

## PERMANENT-MAGNET INDUCTION GENERATORS: AN OVERVIEW

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### Abstract

The advantage of using a permanent-magnet induction generator (PMIG) instead of a conventional induction generator is its ability to suppress inrush current during system linking when synchronous input is performed. Induction machines excited with permanent-magnet (PM) are called permanent-magnet induction generators. This paper presents an exhaustive survey of the literature discussing the classification of permanent-magnet machines, process of permanent-magnet excitation and voltage build-up, modelling, steady-state and performance analysis of the permanent-magnet induction generators.

Keywords: Axial-flux permanent-magnet machines, Radial-flux permanent-magnet machines, Transverse flux permanent-magnet machines, PMIG.

### 1. Introduction

The rate of depletion of the conventional energy sources is increasing day by day. This has introduced the application of non-conventional energy sources over the conventional energy sources. The non-conventional or renewable energy sources such as solar, wind, small scale hydro power plants, biogas etc. is also contributing environmental protection than that of the conventional energy sources [1]. Induction generators are becoming more and more popular in the application of renewable energy sources. There are several advantages of induction generators such as ruggedness, brushless (in squirrel cage construction), absence of separate DC source for excitation, easy maintenance, self protection against severe overloads and short circuits etc. Also they do not need any frequency control equipment and have low initial investments and maintenance cost [1]. But the performance of an induction generator is poor in terms of voltage

**Abbreviations**

AFPM	Axial-flux permanent-magnet machines
FEM	Finite element analysis
PM	Permanent magnet
PMIG	Permanent-magnet induction generator
PMIM	Permanent-magnet induction machines
RFPM	Radial-flux permanent magnet machines
TFPM	Transverse-flux permanent-magnet machines

regulation as it requires a magnetizing current from the source for excitation. The power factor, voltage regulation and efficiency can be improved by the use of PMIG [2-3]. In PMIG, permanent-magnets are incorporated in the conventional rotor of an induction generator [2-10]. The paper presents an overview of permanent-magnet induction generators. The paper is structured as follows. Section II presents the classification of permanent-magnet machines. A literature on the process of permanent-magnet excitation, voltage build-up, and modelling is presented in section III and IV, respectively. Performances under steady state condition have been presented in section V, and VI, respectively.

## 2. Classification of Permanent-Magnet Machines

On the basis of direction of flux-path and the structure, the permanent-magnet machines can be categorized as follows [11]:

- Radial-flux permanent magnet machines (RFPM)
- Axial-flux permanent-magnet machines (AFPM)
- Transverse-flux permanent-magnet machines (TFPM)

### 2.1. Radial-flux permanent magnet machines (RFPM)

The radial-flux permanent magnet machines Radial-flux permanent magnet machines are those machines which produce the magnetic flux in the radial direction having permanent-magnet excitation. Compared to the axial flux machines, the radial flux machines is economically a better option, especially for large direct-drive wind turbines. In the radial-flux machines, the stator is designed with electrical grade steel laminations with distributed windings. Surface mounted radial-flux permanent-magnet machines for large direct-drive applications have been discussed in detail by Grauers and Dubois [12, 13]. The radial-flux PM machine with flux concentration has been discussed and compared to the machine with surface mounted PM in [14]. Compared to the axial-flux permanent-magnet machines, the radial-flux permanent-magnet machines have the advantages of higher torque/mass ratio, small outer diameter, small amount of PM, easier to maintain air-gap in small diameter [11].

### 2.2. Axial-flux permanent-magnet machines (AFPM)

The axial-flux permanent-magnet machines are those machines which produces the flux in the axial direction having permanent-magnet excitations. Axial-flux machines have simple winding, low cogging torque, short-axial length of the

machine, and higher torque/volume ratio compared to the radial-flux machines. These machines have also been discussed in detail [15-17]. Compared to the radial-flux permanent magnet machines, the axial-flux permanent magnet machines have the advantages of simple winding, low cogging torque and noise (in slot less machine), short axial length of the machine, and higher torque/volume ratio [11].

### **2.3. Transverse-flux permanent-magnet machines (TFPM)**

The transverse-flux permanent-magnet machines are the machines where the magnetic flux path is perpendicular to the direction of the rotation of rotor. Compared to the AFPM and RFPM, these machines are available with increase in the space for the windings without any decreasing of the available space for the main flux. TFPM machines seem to be a better option, especially for direct-drive turbines because of its high specific torque [11]. Surface mounted TFPM machines have been discussed in detail [18-21]. Compared to the axial-flux permanent-magnet and radial-flux permanent-magnet machines, the main advantages of TFPM are higher force density, considerable low copper loss, and simple winding [11].

## **3. Process of PM Excitation and Voltage Buildup**

The permanent-magnet induction machines (PMIM) combines the advantages of both PM synchronous machines and an induction machines. The generator can be directly coupled to the turbine and grid if we use PMIM as a generator. Thus no requirement of gear box and frequency converter, and this reduces the wind turbine losses.

Hagnokort et al. [22] and Tröster et al. [23] also did the latest investigations at Darmstadt University of Technology. Physical background of PM excitation in an induction motor was described by Douglas [24]. Low and Schofield [4] first used the concept of PMIG for wind power applications. Ackermann [5] tell the single phase permanent-magnet induction machine.

Tsuada et al. [6] analyzed the magnetic field of the permanent-magnet induction generator. They observed that in PMIG, the stator is made similar to an induction machines equipped with a three phase winding. But it is different from an induction machine because it has two rotor parts, an outer rotor squirrel cage rotor and an inner PM rotor. When the squirrel cage rotor is rotated by some external means, the PM rotor also rotates with the squirrel cage rotor. When the speed of the squirrel cage rotor comes above the synchronous speed, the PM rotor starts to rotate synchronously with the rotating field of the stator. It means the slip becomes negative, and the PMIM feed power to the grid. The process of voltage build up is similar to just like a D.C. generator. The voltage builds up according to PM excitation in the rotor. Thus it depends also upon the used PM material is the induction machine.

## **4. Modelling of PMIG**

To analyze the steady-state performance of the PMIG, various models and their applications [2, 3, 7, 9, 25, 26] have been discussed. These are being described as follows:

***d-q reference model***

The d-q reference model for a permanent-magnet induction machine was first described by Douglas [24]. The two components of the current  $I$  are the quadrature current and the direct current components. The quadrature current component is the current that balances current in the squirrel cage and the direct current component is the magnetizing current component.

***Impedance-based model***

In [2, 3], the performance of the PMIG using an impedance model based on a conventional single phase equivalent circuit with p.u. parameter has been analyzed. The impedance model was also described in detail in [7, 25]. The results were also compared and verified with the experimental results for a prototype model of PMIG.

***FEM Model***

Troster et al. [23] discussed the finite element analysis (FEM) for a PMIM. The two-dimensional FEM method was used to clarify the performance of a PMIG when the grid voltage is unbalanced. Based on the position of the squirrel cage rotor and the PM rotor, and the spatial distribution of the primary and secondary current, the 2D FEM method was used. Tsuda et al. [9] presents a 2D-FEA, the phasors of primary and secondary currents were calculated from the equivalent circuit, and the input data for the 2D-FEA was found by converting these phasors into the space vectors. They observed that the internal magnetic fields of the PMIG can be easily analyzed without complicated calculations. Troster et al. [26] described the FEM of a PMIM. Due to the computational time a 2D model was used. They also found that how the characteristics (e.g. torque, efficiency, power factor) depend upon the height of the machine.

**5. Steady State and Performance Analysis of the PMIG**

Both from the design and operational points of view, steady-state analysis of PMIG is definitely of interest. In an isolated system, both the terminal voltage and frequency are unknown, and required to be computed for a given speed, capacitance, and load impedance. A few articles [2, 3, 6-8, 10, 27] on the steady-state and performance analysis of PMIG have been presented. The contribution of the important papers is presented in this section. Fukami et al. [2] developed a mathematical model to obtain the steady-state performance of the PMIG using the equivalent circuit impedance of the machine. The non-linear equations were solved through the iteration method. Tsuda et al. [3] used the method of symmetrical component and 2D FEM to compute the steady state performance of the PMIG. In the symmetrical component method, they divided the voltage and current components into the positive and negative sequence components. In addition to this, the generating characteristics of the PMIM in the grid connection were also calculated and were compared with the experimental results. Ackermann [5] also computed the performance of a single-phase permanent magnet induction machine. He solved the field equations through the analytical

method. The results were also compared with the experimental results. Fukami et al. [7] described an equivalent circuit model for PMIG. Performance characteristics were calculated and the results were also compared and verified through the experimental results. Tsuda et al. [8] tells the steady-state performance of the PMIG operated on a single-phase power grid. Performance equations were derived using the method of symmetrical components, while the curve-fitting method was implemented for the modelling of the non-linear parameters in the equivalent circuit. They observed that, for this mode of operation, the output power of the PMIG was 1.5 times as much as that of a general-purpose induction generator (GPIG) of the same size. Potgieter et al. [10] discusses the performance of a PMIG with a prototype model of 9 kW machine.

## 6. Conclusion

The use of a PMIG offers many advantages over a conventional induction generator. PMIM as a generator reduces the magnetizing current from the grid, and also improves the power factor and efficiency. This article has presented a comprehensive literature on some important aspects of PMIG such as the process of PM excitation, modelling, and steady-state performance. It is expected that PMIG will be utilized more and more in future in renewable energy sources.

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