

Lead-Unity-Lag Electric Power Generation System

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ABSTRACT

This paper introduces a novel method for an electric power generation system (EPGS) employing a lead-unity-lag (LUL) permanent-magnet (PM) generator operation for a direct current (DC) power distribution bus. In addition, background information of the prior art for a leading power factor EPGS is discussed. The concept of the new approach is defined and a comparative analysis between the new and old state-of-the-art solutions are documented. The performance features and technical details of the system parameters with respect to power generation system requirements are presented and discussed. Analysis and testing results are included. Finally, the advantages of this system, a conclusion, and recommendations for future work are provided.

Test results from a system having elements of this novel approach are included. With this method for an LUL EPGS, the capability of the high-performance electric power generation systems is improved substantially. The new method will contribute to overall aircraft energy optimization.

The new approach may find applications in future initiatives like the integrated vehicle energy technology (INVENT) demonstration, joint strike fighter (JSF) upgrade, engine embedded generation for military and commercial applications, unmanned aerial vehicles (UAVs), and unmanned combat air vehicles (UCAVs).

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INTRODUCTION

Aerospace Trends in Power Generation Systems

Power generation systems play a significant role in the modern aerospace/military industry. This is particularly true in the area of more electric architecture (MEA) for aircraft and spacecraft.

The commercial aircraft business is moving toward no-bleed air environmental control systems (ECSs), variable-frequency (VF) and DC power distribution buses, and electrical actuation. A typical example is the Boeing 787 platform. The next-generation Boeing airplane (a replacement for the 737) and the Airbus replacement for the A320 will most likely use MEA. Some military aircraft already utilize MEA for both primary and secondary flight control. Military ground vehicles have shifted toward hybrid electric technology. In these cases, the main propulsion is performed by electric drives. This demonstrates that substantial need and demand has arisen for improved electric power generation performance. Future space vehicles will require electric drives for thrust vector and flight control actuation demanding more high-quality electric power (Reference 3).

These systems must be more robust and will offer greatly reduced operating costs and safety compared with existing hardware (Reference 4).

These recent aerospace trends have created a significant increase in EPGS needs. This has led to increased operating voltages and reduced system losses, weight, and volume (Reference 5). A new set of power quality and electromagnetic interference (EMI) requirements has been created to satisfy both quality and performance issues (Reference 6). The result has been a significant increase in the number of installed generators, creating challenges for utilizing this equipment on the new platforms (Reference 7). Therefore, overall system performance improvement and power density improvements are necessary for the new-generation systems (Reference 8). Cost is an additional driver that must be addressed to make the new platforms affordable (References 9 and 10). This paper addresses systems using permanent-magnet machines (PMM) primarily for high-speed, gearless, oil-free integrations as a part of auxiliary power units (APUs), power and thermal management systems (PTMS), and emergency power units (EPUs). However, some of the conclusions could be extended to main-engine-embedded EPGSs. For the first time, the subject matter was addressed in Reference 1. A study of the problem from a

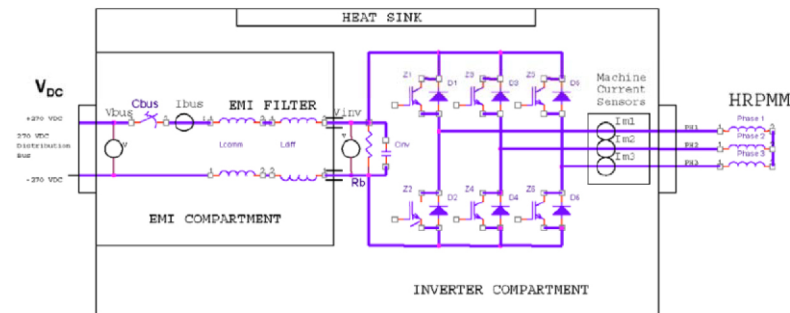


Figure 1. Power Topology of an HRPMM-based System

statistical (Six Sigma) perspective for different types of electric generators has been presented in Reference 2. An excellent historical perspective of the integration of various generators with engines is provided in Reference 11. Most of the electric machines used today were invented in the beginning of the electrical era when the theory was created (Reference 12). However, at that time technologies were not developed to a level that could implement complex control algorithms. The electric machine transient phenomenon and control are addressed in depth in (Reference 13). Nevertheless, there are still broad areas for potential improvement due to the progress of power electronics allowing implementation of modern control theory, which will be addressed in this paper.

New aerospace and military electrical equipment trends have significantly increased platform electrical power generation needs. The overall result has been a significant increase in the challenges to accommodate that electrical equipment. This has led to increased operating voltages, increased current, and efforts to reduce system losses, weight, and volume. The latest tendency as a part of MEA is the energy-efficient aircraft where electric power and heat management go hand in hand. Therefore, overall system performance improvement and specifically power density increases are necessary for the new-generation hardware.

Leading Power Factor Based Electric Power Generation System

An EP GS suitable for MEA that meets the requirements outlined above is achieved by using a high-reactance permanent-magnet machine (HRPMM) based system (Reference 9). The power topology of this EP GS is shown in Figure 1.

The topology contains a three-phase bridge, a DC link capacitor bank, an EMI filter for a DC bus, and a DC contactor. Current and voltage measurement devices required for control and protection purposes are shown. The contactor is not a mandatory component for all applications. This simple topology satisfies all generation functional requirements. The topology has bidirectional power flow capability by applying the appropriate voltage to the machine terminals. Synchronous rotation of the electric machine is

performed for continuous motoring or self-start. During power generation the system actively regulates DC bus voltage to the desired value.

A unique feature of this topology is providing short-circuit current at the DC bus during power generation to clear the fault. If the DC bus is overloaded, the control system reduces the output voltage linearly to prevent components from overloading. Below certain voltage levels, control of the 3-phase bridge is not possible. Here a pure diode rectification is used. The reactance of the machine is selected such that the short circuit current of the machine (I_{SC}) satisfies the requirements of the DC bus short circuit current (I_{DCSC}). The typical ratio between these two currents is: $I_{DCSC} = 1.35 * I_{SC}$. The ratio may vary depending on component selection for the bridge and the EMI filter.

When a short circuit occurs within the power electronics, within the machine, or within the interface between the power electronics and machine, normal control of the generation process will be instantly discontinued. The fault current will be limited by the HRPMM and will be comparable to the operating current. Prime mover shutdown would follow if the prime mover was dedicated to the power generation system only.

In some applications with a higher level of integration or for main engine power generation systems, the prime mover has other more critical functions besides power generation. Therefore, the prime mover must continue rotation after power generation failure. In this type of system, two important features must be implemented to address this concern.

- The electric machine thermal design should satisfy continuous short-circuit operation. This capability would not penalize the machine since the short-circuit current would be similar to the operating currents. Furthermore, the short-circuit current would not have higher harmonics resulting from chopping modulation. Therefore, steel losses will be lower.
- The PMs, regardless of the reactance, are sensitive to nonsymmetrical faults, i.e., when not all machine terminals are shorted. The reason is the negative sequence currents may develop rotor overheating. This type of fault can be mitigated by artificially shorting all terminals of the HRPMM by using

three of the switches in the three-phase bridge. The bottom three switches or the top three switches can be used. For a better thermal balance, the bottom three and the top three switches can be alternated. If there is no DC link voltage or the bus contactor is open, all six switches can stay closed continuously.

Phasor diagrams in a complex plane will be used for a better understanding of system operation and for providing qualitative assessments. Using [equation \(1\)](#), a phasor diagram of an HRPMM in generating operation can be created as follows:

$$V_T = 3 * E_{EMF} - I_M * Z_S \quad (1)$$

where V_T is the machine terminal voltage, E_{EMF} is the machine back EMF voltage, I_M is the machine phase current, and Z_S is the machine stator winding impedance.

The phasor diagram is shown in [Figure 2](#).

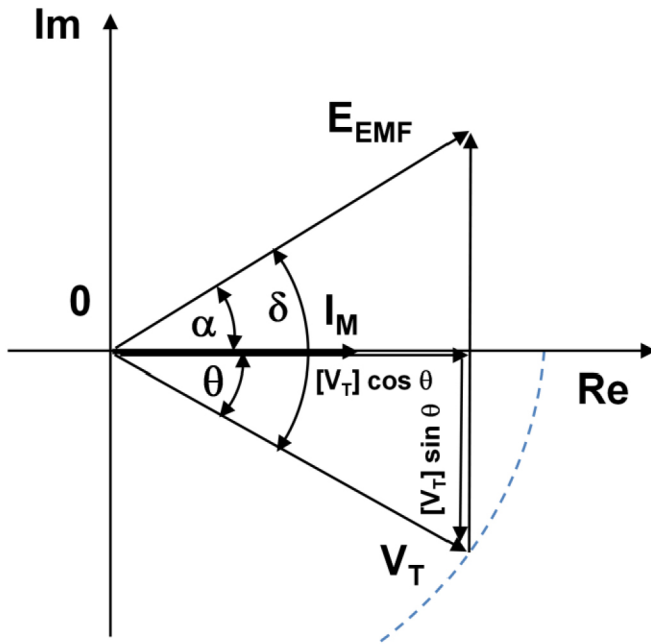


Figure 2. Phasor Diagram for the per-Phase Analysis

The phase current, I_M , is aligned with the Re axis of the complex plane. The leading power factor (PF) control is achieved by maintaining the power factor angle $\theta < 0$ (negative). That means the machine phase current is ahead of the terminal voltage. The terminal voltage V_T is decomposed into two components, real $[V_T] \cos(\theta)$ and imaginary $[V_T] \sin(\theta)$. The other important angle is α , which is the angle between the EMF and the phase current. The power angle, δ , defines the angle between the EMF phasor and the terminal voltage phasor as follows:

$$V_S = jX_S I_M = j\omega L_S I_M \quad (2)$$

where V_S is the machine internal voltage drop, X_S is the machine stator reactance, I_M is the machine phase current, ω is the machine electrical speed, and L_S is the machine stator inductance.

As previously stated, the resistance of the stator winding is intentionally omitted for simplification purposes.

Solving the phasor diagram for the active power delivered to the load for the three phases results in [equation \(3\)](#),

$$P_T = 3 * \frac{V_T * E_{EMF} * \sin(\delta)}{X_S} \quad (3)$$

where P_T is the machine shaft power, V_T is the machine terminal voltage, E_{EMF} is the machine back EMF voltage, and X_S is the machine stator reactance.

It is important to understand the influence of several parameters, such as V_T , E_{EMF} , L_S , and δ , from a system optimization perspective.

Leading Power Factor System Analysis

For system evaluation purposes, the system parameters in [Table 1](#) are used for the following analysis. This HRPMM-based system is designed to deliver 150-kW output power.

Table 1. Design Input Conditions/Constraints for a Leading PF System

Parameter	Description	Value
P_{Load} , kW	Output power at the load	150
η_{pe} , %	Efficiency of the power electronics	95
η_m , %	Efficiency of the electrical machine	93.5
V_{DC} , Volts	Output DC voltage	270
SC_{factor} , %	Max. short-circuit DC current above max. operating current	40
V_T , Vrms, L-N	Machine terminal voltage	100
E_{EMF} , Vrms, L-N	Machine BEMF voltage	100
Frequency, Hz	Machine electrical frequency	1000
X_S , ohms	Machine reactance	0.174

Power angle (δ) vs. output power

Machine shaft power, P_T , is expressed in [equation 4](#) as:

$$P_T = 3 * \frac{V_T * E_{EMF} * \sin(\delta)}{X_S} \quad (4)$$

where P_T is machine shaft power, V_T is the machine terminal voltage, δ is the power angle, E_{EMF} is machine back EMF voltage, and X_S is the machine stator reactance.

Expressing output power in terms of shaft power,