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The High Response and Precision Control of ETC Module without the Hall Position Sensor for Detecting Rotor Position of BLDC Motor

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Abstract

This paper describes the high response and high precision position control of ETC module using BLDC motor without the hall sensor for detecting a rotor position. The proposed ETC control system, which is mainly consisted of a BLDC motor, a throttle plate, a return spring and reduction gear, has a position sensor with an analogue voltage output on the throttle valve instead of BLDC motor for detecting the rotor position. So the additional commutation information is necessarily needed to control the ETC module. For this, the estimation method is applied. In order to improve and obtain the high resolution for the position control, it is generally needed to change the gear ratio of the module or the electrical switching method etc. In this paper, the 3-phase switching between successive commutations is adapted instead of the 2-phase switching that is conventionally used. In addition, the position control with a variable PI gain is applied to improve a dynamic response during a transient period and reduce vibration at a stop in case of matching position reference. The mentioned method can be used to estimate the commutation state and operate the high-precision position control for the ETC module and the high response characteristics. The validity of the proposed method is examined through the experimental results.

Keywords: electrical throttle control, high-precision position control, commutation estimation method

1 Introduction

In automotive traditional engines the air coming into the intake manifold, and therefore the power generated, strongly depends on the angular position of a throttle valve.

In traditional systems the throttle position is actuated by a mechanical link with the accelerated pedal, directly operated by the driver.

But in recent years an electronic throttle is increasingly being used in automotive engines in order to provide implementation of engine-based vehicle dynamics systems and the increasing requirements in terms of emissions control, drivability and safety have led to the development drive by wire.

Automatic air flow control requires the additional actuators: for example, step motor, dc motor and brushless dc motor (BLDC). In case of BLDC motor among them, it has an advantage of reliability and higher performance although it has a slightly high cost of production.

Generally an electronic throttle control system should meet the following requirements in a view of engineering practice. Settling time of the position control system should be less than 100 ms for any operating point for any reference step change. The steady-state error should be less than 0.1 degree and no overshoot of the step response is allowed: this requirement is particularly important for the large signal mode in order to avoid hitting the mechanical stops at the maximum position. Low level of vibration in the throttle position signal and the commanded signal is required in order to avoid excessive potentiometer and transmission wear and motor losses.

Robustness of the control system with respect to variations of process parameters is needed, which can be caused by production deviations, variations of external conditions and aging. In order to satisfy the requirements on fast and accurate throttle response, the linear controller is designed well for the large signal operating mode and the friction influence needs to be considered for the small signal operating mode. This can be usually done either by improving the electronic throttle mechanical/electrical design or by applying a compensation algorithm.

In this paper, the electronic throttle is a BLDC servo drive which has 3 level cascaded control structure and 3 phase excitation method. The outer position controller is designed as a PI controller with the variable gains based on speed difference for the high performance at the steady sate and transient period. The inner current loop with a PI controller is used to develop a maximum torque for tracking a speed command and compensating the load disturbance including air mass flow and friction etc. The validity of the proposed method is examined by experimental test.

2 Control of ETC Drive System

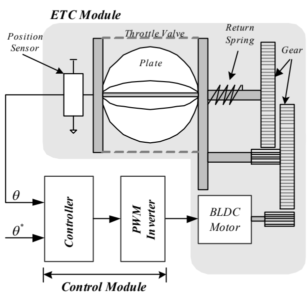


Figure 1: The conceptual ETC module

Fig.1 shows the conceptual electronic throttle controller module. It is mainly consisted of BLDC motor, a throttle plate, a return spring, a reduction gear and position sensor with an analogue voltage output (i.e. potentiometer) on the throttle valve instead of BLDC motor for detecting rotor position.

The throttle plate motion is constrained by a return spring that returns the plate into its initial position in case of power supply failure. In general, the electronic throttle body has limp-home position, thus allowing the driver to limp the vehicle home. But the applied system has the bypass of the throttle valve whose section is regulated through the solenoid-type valve at the mentioned condition. So there isn't nonlinear characteristic by the return spring.

2.1 Linear model of BLDC motor

Fig.2 shows the equivalent circuit of BLDC motor with Inductance ($L_x, x = a,b,c$), resistance (R) and back EMF ($e_x, x = a,b,c$) proportional to the rotation speed of motor.

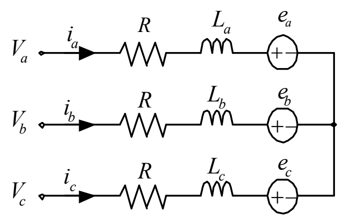


Figure 2: Equivalent circuit of BLDC motor

The corresponding equation is the following that

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} R\,0\,0 \\ 0\,R\,0 \\ 0\,0\,R \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_b & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad (1)$$

where

$L_a = L_b = L_c = L_s$	: self inductance
$L_{ab} = L_{bc} = L_{ca} = M$	: mutual inductance
i_a, i_b, i_c	: phase current
v_a, v_b, v_c	: phase voltage

If considering self-and mutual inductance in eq. (1),

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} R\,0\,0 \\ 0\,R\,0 \\ 0\,0\,R \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad (2)$$

And then substituting $i_a + i_b + i_c = 0$ in eq. (2)

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \frac{d}{dt} \begin{pmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad (3)$$

where $L = L_s - M$

Therefore the output and torque equation are expressed as the following that

$$P_{out} = e_a i_a + e_b i_b + e_c i_c \quad (4)$$

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_{mech}} \quad (5)$$

where ω_{mech} : mechanical speed

2.2 Control of ETC Module

In General, two phase excitation method is used to operate the ETC Drive System using BLDC Motor in which the commutation of current depends on the back-EMF of BLDC motor including position information of rotor.

Therefore it is essential to detect the rotor position with/without a hall sensor and then sequentially to conduct the phase current as shown in fig.3.

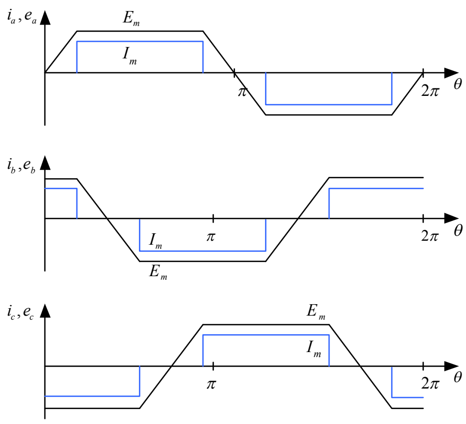
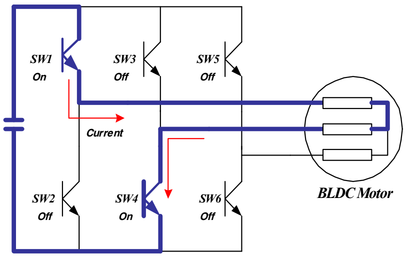


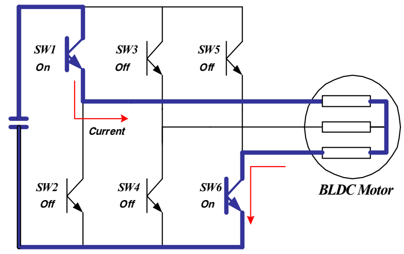
Figure 3: Back-EMF vs. Phase Current of BLDC

In this paper, the ETC module has a position sensor with an analogue voltage output on the throttle body instead of BLDC motor for detecting rotor position. So an indirect estimation method is needed to control the ETC module.

Fig.4 and 5 show the conduction path and a sensor output when BLDC motor is driven by the change of switching state at two phase excitation.



(a) Conduction Path 1 (SW1→SW4)



(b) Conduction Path 1 (SW1→SW6)

Figure 4: Conduction path in 2 phase excitation

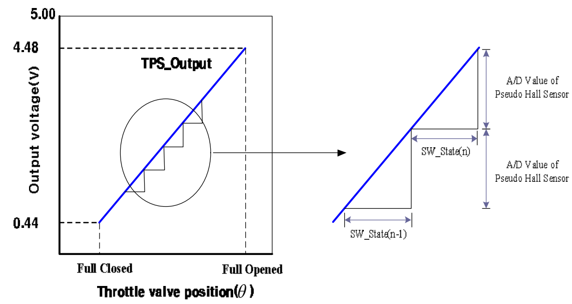


Figure 5: TPS voltage output in 2 phase excitation

The mentioned estimation method is to use the step-like position sensor output based on the A/D conversion value of containing next or previous switching state indirectly to determine the phase commutation.

Therefore if there is any position of rotor, it is possible to obtain the position information for commutation through the discrete output signal of throttle position sensor.

In case of two phase excitation, however, the position control is operated by 60 degree in electrical angle and so it is needed to raise the reduction ratio of module or pole number of motor for a high precision control.

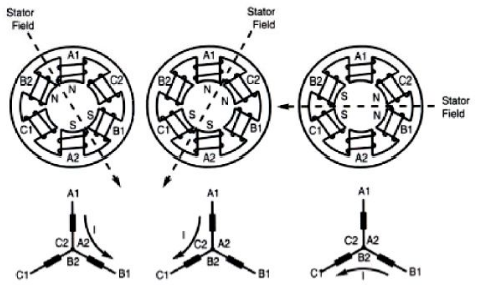
But these changes can be resulted in decreasing a dynamic response of the module, although it is directly increasing the resolution of position control.

In addition, the mentioned method has a burden of increasing the rotation speed of motor at no-load condition or/and the developed torque at lock condition for improving dynamic response.

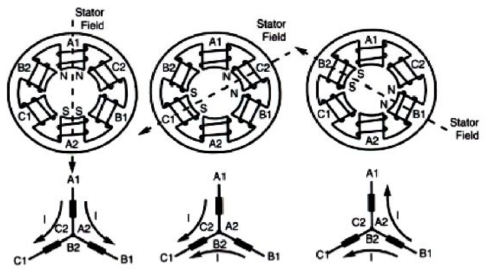
3 The Proposed Control Method

In this paper, it is applied to the three phase excitation method instead of the two phase excitation, the common method of operating BLDC motor, as shown in fig.6 that can improve the high resolution and precision without the additional change of the mechanical or electrical specification design, for example, a reduction ratio and pole number of BLDC motor.

In General, two phase excitation method has the higher average torque and the lower usage of torque than three phase excitation. But because the position control of motor can be operated in the only energized stator windings in case of two phase excitation method, it is difficult to do high resolution position control of motor between the energized windings.



(a) 2 phase excitation method



(b) 3 phase excitation method

Figure 6: Comparison of excitation method

On the other hand, the applied method can achieve a high-precision control at any position and the shape of phase current is not rectangular waveform but a sinusoidal one.

Fig.7 shows that the correlation of throttle valve position output and the conducted current waveform per mechanical cycle, of which the throttle plate moves from the full-closed state (0 degree) to the full-open state (90 degree) or to the contrary and also an electrical cycle has 4 times of a mechanical one considering BLDC motor with 6 slots and 4 poles.

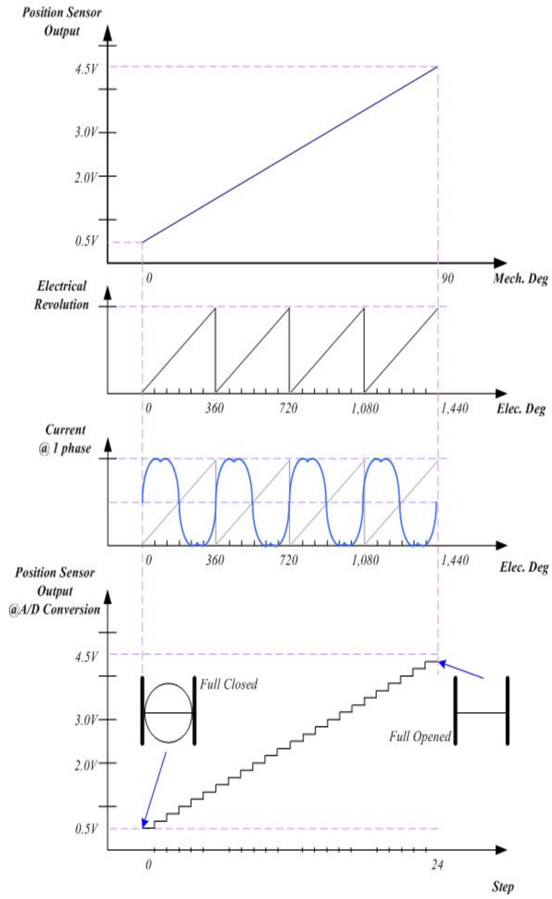


Figure 7: Position output & current waveform

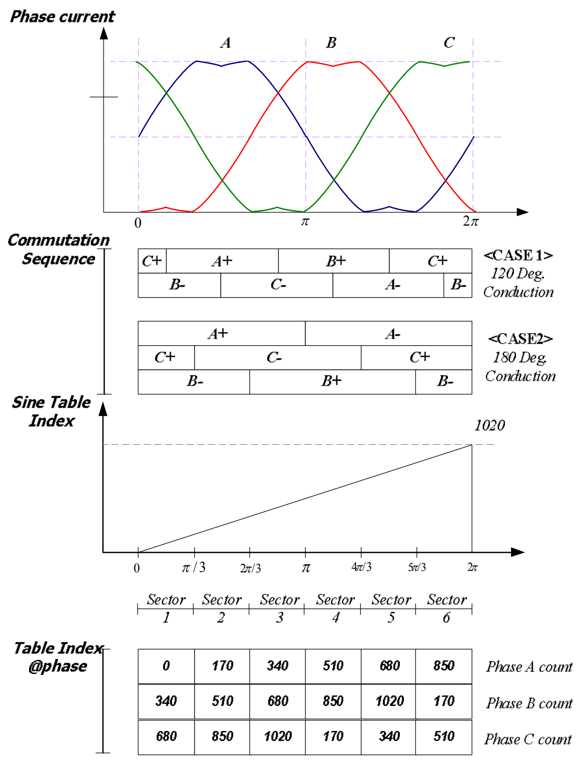


Figure 8: Table composition for high-precision position control

In the mentioned scheme, a sine table with 1020 index per electric cycle as shown in fig.8 is used to conduct the phase current at operation and through the look-up table the position resolution for high precision control can be improved.

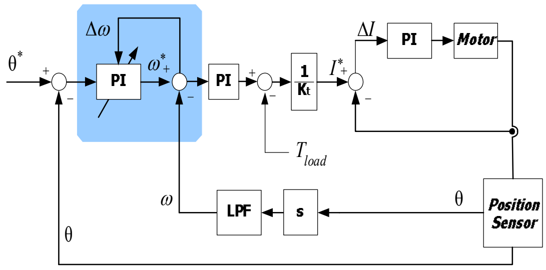


Figure 9: Control block diagram

Fig.9 shows the control block diagram with 3 level cascaded control structure. It is mainly consisted of current control, speed control and position control loop with a variable PI gain.

The inner current loop with a PI controller per 100 usec is used to develop a maximum torque for tracking a speed command and compensating the load disturbance including air mass flow and friction.

It is needed that the gain scheduling, as shown in fig.10, is applied to control motor for high response during transient period and to cancel out vibration at a settling zone including a stop state in case of matching position reference.

For this, the speed difference according to the position command is used to change P gain and I gain respectively.

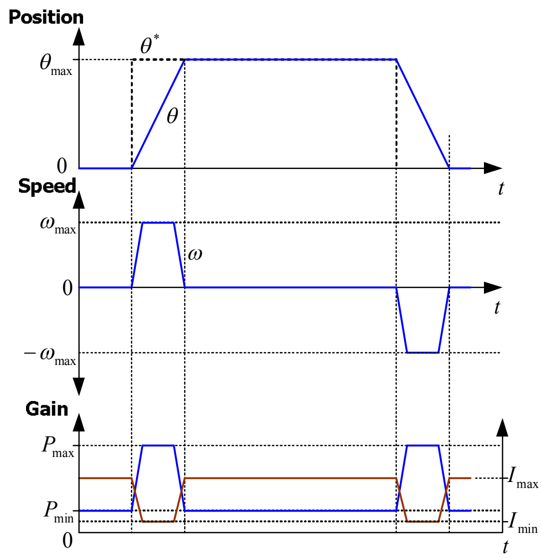


Figure 10: PI Gain Scheduling Scheme for High Precision and High Response Position Control

4 Designed System

Fig.11 shows the overview of the electronic throttle control system. From fig.11, it may be seen that the control system consists of three parts.

The first part is composed of the inverter that has a shunt resistor for current feedback control and six switching device. The second is the electronic throttle body that has BLDC motor, a return spring, a position sensor and reduction gear. Finally there are the processor and user interface blocks for the control part. In addition, TMS320F2812 is used for the control processor and the built-in 12 bit A/D converter is used for the position control and the inner current control respectively.

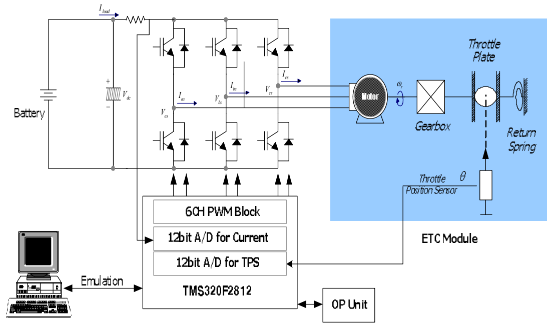


Figure 11: System composition

The inverter can be operated at the rated voltage of 12V and the rated current amounts to about 3A for providing the rated output power of 50W. Table 1 shows the main specification of ETC control system and fig.12 is the prototype system for exercising the proposed algorithm.

Table1: Main specification of ETC control system

Rated Voltage[V]	12
Rated Current[A]	2.5
Switching freq. [kHz]	10
Pos. sensor output [V]	0.44(min)~4.48(max)
BLDC motor	6slot/ 4pole
Motor speed[rpm]	Max. 6,000
Reduction ratio	16 : 1

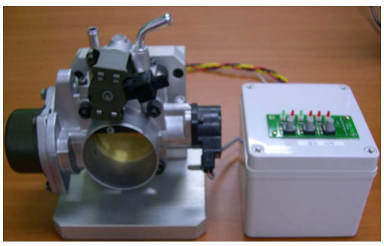


Figure 12: External view of the prototype system

5 Experimental results

Fig.13 shows the 3 phase switching waveform when the electronic throttle is periodically operated towards up or down direction.

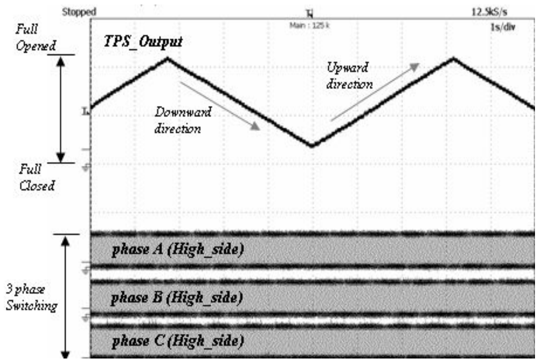


Figure 13: TPS output & switching waveform of 3 phase excitation

Fig.14 shows a smooth throttle position trajectory and the commutation phase current. In the first step command and the second ramp command respectively, the phase current has 4 cycles until the throttle valve moves from the closed state to the open state. And at the change of position command, the direction of phase current is reversed as shown.

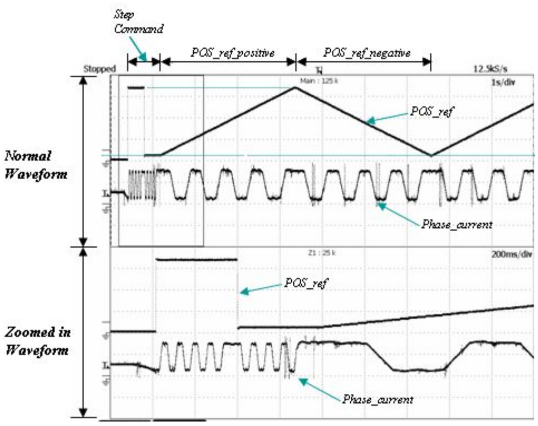


Figure 14: Reference position vs. phase current

Fig.15 illustrates the step response characteristics for different small step changes of reference position. The prototype controller has a minimum position resolution of 0.128 degree due to A/D resolution and the noise level in the control board. In a small difference of step command, it has some delay to reach the target position because of some residual effects and the friction influence.

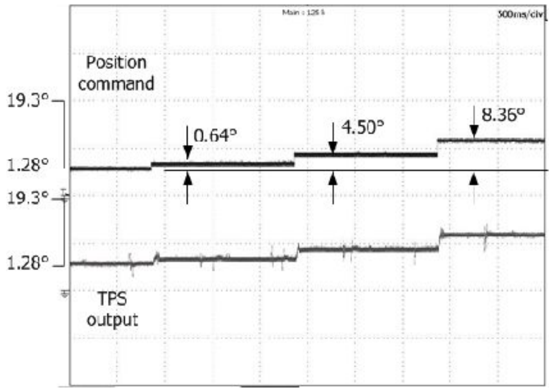
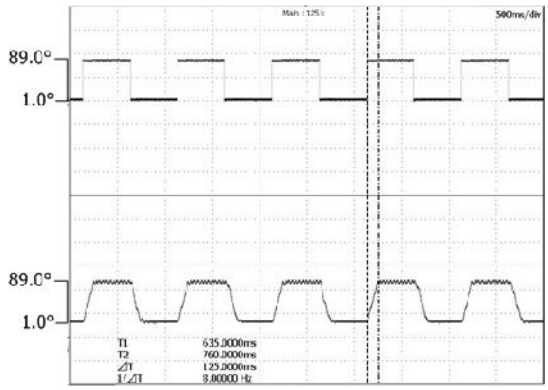
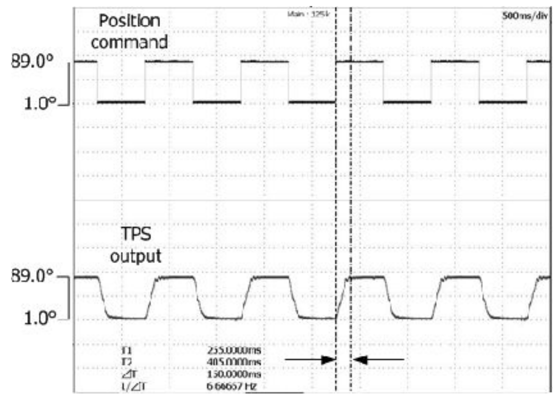


Figure 15: Small step response of control system



(a) Step responses without a variable PI controller



(b) Step responses with a variable PI controller

Figure 16: Experimental responses with and without a variable PI controller

Fig.16 demonstrates that the application of a variable PI controller for position control results in a significant reduction of when the throttle valve reaches the target position through the two extreme positions, set to 1.0 degree and 89 degree, respectively, for safe reasons. A position response is shown in fig 16(b), 150 msec.

6 Conclusion

This paper proposes the high response and high precision control of ETC module using BLDC motor without the hall sensor for detecting a rotor position. In the prototype system, it is used the cascaded 3 level cascaded control structure and 3 phase excitation method. It enables the solutions of the control problem with the suitable control algorithm and implementation technology. In addition, the use of variable PI controller has an effect on the reduction of vibration and the improvement of response. The experimented results confirm the feasibility of the proposed approach.

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