Dynamic Multilevel Optimization of Machine Design and Control Parameters for PMSM Drive System Based on Correlation Analysis

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***Abstract*—In this paper, a multilevel optimization method is proposed for a motor drive system which includes a surface mounted permanent magnet synchronous machine (SPMSM), the converter/inverter, and the control schemes. Firstly, the multilevel optimization is described by using the problem matrix which may be used to allocate the design variables on different levels. The parameters in the problem matrix are deduced by using correlation analysis. Secondly, the architecture and implementation of Multilevel Genetic Algorithm (MLGA) are carried out. As one of the advantages of MLGA, the dynamic adjustment strategy of GA operators is utilized to improve optimal performance. The algorithm is applied to a three-level optimization problem in which the optimization of SPMSM design and the control parameters of drive are considered in different levels. Finally, some results and discussions about the application of the proposed algorithm are presented.**

I. INTRODUCTION

Multilevel optimization is an effective method to solve complex optimization problem and it has been reported. Bartheley [1] used problem matrix method to describe the relationship between the objective functions and variables. Q. S. Li, et al. [2] presented Multilevel Genetic Algorithm (MLGA) for the optimization of actively control building under earthquake excitations. Multilevel optimizations are difficult to solve due to the characteristics of nonlinearity, multi-modal functions and mixed discrete variables.

Permanent magnetic synchronous machines (PMSMs) have been an attractive choice for many applications because of its high efficiency and power density. In this paper, MLGA is presented for design optimization of a motor drive system consisting of the drive circuit and an SPMSM controlled by using Field Oriented Control (FOC) to minimize the cost of copper and permanent magnets, and to maximize the efficiency of the motor and the drive system as well as the overshoot and ripples of output torque, speed and d-axis component of current. The finite element analysis (FEA) of the motor is used to calculate the no-load magnetic field, the back-electromagnetic force (back-EMF), the d- and q-axis components of the stator winding inductances.

II. FORMULATION OF MULTILEVEL OPTIMIZATION PROBLEM

In multilevel optimization problems, the relationship between the design variables, constraints and objective functions can be described by a Problem Matrix, as shown in Fig.1. In Fig. 1, the symbols $\boldsymbol{P}_{xx}$, i.e. P-values, are the coefficients, which indicate the relative importance between design variables and objective functions, as well as constraints in Correlation Analysis [3]. The larger the P-value is, the less relative importance of the design variable for the objective function is. In this paper, the samples of variables are determined by Design of Experiment (DOE) method. Some commercial statistic software packages, such as Minitab, can provide the module for the relative importance analysis.

$$\begin{array}{c|cccccc|}
\text{Design variables} & x_1 & x_2 & x_3 & x_4 & \cdots & x_m \\ \hline
\text{Objective function} & P_{01} & P_{02} & P_{03} & P_{04} & \cdots & P_{0m} \\ \hline
\text{Constraint 1} & P_{11} & P_{12} & P_{13} & P_{14} & \cdots & P_{1m} \\
\text{Constraint 2} & P_{21} & P_{22} & P_{23} & P_{24} & \cdots & P_{2m} \\
\vdots & & & \vdots & & & \\
\text{Constraint n} & P_{n1} & P_{n2} & P_{n3} & P_{n4} & \cdots & P_{nm} \\ \hline
\end{array}$$

Fig. 1. Problem matrix

According to P-values in the Problem matrix, the design variables may be arranged on diverse levels. For one objective function, the variables possess similar P-values will be managed on the same level.

III. MULTILEVEL GENETIC ALGORITHM

The architecture of MLGA is shown in Fig. 2. In MLGA the design optimization variables are classified and allocated to different levels according to the relative importance among the variables and objective functions, constraints, as well as the practical engineering weight and optimization sequence. The variables on different levels are encoded independently. Each level may have multiple populations and each of them can adopt different dynamic genetic operators and parameters. Furthermore, the relationship between sub-problems in multilevel problems can be handled by MLGA.

An independent GA can be described as follows.

$$GA=(\boldsymbol{PO}, \boldsymbol{PS}, \boldsymbol{IS}, \boldsymbol{FIT}, \boldsymbol{SO}, \boldsymbol{CO}, \boldsymbol{MO}) \tag{1}$$

where, $\boldsymbol{PO}$, $\boldsymbol{PS}$, $\boldsymbol{IS}$, $\boldsymbol{FIT}$ represent the population, the population size, the encoding length and the fitness value, respectively; $\boldsymbol{SO}$, $\boldsymbol{CO}$, $\boldsymbol{MO}$ are the genetic operations, i.e. selection, crossover and mutation.

The MLGA can be described as follows.

$$GA_{ij}=(\boldsymbol{PO}_{ij}, \boldsymbol{PS}_{ij}, \boldsymbol{IS}_{ij}, \boldsymbol{FIT}_{ij}, \boldsymbol{SO}_{ij}, \boldsymbol{CO}_{ij}, \boldsymbol{MO}_{ij}) \tag{2}$$

where, GA_{ij} stands for applying the independent GA to the *i*th level and the *j*th module. In the view of the reaction between different levels and adjoint sub-modules on the same level, GA_{ij} can be described as follows.

$$\begin{aligned} GA_{ij}=(&\boldsymbol{PO}_{ij}(GA_{i,j\text{-}1}, GA_{i\text{-}1,j}, GA_{i,j+1}),\\ &\boldsymbol{PS}_{ij}(GA_{i,j\text{-}1}, GA_{i\text{-}1,j}, GA_{i,j+1}),\\ &\boldsymbol{IS}_{ij}(GA_{i,j\text{-}1}, GA_{i\text{-}1,j}, GA_{i,j+1}),\\ &\boldsymbol{FIT}_{ij}(GA_{i,j\text{-}1}, GA_{i\text{-}1,j}, GA_{i,j+1}),\\ &\boldsymbol{SO}_{ij}(GA_{i,j\text{-}1}, GA_{i\text{-}1,j}, GA_{i,j+1}),\\ &\boldsymbol{CO}_{ij}(GA_{i,j\text{-}1}, GA_{i\text{-}1,j}, GA_{i,j+1}),\\ &\boldsymbol{MO}_{ij}(GA_{i,j\text{-}1}, GA_{i\text{-}1,j}, GA_{i,j+1})\ ) \end{aligned} \tag{3}$$

The GA_{ij} can be affected by upper level $GA_{i\text{-}1,j}$ or same level mudles, $GA_{i,j\text{-}1}$ and $GA_{i,j\text{-}1}$.

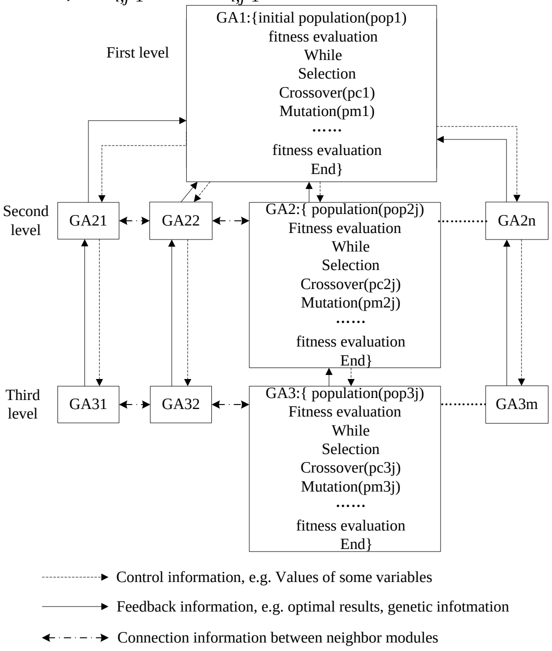


Fig. 2. Block diagram of MLGA

The implementation process of MLGA is as Fig. 3.

IV. APPLICATION OF MULTILEVEL OPTIMIZATION USING MLGA

In order to verify the proposed methods, an SPMSM controlled by FOC, rated at 950W output power, 2000 r/min speed and 128V line-to-line voltage, is used to verify the MLGA for multilevel optimization.

A. Determination of Multilevel Optimization Model

In the numerical example, a three level optimization model is selected, as shown in Fig. 5. Layer 1 and 2 optimize the structure of SPMSM, and the third level corresponding to the control layer. It is easily to divide the optimization model of SPMSM into two layers, that is, the structure level and the control level.

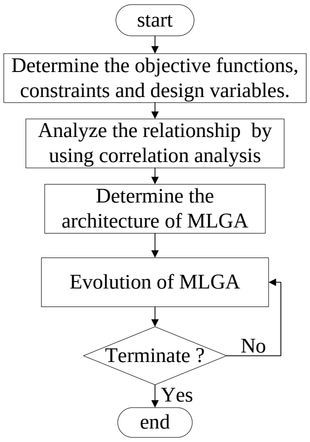


Fig. 3 Flowchart of MLGA

For the structure level of SPMSM, Correlation analysis and DOE are selected to determine the problem matrix, according to this theory, the P-values which describe the relative influence between design variables and object functions as well as constraints are analyzed by Minitab, a commercial statistic package.

The problem matrix is shown in Fig. 4.

Variables	*hm*	*bm*	*Ns*	*WindD*
max $f_{1\text{-}2}(\boldsymbol{X})$	0.270	0.666	0.001	0.000
$P_2 > 945\text{W}$	0.005	0.25	0.32	0.005
$Sf < 78\%$	1.000	1.000	0.000	0.000

Fig. 4. Problem matrix of MLGA for SPMSM

In Fig. 4, the P-values of *Ns* and *WindD* are less than those of *hm* and *bm* with respect to objective function. That is, *Ns* and *WindD* have important influences on efficiency and costs. Therefore, *hm* and *bm* are regarded as the variables of Level 1 and *Ns* and *WindD* are assigned to Level 2.

B. Multilevel Optimization Model

In the level 1 and level 2, the structure of the SPMSM, and in this model, the stator and rotor cores are not permitted to be modified due to manufacture limitation. That is, the coil pitch, parallel branches and wires per conductor of 3-phase windings are fixed. The magnet thickness and width, the diameter of conductor and the conductors per slot are chosen as design variables.

The optimization objective to level 1 and level 2 are to achieve maximum of efficiency with reasonable cost of conductors and magnets. The constraints are fill factor and rated output power. The optimization model of level 1 and level 2 can be described as (4).

$$\begin{aligned} &\max\ f_{1-2}(X_1) = K \Big/ \left(\omega_1 \frac{\cos t(\text{Cu})}{\max(\text{Cu})} + \omega_2 \frac{\cos t(\text{PM})}{\max(\text{PM})} + \omega_3 \frac{100-\eta}{100} \right) \\ &s.t.\ \ sf < 0.78 \\ &\qquad p_2 > 745\text{W} \end{aligned} \tag{4}$$

where, design variable $\boldsymbol{X_1}$=[*hm bm Ns WindD*]; *hm* and *bm* are the magnet thickness and width. *Ns* and *windD* are the conductors per slot and the conductor diameter, which are all discrete variables. *Max*(Cu) and *Max*(PM) are possible maximum of the cost of stator windings and permanent magnets, respectively; *Cost*(Cu) and *Cost*(PM) represent the cost of stator windings and magnets, respectively; η is the efficiency of SPMSM, K, ω_1, ω_2 and ω_3 are weight factors defined by designer. P_2 is output power and sf is fill factor.

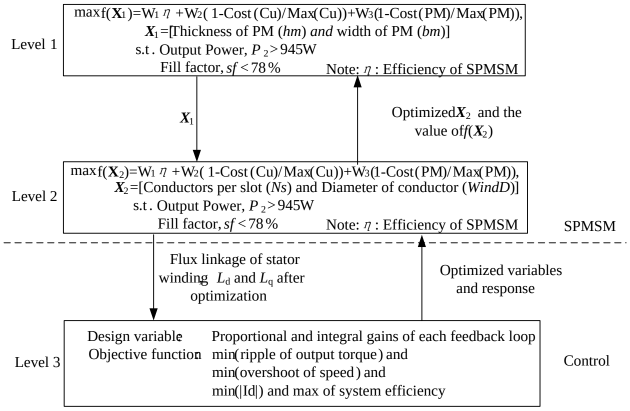


Fig. 5. Three-level structure of optimization

In the level 3, FOC was selected as the control strategy in this paper, it is known that FOC machines need two constants as in put reference: the torque component (aligned with the q co-ordinate) and, the flux component (aligned with the d co-ordinate). For the direct component of stator current only serves to produce waste heat and aggravate bearing wear, so the flux component corresponding to the *d* co-ordinate is set as zero in order to minimize the direct component of stator current. The referenced speed is set as rated 2000 rpm. The block diagram of SPMSM motor drive is shown in Fig. 4. Three PI controller are used for current (*d* co-ordinate and *q* co-ordinate component respectively) and speed control, Integral gain factor and proportional gain factor of PI controller to *d* co-ordinate and *q* co-ordinate component of stator current and speed are chosen as design variables, account to six variables. In the control layer the objective is to minimal the ripple of output torque and the overshoot of rotor speed minimal direct component of stator current Id in order to maximum the system efficient, and the objective can be formula as (5):

$$\begin{aligned} &\min f_3(X_2) = \alpha_1 \cdot Tqripple + \alpha_2 \cdot Ovshtspd + \alpha_3 \cdot I_d \\ &s.t. \quad Tqripple \le 0.5 \\ &\qquad Ovshtspd \le 0.5\% \\ &\qquad I_d \le 0.45A \end{aligned} \tag{5}$$

where $\boldsymbol{X}_2$ is design variables, *Tqripple* output of the torque ripple , *Ovshtspd* is overshoot of speed, I_d is direct component of stator current, α_1, α_2, α_3 are weight factors same as (4). It is worth mentioning that the control layer is implemented with the response optimization toolbox in MATLAB. Fig. 6 describes the FOC vector control block diagram used in the control layer of SPMSM, The optimization process of level three is terminated when all the constraints are met.

The design variable $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ are set of mixed-discrete variables and $f_{1\text{-}2}(\boldsymbol{X}_1)$ and $f_3(\boldsymbol{X}_2)$ are multi-modal objective functions.

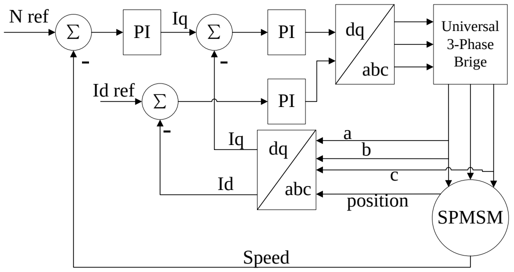


Fig. 6 FOC control block diagram

C. FEM for no-load EMF and L_{ad} and L_{aq}

On Level 1, considering the nonlinear characteristics of the core, the static FEM is applied to calculate the no-load EMF per turn and the d- and q-axis components of inductances, i.e. L_{ad} and L_{aq}, per turn to acquire the high accurate parameters when the magnet thickness and width are changed. Before solving L_{ad} and L_{aq}, the nonlinear FEM should be conducted excited by permanent magnets only and the permeability of each finite element needs to be saved. When linear FEM is applied to calculate L_{ad} and L_{aq}, the saved permeability will be assigned to corresponding elements. Fig. 7 pictures the magnetic field distribution when L_{aq} is calculated. Fig. 5 shows the three-level architecture of optimization for SPMSM.

D. Dynamic Adjustment of GA Operator

In order to overcome the optimization process converged to the local optimal, on each level, if the fitness maintains in a defined interval during several consecutive generations, the mutation operator P_{mu} is automatically adjusted according to (6)

$$P_{mu} = \begin{cases} P_m & , n_{unchange} = 0 \\ \dfrac{n_{unchange}}{maxgeneration}\,\omega & , n_{unchange} > 0 \end{cases} \tag{6}$$

where P_{mu} is dynamic mutation value, P_m is initial mutation value, $n_{unchange}$ is the number of unchanged consecutive generations of population fitness, ω is the regulator and *maxgeneration* is the terminating iteration.

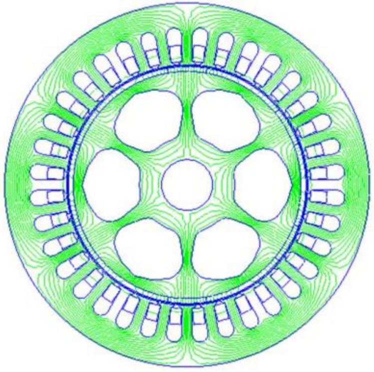


Fig. 7 Magnetic field distribution when L_{aq} is calculated.

E. Numerical results

The design variables, optimal results and comparison of MLGA and traditional GA on Level 1 and 2 are listed in TABLE I.

8. OPTIMIZATION

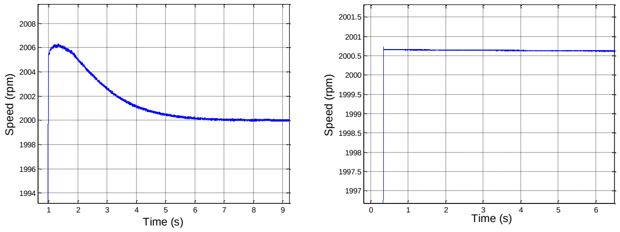
The proportional and integral gains calculated on the third level are listed in Table. 2. Fig. 8 illustrates the speed of SPMSM before and after PI controller parameters optimization. It can be seen from Fig. 8 that the overshoot of the rotor speed not larger than 0.7 rpm. Fig. 9 shows that the efficiency increased about 2.5%, and the output electromagnetic torque are more smooth and the ripple is lower as shown in Fig. 10. From Fig. 11 we find that the *d* co-ordinate component of stator current if decreased to nearly zero rapidly after optimization.

TABLE I
OPTIMAL RESULTS FOR SPMSM IN LEVEL 1 AND 2

Variables and performances	Original design	Multilevel GA	Traditional GA
Thickness of PM, h_m / cm	0.18	0.23	0.21
Width of PM, b_m / cm	3.14	3.03	3.03
Conductors per slot, *Ns*	72	67	66
Diameter of conductor, *WindD* / mm	0.5	0.56	0.56
Back-EMF, E_0 / V	66.0	61.9	60.9
q-axis component of current, I_q / A	4.78	5.27	5.37
d-axis component of current, I_d / A	1.60	0.05	0.15
Efficiency, η (%)	83.7	86.4	86.1
Cost of winding / RMB	72.6	84.7	83.5
Cost of PM / RMB	41.3	50.9	45.5
Output power , P_2 / W	946	949.5	951
Fill factor, *sf* (%)	67	77.7	76.5

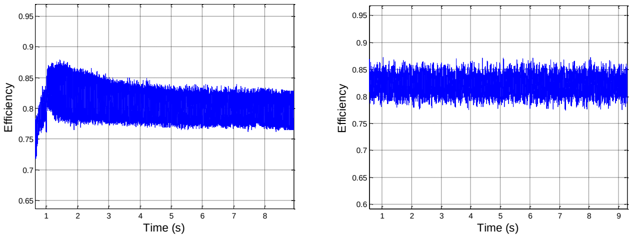
TABLE II
OPTIMAL RESULTS FOR CONTROL IN LEVEL 3

Variables and performances	Initial values	MLGA
Proportional gain in speed loop	1	18
Integral gain in speed loop	1	0.2
Proportional gain in I_d loop	1	20
Integral gain in I_d loop	1	0.32
Proportional gain in I_q loop	1	29
Integral gain in I_q loop	1	2



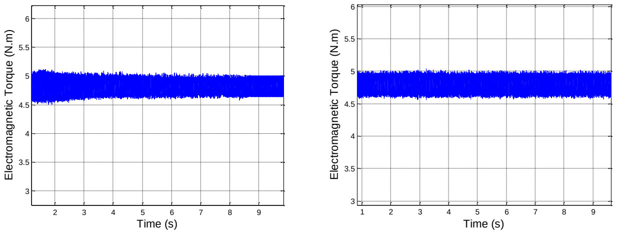
(a) Before optimization (b) After optimization

Fig. 8. Transient speed before and after optimization



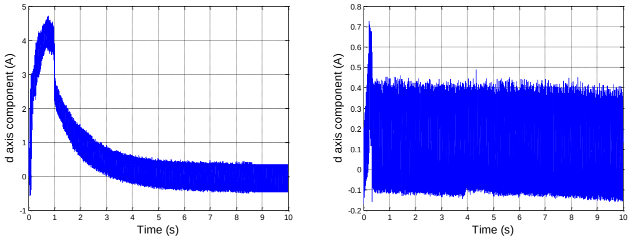
(a) Before optimization (b) After optimization

Fig. 9. Efficiency before and after optimization



(a) Before optimization (b) After optimization

Fig. 10. Electromagnetic torque before and after optimization



(a) Before optimization (b) After optimization

Fig. 11. *d*-axis component of stator current before and after optimization

V. CONCLUSION

According to the features and decision-making sequences, many real-world optimization problems in the engineering systems could be solved in multilevel procedures. This paper proposes an MLGA algorithm for SPMSM drive system to achieve complex multi-objective functions. The Correlation analysis is applied to construct the three-level structure and dynamic mutation operators on each level may dependently improve the convergence of the MLGA. It can be seen that the performances of both SPMSM and its controller can be optimized by using MLGA.

VI. REFERENCES

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