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# Comparison of an Interior Mounted Permanent Magnet Synchronous Generator with a Synchronous Reluctance Generator for a Wind Application

Poopak Roshanfekr, Torbjörn Thiringer, Sonja Lundmark, and Mikael Alatalo

***Abstract*—**This article presents a performance comparison of an interior mounted permanent magnet synchronous generator (IPMSG) with a synchronous reluctance generator (SynRG) with the same size for a wind application. It is found that using the same geometrical dimensions, a SynRG can convert 74 % of the power that an IPMSG can convert, while it has 80% of the IPMSG weight. Moreover it is found that the efficieny for the IMPSG is 99% at rated power compared to 98.7% for the SynRG.

***Keywords*—**Interior mounted permanent magnet synchronous generator (IPMSG), synchronous reluctance generator (SynRG), wind energy, annual energy efficiency.

## I. Introduction

THE synchronous reluctance machine (SynRM) has a long history. The first SynRM was introduced by Kostko in 1923 [1]. The synchronous reluctance motor was developed particularly in the 1960's as a line-start synchronous AC motor [2]. During the 1990's a substantial amount of work and research on the design and control of synchronous reluctance motors have been done [2]-[8]. Recently, the SynRM have been further improved [9]-[11].

Even though most of the researchers have explored the application of the reluctance machine as a motor, the field of the synchronous reluctance generator (SynRG) has also been brought to attention [12]-[14]. Several applications for synchronous reluctance machines are proposed in [15]. One of the interesting applications of the SynRG is for wind turbine generation systems [14], since SynRGs are robust, inexpensive and they have a simple rotor construction. In addition, a SynRG has no cogging torque. Moreover, they have low noise emission and are suitable for variable speed operation. Although synchronous permanent magnet motors often are a very good choice for many variable-speed drive applications, the advantages of using synchronous reluctance motors is that, the today very expensive magnets are not needed.

In [14] a small wind turbine generation system with SynRG has been investigated. However, the system is not compared with any other generation systems.

The purpose of this paper is to compare a modern wind turbine generator type, the IPMSG, with a generator using the synchronous reluctance principle. In order to perform this comparison 5MW IPMSG for wind applications is formed into a SynRG with the same size and design features. Moreover a target is to demonstrate how much power that can be converted from the SynRG with the same volume as the IPMSG. In addition; a goal is to compare the weights of the machines. Finally an objective is to determine and compare the losses and the annual energy efficiency for the generators.

Poopak Roshanfekr, Torbjörn Thiringer, and Sonja Lundmark are with the Chalmers University of Technology, Göteborg, Sweden (e-mail: poopak@chalmers.se, torbjorn.thiringer @chalmers.se, sonja.lundmark@chalmers.se).

Mikael Alatalo is with the Chalmers University of Technology and Aros electronics AB, Göteborg, Sweden (e-mail: alatalo@chalmers.se).

## II. Permanent Magnet Synchronous Machine Operation

The equations for the permanent magnet synchronous machine in the dq-component can be written as

$$u_{sd} = R_s i_{sd} - \omega_{el} L_q i_{sq} \tag{1}$$

and

$$u_{sq} = R_s i_{sq} + \omega_{el} L_d i_{sd} + \omega_{el} \Psi_m \tag{2}$$

The torque is formed as;

$$T = \frac{3}{2} p\left[\Psi_m i_{sq} + \left(L_d - L_q\right) i_{sq} i_{sd}\right] \tag{3}$$

where $u_{sd}$ and $u_{sq}$ are the stator voltage in d and q axis, $R_s$ is the armature phase resistance, $\omega_{el}$ is the electrical speed ,$L_d$ is the d-axis inductance, $L_q$ is the q-axis inductance ,$i_{sd}$ and $i_{sq}$ are the stator current in d and q axis respectively and $\Psi_m$ is the flux linkage originating from the magnets.

## III. Synchronous Reluctance Machine Operation

Equations (1) and (2) are also valid for the SynRM, with the remark that $\Psi_m$is equal to zero in the SynRM. The SynRM torque in the dq-coordinate system can, therefore be simplified to

$$T = \frac{3}{2} p\left(L_d - L_q\right) I^2 \sin(2\theta) \tag{4}$$

where $p$ is the number of pole pairs,$L_d$ is the d-axis inductance ,$L_q$ is the q-axis inductance, $I$ is the stator current and $\theta$is the current angle. More information about (4) can be found in [9]. The SynRM torque under constant current condition based on (4) is for a given current magnitude maximum when $tan\theta=1$.

This represents the Maximum Torque Per Ampere (MTPA) control strategy of the SynRM. The operation diagram of a SynRM is shown in Fig. 1 [9].

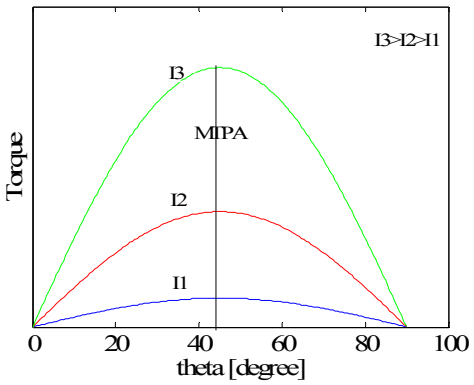


Fig. 1 Operation diagram for SynRM with constant current

As can be seen from Fig. 1 the maximum torque is achieved when $\theta=45°$. However, this is for linear (unsaturated) conditions. When the machine comes into saturation, the MTPA angle will be higher than 45°, see [16]. There are other possible operation points for the SynRM, if a different control strategy is applied. However, since in this paper the MTPA control strategy is used, they are not considered.

## IV. Interior Permanent Magnet Generator Design and Losses

A 5MW IPMG is designed using the finite element method (FEM) program Maxwell 2D. The cross-section of the machine is shown in Fig. 2 and the data of the machine is shown in Table I.

The iron losses of the machine for different speed are taken from the FEM program and the copper losses are calculated according to

$$P_{cu} = 3R_s I^2 \quad (5)$$

where $R_s$ is the armature phase resistance and $I$ is the stator current.

The maximum AC-voltage that the converter can produce is assumed to be 3.88 kV phase RMS voltage. This corresponds to a dc-link voltage of 10 kV [17]. With this voltage maximum torque per ampere operation can be obtained up to 555A. This current level is used as the maximum continuous current level for this machine.

TABLE I
Machine Data

| Symbol | Quantity | Value |
|---|---|---|
| P | rated output power | 5 MW |
| $2p$ | number of poles | 8 |
| $Q$ | number of slots | 72 |
| $f$ | frequency | 50 Hz |
| $n$ | rated speed | 750 rpm |
| $R_s$ | armature phase resistance | 0.0374 Ω |
| $D_1$ | outer stator diameter | 1100 mm |
| $D_2$ | inner stator diameter | 758 mm |
| $g$ | air-gap length | 3 mm |
| $I$ | RMS stator line current | 555 A |

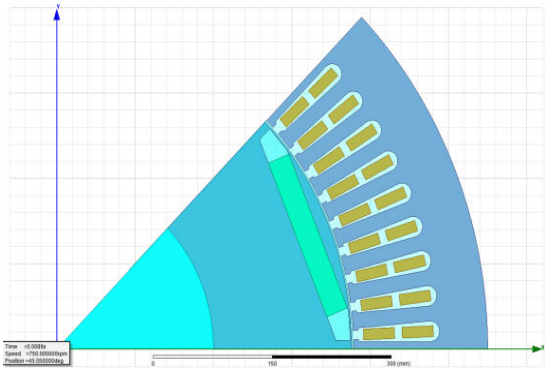

Fig. 2 Cross-section of the IPMSG

The rotor speed of the turbine and the generator power versus wind speed are shown in Figs. 3 and 4.

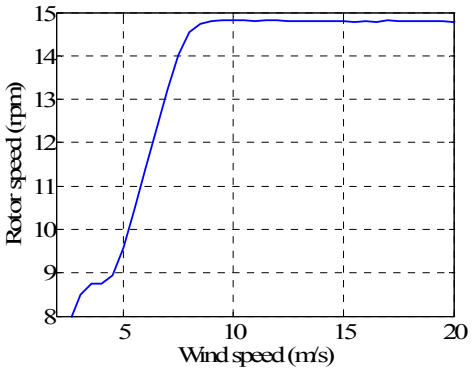


Fig. 3 Rotor speedversus wind speed for the investigated wind turbine

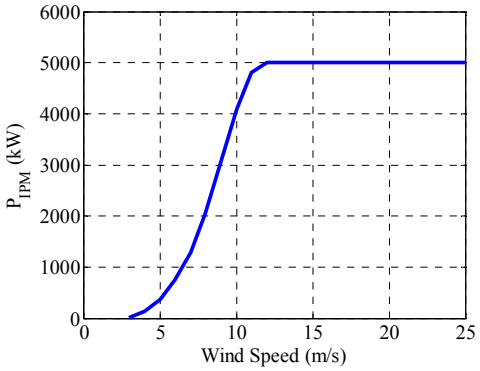


Fig. 4 Power versus wind speed for the investigated wind turbine system

A gearbox with the ratio of 50.67 is considered to increase the speed to be suitable for the generator. The machine losses of the IPMSG are shown in Figs. 5 and 6.

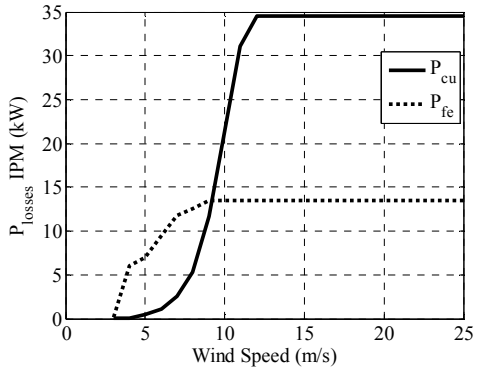


Fig. 5 Copper and iron losses for the IPMSG

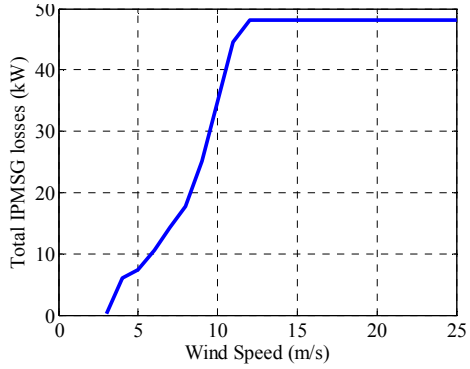


Fig. 6 Total losses for the IPMSG

## V. Synchronous Reluctance Generator Design and Losses

A SynRG with exactly the same size as the IPMSG is designed in Maxwell 2D. The cross-section of the machine is shown in Fig. 7.

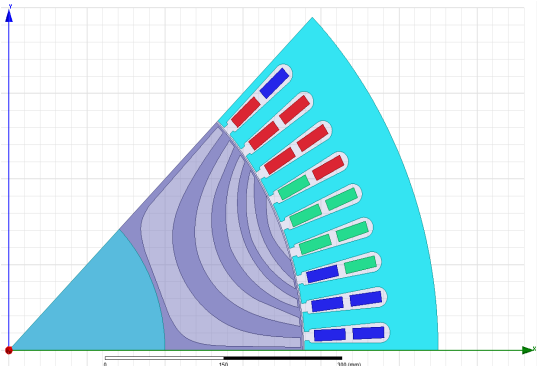

Fig. 7 Cross-section of the SynRM

The maximum power level that can be obtained with the SynRG is 3.7 MW, i.e. 74% of the power level that can be obtained with the IPMSG.

The copper and ironlosses as well as the sum of them for the SynRG are shown in Figs. 8 and 9, respectively.

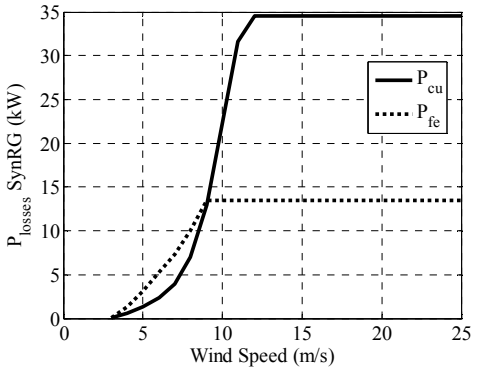


Fig. 8 Copper and iron losses for the SynRG

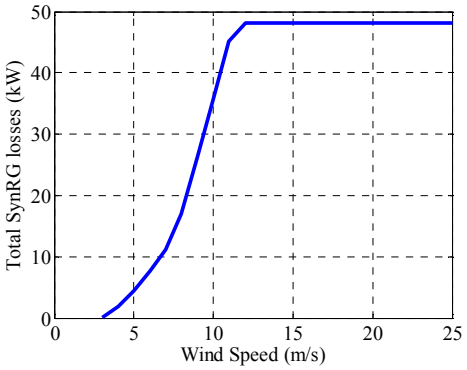


Fig. 9 Total losses for the SynRG

From Figs. 6 and 9, it can be seen that even though the total losses for both machines at the rated operating point are the same, the IPMSG has higher losses in lower wind speeds. For example for 7m/s wind speed the total losses for IPMSG is 14.3kW while this value for SynRG is 11.2kW.

The efficiency of the IPMSG and SynRG (considering copper and iron losses) is shown in Fig. 10.

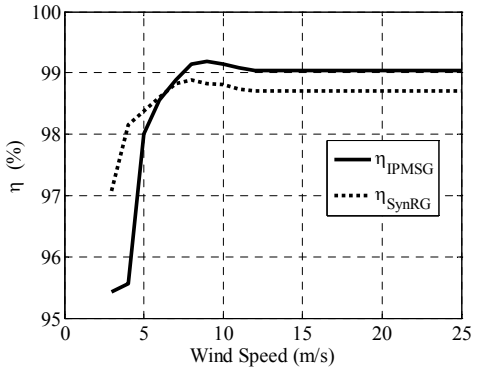


Fig. 10 Machine efficiency

## VI. Annual Energy Efficiency

After having determined the power capacity of the SynRM, it is now time to investigate its energy efficiency in relation to the IPMSG. The comparison will be done in relative terms, in order to account for that the larger size is needed for the SynRG.

In wind energy applications, the wind speed is often low and accordingly, the efficiency at low power levels is of higher importance. Therefore, in this section, the annual losses of the machines are studied. To calculate the annual loss energy of the machine, $E_{\bar{\omega}}$, (6) is used for different average wind speeds. $P(\omega)$ is the sum of copper and iron losses of the machine, $T$ is the number of hours per year and $f(\omega)$ is the probability of having wind speed $\omega$ during the year which is calculated using

$$E_{\bar{\omega}} = T\int \left(f(\omega)P(\omega)\right)d\omega \tag{6}$$

$$f(\omega) = \left(\frac{k}{C}\right)\left(\frac{\omega}{C}\right)^{k-1} \exp\left[-\left(\frac{\omega}{C}\right)^{k}\right] \tag{7}$$

where $k$ is the shape factor which is considered to be 2, $\omega$ is the wind speed and $C$ is the scale factor which is calculated according to

$$C = \frac{\bar{\omega}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{8}$$

where $\bar{\omega}$ is the average wind speed and $\Gamma$ is the gamma function which is expressed in (9).

$$\Gamma(x) = \int_0^{\infty} t^{x-1}e^{-t}dt \tag{9}$$

The annual energy efficiency, $E$ in percentage, of the generator is calculated using the expression below:

$$E = \left(1 - \frac{E_{loss}}{E_{power}}\right)100 \tag{10}$$

where $E_{loss}$ is the annual loss energy of the machine and $E_{power}$ is the annual mechanical power energy of the machine.

The annual energy efficiency of the generators is shown in Fig. 11.

## VII. Weight Comparison

As mentioned in section V the SynRM has exactly the same size as the IPMSG. Therefore the weight of the copper and stator iron are the same for both machines. However, in spite of the same size of the rotor of the machines, the rotor weight of the SynRM is lighter than IPMSG because of the air-filled barriers. The weight of the machines is compared in Table II. The values show that the total active material weight of the SynRM is 80% of that of the IPMSG.

TABLE II
Machine Active Material Weight

| Symbol | Quantity | IPMSG Value | SynRM Value |
|---|---|---|---|
| $W_{stator}$ | stator core steel weight | 2397 kg | 2397 kg |
| $W_{copper}$ | copper weight | 831 kg | 831 kg |
| $W_{rotor}$ | rotor core steel weight | 1820 kg | 1050 kg |
| $W_{magnet}$ | permanent magnet weight | 312 kg | - |
| $W_{total}$ | total active material weight | 5360 kg | 4278 kg |

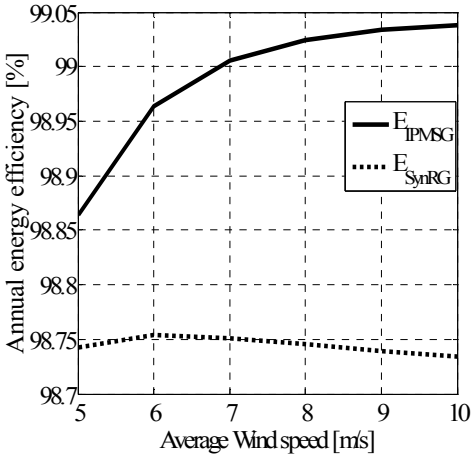


Fig. 11 Annual energy efficiency of the generators

## VIII. Conclusion

This paper addressed a 5MW interior mounted permanent magnet generator for a wind turbine, as well as an alternative. A SynRM with the same size as the IPMSG is designed and the power of this machine is compared to the IPMSG. The MTPA strategy is used for different wind speeds. The copper and iron losses are calculated for both machines. Moreover, the efficiencies and the annual energy efficiencies of the machines are calculated. It is found that the maximum power

level that can be obtained with the SynRM is 74% of the power level of the IPMSG with the same size and geometry features. Moreover, it was found that the SynRM has 80% of the IPMSG weight. The efficiency of the rated power for the IPMSG is 99% and for the SynRM is 98.7%.

## ACKNOWLEDGMENT

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