

A Direct Torque-Controlled Induction Machine Bidirectional Power Architecture for More Electric Aircraft

Tim C. O'Connell and Jason R. Wells

PC Krause & Associates, Inc.

Peter T. Lamm and Laurence B. DeWitt

US Air Force Research Laboratory

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ABSTRACT

The performance of a more-electric aircraft (MEA) power system electrical accumulator unit (EAU) architecture consisting of a 57000 rpm induction machine (IM) coupled to a controllable shaft load and controlled using direct torque control (DTC) is examined through transient modeling and simulation. The simplicity and extremely fast dynamic torque response of DTC make it an attractive choice for this application. Additionally, the key components required for this EAU system may already exist on certain MEA, therefore allowing the benefits of EAU technology in the power system without incurring a significant weight penalty. Simulation results indicate that this architecture is capable of quickly tracking system bus power steps from full regenerative events to peak load events while maintaining the IM's speed within 5% of its nominal value.

INTRODUCTION

The proliferation of more-electric architectures in both military and commercial aircraft continues to increase the complexity of designing and specifying airborne electric power systems. As an alternative to a previously proposed ultracapacitor-based EAU [1], a high-speed (57000 rpm) IM coupled to a controllable shaft load is proposed here. When controlled appropriately, the shaft load acts analogously to a flywheel to buffer the aircraft power bus during transients, and an external bleed air supply coupled to the shaft can be used for additional power as needed. The high shaft speed allows the IM to

achieve a high power rating (120 kW/160 Hp) at a relatively low torque (20.1 Nm), which means the machine's size, and ultimately its weight, can be reduced. Because it runs at a tightly controlled speed, the IM's power input or output can be actuated in response to the aircraft bus generator requirements by varying the electromagnetic torque applied through the stator windings. A key advantage of this alternative architecture is that it requires no additional hardware, only a modified control algorithm for existing adaptive power and thermal management system (APTMS) hardware. This potentially eliminates the need for additional weight to achieve EAU functionality.

The controllable load in the proposed architecture is an APTMS that uses engine bleed air to power an air cycle system (ACS) consisting of a power turbine, compressor, and cooling turbine, all co-mounted on the IM shaft. The ACS cold-air output varies with the shaft torque applied by the APTMS. When the aircraft power system dc bus requires voltage support, the combination of the bleed air supply and the shaft rotational inertia serves as an energy storage reservoir, analogous to the electric charge in an ultracapacitor-based system, which the APTMS can draw on to convert the stored energy into electrical energy via the IM. That energy is then delivered to the electrical distribution unit (EDU) to buffer the bus against unwanted transients. This process is also reversible. During regenerative events the APTMS can sink power by increasing the torque applied to the shaft by the IM in order to both transfer power into rotational inertia and increase cold-air output.

Although a wide variety of IM control techniques could be successfully employed to achieve the desired EAU behavior of the system, this paper details an approach based upon DTC. The primary motivation for this choice is the fast control dynamics of DTC that enable the EAU to rapidly mitigate transient power spikes. Although each system designer would need to choose the algorithm that best meets the needs of their application, a brief discussion of the advantages and disadvantages of DTC are presented here to provide a starting point for the interested reader.

DTC is a vector control algorithm for induction machines that controls the machine flux (stator, rotor, or air gap) and torque independently by using optimal inverter switching vectors [2], [3]. Unlike most other vector controllers, DTC requires no coordinate transformations, making it relatively simple to implement. The flux and torque are maintained within defined hysteresis bands in order to obtain fast torque response under dynamic machine conditions [4]. Additionally, DTC generates the inverter switch states directly, so no separate voltage modulation block is needed, as it would be in a pulse width modulated (PWM) controller, for example. Despite these advantages, DTC does have some disadvantages including potentially poor performance during low-speed operation and during rotation direction changes, when torque tracking can be lost. However, because the IM in this application only spins in one direction under tight speed regulation, these disadvantages are not significant. Additionally, the flux and torque hysteresis control creates a switching frequency that is neither constant nor known *a priori*, which complicates the design of current and torque ripple damping filters.

In the sections that follow, a brief overview of DTC theory is given, followed by details of the models used for the IM, APTMS load and DTC-controlled inverter. An integrated system is simulated and performance results presented indicating that the IM-based EAU could be a viable alternative to previously proposed EAUs that are based upon electrical energy storage. Finally, key conclusions that can be drawn from the simulations are presented with additional discussion of the next steps required to develop the proposed EAU topology.

DTC THEORY

IM torque expressed in stator qd variables is given as

$$T_e = \frac{3}{2} \frac{P}{2} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (1)$$

where P is the number of poles, and λ_{ds} , i_{ds} , λ_{qs} , and i_{ds} are the stator d - and q -axis flux linkage and current, respectively. In the stationary reference frame with the d -axis aligned with the x -axis ($\omega = 0$, $\theta = \pi/2$) the stator flux linkages λ_{as} , λ_{bs} , and λ_{cs} are found from

$$\begin{pmatrix} \lambda_{qs} \\ \lambda_{ds} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1 & -1/2 & -1/2 \end{pmatrix} \begin{pmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{pmatrix}. \quad (2)$$

The machine abc voltages V_{as} , V_{bs} , and V_{cs} are

$$\begin{pmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{pmatrix} = \begin{pmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{pmatrix} \begin{pmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{pmatrix} + \frac{d}{dt} \begin{pmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{pmatrix} \quad (3)$$

where r_s is the stator resistance and i_{as} , i_{bs} , and i_{cs} are the stator phase currents [5]. When the machine speed is not too low the second term on the right-hand side of (3) dominates the first term and the machine abc flux linkages can be approximated by integrating the corresponding voltages. Thus, the applied abc voltages can be used to increase or decrease the stator flux linkages. By maintaining the flux linkage magnitude at a specified value and moving its direction around appropriately the machine torque can be quickly controlled. This is the basis of DTC.

A three-phase inverter with six switches, as shown in Figure 1, has eight possible switching vectors that avoid shorting the source bus. Using the top switch in each phase leg as the reference, the leg is represented by a 0 if this switch is OFF and by a 1 if this switch is ON. Each switch configuration can thus be represented by a three-digit binary number. For example, switch state 110 denotes the top switch being ON in columns 1 and 2 but OFF in column three. Vectors 111 and 000 are not unique; neither delivers energy to the machine and they are therefore not considered active switch states.

The six active states switch one load phase impedance in series with the parallel combination of the remaining two. Thus each abc (line-to-neutral) voltage is either $\pm \frac{V_{dc}}{3}$ or $\pm \frac{2V_{dc}}{3}$, where V_{dc} is the bus voltage. These can be transformed to qd coordinates using the same transformation matrix as in (2). The results are listed in Table 1. Treating V_{ds} and V_{qs} as the x - and y -components, respectively, of a voltage space vector, the six active voltage space vectors can be mapped in the qd -plane, as shown in Figure 2 [4]. Each vector is labeled as indicated and defines the center of a 60° segment of the plane. These sectors are labeled $\alpha(1)$ - $\alpha(6)$ as shown.

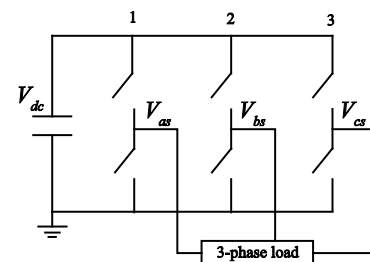


Figure 1: Three-phase inverter with phase legs, line and bus voltages labeled



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Table 1: Converter switching states and their corresponding stator voltages

Switch State	V_{as}	V_{bs}	V_{cs}	V_{ds}	V_{qs}	Sector
000	--	--	--	0	0	$\alpha(8)$
001	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$-\sqrt{3}V_{dc}/3$	$\alpha(5)$
010	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$	$\sqrt{3}V_{dc}/3$	$\alpha(3)$
011	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	0	$\alpha(4)$
100	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	0	$\alpha(1)$
101	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-\sqrt{3}V_{dc}/3$	$\alpha(6)$
110	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	$\sqrt{3}V_{dc}/3$	$\alpha(2)$
111	--	--	--	0	0	$\alpha(7)$

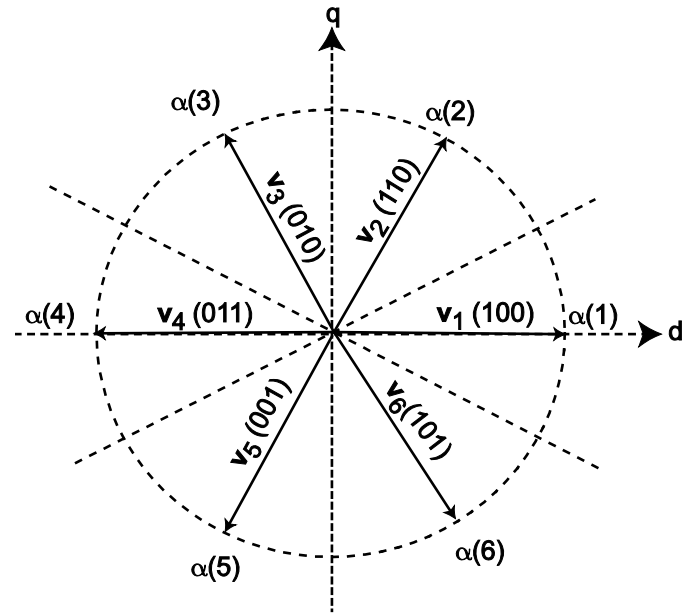


Figure 2: Switching-voltage space vectors for three-phase inverter. (111) and (000) vectors lie at the origin.

Referring to Figure 2, if the machine flux resides in sector $\alpha(1)$ and a torque increase is desired, the stator flux direction should be shifted to $\alpha(2)$ or $\alpha(3)$. This can be accomplished by applying voltage vector $\mathbf{v}_2$ or $\mathbf{v}_3$, respectively. Applying $\mathbf{v}_2$ will increase the flux magnitude while applying $\mathbf{v}_3$ will decrease it. Similar arguments can be made when the flux resides in any of the six sectors and it is desired to either increase or decrease the flux or torque. The optimal voltage switching table shown in Table 2 is the result [4]. In Table 2, a desired flux increase is represented by $d\lambda = 1$ and a desired decrease by $d\lambda = 0$. Desired torque increase and decrease are represented by $dT_e = \pm 1$, respectively. If no torque change is necessary, the flux direction or magnitude need not be changed, and one of the two inactive vectors is applied. This is commanded with $dT_e = 0$. Typically these states are chosen to minimize the switching frequency of each switch, so whichever state (111 or 000) requires fewer total switches is the one chosen.

Table 2: Optimal voltage switching vector look-up table

$d\lambda$	dT_e	$\alpha(1)$	$\alpha(2)$	$\alpha(3)$	$\alpha(4)$	$\alpha(5)$	$\alpha(6)$
1	1	$\mathbf{v}_2$	$\mathbf{v}_3$	$\mathbf{v}_4$	$\mathbf{v}_5$	$\mathbf{v}_6$	$\mathbf{v}_1$
1	0	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$
1	-1	$\mathbf{v}_6$	$\mathbf{v}_1$	$\mathbf{v}_2$	$\mathbf{v}_3$	$\mathbf{v}_4$	$\mathbf{v}_5$
0	1	$\mathbf{v}_3$	$\mathbf{v}_4$	$\mathbf{v}_5$	$\mathbf{v}_6$	$\mathbf{v}_1$	$\mathbf{v}_2$
0	0	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$	$\mathbf{v}_7/\mathbf{v}_8$
0	-1	$\mathbf{v}_5$	$\mathbf{v}_6$	$\mathbf{v}_1$	$\mathbf{v}_2$	$\mathbf{v}_3$	$\mathbf{v}_4$

Hysteresis bands for both stator flux linkage and machine torque are specified, and the inverter is switched according to Table 2 in order to remain within those bands. Defining the flux linkage and torque hysteresis band half-widths as $\Delta\lambda$ and ΔT_e , respectively, and the flux linkage and torque references, respectively, as $\lambda_{s,ref}$ and $T_{e,ref}$, the hysteresis switching rules in Table 3 are obtained. Torque and flux are controlled separately, and typically the flux magnitude is set to its maximum allowable value (determined from machine ratings) and the torque is varied quickly. Usually a speed control loop is wrapped around the DTC controller in order to generate the necessary torque reference commands. However, in the present application a torque command is readily calculated from the required EAU power and shaft speed, so no speed control loop is needed for the DTC. Rather, the shaft speed will be regulated via the controllable APTMS.

Table 3: Flux and torque hysteresis switch transition rules

	Current state	Switch condition	New state
$d\lambda$	1	$\lambda_s \geq \lambda_{s,ref} + \Delta\lambda$	0
	0	$\lambda_s \leq \lambda_{s,ref} - \Delta\lambda$	1
dT_e	1	$T_e \geq T_{e,ref} + \Delta T_e$	0 or -1
	0	$T_e \leq T_{e,ref} - \Delta T_e$	1
	-1	$T_e \leq T_{e,ref} - \Delta T_e$	0 or 1

MODEL DETAILS

The model was developed using Simulink software. It consists of three main blocks, each of which will be