

Stator Side Voltage Regulation of Permanent Magnet Generators

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ABSTRACT

Permanent magnet AC generators are robust, inexpensive, and efficient compared to wound-field synchronous generators with brushless exciters. Their application in variable-speed applications is made difficult by the variation of the stator voltage with shaft speed. This paper presents the use of stator-side reactive power injection as a means of regulating the stator voltage. Design-oriented analysis of machine performance for this mode of operation identifies an appropriate level of machine saliency that enables excellent terminal voltage regulation over a specified speed and load range, while minimizing stator current requirements. This paper demonstrates that the incorporation of saliency into the permanent magnet generator can significantly reduce the size of the reactive current source that is required to regulate the stator voltage during operation over a wide range of speeds and loads.

INTRODUCTION

Permanent magnet (PM) AC synchronous generators are simple, robust, and reliable and have many properties that make them attractive for power system applications, particularly at low power ratings [1]. The use of stator side voltage regulation with such a machine represents an alternative to other sources of variable-frequency, constant-voltage AC power systems with unique features. Other approaches include the use of wound-field synchronous machines commonly applied on aircraft [2] and induction machines which are less common. The proposed approach eliminates the brushes and/or rotating rectifier diodes that are often used in the wound-field synchronous generator. While both the proposed approach and the induction machine based approach can be implemented using an inverter

as the reactive power source, the proposed approach also has potential efficiency advantages over induction machine-based power systems. The power converter used to provide the reactive power to the PM generator typically also has a natural DC power output that can be used to feed a secondary DC power bus if so desired [3].

In spite of their potential advantages, PM generators have not found widespread use in small power system applications. In this context, small power systems refer to non-grid connected power systems with a single generator such as automotive electrical systems [4]. In general, the variation of their output voltage as the speed and load varies is among the biggest obstacles to their potential application in power systems. It has been shown previously [5] that injecting reactive current into the stator circuit of PM generators provides a means of regulating their terminal voltage over a desired speed and load range. This paper extends the state-of-the-art by showing that the use of an interior permanent magnet (IPM) machine with a high magnetic saliency can significantly reduce the weight, volume, and cost of the injection current source, making this approach more appealing for a variety of weight and cost-sensitive applications.

The following section presents the evolution of the concept and an introduction to the approach along with a conceptual schematic of the proposed configuration. A steady-state analytical formulation that identifies the relationships between the machine parameters including the characteristic current and saliency ratio is presented in the next section. Desirable machine properties that make the proposed approach practical are presented, followed by a discussion of challenges and opportunities for future development of the technology. The concluding section provides a summary discussion of the results.

AC PRIMARY DISTRIBUTION POWER SYSTEMS

An AC primary distribution system distributes high-quality AC power that is directly usable by the loads. The current state-of-the-art in vehicular AC primary distribution small power systems is found in modern commercial aircraft. Variable-frequency or 400 Hz AC power is distributed as the primary source of power. A simplified block diagram of the starter/generator and the primary power conversion components is shown in Figure 1.

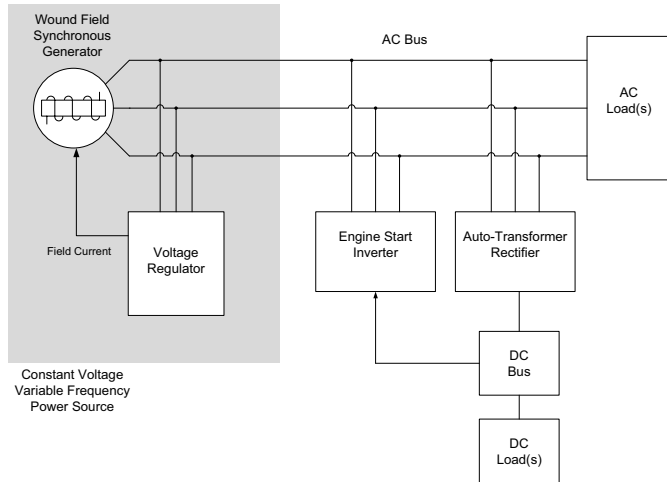


Figure 1. Simplified block diagram of a commercial aircraft power system architecture with starter/generator capability.

The power system consists of a wound-field synchronous generator, a voltage regulator, an auto-transformer rectifier, and an engine-start inverter. The voltage regulator adjusts the field current of the synchronous machine to maintain constant stator voltage. The DC loads are fed by a passive rectifier and the AC loads are fed directly. An engine-start inverter is used to operate the generator as a motor during engine starting. The engine-start inverter can be switched out of the power system after engine start has been accomplished so that the inverter can be used to perform other motor control tasks.

A potential improvement to the system is to combine the passive rectifier and the engine-start inverter into one unit using an active rectifier. The block diagram of such a system is shown in Figure 2. The active rectifier is a voltage-source inverter that is capable of handling bi-directional power flow between the AC and DC bus. The active rectifier can operate in a way that takes power from the AC bus and provides voltage-regulated DC power. The active rectifier is also capable of operating in a way that takes power from the DC bus and provides variable-voltage, variable-frequency AC power to the AC bus. The active rectifier is therefore capable of operating as a replacement for the passive rectifier and also as a replacement for the engine-start inverter.

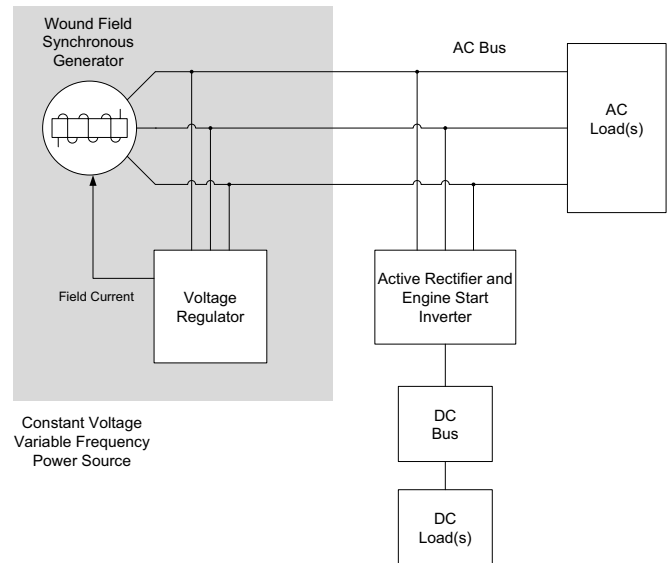


Figure 2. Simplified block diagram of an alternate AC primary distribution power system.

The system as shown in Figure 2 is still based on a wound-field synchronous machine. The wound-field synchronous machine has some disadvantages. The rotor electromagnet uses current flow to develop the magnetic flux for the machine. The resistance of the electromagnet causes power dissipation directly in the rotor. The spinning rotor represents a more difficult heat removal problem than the stationary stator winding. The field current also has to be transferred to the rotor. Brushes and a rotary transformer are the two predominant means of accomplishing the task. The rotary transformer approach is more popular due to reliability problems with brushes but the approach requires that rectifier diodes be physically placed on the rotor. The presence of copper windings and semiconductor devices on the rotor both detract from the reliability of the wound-field synchronous generator.

On the other hand, permanent magnet generators have a comparatively simple rotor structure. The rotor structure of a permanent magnet generator does not have a winding for field current or rectifier diodes to rectify the field current. The permanent magnet generator is therefore an attractive alternative to the wound-field synchronous machine in vehicular applications where the generator is likely to be exposed to high temperatures and high levels of vibration. Nevertheless, the rotor of a permanent magnet generator has mechanical problems associated with the mounting of brittle permanent magnets that usually have temperature coefficients of expansion that are different from that of the iron or steel used to construct the rotor.

A STATOR-SIDE VOLTAGE REGULATED PMG-BASED POWER SYSTEM

PM generators do not have an inherent mechanism for voltage regulation like the DC field current in a synchronous generator. The speed of the generator, the

magnitude of the load current, and the power factor of the load current together determine the stator voltage, dependent on the machine electrical parameters. For a given speed and load, the machine terminal power factor can be varied to regulate the stator voltage to a desired value. Any convenient source of reactive power or, equivalently, a source of AC current that is orthogonal to the stator voltage can be used to regulate the voltage. Figure 3 shows the block diagram of proposed approach. No additional rectifiers are required, the entire DC system is fed from the DC output of the active rectifier/engine start inverter, rated appropriately.

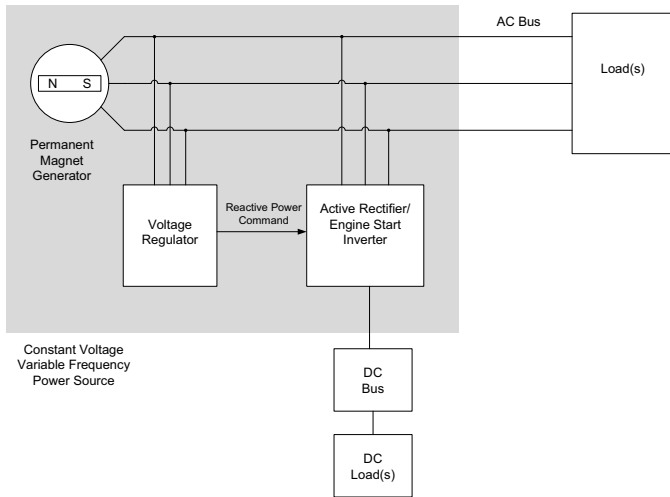


Figure 3. Block diagram of a stator-side voltage-regulated permanent magnet generator-based power system.

This paper focuses exclusively on the properties of the AC circuit of the power system. Figure 4 shows a block diagram of the system.

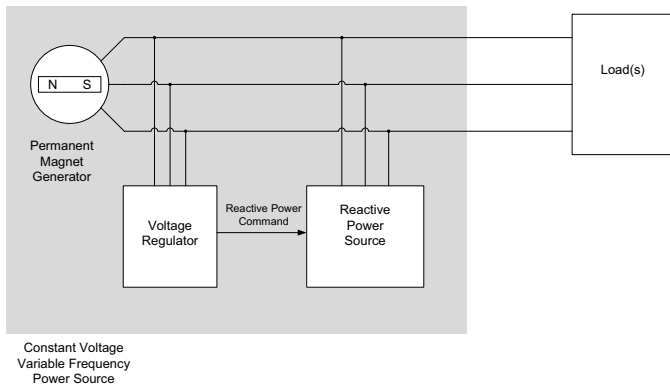


Figure 4. Block diagram of an AC primary distribution with only AC loads.

STEADY-STATE GENERATOR SCALING

A dq equivalent circuit model of the machine in the synchronously-rotating reference frame has been adopted [6] to develop the steady-state dependencies

between the machine parameters and operating conditions. The governing equations of the PM AC generator determined by this model can be solved under conditions of constant stator terminal voltage. The d - and q -axis stator voltages are given by:

$$\begin{aligned} v_d &= -\omega_e L_q i_q \\ v_q &= \omega_e L_d i_d + \omega_e \Psi_m \end{aligned} \quad (1)$$

where ω_e is the radian frequency, Ψ_m is the magnet flux, L_d is the d -axis inductance and L_q is the q -axis inductance. The torque expression is given by:

$$T = \frac{3p}{2} [\Psi_m i_q + (L_d - L_q) i_d i_q] \quad (2)$$

where i_q is the q -axis stator current, i_d is the d -axis stator current, and p is the number of pole pairs. The magnitude of the stator voltage is given by

$$v_s = \sqrt{v_d^2 + v_q^2} \quad (3)$$

For regulated operating conditions, the square root of the sum of the squares of the d - and q -axis voltages is held constant. Furthermore, the magnitude of the stator current is given by

$$i_s = \sqrt{i_d^2 + i_q^2} \quad (4)$$

The amount of stator current required to maintain a constant stator voltage can vary significantly as a function of generator parameters for a specified range of load power and power factors. The variation is particularly significant when the generator must operate over a range of different speeds.

Careful design of the PM generator can significantly reduce the maximum stator current required to accommodate constant-voltage operation over a specified range of speeds and loads. In order to highlight the major generator design parameters that influence the machine's operating characteristics, the saliency ratio ζ and characteristic current I_{ch} of the machine are defined as:

$$\zeta = \frac{L_q}{L_d}, \quad I_{ch} = \frac{\Psi_m}{L_d} \quad (5)$$

The equation for torque can be reformulated in terms of the characteristic current and saliency ratio as (6)