

Advanced Electric Drives for Aerospace More Electric Architectures

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ABSTRACT

This paper discusses the problem of obtaining electric machines (EM) for advanced electric drives (AED) used in more electric architecture (MEA) applicable to aircraft, spacecraft, and military ground vehicles. The AED are analyzed by those aspects of Six Sigma theory that relate to critical-to-quality (CTQ) subjects. Using this approach, weight, volume, reliability, efficiency, and cost CTQ are addressed to develop a balance among them, resulting in an optimized system. The influence of machine controllers and system considerations is discussed. As a part of the machine evaluation process, speeds, bearings, complexities, rotor mechanical and thermal limitations, torque pulsations, currents, and power densities are considered. A methodology for electric machine selection is demonstrated. An example of high-speed, high-performance machine application is shown. A system approach is used for overall electric machine selection and optimization. The presented material is a synopsis of the extensive engineering experience accumulated in Honeywell International.

INTRODUCTION

The EM for AED play a significant role in the modern aerospace/military industry. This is particularly true in the area of MEA for aircraft, spacecraft, and military ground vehicles. The commercial aircraft business is moving toward no-bleed air environmental control systems (ECS), variable-frequency (VF) and direct current (DC) power distribution buses, and electrical actuation. A typical example is the Boeing 787 platform. The next-generation Boeing airplane (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 migrated toward hybrid electric technology. In those cases, the main propulsion is performed by electric drives. Therefore, substantial

demand for improved electric drive performance has arisen [1]. Future space vehicles will require electric drives for thrust vector and flight control actuation [2]. These systems must be more robust and will offer greatly reduced operating costs and safety compared to the existing Space Shuttle hardware [3].

These new aerospace trends have created a significant increase in AED needs. This leads to increased operating voltages, and reduced system losses, weight, and volume [4]. A new set of power quality and EMI requirements has been created to satisfy both quality and performance issues [5]. The overall result is a significant increase in the installed EM, creating challenges for utilizing this equipment on the new platforms [6]. Therefore, overall system performance improvement and power density increase are necessary attributes for the new-generation machines [7]. Cost is an additional driver that must be addressed to make the new platforms affordable [8].

STATISTICAL METHODS FOR EM OPTIMIZATION

The EM can be analyzed by those aspects of Six Sigma theory that relate to CTQ [9]. CTQ is one of a select few characteristics of an end-unit product or model that can have a significant impact on product performance. Using this approach, weight, volume, reliability, efficiency, and cost CTQ will be addressed to develop balance among them, resulting in an optimized design. Brief descriptions of the selected CTQs follows:

- The weight (W) is one of the most important CTQs for an aerospace application. This product characteristic directly affects overall vehicle performance.
- The volume (V) becomes an important CTQ, particularly recently when the installed electric drives and overall power electronics content is increased substantially. This results from the latest MEA tendencies.

- The reliability (R) directly affects mission success and performance, maintenance, repair, and dispatchability.
- The efficiency (E) becomes a major driver for fuel saving in an environment where a large amount of energy is converted from mechanical to electrical.
- The cost (C) is directly related to the affordability of a new platform.

Relative weight coefficients (RC) are assigned to each CTQ to define customer priorities or relative weights (RW). The product of a CTQ and the corresponding RC results in an RW for this CTQ. In formula (1), $i = 1, 2, 3, \dots, m$, where m is the number of the selected CTQ. In this example m is 5. The indexes 1 through 5 can be replaced directly with the abbreviations W, V, R, E, and C adopted earlier in this paper.

$$RW_i = RC_i \cdot CTQ_i \quad (1)$$

The relation of all RW expressed by a function F results in an optimal design (OD). F is typically a sum function. See formula (2). However, different functions can be used.

$$OD = F(RW_W, RW_V, RW_R, RW_E, RW_C) \quad (2)$$

Key characteristic (KC) is a parameter the value and variation of which is key to a CTQ. Identifying a parameter as a KC levies a requirement that the supplier measure and report the statistics for that parameter. Typical for an electric drive system KC are high-speed capability, rotor thermal limitations, torque-to-inertia ratio, windage losses, and power density.

It is important to understand the relation between CTQ and KC. This is where the transfer functions are introduced. Formula (3) in generalized form describes the dependence of i numbers of CTQ on n numbers of KC. Where $j=1,2,3,\dots,n$. A transfer function f is defined for each CTQ.

$$CTQ_i = f_i(KC_1, \dots, KC_j, \dots, KC_n) \quad (3)$$

Expression (4) is a specific example for the selected five CTQs in this paper.

$$\begin{aligned} W &= f_W(KC_1, \dots, KC_j, \dots, KC_n) \\ V &= f_V(KC_1, \dots, KC_j, \dots, KC_n) \\ R &= f_R(KC_1, \dots, KC_j, \dots, KC_n) \\ E &= f_E(KC_1, \dots, KC_j, \dots, KC_n) \\ C &= f_C(KC_1, \dots, KC_j, \dots, KC_n) \end{aligned} \quad (4)$$

Figure 1 shows a flowchart defining the sequence of the statistical method for electric drive optimization from an electric machine perspective. The process starts with CTQ selection and finishes with an OD solution.

In block 1, the CTQs are selected. For the purpose of this example W, V, R, E, and C will be used. In block 2, initial targets for all CTQs are allocated. Block 3 defines the RW for each CTQ. Block 4 calculates the relative weight coefficient based on RW and CTQ. The preliminary OD is calculated in block 5. In block 6 a

design approach is selected. This includes selection of EM, cooling system, electrical and mechanical integration and interfaces. Block 7 identifies KC related to CTQ. Block 8 creates transfer functions f_i , which correlates the KC with CTQ. In block 9 the new CTQs are calculated based on a specific design. In block 10 the OD is calculated based on the newly calculated CTQ on a specific design. Block 11 branches the process in two directions. Upon optimal design achieved transition to block 12 is performed toward completion of the process. In case of non satisfactory results for OD, the process is returned before block 6 for selection of a different design. This closed loop may be repeated several times until OD is achieved.

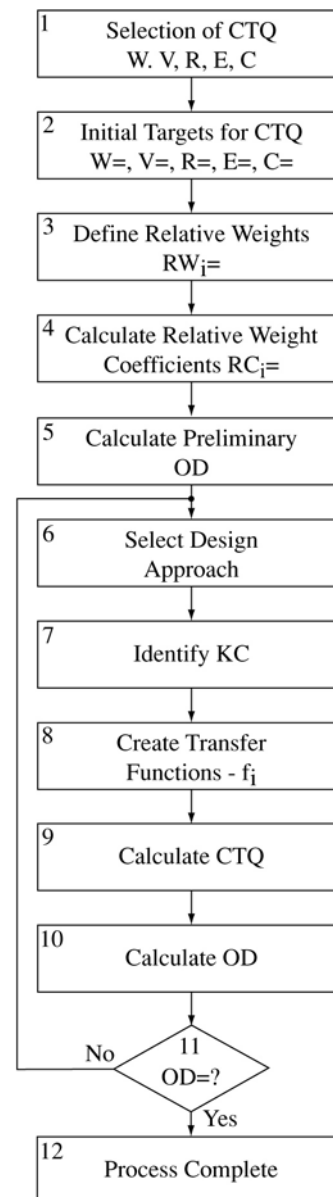


Fig. 1. Statistical Method for Electric Drive Optimization

ELECTRIC MACHINE CONSIDERATIONS

The electric machine history is more than 100 years old. Most of the electric machines used today were invented in the beginning of the electricity era, when the electric machine theory was created [10]. Over the years, substantial improvements have been achieved, primarily in the area of magnetic materials and bearing systems. Most recently, permanent magnet machines have made substantial advancement due to development of stronger and inexpensive magnets. The electric machine improvements as a part of an electric drive must be considered in conjunction with electrical and mechanical system integration. Availability of low-cost power electronics and advances in non-conventional bearing systems along with more efficient cooling methods boosted the electric machine toward better performance.

A. OUTPUT EQUATION OF AN ELECTRIC MACHINE -

An optimal machine design process starts from a good understanding of the machine variables expressed by the output equation in formula (5). This equation represents the output power of a machine as a function of the basic geometry and electromagnetic characteristics [1].

$$P = C \times B_L \times AC \times D^2 \times L \times N \quad (5)$$

P is the mechanical power delivered to the shaft; N is the shaft speed; L is the length of the magnetically active machine; D is the rotor (or air-gap) diameter; AC is the specific electric loading, which is the armature ampere conductors per unit length of armature periphery at the air-gap; B_L is the machine magnetic loading which represents the average flux density over the air-gap; and C is a machine constant dependent on various factors like rotor pole and stator winding arrangements. The product $D^2 \times L$ represents the machine air-gap volume and is a measure of the used active materials.

It is logical that the total weight and volume of an electric machine is proportional to the air-gap volume. Therefore, provisions to minimize this number must be applied aggressively. Looking at the output equation, it can be concluded that increasing the speed, N, is one of the most powerful provisions for weight and volume savings. Increases of B_L and AC are typically associated with use of more expensive materials and/or penalty to the cooling system. Therefore, these provisions must be carefully approached to achieve required performance and cost targets. Also, overall system efficiency may be affected. Nevertheless, an aggressive research for materials improvement is in progress.

B. INTEGRATION OF ELECTRIC MACHINES -

The high-performance machines for aerospace applications typically drive high-speed compressors, fans, pumps, and actuators. The operating speeds cover a broad range, from 10 to 200 krpm. Increasing the speed is one of the most powerful provisions for improved performance, as concluded in the previous paragraph. However, increasing the speed presents mechanical integration complications. These are rotor-dynamic behaviors related to the critical speeds phenomena. This

applies not only to the electric machine but also to the entire rotating group – machine and loads. The magnitude of the air-gap plays an important role. Transition to foil [11] and magnetic bearings creates an excellent opportunity for speed increase and reliability improvement.

The highest-speed drives are typically for compressor applications, which may go up to 200 krpm. The conventional metal or ceramic bearings do not work at these speeds. Here is where foil or magnetic bearing systems find their place. The acceleration and deceleration time may not be a critical requirement. Hence, high torque-to-inertia ratio is not required. A ratio of L to D of two is selected as a rule of thumb. Of course, extensive rotor dynamic analysis is required to verify proper mechanical integration early in the design process. A two-pole machine is always selected to have the lowest fundamental frequency at max speed for easy integration with the power electronics.

Fan implementation is the next high-speed application. The speeds are well within conventional bearing capabilities. However, for improved reliability, foil bearings are highly desirable. A higher number of machine poles can be selected for improved performance. The fundamental of the machine current is multiple of the mechanical frequency, however it is low enough for easy integration with the power electronics. Electrical fundamental frequencies above 1.5 kHz should be avoided to prevent distorted stator currents resulting in increased machine losses and electromagnetic interference (EMI) difficulties.

The pump drives are used for fuel, hydraulic, or cooling liquids. The speed is typically lower than that of a fan. Rotor-dynamic behavior usually does not create problems. To improve reliability, use of a seal is avoided and submerged rotor operation is implemented. This is the application where air-gap increase reduces windage losses significantly.

The most important parameter for a machine used for high-performance actuation is the L to D ratio. This number is typically 4 and contributes substantially to fast dynamic system response. These machines have a very long rotor and stator, which creates fabrication complications. Integration is normally with a gearbox and does not create major challenges from a rotor-dynamics perspective. A direct-drive, no-gearbox system is possible, however weight penalty is often experienced. Conventional grease-pack bearings are used in most applications. A bidirectional power converter is required to provide the dynamic breaking function required for fast response. Often, power regeneration to the bus is not allowed and a dissipating element internal to the power electronics is required.

C. ELECTRIC MACHINE CLASSIFICATION -

Small family EMs are reviewed in Figure 2, which contains the most popular representatives used in the AED for aerospace applications. Level 2 separates brushless and brush-type machines. Not surprisingly, the brush-type machines did not evolve past Level 3. The mechanical