

# Integrated Optimal BLAC Motor Design Process for Electric Booster Brake System

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In this paper, an integrated optimal motor design process that can consider the motor performance in steady-state and transient-state and thermal characteristics of the motor. To simulate the motor performance in steady-state and transient-state, the finite element method (FEM) and an MATLAB/SIMULINK model of the vector controlled are used. Especially, to obtain the available motor operating time for the load condition that has a lot to do with the thermal characteristics of the motor, the interpolated experiment data by using the cubic spline interpolation method are utilized to predict coil temperature rise more accurately. Then all objective functions are modeled by using design of experiment (DOE), moving least square method (MLSM). Finally, the optimal points of BLAC motor for electric booster brake system is obtained by using constructed multi objective functions.

*Index Terms*—Torque Ripple, Optimal Design, BLAC Motor

## I. INTRODUCTION

Nowadays, the combined research of motor design and motor control is well treated to get a more detailed analysis result for the motor behavior. For that purpose, Sarikhani et al. [1] and Tsampouris et al. [2], in a recent comprehensive method, have presented a more improved motor control parameter modeling which can consider the back EMF harmonics and cogging torque, combining to the optimal motor design and the new combined optimization of steady-state and transient-state operation of the overall system, respectively. However, these methods are not considered the motor control parameters' variation and coil temperature rise according to changing motor operating condition such as ambient temperature and load condition. For considering the effects of loading, Seong et al. [3] are proposed analysis method utilized with an equivalent thermal resistance model. But the equivalent thermal resistance model has not a good agreement comparing with experiment results in transient state. Especially, in the electric booster brake system, it is more important to accurately estimate the coil temperature rise for load condition in transient state than any other applications.

In this paper, an integrated optimal motor design process that can consider the motor performance in steady-state and transient-state and the thermal characteristics of the motor. To estimate the motor performance in steady-state and transient state, the FEM and an MATLAB/SIMULINK model of the vector controlled are used. And to approximate the available motor operating time for load condition that has a lot to do with the thermal characteristics, the interpolated experiment data by using the cubic spline interpolation method are utilized to predict coil temperature rise more accurately. Then the objective functions are modeled by using, MLSM [4], and FEM. Finally, the optimal points of the BLAC motor are obtained by using constructed multi objective functions.

## II. OPTIMAL DESIGN STRATEGY IN BRAKE SYSTEMS

As a one of the main devices in electric booster brake system, the motor is required to be more less weight and quick

responsiveness in transient state and low torque ripple. As an effort to improved motor performance we developed the optimal BLAC motor design strategy as shown in Fig. 1.

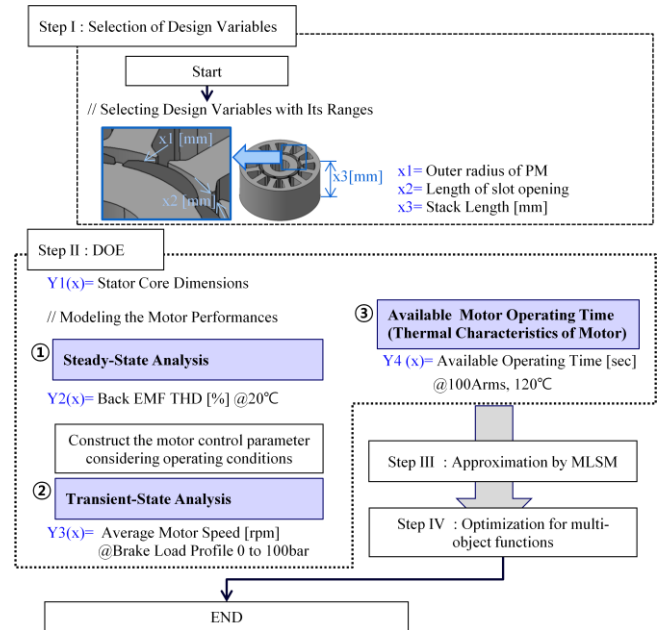


Fig. 1. Integrated optimal design process.

## III. MODELING THE MOTOR PERFORMANCES

To model the responses for the motor performance, the moving least-square function is utilized [4] as in the following equations, which expresses the sum of weighted errors:

$$L_y^i(x) = \varepsilon^T W(x) \varepsilon = (y - X\beta)^T W(x) (y - X\beta) \quad (1)$$

where  $W(x)$  is a function of the location which can be obtained from a weighting function.  $L_y^i(x)$  is  $i$ th moving least squares functions for the  $i$ th responses for motor performances. The weighting function uses the Gaussian function.

### A. Motor Performances at Static-State

To analysis motor performance at static-state such as back-EMF and torque ripple by changing motor geometry, the 2D FEM is used.

## B. Motor Performances at Transient-State

By using the motor control parameters, the integral MATLAB/SIMULINK model of the vector controlled [5] is used to obtain the motor speed response for the system load profile as shown in Fig 2

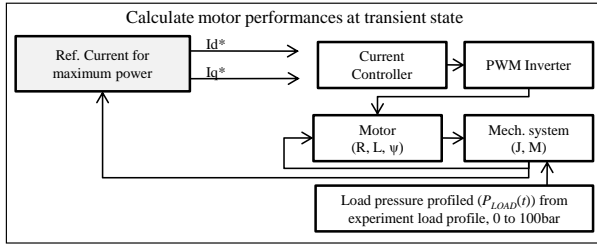


Fig. 2. Current vector control strategy by experiment load profile

In the step, the experiment load pressure profile  $P_{LOAD}(t)$  is translated to load torque  $T_{LOAD}(t)$  as (2)

$$T_{LOAD}(t) = P_{LOAD}(t) \cdot Kp \quad (2)$$

where  $T_{LOAD}(t)$  is load torque profile for the time,  $P_{LOAD}(t)$  is load pressure profile for the time obtained by experiment results,  $Kp$  is pressure per motor torque obtained by gear ratio and gear efficiency.

Also an average motor speed,  $N_{AVG}$ , at transient state can be calculated as (3)

$$N_{AVG} = \frac{1}{t} \int_0^{t_{req\_QuickBrake}} N(t) dt \quad (3)$$

where  $t_{req\_QuickBrake}$  is allowed max time for quick brake mode.  $N(t)$  is motor speed for the time as an analysis result at transient state.

To satisfied the quick responsiveness for the brake system, the average motor speed,  $N_{AVG}$ , should be meet the system requirement during the designated time,  $t_{req\_QuickBrake}$ .

## C. Available Motor Operating Time

The calculating process of available motor operating time is illustrated as shown in Fig. 3.

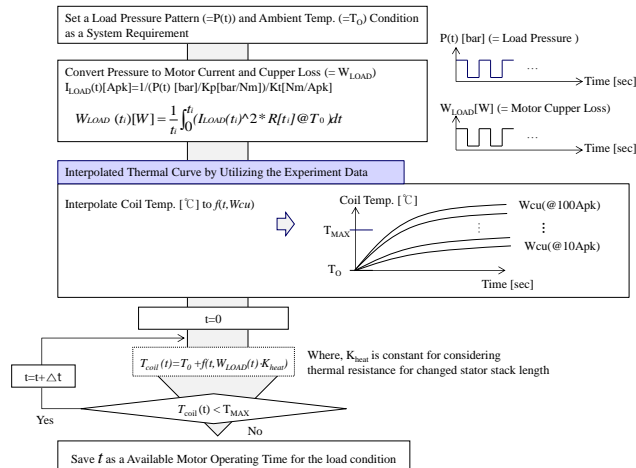


Fig. 3. Calculation of available motor operating time

To estimate the coil temperature rise, the cubic spline interpolation method is used as following

$$T_{Coil}(t) = T_0 + f(t, W_{LOAD}(t) \cdot K_{heat}) \quad (4)$$

where,  $T_0$  is ambient motor temperature,  $f(t, W_{LOAD}(t) \cdot K_{heat})$  is interpolated coil temperature by using cubic spline interpolation and experiment data,  $W_{LOAD}(t)$  is integrated copper loss which is consumed from zero to  $t$ , and  $K_{heat}$  is coefficient for considering changed heat transferred dimension due to the varied stator stack length.

The available motor operating time in transient-state is calculated by counting the time until the coil temperature is reached to the limitation of coil specification from the ambient temperature. The objective functions are constructed as followings and optimized

*Find* : Outer Radius of PM, Length of SO, Stack Length

*Minimize* : Stator Core Dimension

*Subject to*

$$Y2(x) < 0.6, Y3(x) > 6700, Y4(x) > 40$$

As an optimal design results, the approximated objective functions by MLSM has a good agreement with the simulation results by FEM as TABLE I. By using approximated objective functions, the optimal design is conducted to minimize the motor size that can satisfy the minimum motor required performance for the system.

TABLE I  
OPTIMIZED DESIGN RESULTS

Objective functions	Initial model	Optimized model		
		MLSM Results	FEM Results	Diff [%]
Y1: Stator Core Dimension [cm <sup>3</sup> ]	138	130	130	0
Y2: Back EMF THD [%]	0.518	0.527	0.517	1.90
Y3: Average Motor Speed [rpm]	6773	6762	6771	-0.13
Y4: Available Operating Time@11.3bar,120°C	47.4	40.0	39.3	1.75

## IV. CONCLUSION

This paper investigated an integrated optimal motor design process including the design, the control, and the thermal characteristics of the motor. As the optimal design results, the motor performance in steady-state and transient-state and the targeted operating conditions were satisfied the requirements of the electric booster brake system. Also it shows the usefulness of the optimal motor design process.

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