady state d-axis capacitor current. I_{cqs} is the steady-state q-axis capacitor current. X_{cds} is the steady state d-axis capacitive reactance. X_{cds} is the steady-state q-axis capacitive reactance.

$V_{cds} = V_c sin\delta = V_L \sin\delta$

$V_{cqs} = V_c cos\delta = V_L \cos\delta$ and

V_c is the per phase capacitor voltage. In terms of load impedance, the generator phase full-load voltage can be represented as $V_L = I_L Z_L$. I_L is the generator per phase load current. Z_L is the generator load impedance given as:

$$Z_L = \sqrt{(R^2{}_L + jX^2{}_L)} \tag{5}$$

R_L is the resistive load, X_L is the reactive load, taken from paper [27] as:

$$X_L = \frac{R_L}{\omega_e} \times \sqrt{\left(\frac{1}{cos\,\varphi}\right)^2 - 1} \tag{6}$$

where ω_e is the electrical speed in radian per seconds and $cos\,\varphi$ is the generator power factor.

The steady-state equations of (1) through (5) suggest the per-phase equivalent circuits of the IPMSG shown in Fig. 2. The steady-state phasor diagram in Fig. 3 is drawn for a lagging power factor condition. The excitation capacitor current leads the terminal voltage by an angle φ, which is the load power factor angle. The load current also lags the terminal voltage by an angle δ. The steady-state d-q axis stator currents can be obtained from the phasor diagram in Fig. 3 as follows:

$$I_{ds} = I_L \sin(\phi + \delta) - I_c \cos\delta \tag{7}$$

$$I_{qs} = I_L \cos(\phi + \delta) + I_c \cos\delta \tag{8}$$

where I_c is the capacitor current.

Making $I_L = \frac{V_L}{Z_L}$ and $I_c = \frac{V_L}{X_c}$, the angle can be derived by substituting (7) and (8) into (2) to yield (9).

$$I_L Z_L \sin\delta = X_{qs}[I_L\, cos(\delta + \varphi) + I_c \cos\delta] - R_m[-I_L\, sin(\delta + \varphi) - I_c \cos\delta] \tag{9}$$

Rearranging with some algebraic manipulations gives load angle as:

$$\delta = tan^{-1}\frac{R_m + (X_{qs}\cos\varphi - R_m \sin\varphi)X_c}{X_c - X_{qs} + (X_{qs}\sin\varphi + R_m\cos\varphi)X_c} \tag{10}$$

where $X_c = \frac{1}{\omega_e C}$ and C is the capacitance of the capacitor.

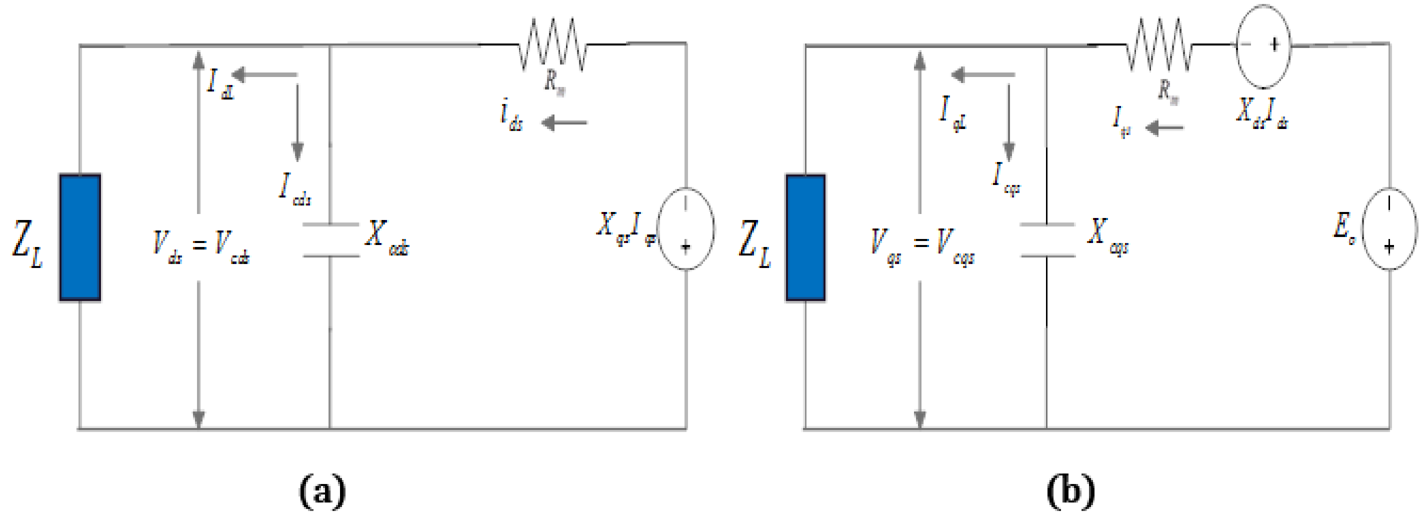

Figure 2: The steady-state equivalent circuit of the IPMSG (a) d-axis (b) q-axis

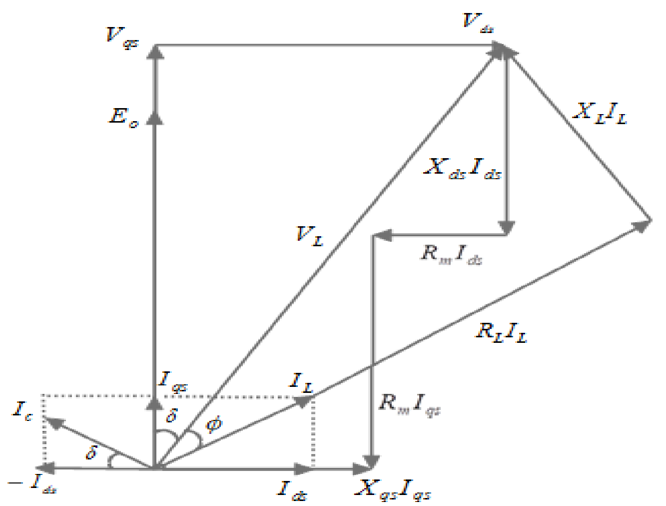

Figure 3: The phasor diagram of the IPMSG at lagging power factor

The full-load terminal voltage can also be derived in terms of the load angle, δ by substituting equation (10) into equation (1), to give equation (11):

$$V_L = \frac{E_o Z_L}{Z_L X_c \cos\delta + X_c X_{ds} \sin(\delta+\varphi) + R_m X_c \cos(\delta+\varphi)} \quad (11)$$

Similarly, the load current can be expressed as:

$$I_L = \frac{E_o}{Z_L X_c \cos\delta + X_c X_{ds} \sin(\delta+\varphi) + R_m X_c \cos(\delta+\varphi)} \quad (12)$$

The total output power of a three-phase IPMSG supplying an isolated load can be derived from equation (13)

$$P_o = 3\frac{{V_L}^2}{Z_L}.\cos\varphi \quad (13)$$

Dividing (9) by I_L and substituting with (11) into (12) yields the output power as:

$$P_o = \frac{3{E_o}^2 \cos\varphi.\left[2X_c X_{qs} \cos(\delta+\varphi) - ({X^2}_c R_m \sin(\delta+\varphi))\right] \sin\delta}{\left[X_{qs} \cos\delta . \cos(\delta+\varphi) - (2X_c R_m \sin\delta) + ({X^2}_c X_{ds} \sin\delta \sin(\delta+\varphi)^2\right]} \quad (14)$$

For the steady-state analysis, the voltages have been normalized to the corresponding no-load voltage of 110 V against the armature current. The load characteristics were deduced by gradually loading the generator from no-load to full-load until it reaches pull-out at a terminal voltage. The capacitor value is given as 52μF, and for a given power factor loading, only the value of the resistive load is adjusted for corresponding values of inductive load.

3.0 RESULTS AND DISCUSSION

The steady-state performance of the IPMSG is presented in this section, using Equations (5) - (14). Fig. 4 shows the variation of load voltage to load current when the IPMSG is operating at different inverse saliency (K_r) with and without a capacitor.

When the generator is operated without capacitive assistance, as illustrated in Fig. 4(a), a nearly levelled voltage load characteristics was achieved when the ratio, Kr is 4; and above this value, the terminal voltage increases with load current over most of the practical current range. This is similar to the report found in [27].

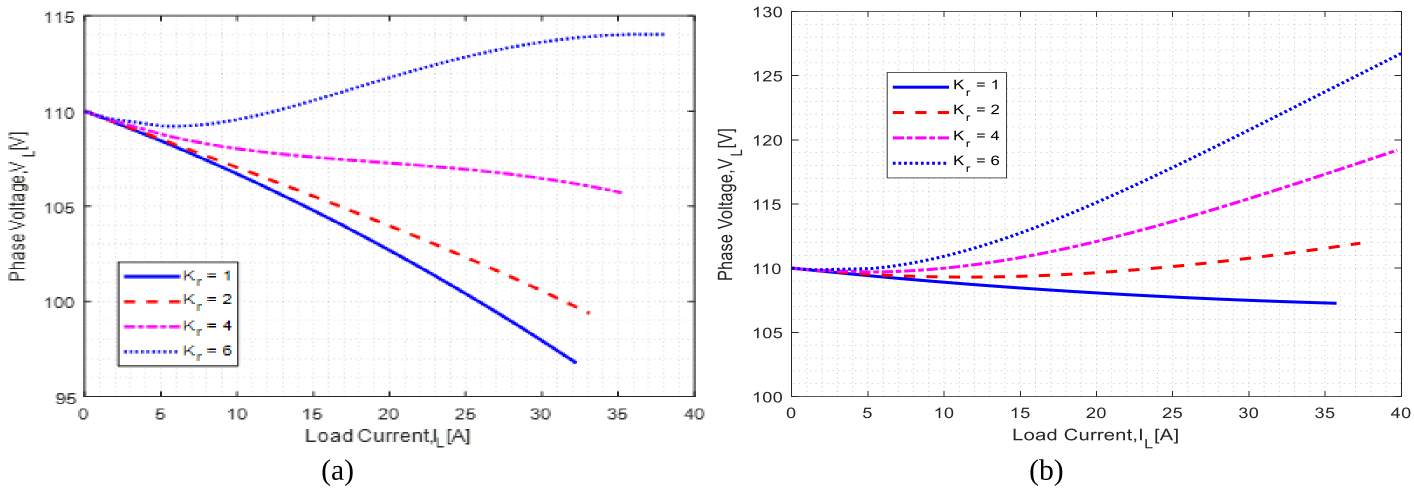

Figure 4: Steady-state load characteristic of the IPMSG at different inverse saliency ratios, at rated voltage, nominal speed of 1500 rpm and unity power factor (a) without capacitor (b) with capacitor

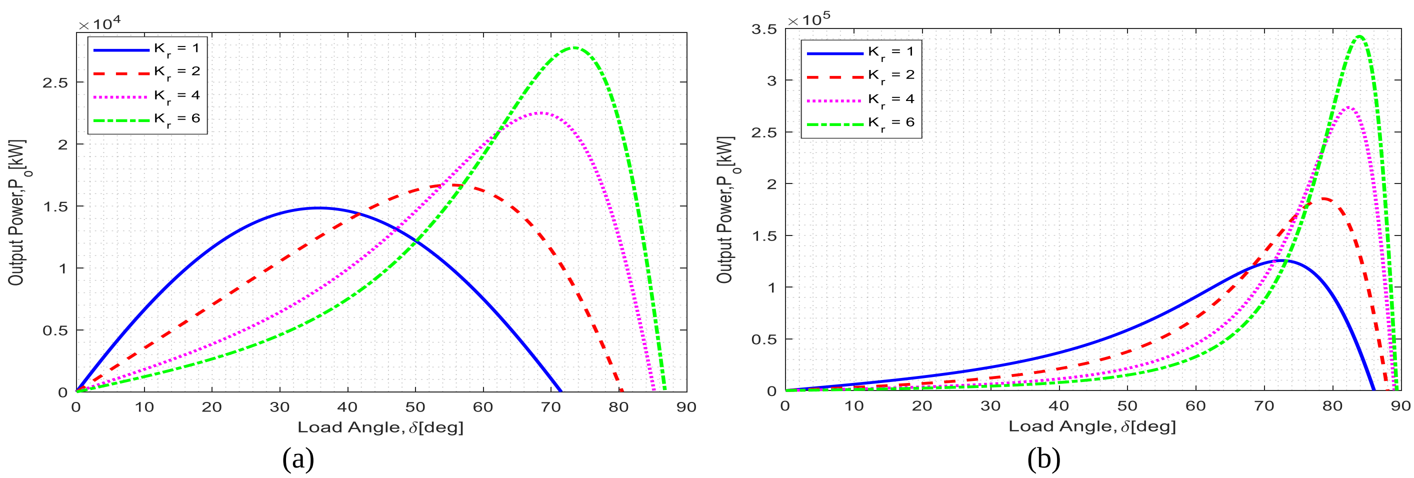

Figure 5: Effect of inverse saliency ratio on power-load angle characteristics of IPMSG operating at 1500 rpm and 1.0 power factor (a) without capacitor (b) with capacitor

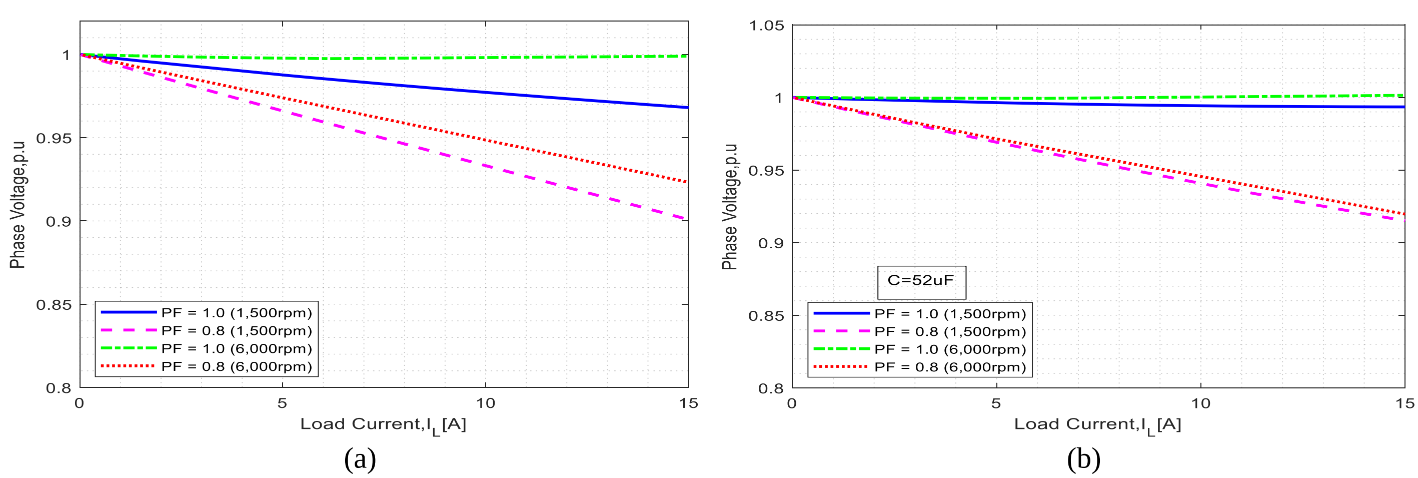

Figure 6: Steady-state load characteristic of the IPMSG at different power factors and rotor speed, (a) without capacitor, (b) with capacitor

Below the inverse saliency ratio of 4, the IPMSG lagging power factor could not be improved. When capacitor was included as illustrated in Fig. 4(b), better-levelled voltage load characteristics were possible from Kr=2 and above at increasing load current. From the two scenarios, using an inverse saliency ratio of 2, the percentage voltage regulation of the IPMSG without a capacitor obtained was 3.8% and that of the IPMSG with a capacitor was 1.8%.

Fig. 5 shows the output power of the IPMSG with and without a capacitor. It is obvious from Fig. 5(a) that the output power increases as the inverse saliency ratio increases. The generator power increased from about 1.5kW to about 2.7 kW when the saliency ratio increased from 1 to 6. However, a better performance was seen in Fig. 5(b) when the capacitor was included. The effect of the capacitor on the power-load angle characteristics of an IPMSG when operating at nominal speed (1500 rpm) and supplying a unity-power-factor load shows that for a given value of the inverse saliency ratio, the maximum power condition occurs at a load angle which is less than 90 degrees.

The maximum power output of the generator with a capacitor occurs at a load angle that is close to 90 degrees with an improved output power curve. The generator power increased from about 1.7 kW to about 3.4 kW when the saliency ratio increased from 1 to 6.

Fig. 6(a) shows the performance of the IPMSG operating at different rotor speeds of 1500 rpm and 6000 rpm and different power factors of 0.8 and 1.0 for the various rotor speed, in p.u. The voltage regulation at full-load 0.8 lagging power factor when the generator operated at the nominal speed of 1500 rpm was seen to be 11 %; for 0.8 lagging power factor and 0.8 % when the generator operated at 1.0 factor lagging. When the generator speed became higher than the nominal speed by making it four times the rated speed (which is 6000 rpm), the full-load terminal voltage was as well levelled with full-load open-circuit voltage at 1.0 power factor. That is a 0 % drop for a 0.8 lagging power factor, and the voltage drop was seen as 2 %.

Obviously at a fixed load power factor, increasing the prime-mover speed of the generator can reduce the voltage drop. This is similar to what is reported in [27]. But then, a further increase of the generator's prime-mover speed could be unhealthy for a generator that is designed for a particular speed.

Fig. 6(b) showed the load characteristics of the IPMSG with a fixed capacitor (52 μF) at a nominal speed of 1500 rpm and when the generator is made to operate at 6000 rpm (by increasing the prime mover speed to 4 times the nominal speed, also in p.u. The generator operated at a load power factor of unity and 0.8 (lagging). The percentage voltage drop at full-load when the generator operated at the nominal speed of 1500 rpm was seen to be almost levelled at unity power factor, giving 2 % voltage regulation; and 9 % voltage drop at 0.8 power factor lagging.

When the generator speed became higher than the nominal speed by making it four times (that is 6000 rpm), the terminal full-load voltage also was higher than the terminal open-circuit voltage. A negative voltage drop of -0.8 % was also seen at this condition for unity power factor; and a voltage drop of 2 % for 0.8 lagging. Apparently, with a given capacitance and load power factor, reducing the prime mover speed of the generator can reduce the voltage drop as a result of the leading current supplied by the capacitor.

4.0 CONCLUSION

The performance improvement of a 1.250 kVA IPMSG with a fixed capacitor and different inverse saliency ratios was presented in this study. The steady-state performance analysis of the generator showed that the load capacity of the generator can be improved if the inverse saliency of the generator is increased. Since the use of inverse saliency ratio is inefficient at certain lagging power factors, a fixed capacitor was utilized to improve the generator lagging load power factor of the generator at every given inverse saliency ratio and fixed machine speed.

At an inverse saliency ratio of 2, under the given condition, the percentage voltage regulation of the IPMSG without a capacitor was calculated as 3.8% and that of the IPMSG with a capacitor given as 1.8%. The addition of a capacitor contributed to regulating the voltage level at increasing load current. Improving the terminal voltage implies enhancement of the output power. Therefore, capacitor compensation did not only improve the load power factor but also increased the ultimate output of the generator by increasing the current carrying capacity of the stator windings.

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