ELECTRIC MACHINE TORQUE PRODUCTION 101

Best Electric Machine, 2014

INTRODUCTION:
The following discussion will show that the symmetrical (or true dual-ported) transformer electric machine as only provided by the Synchro-Sym electric machine system (**SS-EMS**) has considerably higher peak torque potential than any asymmetrical transformer electric machine system, such as the induction electric machine system (**I-EMS**), which again has considerably higher peak torque potential than any permanent magnet (PM) electric machine system (**PM-EMS**), if the electric machine systems are optimally designed. All contestants are considered "systems" with electronic control of the flux but with the SS-EMS using proprietary Brushless Real Time Control (BRTC).

BACKGROUND INFORMATION:
The PM electric machine system (PM-EMS) is a synchronous electric machine and as a result, the PM-EMS does not rely on speed-based induction for operation (although synchronous electric machines may sometimes experience speed-based induction). "Speed-based induction" refers to the asynchronous speed (i.e., slip) between the rotor and stator, which is on the order of magnitude of the electrical excitation frequency and the mechanical frequency of rotation (i.e., movement) of the rotor. The Induction (e.g., with a squirrel cage rotor winding set) electric machine systems (I-EMS) and the reluctance electric machine systems are asynchronous electric machine systems that must rely on speed-based induction (i.e., slip) for operation. With effectively a shorted rotor winding set and therefore a single electrical port, the I-EMS has an asymmetrical transformer circuit topology with the electrical power of the rotor winding set dependent on induction (or the mutual magnetic coupling) with the electrical power of the stator winding set (or armature) and as a result, the power rating of the stator winding set must include the power rating of the rotor winding set. The Synchro-Sym electric machine system (SS-EMS) with a rotor armature or active multiphase winding set under brushless real time control (BRTC) as well as a stator armature is the only wound-rotor doubly-fed *synchronous* electric machine system and like any synchronous electric machine systems, the SS-EMS experiences speed-based induction but does not rely on speed-based induction for operation. In contrast to the asymmetrical transformer electric machine systems, the SS-EMS is a symmetrical (or true dual-ported) transformer circuit topology with direct but independent ports to electrically power the rotor and stator winding sets (or armatures) and as a result, the power rating of the stator and rotor winding sets are independent as well.

The high permeability of the magnetic core of an electric machine offers a low resistance path to magnetic flux to effectively focus the flux specifically across the thin air-gap between the rotor and stator assemblies. The flux in the magnetic core and across the air-gap (flux path) is produced by a permanent magnet (PM) with coercivity or an electromagnet (i.e., winding set) with magneto-motive-force or MMF, which is the product of the winding-turns and the current, in accordance to Ampere Circuital Law. For electric machines, there is magnetizing MMF

(**$\mathbf{MMF_M}$**) and torque MMF (**$\mathbf{MMF_T}$**), which are orthogonal vectors of current established by the path of the winding conductors. The "vector sum" of the MMF_M and MMF_T or $\sqrt{MMF_M{}^2 + MMF_T{}^2}$ is the total MMF (**$\mathbf{MMF_{TOTAL}}$**) in the magnetic path of the electric machine. In contrast to an electromagnet, the total MMF (**$\mathbf{MMF_{TOTAL}}$**) of a PM is effectively $\sqrt{Coercivity^2 + MMF_T{}^2}$. Note: *As the vector sum of all magnetic flux and the actual flux in the core, the saturation limit should be referenced to* ***$\mathbf{MMF_{TOTAL}}$*** *and not to the individual flux vectors; particularly for transformer electric machines where some flux vector components subtract from each other*.

In accordance to Ampere Circuital Law, the magnetic core material with low resistance (i.e., high permeability) path and the thin air-gap significantly reduces the amount of MMF_M to produce the "magnetizing flux density" in the air-gap for electric machine operation. But all magnetic core material only holds a bounded amount of magnetic flux before the core saturates, which magnetic material research is trying to remedy. Once saturated, the highly permeable magnetic core looks like the very low permeable (or high magnetic flux resistance) air-gap but with the extraordinary length of the entire magnetic path. As a result, increasing MMF_{TOTAL} beyond core saturation does not contribute to the production of flux density (or torque) but instead produces excessive dissipation in accordance with the I^2R loss of the effectively useless MMF.

In accordance with Lorentz relation, force (or torque) is equal to the cross product between the air-gap Flux (magnetizing MMF or persistent PM coercivity) and the torque MMF. For PM-EMS, the torque MMF of the stator winding set pushes (or pulls) against the air-gap flux field established by (and physically locked to) the rotor PM, which moves the mobile rotor with a bearing assembly with work performed on the rotor but with an equal and opposite action against the immobile stator winding set with no work performed on the stator. For transformer type electric machines, such as the I-EMS and the SS-EMS, with winding sets on the rotor and stator, the torque MMF of the rotor winding set pushes (or pulls) against the air-gap flux field established by the orthogonal magnetizing MMF, which moves the mobile rotor with a bearing assembly with work performed on the rotor but with an equal and opposite action against the immobile stator windings with no work performed on the stator.

All PM(s) in this whitepaper are considered high coercivity (e.g., MMF) rare-earth (RE) PM(s), such as dysprosium doped neodymium or samarium-cobalt. The high remanence (e.g., Flux Density) of a RE-PM is always less than the flux density potential of a winding set of an electric machine (with the usual thin air-gap) but likely beyond the practical saturation limit of the core material as applied in an electric machine design. Ferrite PM(s) with very low coercivity and remanence are not considered competitively viable.

In conclusion, MMF_M sets up the magnetizing air-gap flux density in accordance to Faraday's Law and Ampere Circuital Law, which is inversely proportional to the depth of the air-gap by reasonably neglecting the entire path length of the highly permeable magnetic core. MMF_T, which is orthogonal to the magnetizing air-gap flux density, establishes torque in accordance to the Lorentz Relation. The core saturation limit as a result of increasing MMF_{TOTAL} determines the peak torque potential of any electric machine, assuming the I^2R loss of the electric machine MMF_{TOTAL} is properly dissipated or cooled.

TORQUE PRODUCTION BETWEEN THE PM-EMS, THE I-EMS, AND THE SS-EMS:

PM EMS: In accordance to the legend of Figure 1 – Flux Vectors of Synchronous EM, the persistent PM Flux vector (i.e., red PM Flux vector) establishes the magnetizing flux density vector in the air-gap by PM coercivity. As the MMF_T Flux vector (i.e., green MMF_T Flux vector) increases to increase torque, the MMF_{TOTAL} flux vector (i.e., blue MMF_{TOTAL} Flux vector), which is the vector sum of PM Flux vector and MMF_T Flux vector, changes in phase and magnitude with magnitude directly (and quickly) advancing toward core saturation. Therefore, an optimally designed PM-EMS establishes the peak torque and the "MMF_{TOTAL} Flux" at the margin of core saturation, which is 1-1.5x normalized[1] torque. The baseline air-gap flux density must be designed further from the flux saturation limit of the core to provide a safe working margin, which de-optimizes any PM design potential. All PM-EMS control derivatives are fixed by the design parameters of the PM-EMS (assuming synchronism is maintained by precision control).

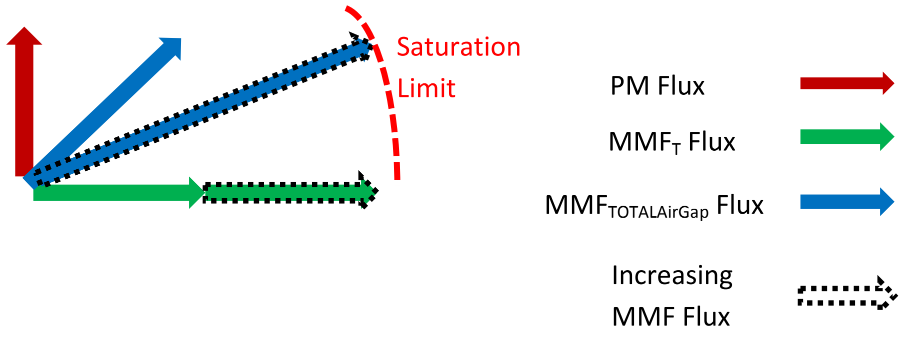

Figure 1 – Flux Vectors of Synchronous EMS

I-EMS: In accordance to the legend of Figure 2 – Flux Vectors of Asymmetrical EMS, once the magnetizing Flux vector (i.e., red MMF_{SM} Flux vector) is setup to meet the stator port voltage in accordance with Faraday's Law, the I-EMS becomes an asymmetrical transformer where current (and voltage) beyond magnetizing current is induced onto the rotor shorted squirrel cage winding set by the mutual magnetic coupling between the stator (i.e., armature) and rotor winding sets (i.e., asymmetrical transformer) as a result of the speed slip between the rotor and stator and the induced voltage drop across the closed loop circuit impedance of the rotor squirrel cage winding. As a result, the stator and rotor torque MMF vectors (green MMF_{ST} vector and yellow MMF_{RT} vector, respectively) increase in conjunction; however, the MMF_{RT} Flux vector is out of phase from the MMF_{ST} Flux vector in accordance with the rotor time constant, which depends on the slip frequency and the temperature varying the rotor

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[1] Normalized torque is the same torque designed to the same speed, the same frequency of excitation, and the same voltage for all contestants. The same torque at the same speed is the same power (i.e., product of torque and speed) at the same speed, the same frequency of excitation, and the same voltage for all contestants.

resistance. Since a component of the MMF$_{RT}$ Flux vector negatively adds to the MMF$_{ST}$ Flux vector (as shown in Figure 2 – Flux Vectors of Asymmetrical EMS) in accordance to transformer circuit operation, the total MMF Flux (i.e., blue MMF$_{TOTAL}$ Flux vector), which is the vector sum of all MMF Flux vectors, advances indirectly and more slowly towards the saturation limit of the magnetic core, which is in contrast to the direct and quick advancement of the PM-EMS. An optimally designed I-EMS establishes the peak torque (and the peak MMF$_{TOTAL}$ Flux) at the margin of core saturation, which is about 2.5x the normalized torque, and as a result, the baseline air-gap flux density is designed closer to the saturation limit of the magnetic core with an appropriate margin for a more optimized design. I-EMS control derivatives are more complex with two variable parameters of concern, rotor time constant, which is temperature dependent and measurement aloof, and slip.

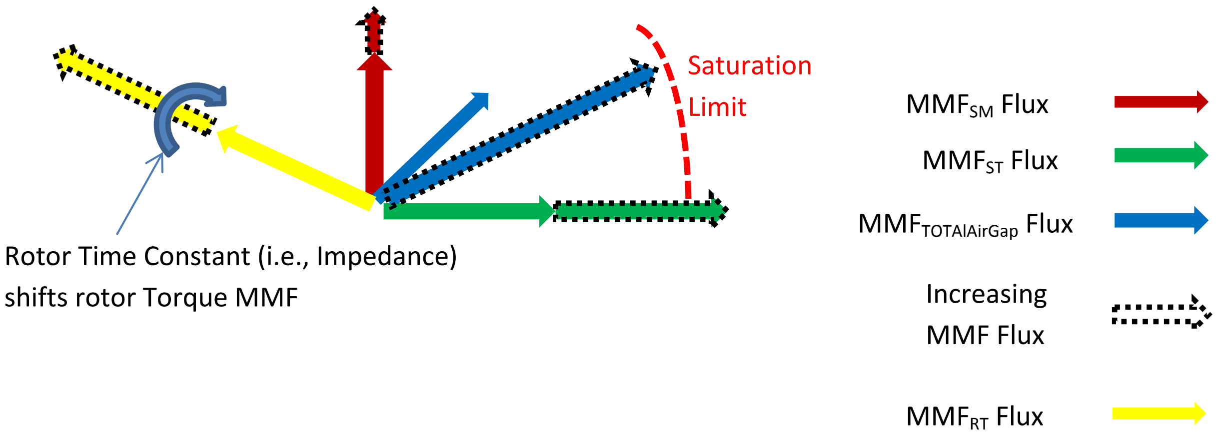

Figure 2 – Flux Vectors of Asymmetrical EMS

SS-EMS: In accordance to the legend of Figure 3 – Flux Vectors of Symmetrical Transformer EMS (SS-EMS), once the magnetizing Flux vector (i.e., red MMF$_{SM}$ Flux vector) is setup to meet the stator port voltage in accordance with Faraday's Law, the SS-EMS becomes an symmetrical (i.e., dual-ported) transformer with brushless real time control (BRTC) automatically compensating for any slip or even the rotor time constant (by absorbing the series resistance and reactive rotor phase shift), which are directly measured through the independent rotor port. As a

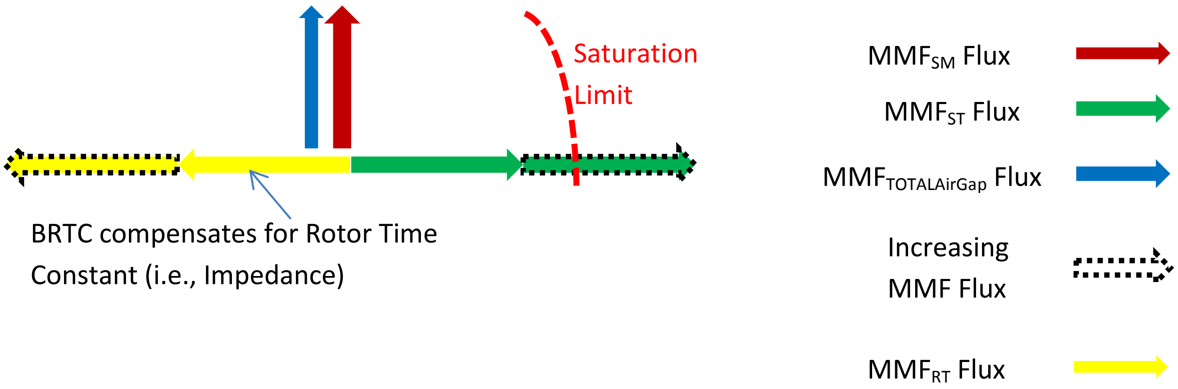

Figure 3 – Flux Vectors of Symmetrical Transformer EMS (SS-EMS)

result, the stator torque MMF Flux vector (i.e., green MMF$_{ST}$ Flux vector) increases in direct conjunction with the rotor torque MMF Flux vector (i.e., yellow MMF$_{RT}$ Flux vector) with the flux vectors cancelling for a total MMF Flux vector (i.e., blue MMF$_{TOTAL}$ Flux vector) simply equal to the MMF$_{ST}$ Flux vector. Furthermore, the air-gap flux remains constant until leakage MMF prevails, which is much higher than any other electric machine, such as the PM-EMS or the I-EMS. As the only electric machine with less concern for core saturation, the baseline air-gap flux density (i.e., MMF$_{TOTAL}$ Flux vector) of an optimally designed SS-EMS is designed close to the core saturation margin and as a result, the SS-EMS can achieve at least 8x normalized torque without concern for flux saturation. With BRTC, the SS-EMS control is the simple adjustment of torque MMF.

PEAK TORQUE POTENTIAL BETWEEN EMS TYPES:
Table 1 – Peak Torque Potential of EMS Types shows the potential peak torque potential of electric machine systems types in relation to "normalized torque."[2]

Table 1 – Peak Torque Potential of EMS Types

EMS PEAK TORQUE POTENTIAL		
Increasing ↓	EMS Type	Peak Torque Potential (Normalized)
	PM-EMS	1-1.5x
	I-EMS (Field Oriented Control Commutation)	2-3x
	Universal EMS (Electromechanical Commutation)	5x
	SS-EMS (Brushless Real Time Control Commutation)	>8x

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[2] Normalized torque is the same torque designed to the same speed, the same frequency of excitation, and the same voltage for all contestants. The same torque at the same speed is the same power (i.e., product of torque and speed) at the same speed, the same frequency of excitation, and the same voltage for all contestants.