Design of BLDCM Driving and Control System for Motorized Treadmill

Qi Zhang, Hui Li, and Li-Bin Wang

Abstract—To satisfy the requirement of developing a new generation of motorized treadmill for a famous domestic manufacturer, a brushless DC motor (BLDCM) driving and control system for motorized treadmill is developed. High integration and reliability of this system are ensured under the condition that intelligent power module (IPM) is used and the protection module is included. Periodic current control method is applied to reduce the average current flowing through the armature winding of the motor when the treadmill is required to start with low speed while large load is added. Piecewise proportion-integration-differentiation (PID) control algorithm is applied to solve the problem of speed fluctuation when impulse load is added. The motorized treadmill of a new generation with the driving and control system has the advantages of high reliability, good speed stability, wide timing scope, low cost, and long life-span. And it is very promising for practical applications.

Index Terms—Brushless DC motor, intelligent power module, motorized treadmill, periodic current control method.

1. Introduction

Along with human life quality is being improved and human pay more and more attention to their own health, body-building equipment has become the pop industry. As the outstanding representation, motorized treadmill attained quick development in the past several years. The appearance of motorized treadmill satisfies the requirements of indoor exercise and round-the-clock exercise and has better effect than traditional land exercise at the same time. According to the market investigation, the driving motor used in motorized treadmills home and abroad at present in the medium-low markets most uses DC motor with brush, has the power of 1.5 HP-2.0 HP, and applies pulse width modulation (PWM) square wave driving technology. They have the following problems: great mechanical noise, short continual working time, high maintenance cost, and short life-span. The driving motor in the high markets most uses AC motor, most has the power of 3.0 HP or so, and most applies vector control frequency conversion technology. Some of them have lifting motors of 1/10 HP and grade changing between 0% and 15%. Although it has good performance, its high cost limits its market.

The brushless DC motor (BLDCM) uses the electronic commutation to replace the mechanical commutation of the traditional DC motor. The BLDCM has the advantages of good timing performance and high operating efficiency, which the DC motor has, and has the advantages of simple structure, convenient maintenance and reliable operation, which the AC motor has. Furthermore, the BLDCM does not need excitation winding, has small volume and has high power density [1]. Motorized treadmill using BLDCM as the driving motor has the advantages of low cost, small mechanical noisy, long continual working time, convenient maintenance, wide timing scope of the running belt, and small speed wave.

In this paper, based on the analysis of the specialties of motorized treadmill load, the design method of BLDCM driving and control system for motorized treadmill is introduced. Several key points which should be paid special attention to in hardware design, the work done on the control algorithm and the design frame of the system software are presented in detail, respectively.

2. Load Specialties of Motorized Treadmill

The process of linear acceleration of the speed of the running belt from zero to the speed value set by the user can be finished through acceleration once or several times after motorized treadmill receives the instruction sent by the controlling board. Similarly, the process of deceleration can also be finished through deceleration once or several times till the speed equals zero. But through analysis of single acceleration or deceleration process, the ideal movement mode of motorized treadmill can be shown in Fig. 1.

![Ideal movement mode of motorized treadmill](image-url)
The feet of one person alternatively touch the belt when the person runs on motorized treadmills. This pose determines that the load bore by motorized treadmill under the ideal movement mode is impulse load \( I^2 \). As shown in Fig. 2, the load almost is the periodic function of the time and its value does not change greatly.

![Fig. 2. Relationship between load and time.](image)

### 3. Hardware Realizing Method

The BLDCM driving and control system for motorized treadmill mainly consists of power supply module, power driving module, protection module, controller module, speed detection module, and lifter driving module, as shown in Fig. 3. The key points of some modules are given as follows.

#### 3.1 Power Supply Module

The power supply of the main power section is the 220 V AC filtered by the capacitance after directly being rectified. At the same time, through the transformer and the rectifier three independent DC power supply of 15 V, 12 V and 5 V required by the system are attained. 15 V is taken as the controlling signal power supply of the power module driving circuit section. 12 V is taken as the power supply of the BLDCM Hall sensor. 5 V is taken as the power supply of the controller of the system.

![Fig. 3. Driving and control system of BLDCM.](image)

#### 3.2 Power Driving Module

In order to improve the reliability of the hardware system, the intelligent power module (IPM) is chosen as the core element of the power driving module and bootstrap circuit is applied to provide power supply for the high driving circuit of the module.

In Fig. 4, the upper and the lower insulated gate bipolar transistor (IGBT) on the same bridge arm can not be led at the same time. When the lower one is on (take IGBT2 as the example), the bootstrap capacitor charges through the path shown by the red dashed, and the voltage of \( C_1 \) will ascend to \( V_{cc} \); when the upper one is on (take IGBT1 as the example), because the driving circuit consumes the current, the voltage of \( C_1 \) will descend. These two processes are repeated.

![Fig. 4. Bootstrap circuit.](image)

#### 3.3 Protection Module

Because the user of motorized treadmill is human, reliability of this system is very important. IPM itself has the protection functions of short circuit and control supply circuit under voltage. Besides these, protections of over voltage or voltage shortage of the main power supply and overheat of the IPM power module are provided \( I^2 \).

The practicality of BLDCM driving and control system for motorized treadmill is shown in Fig. 5 and Fig. 6.

![Fig. 5. Practicality of BLDCM driving and control system.](image)

![Fig. 6. Motorized treadmill with new driving and control system.](image)
4. Control Algorithm

4.1 Speed Detection Method

The detection of the BLDCM speed is very important to the control of the speed of motorized treadmill. Considering the cost, and taking the photoelectric coded disk is not used as the precondition, the normal method is to count the varieties of Hall signal during a period of time and to use it to calculate the speed of the BLDCM (method one). The disadvantage of this method is that the speed precision calculated seriously depends on the time of sampling period. If the sampling time is too short, the degrees of the Hall signal will reduce. It is obvious that the speed precision calculated is not enough. If the sampling time is too long, the adjusting time will become longer and because the speed change can not be dealt with in time, the response will become slower. Based on these reasons, the method of recording the Hall signal change was given up in this design, and the method of recording the time interval of two Hall signals change was applied (method two). The data attained through the two methods of testifying the speed is shown in Table 1. Contrasting them with the speed measured through the equipments, the latter is more accurate can be seen. It provides good basis for closed loop control.

<table>
<thead>
<tr>
<th>Case</th>
<th>Speed (r/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>237 880 1174 1220 1487</td>
</tr>
<tr>
<td>Method 1</td>
<td>225 850 1150 1250 1450</td>
</tr>
<tr>
<td>Method 2</td>
<td>238 880 1172 1220 1486</td>
</tr>
</tbody>
</table>

4.2 Start Process of Motorized Treadmill

It’s required that the BLDCM can start with a lower speed stably when a person within 200 kg is standing on the running belt. The inducting voltage of the armature winding in BLDCM is

\[ E = C_e \Phi_d n \]  

where \( C_e \) is the voltage constant, \( \Phi_d \) is the magnetic flux per pole, \( n \) is the rotating speed of the BLDCM.

Within every leading time period the voltage balance equation is

\[ U - \Delta U = E + 2I_a R_a \]  

where \( U \) is the voltage of the power supply, \( \Delta U \) is the saturation voltage drop of the IGBT, \( I_a \) is the phase current through the armature winding, \( R_a \) is the phase resistance.

Substituting (1) into (2) we obtain

\[ I_a = (U - 2\Delta U - C_e \Phi_d n) / (2R_a) \]  

Taking the reference of Fig. 1, and assuming \( t_1 = 0 \) and \( n_1 = 0 \), then this figure describes the start process of the BLDCM.

The system requires it can start with low speed and high torque, so \( n_2 \) is smaller and \( t_2 \) is bigger. Then, during the start instant (3) can be transformed to the following equation:

\[ I_a = (U - 2\Delta U) / (2R_a) \]  

Generally, \( \Delta U \) and \( R_a \) are very small. Then we can know: with low speed and high torque of the BLDCM, the current flowing through the armature winding in the start process is so strong that it can easily burn the power element. Several methods were applied to solve this problem. Firstly, choosing suitable PWM frequency is very important. Secondly, periodic current control method was applied. That is, in every carrier wave period of PWM, corresponding IGBT should be opened according to the normal steps and the current size should be detected. If the current value is bigger than the value set in advance, then the IGBT and PWM should be off and this condition will be kept until the end of this period. Through this method, not only the possibility of damage of peak value voltage can be reduced, but also the dependence on the voltage change ratio of the motor in the start process can be reduced, then the reliability and the adaptability of the controller can be improved. The start process of the BLDCM is shown in Fig. 7.

![Fig. 7. Start process of the BLDCM.](image)

4.3 Speed Control Method

The movement equation of the BLDCM is

\[ T_e - T_L = J \frac{d\omega}{dt} = J \alpha_L \]  

where \( T_e \) is electromagnetic torque, \( T_L \) is load torque, \( J \) is rotating inertia of the system, \( \alpha_L \) is the angle acceleration of the BLDCM. Obviously, under the effect of impulse load, the speed wave of the running belt will be very large. Piecewise proportion-integration-differentiation (PID) control algorithm was applied to solve this problem.

To avoid problems of difficult measurement of kinds of parameters on the start stage of motorized treadmill, fuzzy self-tuning PID control was applied on the low speed stage. It makes the BLDCM operate stably, as shown in Fig. 8 and Fig. 9.
The expression of the PI control algorithm on the normal position is \[ U_k = K_p e(k) + K_i \sum_{j=0}^{k} e(j)T \] (6)

where \( U_k \) is the \( k \)th output, \( K_p \) is proportion parameter, \( e(k) \) is the \( k \)th error, \( K_i \) is integration parameter, \( T \) is the sampling period.

Through applying this method, good control effect was achieved in the circumstance of medium and high speed of the BLDCM, and the speed curve on speed shift stage seemed smooth, and the overshoot was restrained greatly, as shown in Fig. 10 and Fig. 11.

![Fig. 10. Decelerate effect when traditional PID control algorithm is applied.](image)

![Fig. 11. Decelerate effect when anti-saturation integral PI control algorithm is applied.](image)

In the high speed operating circumstance, when the real rotating speed is lower (or higher) than the rotating speed set in advance, if applying traditional PI control algorithm, the output PWM Duty ratio will add ceaselessly even reach the limit position because of integral function and change in one direction. Therefore, during reverse speed adjustment, the duty ratio will stay on the limit position and it can’t be adjusted correspondently along with the error in time, the whole system will lose control. Even if it does not enter the limit position, it will spend more time when exiting the saturation zone because of too much integral addition. It will lead to big overshoot and this is extremely bad to the operation of motorized treadmill. Therefore, anti-saturation integral PI control algorithm was applied on the medium and high speed stage, (because differentiation parameter is too sensitive to interfere, and the speed wave can’t be avoided, differentiation parameter is missed to attain convenient control). Before calculating \( U_k \), whether \( U_{k-1} \) calculated last time has gone beyond limit scope or not should be judged firstly in this algorithm. Assuming this scope is \( A \), if \( U_{k-1} > A \), then \( U_k \) can only be added with negative error; if \( U_{k-1} < -A \), then \( U_k \) can only be added with positive error.

5. Software Design Method

The core of the BLDCM driving and control system for motorized treadmill is the microcontroller PIC18F4331. Its
basic functions are shown below.

1) Through detecting the Hall signal of BLDCM, corresponding driving and control instructions were sent to maintain the regular running;
2) Closed loop control algorithm was applied to ensure the stability of the speed of the BLDCM;
3) Through running the inquiry program the instructions coming from the exterior keys were dealt with, such as requiring the motor to accelerate or to decelerate, requiring the running belt to ascend or to descend and so on;
4) All abnormal signals were detected and would be dealt with quickly.

The system program flow chart is shown in Fig. 12. Interruption program flow chart is shown in Fig. 13.

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**Fig. 13.** Flow chart of interruption program.

6. Conclusions

In this paper, a BLDCM driving and control system for motorized treadmill of a new generation is presented after analyzing the characteristic of its load. With the assistant of protection circuit, IPM, a kind of advanced power module is used to work as the core power element. To reduce the average current flowing through the armature winding of the motor when low speed is required and large load is added in the start process of the treadmill, proper PWM frequency is chosen and periodic current control method is applied. To reduce the speed fluctuation when suffering impulse load, piecewise PID control algorithm is applied.

Comparing with traditional motorized treadmill, the system is reliable, efficient, inexpensive and the treadmill of a new generation has wide timing scope, nice speed stability are indicated in the experiments.

**References**


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