# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

There are three basic types of electric machines. They are the dc, synchronous, and induction machines. An interior permanent magnet (IPM) synchronous machine, as the name implies, falls into the category of a synchronous machine. The characterizing feature of a synchronous machine is that its shaft speed is directly proportional to the speed at which the magnetic field in the air gap rotates and, for the case of a synchronous machine operating in generator mode, the frequency of the ac voltage and current at the output terminals of the machine is directly proportional to the speed at which the rotor (and shaft) of the machine is being driven. A useful formula relating the electrical frequency (in Hertz) to the speed at which the shaft of the machine is rotating $N_s$ (in revolutions per minute) is

$$f = \frac{N_s P}{120} \quad , \tag{1.1}$$

where P is the number of poles in the machine.

In the vast majority of synchronous machines the required source of flux needed to produce an electromotive force (emf) in a conductor is established by a direct current (dc) source which feeds a field coil in the rotor via slip rings and brushes [1]. This configuration offers the distinct advantage of providing the ability to control the excitation voltage and power factor of the machine by controlling the field current $i_f$ ; however, the advantage of control also presents two disadvantages - namely, the brushes and slip rings are mechanical devices which, due to friction and electrical arcing, wear out much more quickly than the rest of the machine, and the field current is an external power supply which must be established and controlled. The aforementioned disadvantages are not present in a synchronous IPM machine.

A permanent magnet (PM) machine is so labeled because the magnetic excitation is supplied by a permanent magnet instead of by the field or excitation circuit of a conventional machine. There are numerous configurations used for PM machines including axial and radial air gap configurations. Some of the types of PM machines are

a. dc motor/generator

b. synchronous alternator

c. brushless dc motor

d. digital machines [2]

The four general categories (which are classified according to the placement of the magnet on the rotor) of synchronous PM machines are the peripheral, interior, Lundell, and transverse. The interior permanent magnet (IPM) type, which is the type of PM machine analyzed in this thesis, has magnets which are located in the interior of the rotor. A diagram of one pole of a four pole IPM machine is shown in Figure 1.1.

## 1.2 Review of Previous Work

Permanent magnets are components which, once magnetized by an external magnetic field, retain a usefully large magnetic moment after the magnetizing force is removed. A permanent magnet can therefore become a source of a magnetic field which can interact with electric currents. In order for a magnet to be useful, the magnetization must be able to withstand the presence of high opposing fields , i.e., the permanent magnet must have a high " coercive force." Although permanent magnets have been used in electric machinery for over 100 years ( and as generators for over 60 years) , it is only with the recent dramatic improvements in their properties and availability that has caused their application in electro-mechanical devices to grow rapidly [3].

The first of the “modern day” permanent magnets to be invented was the Alinco magnet in the 1930's. Alinco is still widely used as a permanent magnet today, but, because of its low coercive force and high cost, it has been rarely used in electric machines. One of the biggest problems of Alinco is that if it is used as the magnet in a generator and a short circuit condition occurs, then the magnet can become permanently demagnetized. However, it has been suggested in [4] that by using a stabilization method to ensure the magnet is subjected to demagnetization forces more severe than it will experience when it is being used in a generator, then Alinco magnets can be more safely used in PM machines.

The hard magnetic ferrite permanent magnets (also referred to as ceramics) were introduced in the 1950's. They were much cheaper than the Alinco’s and also had a higher coercive force. With the introduction of the ceramic permanent magnets, electric machine designers were still left with the task of designing a PM machine in which demagnetization would not occur and the field in the air gap was maximized.

One of the methods developed to prevent demagnetization during assembly or dismantling was to use a completed jig, while some designs employed permanent

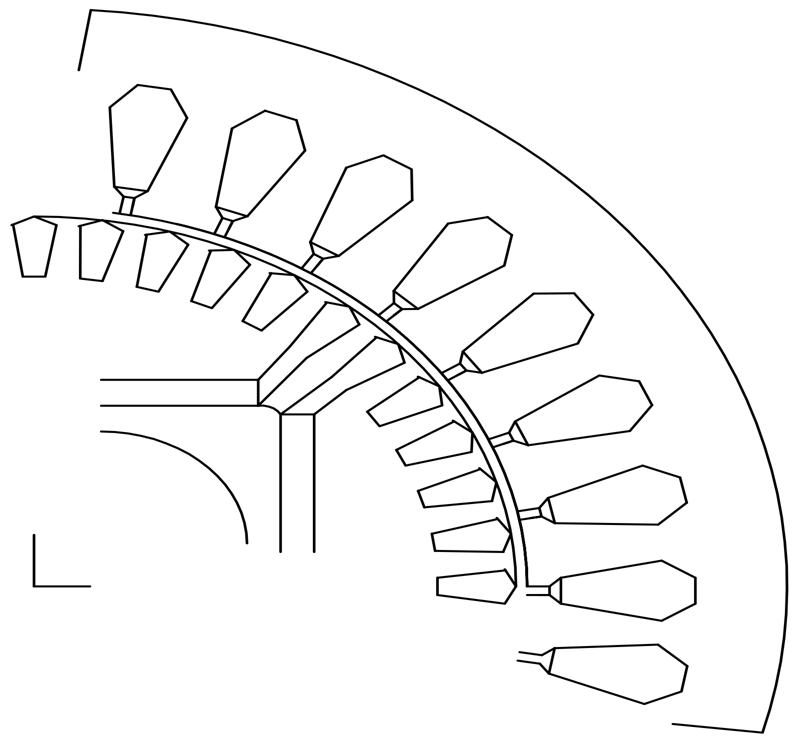

Figure 1.1 Cross-sectional view of one pole of a 4 pole IPM machine

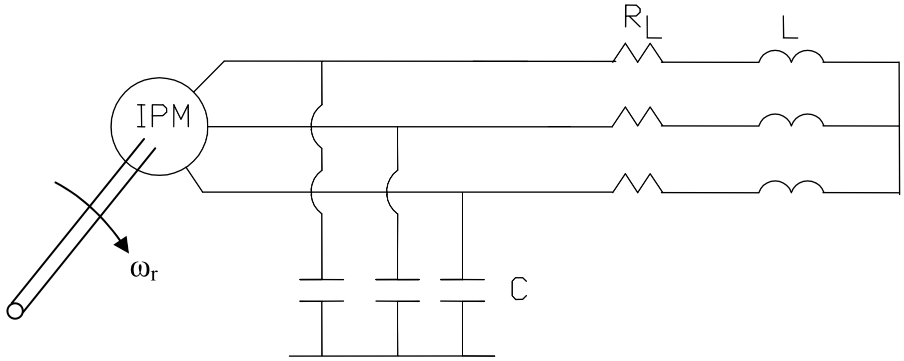


Figure 1.2. Schematic diagram of an IPM generator feeding an RL load with shunt capacitors placed at the terminals of the IPM

magnetizing windings in addition to the magnets so that remagnetization could be preformed after a fault had occurred [5].

There were several ingenious rotor constructions created with ceramic permanent magnets in mind. One such type, called the Lundell claw, makes use of a cylindrical magnet which is axially magnetized. Another type, labeled the transverse, places the magnets between soft-iron poles and the magnet flux is circumferential.

Another type of rotor, called the multistacked imbricated rotor, utilizes an assembly of disc magnets with steel flux guides interleaved and provides a heteropolar field at the rotor surface. The body of work in [5,6,7] explores how this design would behave, first for the ceramic magnets, and then for the new rare earth permanent magnets (REPM's).

The first commercially available REPM was the samarium cobalt magnet and was introduced in 1970. These magnets have coercive forces three to five times those of ceramic and Alinco magnets and, from a technical standpoint, are ideally suited for rotating electric machines; however, their cost was, is, and is expected to remain prohibitively high. A samarium-cobalt IPM machine ( used first as a motor and then as a generator) is described in [7, 8]. In [8], the author points out that, due to the inverse saliency of the IPM machine, the output voltage tends to rise as the load is increased, and that this tendency could be exploited in the design of an IPM generator so that no external voltage regulation schemes are needed.

The neodymium-iron-boron (NdFeB) REPM, introduced in 1983, has the same advantages over the ceramic and Alinco magnets as does the samarium cobalt magnets; but the production cost of the NdFeB REPM was (and is) much lower. It was with the introduction of the NdFeB REPM that a tremendous amount of new and renewed interest in PM machines has arisen.

The numerical analysis of PM machines utilizing finite element techniques has been greatly aided by the astronomical increase in computer hardware and software capabilities; however, the foundation of understanding and the formulation of design methodology of the PM machines was laid many years before the computationally intensive techniques of today were used. An optimal design technique for a PM machine, presented in [10], provides a technique to obtain a quick "first cut" determination of the overall dimensions of a PM machine which is to be used as a generator. The work in [11] explains a method by which the computation of the magnetic field of permanent magnets in iron cores may be determined. A detailed analysis and design of interior and surface magnet PM machines is given in [12], while one of the earlier detailed finite element examinations of interior and surface magnet machines is presented in [13]. With the advances in computational power (and the renewed interest in PM machines) there have been numerous recent programs created to analyze the PM machine in greater and greater detail. The work described in [14,15,16, 17] offer various ways in which to analyze and design PM machines.

The works cited in [18 ,19, 20] analyze a PM generator in the abc reference frame. The authors argue that the natural abc frame of reference is superior to the dq reference frame because no simplifying assumptions ( such as the neglect of magnetic nonlinearities and the neglect of the space harmonics in flux density waveforms or winding flux linkages) are required. Modeling the generator in the abc reference frame has the additional advantage when it is feeding a three phase rectifier ( which was done in [20]) because the rectifier is inherently in the abc frame of reference.

In [21 , 22] , a toothless stator design for permanent magnet generator is developed and analyzed. The toothless stator ( compared with a conventional stator with teeth) offers the advantage of reducing the weight of the machine and eliminating the core loss of the stator teeth.

The TORUS is another type of slotless stator type PM machine. This machine consists of a slotless toroidal stator and a rotor comprising of two discs carrying axis polarized magnets. The TORUS machine described in [23] makes use of NeFeB and has the advantage of being very small and lightweight. Thus, its use as a portable engine-driven generator is attractive.

Typically, a high pole number PM generator has magnets mounted at the surface, but an interior permanent magnet rotor lamination design for generators with a high pole number and capable of withstanding high centrifugal forces is offered in [24]. By burying the magnets, the cost of curving (arching) the magnets is avoided, and less costly flat magnets may be used.

Of principal concern in this thesis is the use of PM machines as stand-alone generators being driven by the wind, water, or diesel engine. The ability to create excitations without the use of the brush/slipring system ( along with their design flexibility) makes the machines particularly attractive. The recent advancements in power electronics and control strategies (along with the improvement in the PM machines themselves) , has made PM machines as autonomous power sources more attractive.

For example, the problem associated with the inability to control the magnet excitation (thereby making it impossible to control the magnitude of the output terminal voltage ) was overcome in [25] (where a PM generator is being driven by a diesel engine and is feeding an isolated load) by connecting a static VAR compensator (SVC) to the terminals of the machine. While SVC technology is certainly not new, the improvements and decline in cost of microprocessors and power electronic switches has made it feasible to implement the systems.

A multi-pole radial field prototype design of a 400 kW, 166 pole PM generator has been built in [26] . The large number of poles means that 60 Hz electrical output can be obtained with the rotor spinning at only 43 rev/min. Such a design would be useful in the scheme suggested in [27] where a wind turbine driven PM machine is directly coupled to one or more induction motors which are used to pump water. The goal of this scheme is to provide irrigation for crops or create water storage for livestock.

The modeling, simulation, and analysis of a wind driven variable-speed PM generator whose output is rectified and then inverted to 60 Hz is discussed in [28]. Also, a comparison between an induction generator, conventional synchronous generator, and a PM generator being used as part of wind energy systems is offered in [29].

## 1.3 Scope of the Work

A two horsepower IPM machine operating in generator mode was tested and analyzed. The modeling of the IPM machine includes the effects caused by the changing saturation and armature reaction dependent axes inductances and magnet flux linkage.

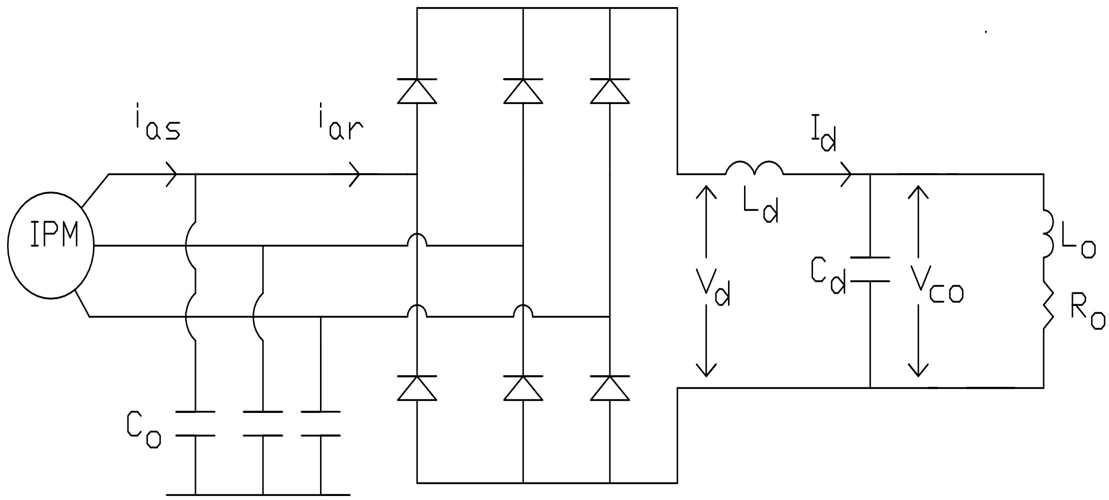


Figure 1.3. Schematic diagram of an IPM generator feeding a 3-phase full bridge rectifier-resistive load

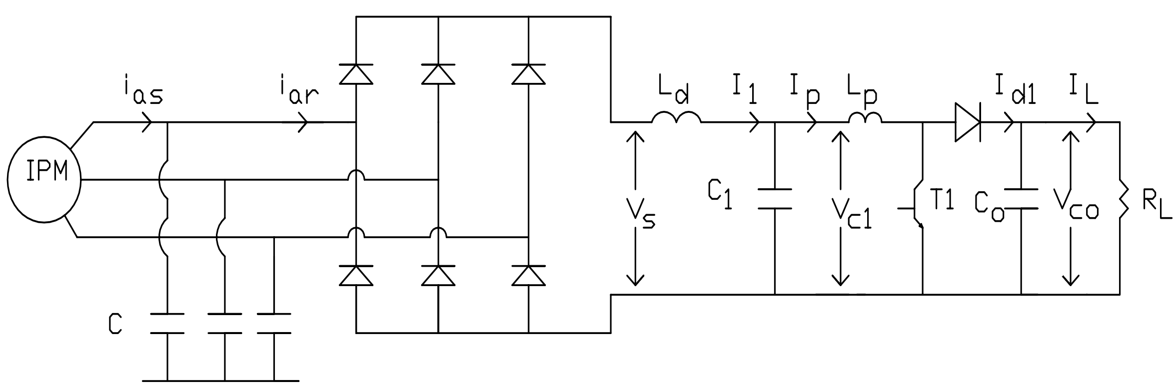


Figure 1.4. Schematic diagram of an IPM generator feeding a rectifier-boost-resistive load

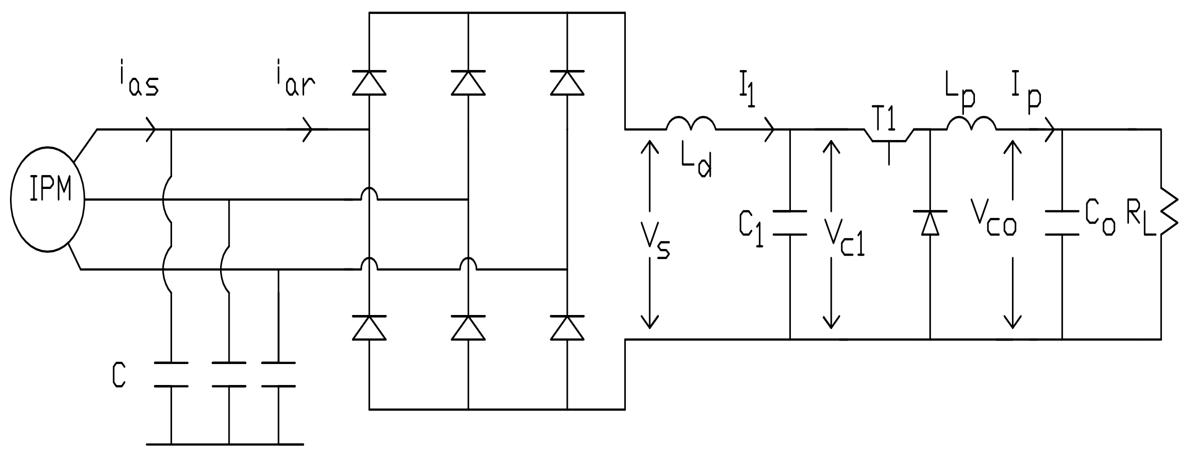


Figure 1.5. Schematic diagram of an IPM generator feeding a rectifier-buck-resistive load

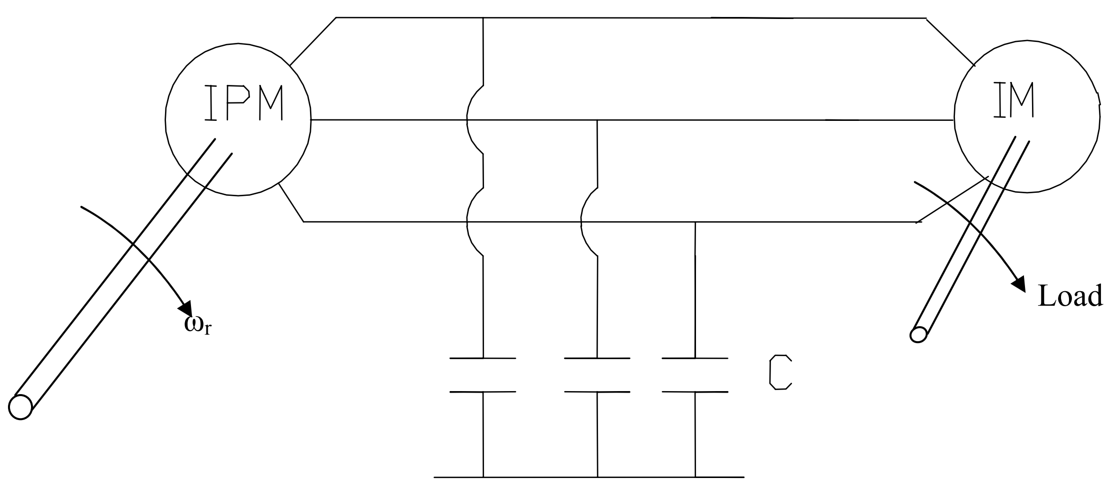


Figure 1.6. Schematic diagram of an IPM generator feeding an induction motor

Experimental data were recorded for the following types of loads presented to the PM machine: an impedance load, a rectifier load, a rectifier-PWM-boost-resistive load, a rectifier-PWM-buck load, and a one horsepower induction motor. Schematic diagrams of each system are shown in Figures 1.2 to 1.6.

A closed form solution, which avoids iterative techniques, was developed to model the impedance load for the cases when there is and is not capacitive shunt compensation. The experimental data for the impedance load strongly corroborate the closed form model.

The simulation of the PM machine feeding the rectifier, rectifier-buck, and rectifier-boost loads takes into account the effects due to commutation. Matlab's Simulink was found to be an excellent tool to model the passive switches of the rectifier and the externally controlled switches of the buck and boost converters [30]. The steady state models developed for the rectifier, rectifier-buck, and rectifier-boost loads made use of switching function theory to model these loads as an effective resistance at the terminals of the PM machine.

The steady state solution for the IPM feeding the induction motor (IM) (performed using the iterative techniques contained in Matlab's "fsolve.m" function file) was corroborated by the experimental data taken. The simulation of the IPM-IM topology feeding three different types of loads is also presented.

Chapter 2 presents the derivation of the dynamic and steady state equations which model the IPM machine. The methods used to determine the parameters and the results of those efforts are also presented.

In Chapter 3, the IPM machine is tested and modeled for the case where it is feeding an impedance load.

Chapter 4 presents the simulation, analysis, and experimental results obtained when the IPM machine, operating in generator mode, is feeding a rectifier-resistive load.

In Chapter 5, the steady state and dynamic models of the IPM machine feeding a rectifier-buck-resistive load are compared with the experimental results.

Chapter 6 compares the results obtained using the steady state and dynamic models of the IPM machine feeding a rectifier-boost resistive load with the experimental data and measured waveforms.

Chapter 7 includes the modeling and experimental results for the case when the IPM machine is supplying power to an induction motor.

In Chapter 8, conclusions are presented and directions for future work are suggested.