Maximum Torque per Ampere Control of Permanent Magnet Synchronous Motor Using Genetic Algorithm

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Abstract

Pengemudian motor sinkron magnet permanen (PMSM) mempunyai banyak keuntungan dibandingkan pengemudian motor lainnya, misal efisiensi tinggi dan kerapatan daya tinggi. Khususnya, PMSM adalah membuka peradaban baru dan semakin intensif dipelajari para peneliti, ilmuwan dan insinyur. Makalah ini menguraikan sebuah pengendali baru unjuk kerja tinggi berbasis algoritma genetik. Skema ini memungkinkan motor dikemudikan dengan karakteristik torsi per ampera maksimum. Makalah ini dengan asumsi fungsi fitness yang tepat, nilai optimal untuk arus listrik sumbu-d dari set poin motor di setiap waktu ditemukan dan kemudian diterapkan ke pengendali. Hasil simulasi menunjukkan keberhasilan operasi dari pengendali yang diusulkan.

Keywords: *algoritma genetik, kendali berorientasi medan, motor sinkron magnet permanen*

Abstract

Permanent magnet synchronous motor (PMSM) drives have many advantages over other drives, i.e. high efficiency and high power density. Particularly, PMSMs are epoch-making and are intensively studied among researchers, scientists and engineers. This paper deals with a novel high performance controller based on genetic algorithm. The scheme allows the motor to be driven with maximum torque per ampere characteristic. In this paper assuming an appropriate fitness function, the optimum values for d-axis current of motor set points at each time are found and then applied to the controller. Simulation results show the successful operation of the proposed controller.

Keywords: *field oriented control, genetic algorithm, permanent magnet synchronous motor*

1. Introduction

In recent years, the permanent-magnet synchronous motor (PMSM) has become increasingly popular for use in high-performance drive applications due to desirable features such as high torque-to-current ratio, high power-to-weight ratio, high efficiency, low noise, and robust operation. The advantageous features of the PMSM for modern drives applications are well established [1, 2]. Their fast and accurate speed response, quick recovery of speed from any disturbance, and insensitivity to parameter variations are some of the important criteria for high-performance drive systems used in robotics, rolling mills, machine tools, and electric vehicles.

Significant efforts are taken to improve PM motor efficiency. Since there are a great variety of PM motor configurations, the efforts are mainly focused on the search for the optimum rotor structure [3]-[7]. However, efficiency can also be improved by intervening in the motor operation principle with automatic control techniques. Several control methods have been proposed in order to reduce the loss of PM motor drives and improve their performance. The copper loss can be minimized by the maximum torque-per-ampere current control [1]. In surface PM motor drives, maximum torque per ampere current ratio is attained by keeping the *d*-axis

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component of the stator current equal to zero ($i_d = 0$). Since the "$i_d = 0$ control" prevents the demagnetization of the PM, it is often employed in interior PM motor drives. However, the i_d current, that provides maximum torque-per-ampere current ratio in interior PM motor drives, is a function of the i_q current and opposes the excitation field of the PM [8]-[10]. But there is not any efficient analytic mechanism to obtain a certain mathematical relation between i_d and i_q.

On the other hand, the optimal control of permanent magnet synchronous motors requires the accurate knowledge of the machine parameters. Generally, the magnetic parameters depend on the saturation level. For machines with interior magnets, all magnetic parameters (L_d, L_q and Ψ_m) show a significant variation with load current [11]. In this paper we use intelligent optimization methods. Intelligent approaches are widely used to control PMS motors in the recent decade [12, 13]. Genetic Algorithms (GA's) is one the most efficient methods for this application. In [14, 15] a GA is used to optimize the PID parameters of the controller. In this work, a new idea is proposed where maximum output torque is ensured with minimum stator current. An unknown function for d-axis current is derived in terms of q-axis current based on maximum torque per ampere criteria. The unknown function is then optimized by a GA including a fitness function, torque per ampere. In this approach the PID controller determines i_q and then i_d will be determined by multiplying i_q and the optimized unknown function. This paper is organized as follows; In section 2 the approximate model of the PMS motor is presented. GA optimization method is presented in section 3. Simulation results are presented in section 4. In section 5, the paper is concluded.

2. PMSM Dynamics

The mathematical model of a PMSM in the d-q synchronously rotating reference frame for assumed sinusoidal stator excitation is given as [13]:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{1}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \Psi_m \tag{2}$$

$$T_e = \frac{3}{4} p[i_q \Psi_m + (L_d - L_q) i_q i_d] \tag{3}$$

where:

L_q, L_d : q and d axis inductances

R_s : resistance of the stator windings

i_q, i_d : q and d axis currents

v_q, v_d : q and d axis voltages

ω_e : angular velocity of the rotor

Ψ_m : maximum flux linkage due to rotor permanent magnet

p : number of poles

T_e : electromagnetic torque

The equivalent circuit of IPM motors is obtained based on (1)-(2) as in Figure 1. There are two torque components associated with the motor torque equation. The first component (Cylindrical torque) is due to interaction between rotor magnet flux and stator q-axis current. The second component (reluctance torque) is due to motor saliency (difference in d and q inductance).

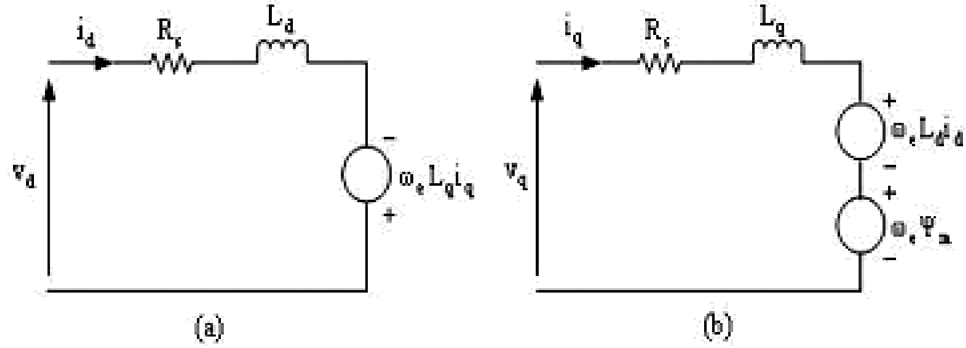

Figure 1. Equivalent circuit of IPM motors; (a) d-axis circuit, (b) q-axis circuit

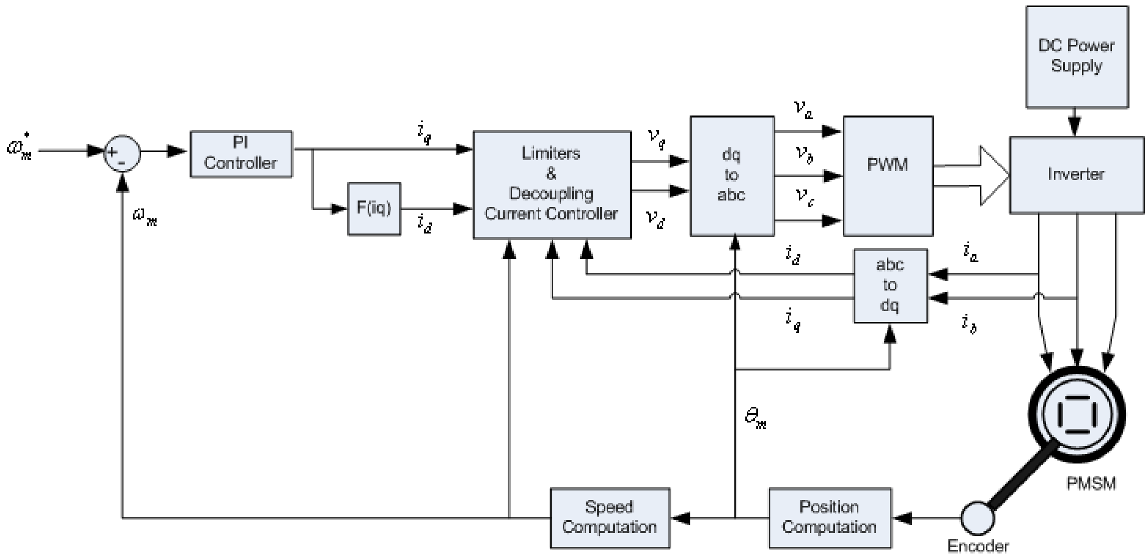

Figure 2. Block diagram of the complete PMSM drive system with the proposed controller

This saliency term is negligible in surface mounted permanent magnet motors. In the case of an interior permanent magnet motor where L_q not equal to L_d, the torque per ampere rating is boosted by the saliency torque term. In motoring operation, a negative i_d injection (as $L_q > L_d$) will contribute to the increase in reluctance torque. Efficient utilization of this reluctance torque component of (3) is most critical for intensive flux weakening operations and efficiency improvement at high speed in hybrid electric vehicles [16] and electric traction drives [17].

The output power is expressed as:

$$P_o = T_e \omega_m = \frac{3}{4} p [\Psi_m i_q + (L_d - L_q) i_d i_q] \omega_m \tag{4}$$

where:

$$\omega_m = \frac{2}{p} \omega_e \tag{5}$$

Finally the output power is simplified as follows:

$$P_o = \frac{3}{2}[\Psi_m \, i_q + (L_d - L_q) i_d \, i_q] \, \omega_e \quad (6)$$

The block diagram of the proposed drive system is shown in Figure 2. Where $F(i_q)$ is to be determined.

3. Research Method

In Genetic Algorithm (GA) is a stochastic global search method that mimics the metaphor of natural biological evolution. GA operates on a population of potential solutions applying the principle of survival of the fittest solution [18]. At each generation, a new set of potential solution is created by the process of selecting individuals according to their fitness in the problem domain and manipulating them like natural genetics.

This process leads to the evolution of populations of individuals that are better suited to their environment than the prior individuals, just as in natural adaptation. This technique is especially useful for complex optimization problems with a large number of parameters that make global analytical solutions difficult to obtain. The main operations of GA are initialization, fitness evaluation, selection, mutation and crossover. Figure 3 shows the procedure of GA.

$P(k)$ represents the population at stage k and $f(k)$ represents the fitness evaluation of the population $P(k)$. According to evolutionary theories, only the most suited elements in a population are likely to survive and generate offspring thus transmitting their biological heredity to new generations [19]. A GA maps a problem onto a set of strings (the chromosomes), each string represent a potential solution.

```
{
    k = 0;
    Initialize P(k)
    Evaluate f(k)
    While not finished
    {
        k = k + 1;
        select P(k) from P(k - 1);
        crossover P(k);
        mutate P(k);
    }
}
```

Figure 3. The simplified procedure of GA

The three most important aspects of using GAs are: (1) definition of the objective function, (2) definition and implementation of the genetic representation, and (3) definition and implementation of the genetic operators.

3.1. Genetic Algorithm Operations

A) *Selection* - The purpose of parent selection in a GA is to give more reproductive changes to those individuals that are the fit. There are many ways to do it, but one commonly used technique is roulette wheel parent selection (RWS). A second very popular way of selection is stochastic universal sampling (SUS) [18]. This way is a single-phase algorithm with minimum spread and zero bias. In this work, we will use SUS.

B) *Crossover (Recombination)* - The basic operator for producing new chromosomes in GA is crossover. Like its counterpart in nature, crossover produces new individuals that have some parts of both parent's genetic material. Single-point crossover, multipoint crossover, uniform crossover, line recombination and intermediate recombination are various crossover techniques [20]. In this study, single–point crossover has been employed. The crossover probability is set to ρ_c.

C) *Mutation* - In natural evolution, mutation is a random process where one allele of a gene is replaced by another to produce a new genetic structure. In GA, mutation modifies elements in the chromosomes randomly with low probability ρ_m, typically in the range 0.001 and 0.01, and modifies element in the chromosomes. The main role of mutation is to provide a guarantee that the probability of searching any individual will never be zero and to recover good genetic material that may be lost through the action of selection and crossover [18].

D) *Reinsertion* - Once selection and recombination of individuals from the old population have produced a new population, the fitness of the individuals in the new population may be determinate. If fewer individuals are produced by recombination than the size of the original population, then the fractional difference between the new and old population sizes in termed a generation gap. To maintain the size of the original population, the new individuals have to be reinserted into the old population. Similarly, if not all the new individuals are to be used at each generation or if more offspring are generated than size of old population then a reinsertion scheme must be used to determine which individuals are to exist in the new population. When selecting which members of the old population should be relocated the most apparent strategy is to replace the least fit members deterministically. The replacement should select and replace the oldest members of the population [18].

3.2. Fitness Function

To select the best suited solution, a criterion is needed. This criterion is fitness function [18]. In control applications, the fitness function is generally referred to minimization of the error between the desired and the real output. As maximum torque per ampere is the main objective in our control strategy, the following function is chosen as a fitness function.

$$fitness(i) = \sum_{t=0} \frac{T(t)}{I_s(t)} \tag{7}$$

So, (7) is the fitness function should be optimized using GA. In other word GA determines the unknown function, $F(i_q)$ at each moment to get the best fitness function and then i_d determine by multiplying i_q and optimized $F(i_q)$.

4. Results and Discussion

The proposed control system has been applied to the PMS motor with parameters as tabulated in Table 1. The simulations have been implemented in the Matlab-Simulink software. Here the proposed controller is compared with a conventional PI controller with $K_P = 0.1$, $K_I = 0.3$. A genetic algorithm with population size of 100 and $\rho_c = 1, \rho_m = 0.01$ is chosen as an optimizer. Initial population is chosen from the intervals $-15 \le i_d \le 15$. The fitness evaluation versus generation number depicts in Figure 4. Evidently, the generation number of 100 can satisfy our objectives. Figures 5 through 9 show the dynamic simulation results of the motor performance for PI controller and the proposed controller. In order to show the controller performance, the motor is started at no load with a reference speed of 200 rad/sec, then the rated load torque is applied at t=1sec.

Table 1. Permanent Magnet Synchronous Motor Parameters

Parameter	Value
Rated output power	1000 W
Rated phase Voltage	138.56 V
Magnetic flux linkage	0.533 Wb
Number of poles	4
Rated torque	3 Nm
Rated speed	1910 rpm
Rated current	5 A
Stator resistance	5.8 Ω
q-axis inductance	102.7 mH
d-axis inductance	44.8 mH
Inertia	0.000329 kgm^2

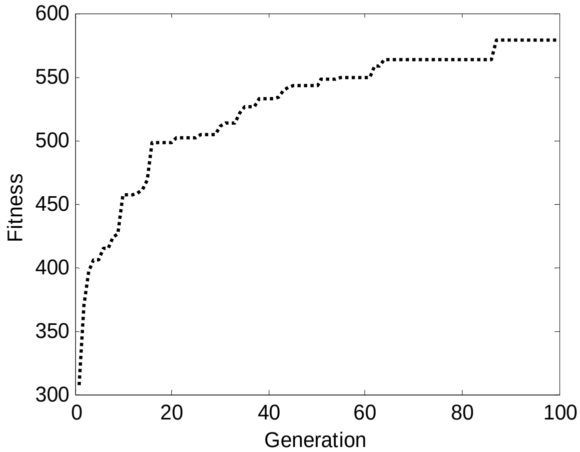

Figure 4. The best values of fitness function at each generation

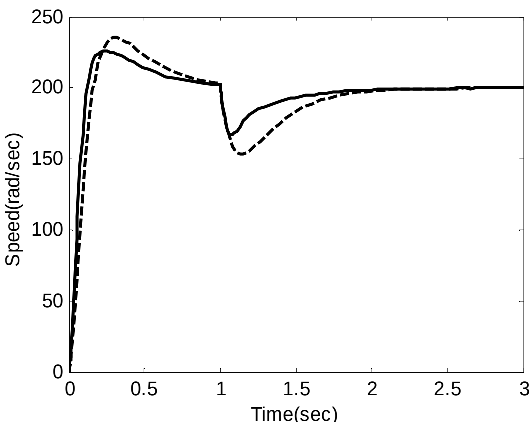

Figure 5. Motor speed when a step load disturbance is introduced at t=1s resulting from PI controller (dotted line) and the proposed controller (solid line)

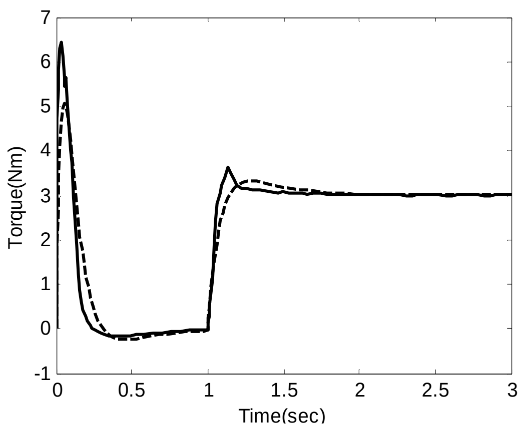

Figure 6. Electromagnetic torque in response to a step load disturbance resulting from PI controller (dotted line) and the proposed controller (solid line)

As shown in Figure 5 the motor can maintain the speed command after the load would applied. The motor torque is shown in Figure 6. The q and d axes currents are depicted in

Figures 7 and 8, respectively. The stator current of phase i_a after passing the transients and coming to steady-state is shown in Figure 9. Obviously, the proposed controller requires less current compared to the conventional controller. The results indicate that the performance of the proposed controller is suitable for high performance and efficient industrial drive applications.

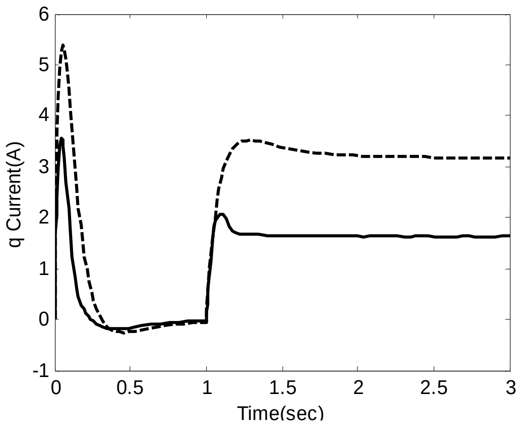

Figure 7. q-axis current in response to a step load disturbance resulting from PI controller (dotted line) and the proposed controller (solid line)

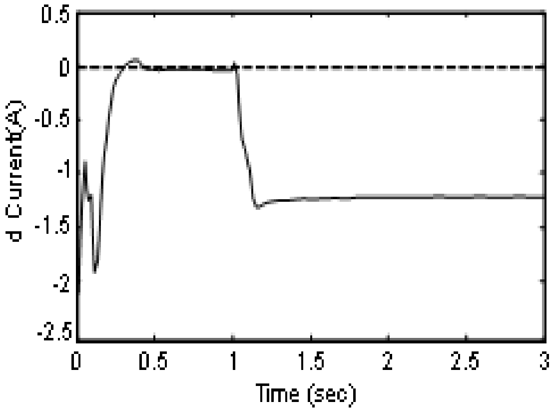

Figure 8. d-axis current in response to a step load disturbance resulting from PI controller (dotted line) and the proposed controller (solid line)

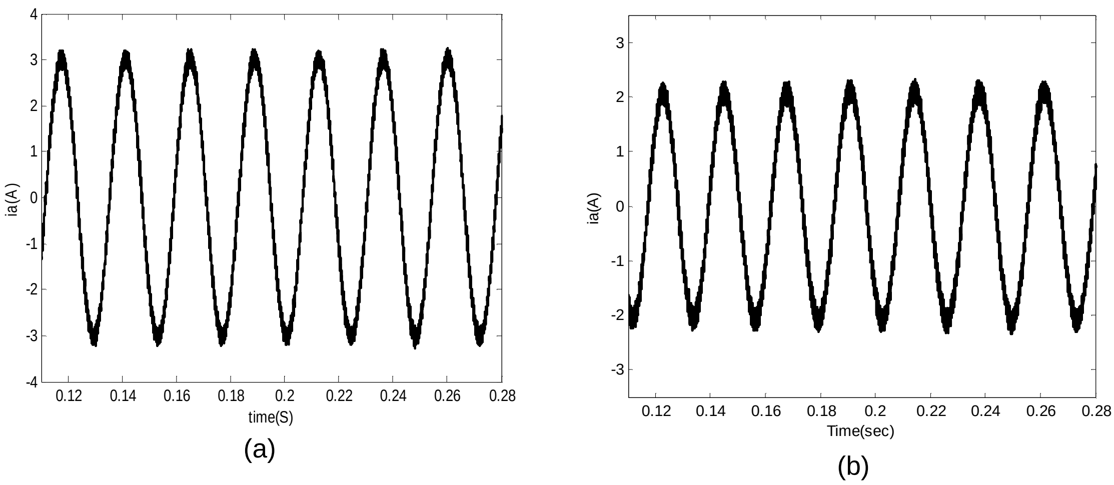

Figure 9. The stator current of phase *a* for the rated load with; (a) PI controller, and (b) the proposed controller

5. Conclusion

A high performance controller was introduced to provide maximum efficiency of PMS motors. In this approach the optimum value of *d* and *q* axes currents are obtained by virtue of a genetic algorithm. An unknown function was supposed as a relation between the currents that provides maximum torque per current. The controller included a PID controller to determine the i_q and a controller based genetic algorithm to determine the i_d. The sum of the torque per ampere values at all the time was defined as a fitness function while the GA optimized the unknown function at each time. Finally, i_d was calculated using the unknown function. A performance comparison of the proposed controller with the conventional PI controller was performed using computer simulations. Simulation results showed that in case of the proposed controller, the maximum torque per stator current of the drive is significantly increased.

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