LiuYang[1], Xia Mingzi[2], and Zhao Jin[3]

Huazhong University of Science and technology(1),(2),(3)

A Novel Adaptive Fuzzy Controller Approach of Brushless DC Motors without Hall and Position Sensors

Abstract. *This paper presents a novel adaptive fuzzy controller approach of brushless DC motors (BLDCM) without hall sensors. The fuzzy controller adopts fuzzy logic to retune the PID parameters online. Based on the mathematical model of BLDCM introduced, a novel adaptive fuzzy control strategies have been designed in MATLAB/SIMULINK. The results have been recorded under various operating conditions. The simulation results showed that the fuzzy PID controller made much better performance than the traditional PID controller in speed responses and system performance.*

Streszczenie. *W artykule opisano nową metodę sterowania bez szczotkowym silnikiem DC bez czujnika Hall'a, z wykorzystaniem regulatora adaptacyjnego opartego na logice rozmytej. Algorytm na bieżąco dostraja nastawy regulatora PID. Badania symulacyjne maszyny, przeprowadzone w programie Matlab-Simulink, wykazały znaczne polepszenie odpowiedzi regulatora PID, dla zadanych zmian. (**Adaptacyjny regulator rozmyty w sterowaniu bezszczotkowym silnikiem DC bez czujnika Halla**)*

Keywords: brushless dc motor, fuzzy controller, sensorless
Słowa kluczowe: bezszczotkowy silnik DC, regulator rozmyty, bezczujnikowy.

1. Introduction

Brushless DC motors have recently been widely used in industrial and household product for its advantages over other kinds in size, efficiency, structure, operating life, dynamic response and speed range[1][2]. Moreover, they require little maintenance, generate less acoustic noise and can be applied in hazardous operation environments. BLDCMs are generally controlled using a three-phase inverter which requires a rotor position sensor like Hall sensors or absolute position sensors to provide a proper commutation sequence. However, the position sensors mentioned above will increase the cost of the motor; making the whole equipment more temperature sensitive and in addition reduce the system reliability. So the drives of BLDCMs without Hall sensors and position sensors are researched deeply [3]-[13].

The classical method of controlling the speed of BLDCMs is proportional-integral-derivative (PID) control. This method is usually applied by tuning the PID parameters (K_p, K_I and K_D). Usually, when suffers from various conditions or sudden change of speed, the system can hardly maintain the good performance achieved under the original parameters without retuning the PID parameters. The fuzzy set theory helps a lot when dealing with uncertainty. A certain mathematic model of the non-linear dynamic BLDCM control system is not necessary when using a fuzzy logic controller. So, despite the varying loads and changing parameters, we can still achieve great performance by combing fuzzy logic control with classical PID control. One triple-outcome fuzzy controller has been designed to update the values of the proportional, integral, and derivative gains online with changing circumstances [14]-[19].

As mentioned above, the fuzzy PID control method is very promising when planted into a sensorless BLDCM. The goal of this paper is to design an adaptive fuzzy controller and make a comparison between the classical PID control and fuzzy PID control. Both speed control strategies with fuzzy PID and classical PID have been designed in MATLAB/SIMULINK. Comparative simulation results in different conditions have shown that the proposed fuzzy PID method offers a better performance than the classical one.

2. Mathematical Model Of BLDCM

The mathematical models and electromagnetic torque of BLDC motors are formed as following mentioned.

1) The three-phase windings are completely symmetrical.

2) The influence of cogging, commutation process and armature reaction is ignored; the magnetic saturation and iron losses are disregarded.

The loss of vortex and hysteresis is neglected and the magnetic circuit is unsaturated.

The voltage equation of BLDC motor can be so represented as:[11]

(1)
$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} (L-M) & 0 & 0 \\ 0 & (L-M) & 0 \\ 0 & 0 & (L-M) \end{bmatrix} p \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix}$$

Where v_{as}, v_{bs} and v_{cs} are stator winding phase voltages. R_s is the rotor resistance and is equal for all the three phases. i_{as}, i_{bs}, and i_{cs} are phase current. e_{as}, e_{bs} and e_{cs} are stator winding phase back electromotive forces(EMF). L is winding phase self-inductance and M is mutual inductance per phase. p is differential operator.

The electromagnetic torque equation is:

(2)
$$T_e = (e_{as}i_{as} + e_{bs}i_{bs} + e_{cs}i_{cs}) / \omega_n$$

The electromagnetic toque can be expressed as:

(3)
$$T_e - T_l - B\omega_n = Jd\omega_n / dt$$

Where T_e is the electromagnetic torque, T_l is the load torque, B is the damped coefficient, J is the moment of the inertia and ω_n is the mechanical speed.

The relationship between speed and position is:

(4)
$$d\theta / dt = P\omega_n / 2$$

Where P is the number of poles in the motor and θ is the rotor electrical position.

3. Adaptive Fuzzy Controller Design

According to the modularization principles and mathematical models, the whole control system is divided into several functional parts which are the BLDCM block, the starter block, the logical inverter block, and the fuzzy PID controller block. The simulation system uses a single closed speed loop control which adopts two different strategies-the traditional PID control and fuzzy PID control. The control strategy is realized by an s-function planted in the logical inverter block and the original PID parameters and the retuned fuzzy PID parameters are passed to it through a mask. Here we use three manual switches to change from one strategy to the other.

A. BLDCM Block

Refer to (1), (2), (3) and (4), we can generate a final form of state space.

(4)

$$\begin{bmatrix} \dot{i}_{as} \\ \dot{i}_{bs} \\ \dot{i}_{cs} \\ \dot{\omega}_m \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L-M} & 0 & 0 & -\frac{f_a(\theta)}{L-M} & 0 \\ 0 & -\frac{R}{L-M} & 0 & -\frac{f_b(\theta)}{L-M} & 0 \\ 0 & 0 & -\frac{R}{L-M} & -\frac{f_c(\theta)}{L-M} & 0 \\ \frac{f_a(\theta)}{J} & \frac{f_b(\theta)}{J} & \frac{f_c(\theta)}{J} & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ \omega_m \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & -\frac{1}{L-M} \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \\ T_L \end{bmatrix}$$

where $f_a(\theta)$, $f_b(\theta)$ and $f_c(\theta)$ are mathematic functions limited between 1 and -1 that express the coefficient relationship between θ and back EMF.

We implement an s-function block to solve the above differential equations and from this we calculate the line currents I_A, I_B, and I_C, the speed ω and the rotor electrical position θ. The phase back EMF e_{as}, e_{as} and e_{as} will be determined by identifying the rotor angle. The diagram of BLDCM is represented in fig.1.

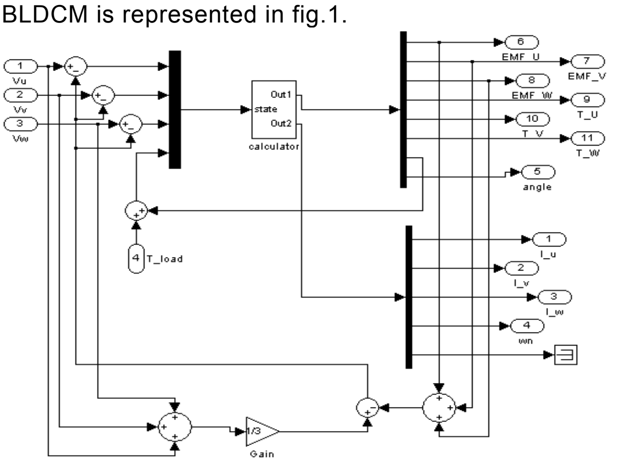


Fig1. The diagram of BLDCM

B. Starter Block

When the simulation suddenly starts, the back EMF has not reached up to a certain measurable value. And since the control strategy designed for sensorless BLDC is highly dependent on the value of back EMF, in order to maintain the initial state of the controller, the motor has to be ramped up open-looped by a starter block which generates three phase input voltage to the BLDC. When the back EMF reaches to a detectable point, the starter block will be cut and the whole system will be switched to closed-loop.

C. Logical Inverter Block

Since the back EMFs vary with the speed, the rotor position information can be obtained by detecting the zero-crossing of the line back EMFs. Thus we can determine the instant of commutation without a Hall-effect sensor. At each sample time, the present speed and the speed error a step time before will be read to calculate the required torque and it is shown as follows,[3]

(5)

$$T_{req} = \left[e \times (K_P + (0.5 \times t_s \times K_I) + \frac{K_D}{t_s}) \right] + \left[e_{-1} \times (0.5 \times t_s \times K_I - \frac{K_D}{t_s}) \right]$$

where K_p is the proportional parameter, K_I is the integral parameter and K_D is the differential parameter, e is the speed error, e_{-1} is the previous time step speed error and t_s is the sampling time.

An S-function is implemented to calculate the torque required, and then according to the rotor's position, an approximated park's transformation is used to calculate the required phase current. Then we use hysteresis control to define the voltage applied for each phase and determine the sequence and time we need for each fire gates.

D. Fuzzy PID Block

The fuzzy PID controller consists of the traditional PID controller and fuzzy logic controller. Usually when the parameters of the system change, we have to retune the PID parameters accordingly, which takes a lot of time and human labor. Fuzzy logic simulates human linguistic rules in reasoning and decision making and adopts human experiences when facing with uncertainty and imprecision. So the fuzzy logic controller can be used to adjust PID parameters on line. After modified, the parameters will be passed to the S-function of logical inverter block. Fig.2 shows the structure of fuzzy logic controller. The fuzzy logic controller consists of the following functions.

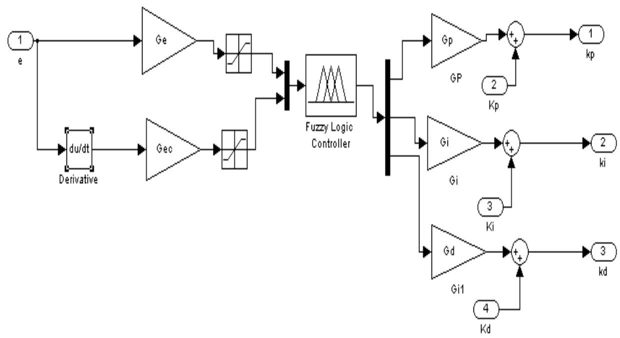


Fig.2 structure of fuzzy logic controller

1) Fuzzification: The fuzzy controller is a dual-input triple output system. By using triangular membership function, fuzzification converts inputs into fuzzy variables and outputs into crisp values. The inputs of fuzzy controller are divided into five linguistic values described as positive big (PB), positive small (PS), zero (Z), negative small (NS), and negative big (NB). Both the fuzzy domain of input and output are defined on the same discourse [-3, 3]. The membership of inputs and outputs is shown in Fig.3.

2) Knowledge base: As summarized below, PID parameters have a great influence on the stable and dynamic performance of controller system.

K_p is proportional to the steady-state error, which reduces as K_p increases. But when K_p gets too large, the overshoot will be so great and impair the steady-state operation instead.

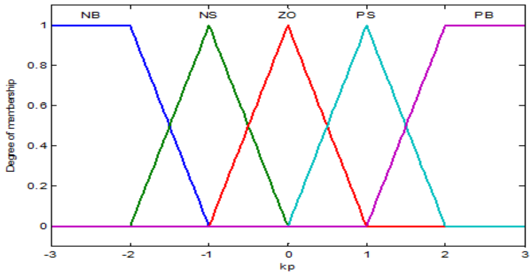


Fig. 3 The membership of inputs and outputs

The climb speed goes faster as K_I increases. But if K_I gets too large, it will affect the steady-state operation by causing torque ripples and a serious overshoot.

The reduction of K_D will increase the climb speed and reduce the torque ripple. But if it gets too small, the system will suffer from an overshoot and a long settling time.

In order to achieve the control goal, the above knowledge and expert experience are collected and translated into some IF-THEN statements. The rules are shown in TABLE I.

Table 1. Fuzzy rules

$\Delta K_P / \Delta K_I / \Delta K_D$		*ec*				
		NB	NS	ZO	PS	PB
e	NB	PB/ NB/NB	PS/ NS/NS	PS/ NS/NS	PS/ NS/NS	ZO/ ZO/ZO
	NS	PB/ NB/NB	PS/ NS/NS	PS/ NS/NS	ZO/ ZO/ZO	NS/ PS/PS
	ZO	PS/ NS/NS	PS/ NS/NS	ZO/ ZO/ZO	NS/ PS/PS	NS/ PS/PS
	PS	PS/ NS/NS	ZO/ ZO/ZO	NS/ PS/PS	NS/ PS/PS	NB/ PB/PB
	PB	ZO/ ZO/ZO	NS/ PS/PS	NS/ PS/PS	NS/ PS/PS	NB/ PB/PB

3) Defuzzification: The control signals real system uses are crisp values, so we must convert fuzzy outputs into them. Here we adopt the most commonly used defuzzification method-centroid method. The formula of defuzzification is given by:

$$z = \sum_{x=1}^{n} u(x)x \Big/ \sum_{x=1}^{n} u(x) \qquad (6)$$

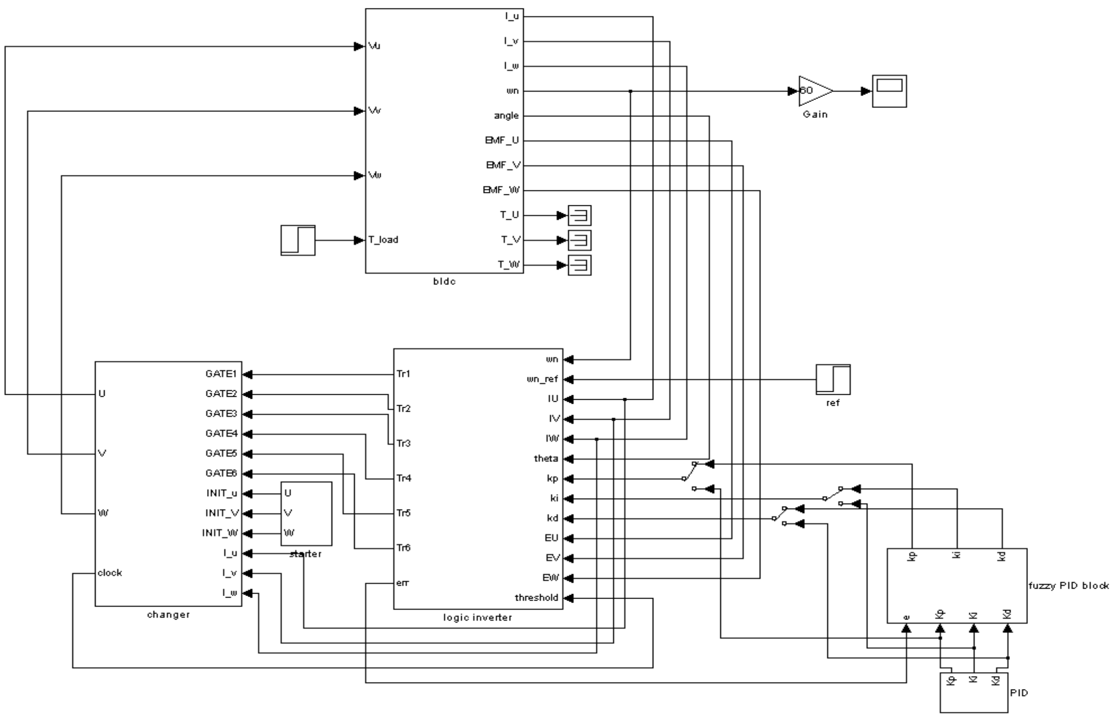


Fig.4 MATLAB/SIMULINK block diagram

1、 Simulation Results

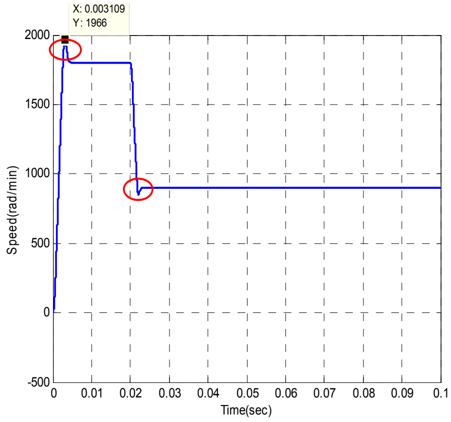
The fuzzy PID strategy used in a BLDCM without any sensors has been simulated. The MATLAB/SIMULINK block diagram is demonstrated in Fig.4

where Z is the defuzzified value and $u(x)$ is the value of the membership.

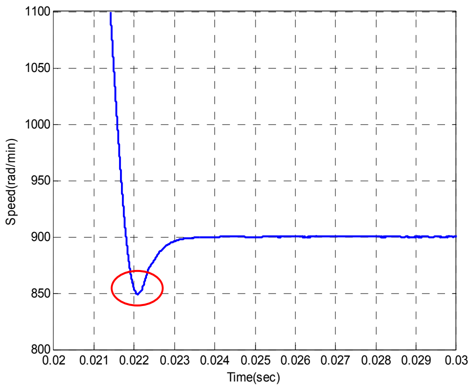
Drive performances of two strategies are compared under various conditions. The parameters of the simulated BLDCM are shown in Table II.

Table II. Parameters of the simulated BLDCM

Rated speed	3600RPM	Coulomb friction	0.018N
Rated current	20A	Self inductance	2.7mH
Rated torque	0.45N.m	Static friction	0.087N
Poles	4	Viscous friction	0.002N
Motor inertia	0.0002 kg-m^2	Winding resistance	0.29Ω
Mutual inductance	2.5mH	Number of phases	3

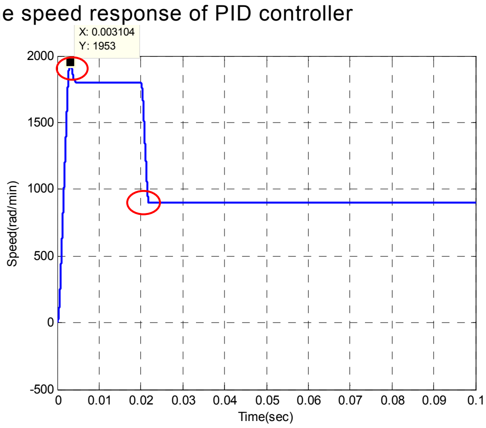


(a)

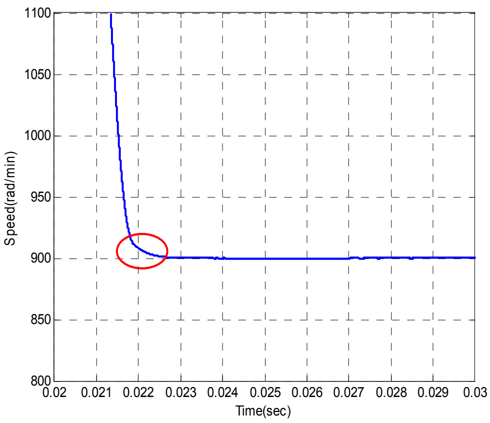


(b)

Fig 5 The speed response of PID controller



(a)



(b)

Fig 6 The speed response of fuzzy PID controller

A reference speed of 1800 rad/min is given at the beginning and a sudden fall is given at 0.02 sec to drop to a speed of 900 rad/s. The simulation runs for 0.1 second. Fig.5 (a) and fig 6 (a) shows the dynamic speed response of two strategies respectively. We can see from the enlarged pictures shown in fig.5 (b) and fig.6 (b) that with the original PID parameters, when the speed reference changes, the system produces a large overshoot. But when we use the proposed fuzzy PID controller, there is no overshoot as we can see highlighted in the circle and the response is also smooth and quick.

Conclusion

In this paper, an approach towards brushless DC motors without sensors has been performed by using fuzzy PID controller. A comparison made between the traditional PID controller and fuzzy PID controller under MATLAB environment shows that fuzzy PID control strategy has important advantages of better dynamic performances and can enhance robustness to some extent.

Plus, the fuzzy control strategy is very simple and feasible. Advance knowledge of the system is not needed. So by making proper adjustments to the fuzzy controller rule table and controller quantization factors, the fuzzy PID controller can be adopted to different systems.

Acknowledgement

This work was supported by the National Natural Science Foundation of China under Grant 60874047 and Grant 61034006.

REFERENCES

[1] S. P. H. Hidayat, "Performance Analysis of Adaptive Neuro Fuzzy Inference Systems (ANFIS) for Speed Control of Brushless DC Motor," in International Conference on Electrical Engineering and Informatics, Bandung, Indonesia, July 2011, pp. 17-19.

[2] W. Chen and C. L. Xia, "Sensorless Control of Brushless DC motor Based on fuzzy logic," in Processing of the 6th World Congress on Intelligent Control and Automation, July 2006, Dalian China, pp. 6298-6302.

[3] O. Scaglione, M. Markovic and Y. Perriard, "First-Pulse Technique for Brushless DC Motors Standstill Position Detection Based on Iron B-H Hysteresis," IEEE Trans. Ind. Electron., May 2012, vol. 59(5), pp. 2319-2328.

[4] M. Villani, M. Tursini, G. Fabri and L. Castellmi, "High Reliability Permanent Magnet Brushless Motor Drive for Aircraft Application," IEEE Trans. Ind. Electron., May 2012, vol. 59(5), pp. 2073-2081

[5] C L. Iepure, I. Boldea and F. Blaabjerg, "Hybrid I-f Starting and Observer Based Sensorless Control of Signal Phase BLDC-PM Motor Drives," IEEE Trans. Ind. Electron., 2011, available:

[6] J. Park, S. Hwang and J. Kim, "Sensorless Control of Brushless DC Motors with Torque Constant Estimation for Home Appliances," IEEE Trans. Ind. Appli., 2011

[7] Y. Y. Wu, Z. Q. Deng, X. L. Wang, X. Ling and X. Cao, "Position Sensorless Control Based on Coordinate Transformation for Brushless DC Motor Drives," IEEE Trans. Power Electron., Sept. 2010, vol. 25(9), pp. 2365-2371.

[8] J. Gao and Y. W. Hu, "Direct Self-Control for BLDC Motor Drives Based on Three-Dimensional Coordinate System," IEEE Trans. Ind. Electron., Aug. 2010, vol. 57(8), pp. 2836-2844.

[9] J. B. Cao and B. G. Cao, "Fuzzy-Logical-Based Sliding-Mode Controller Design for Position-Sensorless for Electric Vehicle," IEEE Trans. Power Electron.,, Oct. 2009, vol. 24(10), pp. 2368-2378.

[10] C. T. Lin, C. W. Hung, "Position Sensorless Control for Four-Switch Three-Phase Brushless DC Motor Drives," IEEE Trans. Power Electron., Jan. 2008, vol.23(1), pp. 438-444.

[11] K. S. Rama Rao, Nagadeven, "Sensorless Control of a BLDC Motor with Back EMF Detection Method using DSPIC," in 2nd IEEE International Conference on Power and Energy, Dec. 2008, Malaysia, pp. 243-248.
[12] S. A. Zabalawi and A. Nasiri, "State Space Modeling and Simulation of sensorless Control of Brushless DC motors Using Instantaneous Rotor Position Tracking," in Conf. Vehicle Power and Propulsion 2007, Arlington, Sept. 2007, pp. 90-94.
[13] R. Somanatham, P. V. N. Prasad and A. D. Rajkumar, "Modeling and Simulation of Sensorless Control of PMBLDC Motor Using Zero-crossing Back E.M.F Detection," in International Symposium on Power Electronics, Electrical Drives, Automation and Motion, May 2006, pp. 984-989.
[14] A. Rubaai and P. Young, "EKF-based PI-/PD-Like Fuzzy-Neural-Network Controller for Brushless Drives," IEEE Trans. Ind. Appli., Nov./Dec. 2011, vol.47(6), pp. 2391-2401.
[15] P. Devendra, G. Rajetesh, K. A. Mary and C. Saibabu, "Sensorless control of Brushless DC Motor Using Adaptive Neuro Fuzzy Inference Algorithm," in 2011 International Conf. Energy, Automation, and Signal, Dec. 2011, pp. 1-5.
[16] D. R. Luo, W. Huang, S. D. Huang, W. Q. Li and L. Zheng, "Simulation Study of the Fuzzy-PID Control System for Brushless DC Motors," in 2011 International Conf. Electrical Machines and System, Aug. 2011, pp. 1-4.
[17] M. L. Hu, J. Q. Qiu, and C. W. Shi, "A Comparative Analysis of Fuzzy PI and PI Speed Control in Brushless DC motor based on DSPACE," in International Conf. Electrical Machines and Systems, Aug. 2011, pp. 1-5.
[18] T. C. Siong, B. Ismail, M. Mohd Faridun, A. R. Siti Rafidah and M. I. Zainuddin, "Study of Fuzzy and PI Controller for Permanent-Magnet Brushless DC Motor Drive," in Proceedings of the 4th International Power Engineering and Optimization Conf., Shah Alam, Selangor, Malaysia, June 2010, pp. 617-521.
[19] A. Rubaai, M. J. C. Sititiche and A. R. Ofoli, "Design and Implementation of Parallel Fuzzy PID Controller for High-Performance Brushless Motor Drives: An Integrated Environment for Rapid Control Prototyping," IEEE Trans. Ind. Appli., July/Aug. 2008, vol.44(4), pp. 1090-1098.

Authors: dr.Yang Liu, Huazhong University of Science and Technology, Wuhan City, Bubei Province, China,
E-mail: yang.liu30@gmail.com
M.Eng Mingzi Xia, Huazhong University of Science and Technology, Wuhan City, Bubei Province, China,
E-mail: cheryl_xia@sina.com
Prof. Dr Jin Zhao, Huazhong University of Science and Technology, Wuhan City, Bubei Province, China,
E-mail: jinzhao617@163.com