Parameters identification of PMSM based on self-adaptive DE algorithm with hybrid mutation operator

C Wang*, Y C Liu, Y Wei, Y Chen, M Y Xu, H H Guo, Q J Zhang and X L Liang

Marine Engineering College, Dalian Maritime University, Dalian, Liaoning, People’s Republic of China

*Corresponding author: chuanwang0101@163.com

Abstract. The parameter identification of permanent magnet synchronous motor (PMSM) is an important and challenging task of power electronic systems, which has an important impact on the control performance of the drive system. Due to hardware limitations, this problem requires both a higher solution quality and a faster convergence speed. Aiming at the parameter identification problem, an adaptive differential evolution algorithm based on hybrid mutation operator (SHDE) is proposed. In this method, a randomly selected optimal solution is mixed with the current population, and a new mutation operator is developed, called "current to best archive". Therefore, the algorithm can use the best search memory to date to generate promising solutions, resulting in a faster evolutionary process. In addition, the SHDO corresponding control parameters are adaptive without the need of trial and error and error processing, and the appropriate control values are obtained. In addition, the parameter estimation program is introduced into the permanent magnet synchronous motor simulation and solved by the Newton-Raphson method without prior assumption and simplification. The framework can be used in any interference-prone working conditions and, unlike other publications, has a wider range of applications. The parameter identification method of permanent magnet synchronous motor drive system under two different operating modes was evaluated. Comprehensive results and statistical analysis show that SHDE can find higher quality solutions with higher convergence speed and probability than other most advanced algorithms.

1. Introduction

Permanent magnet synchronous motors have been widely used in servo control and wind power generation due to their fast torque response, high power density and high efficiency. However, permanent magnet synchronous motor parameters require estimation of rotor speed and position using a sensorless control method. Well, it is difficult to measure parameters due to temperature rise and magnetic saturation. Therefore, in practical applications, the parameter values of the permanent magnet synchronous motor must be accurately obtained before designing the relevant control system. In order to solve this problem, some literature has been published to provide controllers with estimates of machine parameters. One of the off-line measurement methods is based on finite element analysis (FEA) of permanent magnet synchronous motors. Other methods rely on off-line measurement of PMSM parameters during steady-state operation, using an ABC reference frame or a rotating reference frame. The calculation results are saved in a table, and then the controller uses the parameter
information in the PMSM control operation. However, it is difficult to say whether the pre-calculated values are accurate. Some online estimation methods are usually limited to a subset of machine parameters, while offline measurements are used for the remaining parameters. Some researchers use off-line values of stator resistance and inductance to calculate the magnetic flux, position, and velocity of the rotor. Some published papers have developed more sophisticated strategies to identify the parameters of permanent magnet synchronous motors. For example, Liu et al. proposed a parameter adaptive identification method for nonlinear permanent magnet synchronous motors. During the identification process, the dynamic response of the permanent magnet synchronous machine is synchronized with another system having a similar dynamic structure. In another reference, an indirect rotor field oriented control scheme for sensorless speed control of a permanent magnet synchronous motor is proposed. The rotor flux linkage position is the effect of reducing system noise by directly integrating the rotor speed estimate. Adaptive estimation of stator resistance and rotor flux linkage is performed using a stable model reference adaptive system (MRAS) estimator. Bolognani et al. replaced the usual trial and error with a simple matrix selection. The method is based on full normalization represented by the Extended Kalman Filter (EKF) algorithm. In another work, a simplified reduced-order EKF model was established to estimate the winding resistance of the surface-mounted permanent magnet brushless AC motor and the flux linkage caused by the permanent magnet. Two reduced-order EKF models based on rotor position and speed sensorless operation are introduced. An on-line identification method for internal permanent magnet synchronous motor parameters and sensorless control based on identification parameters are proposed. In addition, the method uses neither rotor position nor speed to identify motor parameters. Two new methods are proposed by linear regression and neural network application, and the results of these methods are given. In addition, the calculated design values obtained from the finite element calculation are compared with the experimental values. However, these online parameter identification methods still have some drawbacks. For example, it is difficult to identify all parameters at the same time. In recent years, some evolutionary computation methods inspired by natural evolution have shown strong advantages in various engineering problems, and are more and more popular, such as reconstruction of ship power grid, reactive power optimization, optimization of milling operations. Parameters, optimization of multiple turning operations, structural optimization, etc. Ural design optimization, vehicle component optimization and comprehensive robust design optimization. Evolutionary algorithms such as genetic algorithm (GA), particle swarm optimization (PSO) and differential evolution (DE) perform well on multi-parameter simultaneous optimization. In the past literature, evolutionary computation has been successfully used for parameter estimation of asynchronous motors, DC motors, and hysteresis brushless exciters. In this paper, the genetic algorithm based on real coding is used to estimate the parameters of the induction motor. This paper also proposes a genetic algorithm based rotor time constant estimation method for asynchronous motor. Inductive motor parameters are estimated using a validated particle swarm optimization algorithm. In another paper, an improved induction motor parameter identification optimization function is proposed, in which the velocity error is also considered in the objective function. Some developers have proposed a search dynamic coding algorithm (DEAS) for induction motor parameter estimation, which is superior to Ga. Liu et al. The evolutionary algorithms for multi-parameter estimation of three non-salient permanent magnet synchronous motors are compared. Similar to the reference, the steady state of the permanent magnet synchronous motor model is used without considering the transient process, which may result in an error between the actual value and the identification value under dynamic conditions. In order to simultaneously identify the parameters of the permanent magnet synchronous motor (winding resistance, DQ axis inductance, rotor flux linkage), an adaptive denoising algorithm SHDE is proposed, which combines the mutation operator with the current population and the existing Successful memory is stored in the archive set. In this method, a new mutation operator is proposed, called "current best archive". The new mutation vector is generated by hybridization of existing populations and archives, which records successful individuals in previous searches. This mechanism can be used to balance the population diversity and rapid convergence speed (i.e exploration and development), so as to obtain satisfactory search performance on the permanent magnet synchronous motor parameter identification problem. In addition, the control parameters f and cr are also adaptive,
speeding up the search process by storing previous success values. According to the classification scheme introduced in some previous works, better parameter values, namely F and CR, are stored and designed to generate individuals who are more likely to survive. Therefore, this parameter control mechanism can be called adaptive.

The rest of this paper is organized as follows: Section 2 describes the mathematical formula for parameter identification of permanent magnet synchronous motors. Section 3 details SHDE. The fourth section presents a comparative experiment and analyzes the experimental results. Finally, Section 5 summarizes the conclusions and future work.

2. Problem formulation for parameters identification of PMSM

The electrical model of the PMSM in the rotating $dq$ frame is given as follows [1]:

$$\frac{di_d}{dt} = \frac{1}{L_d} v_d + \frac{1}{L_d} \omega i_q L_q - \frac{1}{L_d} R_i i_d$$

$$\frac{di_q}{dt} = \frac{1}{L_q} v_q - \frac{1}{L_q} \omega i_d L_d - \frac{1}{L_q} R_i i_q - \frac{1}{L_q} \omega \psi_r$$

where $i_d$, $i_q$, $v_d$, and $v_q$ are $dq$-axis stator currents and voltages; $\omega$ is the electrical angular speed; and $R_s$, $L_d$, $L_q$ and $\psi_r$ are the stator resistance, $dq$-axis inductance and the rotor flux linkage, respectively [1].

Also, the motion equation of rotor is shown as follows [2]:

$$\frac{d\omega_m}{dt} = \frac{1}{J} (T_e - T_l)$$

where $J$ is the rotor inertia; $\omega_m$ is the mechanical angular speed; $T_l$ is the load torque; $T_e$ is the machine electromagnetic torque, which is defined as follows [2]:

$$T_e = \frac{3}{2} p \left[ \psi_r i_q + (L_d - L_q) i_q i_q \right]$$

where $p$ is the number of pole pairs. Fig. 1 shows a block diagram of the PMSM drive system based on $dq$-axis. PI represents proportional integral (PI) controller. $A_v$ and $A_i$ are the amplification of speed loop and current loop, respectively.

![Figure 1](image)

**Figure 1.** Block diagram of the PMSM drive system under $dq$-axis.

First of all, the block diagram of parameters identification process of PMSM is displayed as Fig. 2. In the following figure, $i_d(t)$ and $i_q(t)$, $i'_d(t)$ and $i'_q(t)$ represent the actual and estimated current under $dq$-axis at $t$th sampling time, respectively. We can see from the figure, at $t$th sampling time, the parameters of PMSM are identified by using DE algorithm. DE algorithm calculates the best parameters so far to reduce the error between currents of real PMSM machine and PMSM model.
Based on above math model and identification process, at $t$th sample time, we estimate parameters of PMSM according to the following objective function:

$$f = \left( i_d(t) - \dot{i}_d(t) \right)^2 + \left( i_q(t) - \dot{i}_q(t) \right)^2 \quad (3)$$

The variables with “'” mean that they are calculated currents by the optimized parameters. The identified machine parameter values can be computed if Eq. (3) is minimized by the proposed method. Thus, the optimization of Eq. (3) can be regarded as a multidimensional function optimization problem.

### 3. Self-adaptive DE algorithm

Aiming at the parameter identification of permanent magnet synchronous motor, an adaptive self-adjusting mechanism of synchronous motor is proposed. First, the engineering problem requires fast convergence because the hardware cannot afford the computational time cost of an algorithm with slow convergence. Therefore, it may be a good idea to randomly select individuals from a successful archive population for the “currently best archived” mutation. This operation may lead people to find the currently promising search direction. Second, in order to maintain good population diversity, the classic “de-/current to best/1” mutation operator was used because the population was randomly initialized within the legal search range. The results show that the mixed mutation operator can achieve a good balance between convergence speed and population diversity. Third, calculate the median of a successful $F_{set}$ or $CR_{set}$ to accommodate the evolutionary process, thus making a trade-off between mining and exploration. Unlike other previously published works [3, 4], this adaptive mechanism does not add any additional parameters and does not have a cumbersome trial and error process. The overall algorithm description of SHDE is shown in Algorithm 1.

**Algorithm 1.** The pseudo code of SHDE algorithm.

1. Uniformly randomly initialize each individual within the searching range;
2. Calculate the fitness values of the initial population;
3. Set generation number $G = 1$; set population size as $ps$; set function evaluations as $Fes = 1$;
4. Set archive population $X_{ar} = \{\}$; $F_{set} = \{\}$; $CR_{set} = \{\};$
5. while $Fes \leq Max_{Fes}$
   6.   for $i = 1$ to $ps$
      7.     if $X'' = \{\}$
          8.        Randomly select one individual from $X$ as $X''_{p,G};$
      9.     else
          10.        Randomly select one individual from $X''$ as $X''_{p,G};$
      11.     end
     12.   if $F_{set} = \{\}$
        13.     $F = \text{normrnd}(0,5,0,1);$
     14.   else
        15.     $F = \text{median}(F_{set});$
     16.   end
     17.   if rand < 0.5
\[ V_{i,G} = X_{i,G} + F \cdot (X_{best,G} - X_{i,G}) + F \cdot (X_{i,G} - X_{old,G}) \]

else

\[ V_{i,G} = X_{i,G} + F \cdot (X_{old,G} - X_{i,G}) + F \cdot (X_{i,G} - X_{old,G}) \]

end

if \( Cr_{set} == [] \)

\( Cr = \text{normrnd}(0.5,0.1) \);

else

\( Cr = \text{median}(Cr_{set}) \);

end

Randomly select index of individual from \( ps \) as \( j_{rand} \);

for \( j = 1 \) to \( D \)

if \( \text{rand} \leq Cr \parallel j = j_{rand} \)

\( u_{i,G} = v_{i,G} \);

else

\( u_{i,G} = x_{i,G} \);

end

Calculate the fitness value of \( U_{i,G} \);

\( Fes = Fes + 1 \);

if \( f(U_{i,G}) < f(X_{i,G}) \)

\( X_{i,G+1} = U_{i,G} \);

Add successful \( U_{i,G} \), \( F \) and \( Cr \) into \( X^* \), \( F_{set} \) and \( Cr_{set} \);

else

Add \( \text{normrnd}(0.5,0.1) \) into \( F_{set} \) and \( Cr_{set} \);

end

Randomly remove an individual from \( X^* \);

end

while \( \text{length}(X^*) > ps \)

Remove the first element from \( F_{set} \) or \( Cr_{set} \);

end

\( G = G + 1 \);

end

4. Experimental results

We identify the parameters of PMSM during the motor simulation program at 0.5s with two different working conditions, respectively. The best results among the peer algorithms are shown in bold. Moreover, the results of a two-tailed Wilcoxon rank sum test [5,6] at a 0.05 level of significance are provided to statistically show the comparison between SHDE and other algorithms shown in Table 1.

| Method | Min    | Median  | Max     | Mean   | Std   | W-test | \( p \)-value |
|--------|--------|---------|---------|--------|-------|--------|--------------|
| R3PS   | 2.13e-12 | 1.00e-07 | 1.04e-04 | 4.44e-06 | 1.89e-05 | +      | 1.40e-11     |
| CLPS   | 7.66e-08 | 1.99e-04 | 7.60e-03 | 1.31e-03 | 2.23e-03 | +      | 1.40e-11     |
| DNSPS  | 1.54e-09 | 7.10e-03 | 4.76e-01 | 4.42e-02 | 1.01e-01 | +      | 1.40e-11     |
| SaDE   | 2.06e-16 | 6.55e-05 | 2.90e-01 | 2.01e-02 | 6.19e-02 | +      | 7.10e-11     |
The numerical results in Table 1 indicate that the optimal solution determined by SHDE is more advanced than the other methods in the above test system. R3ps, clps, dnsps, sade, l-shade, icpso, and pso are not very good. Although JDE can find the best solution, the average performance of JDE does not meet the needs of all 31 independent operations. This means that the performance of JDE is unstable. De/best/1 yielded similar results, showing poor performance. This may be caused by a highly nonlinear fitness function, that is, the fitness function may have multiple locally optimal multimodal fitness landscapes. In addition, from the test results of Wilcoxon, the algorithm is superior to other competitors. The simulation results show that the method can solve the problem better.

5. Conclusions
Aiming at the application of permanent magnet synchronous motor parameter identification, the SHDE algorithm is proposed. In this paper, the previous successful search memory and current population information are applied to the mixed mutation operator to obtain faster convergence speed and better solution. This mechanism can effectively improve the search ability. The performance of the method is verified on the experimental test system, which shows that the method has strong stability and convergence accuracy. Therefore, the algorithm can be used as an effective tool for parameter identification of permanent magnet synchronous motors.

Acknowledgments
This work is supported by Natural Science Foundation of China under Contract No. 51709027; Doctoral Scientific Research Foundation of Liaoning Province under Contract No. 20170520265; Natural Science Foundation of Liaoning Province, China under Contract No. 2014025006; Education Department General Project of Liaoning Province, China under Contract No. L2014209.

References
[1] Liu K, Zhang Q, Chen J, Zhu Z Q and Zhang J 2011 Online multiparameter estimation of nonsalient-pole PM synchronous machines with temperature variation tracking. IEEE Trans. Ind. Electron. 58 1776-1788.
[2] Jong-Wook K and Sang Woo K 2005 Parameter identification of induction motors using dynamic encoding algorithm for searches (DEAS). IEEE Trans. Power Appar. Syst. 20 16-24.
[3] Qin A K, Huang V L and Suganthan P N 2009 Differential Evolution Algorithm With Strategy Adaptation for Global Numerical Optimization. IEEE Trans. Evol. Comput. 13 398-417.
[4] Zhang J Q and Sanderson A C 2009 JADE: Adaptive Differential Evolution With Optional External Archive. IEEE Trans. Evol. Comput. 13 945-958.
[5] Garcia S and Herrera F 2008 An Extension on "Statistical Comparisons of Classifiers over Multiple Data Sets" for all Pairwise Comparisons. J. Mach. Learn. Res. 9 2677-2694.
[6] Derrac J, Garcia S, Molina D and Herrera F 2011 A practical tutorial on the use of nonparametric statistical tests as a methodology for comparing evolutionary and swarm intelligence algorithms. Swarm Evol. Comput. 1 3-18.