Taguchi-EM-AI Design Optimization Environment for SynRM Drives in Traction Applications

A.A. Arkadan [1] and N. Al Aawar [2]

[1] Colorado School of Mines, Dept. of Electrical Engineering, Golden CO 80401, USA
[2] Marquette University, Dept. of Electrical and Computer Engineering, Milwaukee WI, 53233, USA
aaarkadan@mines.edu

***Abstract*—Multi-objective design optimization environments are used for electric vehicles and other traction applications to arrive at efficient motor drives. Typically, the environment includes characterization modules that involve the use of Electromagnetic Finite Element and State-Space models that require large number of iterations and computational time. This work proposes the utilization of a Taguchi orthogonal arrays method in conjunction with a Particle Swarm Optimization search algorithm to reduce computational time needed in the design optimization of electric motors for traction applications. The effectiveness of the Taguchi method in conjunction with the optimization environment is demonstrated in a case study involving a prototype of a Synchronous Reluctance Motor drive system.**

***Index Terms*—design optimization, Taguchi algorithm.**

I. INTRODUCTION

Internal combustion engines (ICEs) running on fossil fuel and powering vehicles are major contributors to carbon emissions. In traction applications, hybrid and electric vehicles (EVs) utilizing electric motors are increasingly used as viable alternatives to ICE driven systems. As such, the development of reliable efficient electric motors is receiving attention and design optimization environments are utilized by researchers in this field. In this work, we consider Axially Laminated Anisotropic (ALA) Rotor Synchronous Reluctance Motor (SynRM) drives, that possess ideal characteristics for traction applications [1, 2].

This paper presents a design optimization environment that includes a module comprised of an electromagnetic Finite Element (EM) and state space (SS) models of the motor drive system. The EM-SS module is used as a system identifier in the design optimization process. The block diagram of a prototype EV drive system modeled in this work is shown in Fig. 1 and it includes a SynRM motor, the drive power electronics, and associated controllers. As can be appreciated, it is critical that the characterization module of the drive system properly accounts for effects of magnetic saturation and nonlinearities, as well as effects of space and time harmonics when predicting the system performance.

II. MOTOR DRIVE SYSTEM CHARACTERIZATION MODULE

This paper presents a Multi-objective design optimization environment that includes an EM-SS characterization module. The objective of the design optimization environment implemented in this work is to maximize the developed torque while minimizing the torque ripple and total (Ohmic, core, and switching) losses of an ALA SynRM drive system, Fig. 1. This system utilizes a decoupled d- and q-axis current control and a flux controller in the inner loop that are implemented with PI controllers [3]. In addition, the power converter implemented in this case study is of the full wave, 3-phase, PWM Inverter type. The motor is designed for traction applications, Fig. 2, and is rated at 100 KW and 6000-rev/min. The motor stator is constructed from nonlinear magnetic material that holds poly-phase windings similar to a conventional AC machine. The rotor is made of axially laminated anisotropic magnetic silicon steel laminations interleaved with thin insulation layers that form the rotor composite flux path segments.

The integrated EM-SS module used for the characterization of the ALA rotor SynRM generates data required by an artificial intelligence (AI) particle swarm optimization (PSO) based design optimization search algorithm. The SS model that governs the performance of the SynRM is expressed as:

$$\begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \\ \dot{\omega}_m \\ \dot{\theta}_m \end{bmatrix} = \begin{bmatrix} & & & 0 & 0 \\ & A & & 0 & 0 \\ & & & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_a \\ I_\partial \\ I_c \\ \omega_m \\ \theta_m \end{bmatrix} + \begin{bmatrix} V_a \\ V_b \\ V_c \\ F \\ 0 \end{bmatrix}. \quad (1)$$

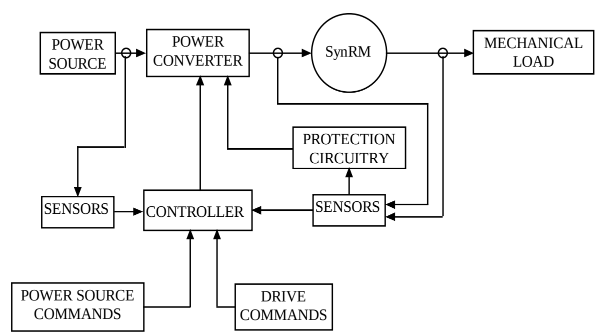

Fig. 1. SynRM drive system.

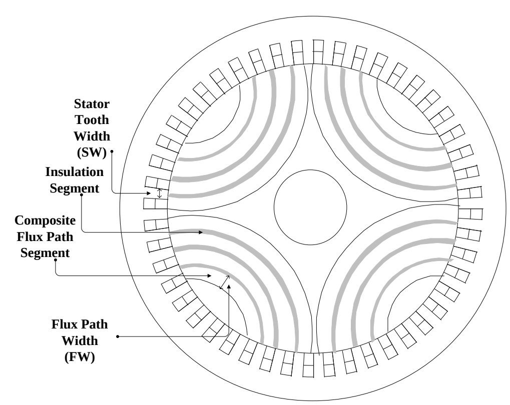

Fig. 2. ALA rotor SynRM cross-section.

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In equation (1), matrix A is given as:

$$A = -inv(L) \cdot \left(R + \omega_m \cdot \frac{dL}{d\theta_m} \right), \quad (2)$$

where L and R are the motor inductance and resistance matrices, respectively, and ω_m is the rotor speed. In addition, the voltages V_a, V_b, and V_c represent the system input voltage vector, which accounts for the drive power electronics and associated controllers [1-3].

III. THE TAGUCHI-EM-PSO DESIGN ENVIRNOMENT

The objective of the design optimization environment is to maximize the developed torque while minimizing torque ripple as well as Ohmic and core losses of the SynRM drive system of Fig. 1. The Input Design Vector, I_{Design}, for the optimization problem consists of the number of flux paths, the stator tooth width (SW), and the rotor flux path width (FW), shown in Fig. 2. The optimization objective function, *OF*, is defined as the weighted sum of the performance indicators that include torque ripple, T_r, the total losses in the machine, T_L, and the developed torque average, T_{avg}, constrained at a desired load, T_d:

$$OF = \alpha \cdot T_r + \beta \cdot T_L + \lambda \cdot |T_{ave} - T_d|, \quad (3)$$

where α and β are the weights of T_r and T_L, respectively and λ is the Lagrangian multiplier.

The EM-PSO optimization environment of Fig. 3 was implemented where the finite element based EM-SS characterization module described above was used to generate needed data to train offline a Fuzzy Logic (FL) model, which is used in turn in a Particle Swarm Optimization (PSO) search algorithm [4]. The input vector of the FL model is the design vector, I_{Design}, and the output is a set of performance indicators. The PSO uses the FL model to evaluate the objective function corresponding to any values of the design vector in the search space. The SynRM drive system was implemented with both Urban and Highway Federal Driving Schedules, Fig. 4. The application of the EM-PSO design environment to the prototype SynRM drive of Fig. 1, operating at 50 Nm and 3000 rpm load conditions, resulted in optimized design performance indicators values, which are compared in Table 1 to corresponding initial design values. An inspection of Table 1 reveals the excellent improvement in the values of the performance indicators.

As can be appreciated from above, a large number of EM and PSO iterations are required to find an optimum design. As such, a Taguchi orthogonal arrays algorithm [5] was employed to reduce computational time needed to reach an optimum design. The Taguchi algorithm was integrated with the EM-PSO design environment of the Fig. 3 and resulted in the Taguchi-EM-PSO design optimization environment of Fig. 5. This algorithm reduces the computational requirements by determining the minimum number of input design parameter's combinations required to cover the whole search space of the optimization problem [5]. The application of the algorithm shown in Fig. 5 to the prototype traction SynRM drive, Fig. 1, operating at the same conditions noted above, resulted in similar performance indicator values as shown in Table 1 and about 80% reduction of needed computational time.

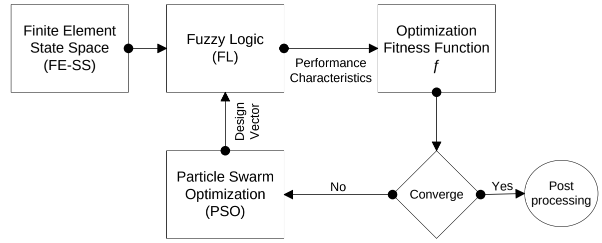

Fig. 3. EM-PSO design optimization environment.

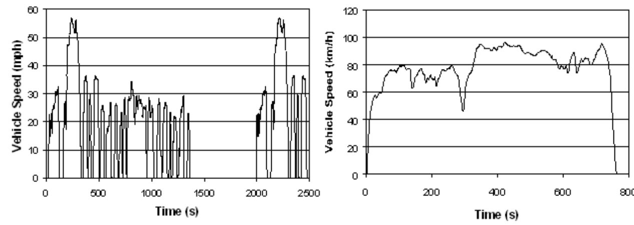

Fig. 4. Federal driving schedules: (a) Urban "FUDS"; (b) Highway "FHDS".

TABLE I
INITIAL AND OPTIMAL DESIGN

DESIGN	INITIAL	OPTIMAL	IMPROVEMENT
LOSSES (W)	6,260	2,400	61%
TORQUE RIPPLE	52%	30%	42%
AVG. TORQUE	90 N.M.	90 N.M.	N/A

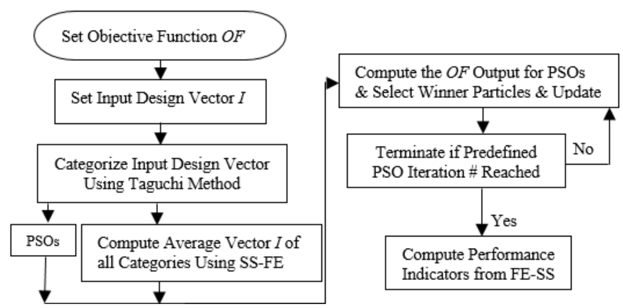

Fig. 5. Taguchi-EM-PSO design optimization environment.

IV. CONCLUSION

This work demonstrates the effectiveness of including a Taguchi algorithm in reducing computational time requirements in design optimization environments for traction applications.

REFERENCES

[1] A. A. Arkadan, F. Isaac, and O. A. Mohammed, "Parameters Evaluation of Axially Laminated Anisotropic Synchronous Reluctance Motor Drives," IEEE Trans. on Magnetics, vol. 36, pp. 1950-1955, July 2000.

[2] A. A. Arkadan, A. Hanbali, and N. Al-Aawar, "Characterization and Design Optimization of ALA Rotor Synchronous Reluctance Motor Drives for Traction Applications," 22nd Annual Review of Progress in Applied Computational Electromagnetics (ACES), pp. 249-256, Florida, U.S., Mar. 2006.

[3] I. Boldea and S. A. Nasar, Vector Control of AC Drives. CRC Press, Boca Raton, FL, pp. 167-200, 1992.

[4] J. Kennedy and R. Eberhart, "Particle Swarm Optimization," Proc. IEEE Int. Conf. on Neural Networks, pp. 1942-1948, 1995.

[5] A. A. Arkadan, N. Al-Aawar, and A. O. Hariri, "EM-Taguchi Identifier for PSO Design Optimization Environment," Presented at the 30th Applied Computational Electromagnetics Society, ACES, Symposium, Jacksonville FL, Mar. 23-27, 2014.