

Interior Permanent Magnet Generator: Generator of New Millennium



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ABSTRACT

The rapid development in the field of permanent magnet material has rekindled interest in the permanent magnet electrical machines. In the last couple of decades, the price of high density permanent magnet has come down to an affordable level. The availability of the material like Neodymium-iron-Boron (NdFeB), has improved the characteristics of many permanent magnet machines such as Brushless DC machine, Permanent magnet synchronous machine, Switch reluctance machine etc. Due to decreasing natural resources, conservation of energy has become one of the most important aspects of our time. It has been proven time and again that higher the efficiency of a machine, the better is its energy saving performance. The use of magnet material can increase the efficiency of the electric machine to a great extent. In a permanent magnet generator, field excitation is provided by permanent magnet material. As a result, the carbon brushes, slip rings, field winding and its copper loss, dc supplies are eliminated. There is also possibility of reducing the size and weight. The concept of permanent magnet generator is not very recent. In fact there exist permanent magnet generators (PMGs) for many years; still their applications are limited. The conventional PMG has a very big disadvantage over other types of generators, due to the constant nature of the field excitation, voltage regulation varies with load. But the interior type permanent magnet machine has an inverse saliency ratio, which can be exploited to improve the voltage regulation characteristic as well as its constant power capability. In this paper, the performance of an Interior Permanent Magnet generator (IPMG) has been discussed. Its option as a grid connected generator has been explored. Its merit and demerit over a conventional synchronous generator have been discussed and analysed.

1. INTRODUCTION

The electrical machine with permanent magnet excitation is gaining more and more attention from the research community as well as the power industry. The development in the field of permanent magnet material has made them affordable. In order to conserve energy, high efficient systems are requirements of our time. The permanent magnet machines are considered to be one of the most efficient electrical machines of the present day. The main advantage of permanent magnet excitation is the omission of carbon brushes, rotor slip-rings, field winding and its losses along with smaller size and weight for the same power rating. But all these merits are offset by the one main disadvantage - the constant rotor magnet field. Since the magnet field can not be altered easily, the terminal voltage of the PM generator will vary with load. But whenever a synchronous generator is connected to a large interconnected power system containing many other generators, the voltage and frequency at its stator terminal are fixed by the whole system. Hence a generator with inherent capability of voltage regulation is desirable. The lack of this capability has limited the conventional permanent magnet generator operation to isolated systems like portable or emergency power supply, field excitation

supply of synchronous generator etc. The development of interior type permanent magnet machine has opened up some new prospects for permanent magnet generator.

2. CONSTRUCTION

In the interior type machines, one or more layers of magnets are buried in the rotor laminations. This type of construction of permanent magnet machine was first suggested by T.M. Jahn in [1]. The buried magnets in the rotor introduce saliency to the structure. In Fig. 1 the rotor of a typical one layer, interior permanent magnet (IPM) machine is shown. The IPM machines can be broadly divided as a) radially laminated machines and b) axially laminated machines. In the radially laminated construction, the rotors are usually designed with one or more layers of permanent magnet material. The lamination of the rotor is like any other conventional machine. The cavities are punched in to rotor laminations to insert permanent magnet material. In axially laminated rotors, many alternating layers of soft magnetic material and permanent magnet material sheets are laid along the machine axis. This design provides a higher saliency ratio but is relatively expensive to construct.

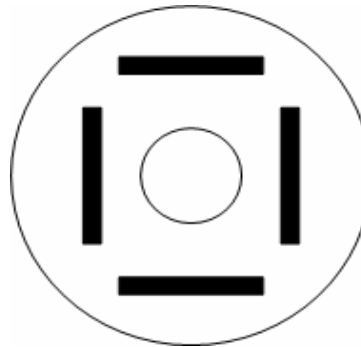


Fig.1 The rotor of IPM machine

3. PRINCIPLES

The steady state performance of an IPM machine is usually modelled with conventional two axes theory. The magnet flux defines a d axis radially through the centre of the magnet and q axis is defined in the inter-polar region.

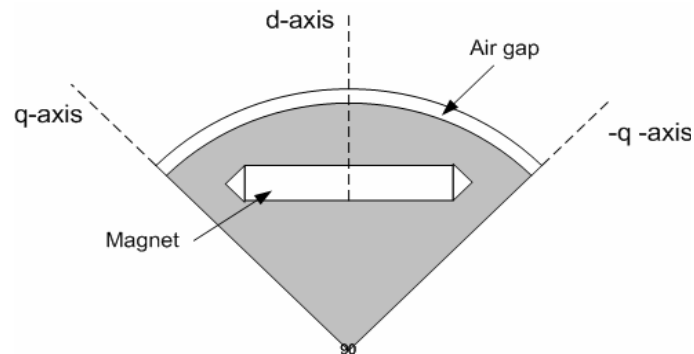


Fig. 2 The d and q axis

In the d-axis, the magnetic fluxes need to cross the two magnets in addition to two air gaps. Since the permeability of rare-earth magnet is almost equal to free space, the magnet thickness in d-axis appears as series air gaps in the d-axis flux path. On the other hand, q-axis flux can pass through the steel pole pieces without crossing the magnet. As a result, q-axis synchronous reactance is greater than the d-axis reactance i.e. $X_q > X_d$. The d and q axis flux of an IPM machine obtained from FE (Finite Element) analysis is shown in Fig. 3. The inverse saliency nature of IPM machine can be exploited for a zero voltage regulation and overcome the disadvantage of the absence of field control [2].

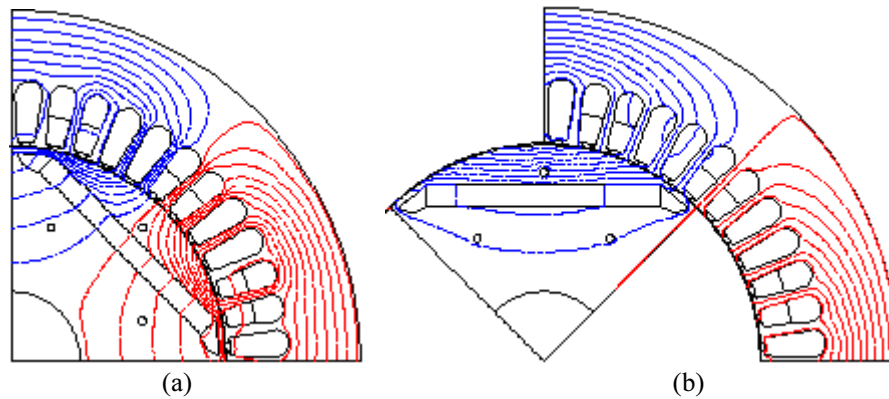


Fig. 3 The axis flux: (a) d-axis flux and (b) q-axis flux

In conventional synchronous machine, d-axis reactance is greater than the q-axis one and saliency has very little affect on terminal voltage, armature current and power in the normal operating ranges. Only at small excitation levels the difference between two become prominent [3]. But in interior permanent magnet (IPM) synchronous generator, due to the inverse saliency in the rotor, regulation characteristic could be quite different from the conventional generator. The Fig. 4 is showing the phasor diagram of an IPMG with resistive load.

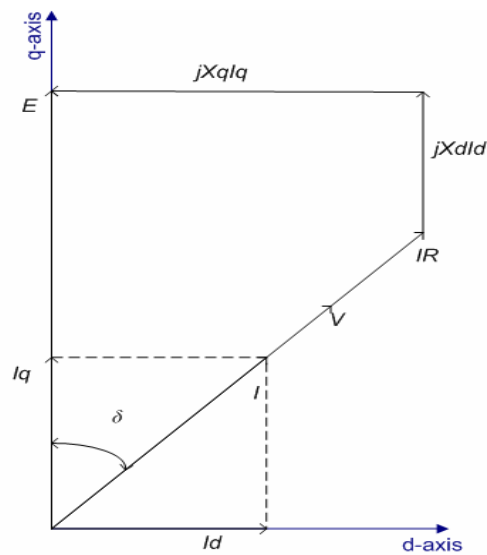


Fig. 4 Phasor diagram of IPM generator

The d and q axis components of voltages from phasor diagram,

$$\begin{aligned} V_d &= V \cos \delta = E - I_d X_d \\ V_q &= V \sin \delta = I_q X_q \\ V &= \sqrt{(E - I_d X_d)^2 + (I_q X_q)^2} \end{aligned} \quad (1)$$

where, V is the terminal voltage, E is the open circuit induced emf, I_d and I_q are the d and q axis component of armature current. With smaller X_d value, the terminal voltage V will tends toward $\sqrt{E^2 + (X_q I_q)^2}$.

Thus, under certain conditions, V may even exceed E resulting in negative regulation. In [2], it was shown that, this phenomenon particularly depends on the saliency ratio $\xi = \frac{X_q}{X_d}$. Since negative regulation could be possible, there exists certain resistive load for which voltage regulation will be zero. The resistive load for which the terminal voltage will be equal to open circuit emf has been derived in [4] with and without neglecting armature resistance. For negligible armature resistance, the load resistance that gives a zero voltage regulation, can be expressed as:

$$R_{\text{Load}} = \frac{X_q}{\sqrt{\xi(\xi - 2)}} \quad (2)$$

The Eq. (2) gives us a design condition for zero voltage regulation-the R_{Load} will have a positive real value only if saliency ratio \hat{i} is greater than 2.

4. GRID INTERFACE

Because of its higher efficiency and possibility of smaller size, IPM generators are considered seriously specially for renewable energy driven turbines. Hence it is necessary to look for a suitable interface between the existing grid and the IPM generator system. Although variable speed capability is comparatively expensive, its ability to save energy makes it almost elemental in new system design. The essential features of a variable speed system are: i) the generator, ii) AC/DC converter ii) DC link iv) DC/AC inverter. For such a system, the inverter can act as an interface between the grid and the IPMG. The inverter is able to generate or absorb real and reactive power, provided both the power angle and the voltage magnitude can be controlled. The inverter could be either voltage source or current source type. In a voltage source inverter (VSI), the power angle is controlled by the device gate signals. In current source inverter (CSI), DC link voltage is controlled by varying the ignition angle. For a strong grid system CSI with harmonic filter is preferred because of its cost effectiveness and efficiency. On the other hand, a self commuted VSI can be used for weak grid or isolated system [5].

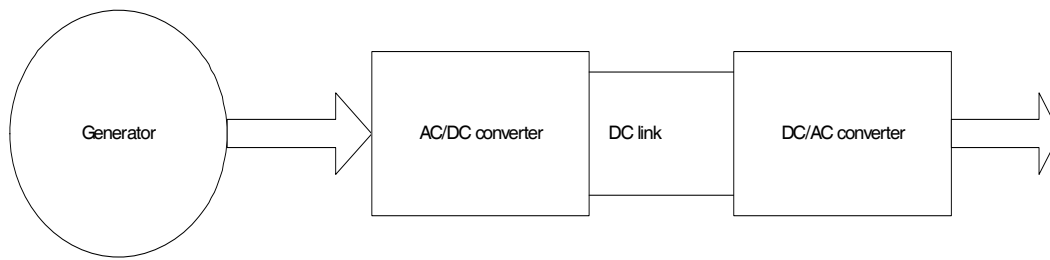


Fig. 5 Block diagram of a variable speed system

5. PERFORMANCE CHARACTERISTICS WITH THREE PHASE IMPEDANCE LOAD

The balance three phase impedance loads are the most common form of loads to any ac generator. In Fig. 6, such a load is shown with an IPM generator.

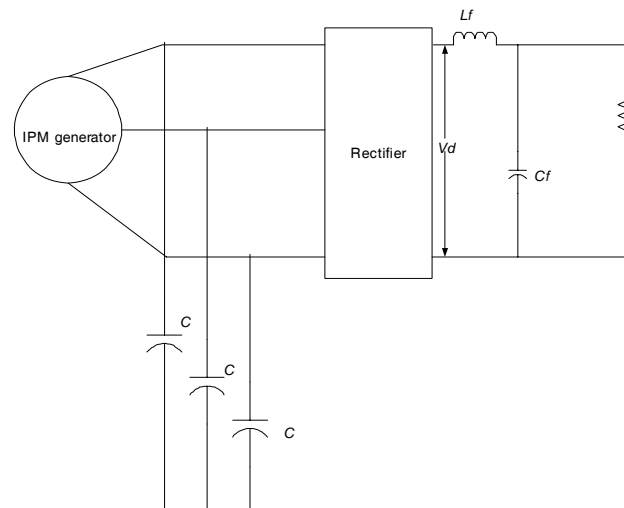


Fig. 6 IPM generator with impedance load

The delta connected shunt capacitors C are connected to the output terminals of generator, to boost its real power capability. It has been shown in [6] that increase of per phase shunt capacitors improves the generator output load power and voltage. The relationship between load voltage and power can be best described with the curve shown in Fig. 7.

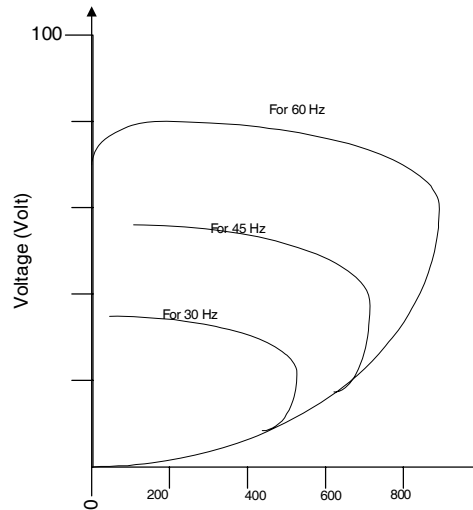


Fig. 7 Load voltage Vs output power

For a particular load range, there exists a negative voltage regulation with the balance impedance load. The careful designing of the machine can result in zero or negative voltage regulation from no load to full load.

6. CONTROL OF IPM GENERATOR

In order to obtain optimum power output from an IPM generator, some control techniques need to be applied. In [7], a control technique has been described for a wind generation system with IPMG. The technique is divided into three parts: i) MPPT (Maximum Power Point Tracking) control, ii) Maximum efficiency control and ii) Maximum torque control. The MPPT control is more specific to wind power generation system. The generator torque is controlled by MPPT controller in such a way that it tracks the optimum torque points for various wind speed. The maximum efficiency and torque control are more general and can be applied to any IPM generator system.

The efficiency of an IPM generator can be expressed as:

$$\eta = \frac{P_{out}}{P_{out} + Loss} \quad (3)$$

The loss includes copper and iron losses. Both the losses are function of current. By minimizing the losses, maximum efficiency condition can be derived.

The generator torque is expressed as:

$$T_g = -\frac{3}{2} p [\psi_{mag} I_q + (L_d - L_q) I_d I_q] \quad (4)$$

where, p = pole pairs,
 ψ_{mag} = flux linkage due to magnet alone, and
 L_d, L_q = d and q axis inductances.

The generator torque is limited by the rated armature current. Under such limitation, a maximum torque control technique can be applied so that output power generation can be optimized.

7. MERITS AND DEMERITS

Like any other system, the IPMG system too has some pros and cons compared to conventional system.

Merits

- Omission of field circuitry and its losses
- Higher efficiency
- Smaller size for same power capability
- More suitable for variable speed operation
- With proper designing zero or even negative voltage regulation is possible.

Demerits

- New emerging technology, hence not yet fully exploited.
- Needs complex control circuitry
- Comparatively expensive
- It can not be directly coupled to existing grid system, needs interface.

8. CONCLUSIONS

The interior permanent magnet generator is showing many promising features as a generator of new millennium particularly with renewable energy sources. In this paper, the performance characteristics of IPM generator have been reviewed and feasibility of its operation as a grid connected generator has been discussed.

9. REFERENCES

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