Design of Self-Tuning Regulator for Brushless DC Motor Speed Control

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Abstract*—Brushless DC (BLDC) motor is one type of dc electric motor that has various advantages such as higher of efficiency, torque under lows peed range, and power density, and lower maintenance because this motor does not use the brush in the commutation process. BLDC drive involves a complex process, so it takes the right control method to control its speed. This paper proposed Self-Tuning Regulator (STR) of Proportional Derivative (PD) controller where the parameters are adapted using fuzzy-logic. STR PD controller also can follow fixed reference faster than PD controller. It can follow speed reference change up and overcome the interference from the outside of a momentary disturbance, and STR PD controller technique had better performance than the PD controller, mainly when the motor was working at speed reference change down, it can minimize of undershoot that caused by PD controller.

***Keywords*—BLDC; PD; STR PD; fuzzy; speed**

I. INTRODUCTION

There are mainly two types dc electric motors used in industry. The first one is the brushed dc motor where the flux is produced by the current through the field coil of the stationary pole structure. The second type is the brushless dc motor where the permanent magnet provides the necessary air gap flux instead of the wire-wound field poles. BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform shape. BLDC motors do not use brushes for commutation [1]. The BLDC motors exhibit better performance in terms of higher efficiency, higher torque under low speed range, higher power density, lower maintenance [2][3]. In practice, the design of the BLDC drive involves a complex process such as modeling, control scheme selection, simulation and parameters tuning etc.[1]. The speed of BLDC motor can be controlled by varying flux/pole, armature resistance and applied voltage [4].

Conventional PID controller algorithm is simple, stable, easy adjustment and high reliability. Normally, PID controller is an optimum choice for controlling the speed as the BLDC motor [5]. However, it has an uncertainty problem due to load as well as in set speed variations of BLDC motor. *Self-Tuning Regulator* (STR) is a popular approach. This regulator can be derived in a simple way which has a strong intuitive appeal [6].

This paper proposed STR PD controller where its parameters are adapted using fuzzy logic. Parameter of Kp and Kd can be adjusted real time. Fuzzy logic utilizes error and error rate as input of system and uses Sugeno method in decision-making process. The are two set fuzzy rule for tuning Kp and Kd, by using this set of rules, the controller can be adapted to any change of parameter.

This experiment also compares the performance of the PD controller with the STR PD controller. System response analysis is done through observation of transient response parameters such as rise time, peak time, settling time, error of steady state, and overshoot or undershoot.

II. METHODOLOGY

A. Diagram Block Design

A self-tuning regulator PD control is directly applied to achieve performance targets of BLDC speed. Block diagram of a control system design is presented in Fig. 1.

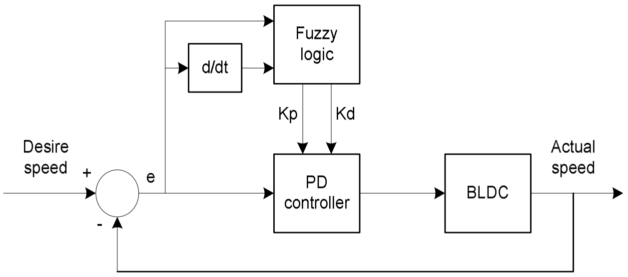


Fig. 1. BLDC speed by self-tuning regulator PD controller.

A fuzzy logic is implemented by receiving the error e and the rate of change in error or delta error (de). In this work, the designed rules are defined according to the prevailing characteristics of the BLDC motor. The fuzzy system based on Sugeno model is performed to tune PD parameters of Kp and Kd. The Kp and Kd values obtained are then processed in the PD algorithm to produce a control signal that can adjust the amount of voltage generated by the electronic speed controler (ESC) to achieve the desired motor rotation speed in units of rotation per minute (rpm), the error value obtained through the difference between the actual speed and set point speed of motor. The derivative from the error value that occurs is also used as an input of the fuzzy system for the transmission of PD parameters.

B. *Design of Hardware Components*

The assembly of hardware components from the BLDC speed control is made by picture as shown in Fig. 2.

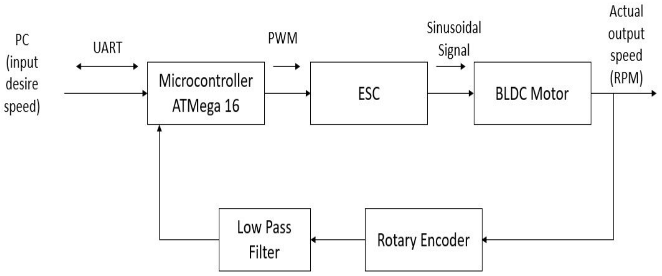


Fig. 2. Hardware component design.

An input speed data in units of rpm will be sent to the microcontroller from the interface program on the computer through serial communication.This micro controller is an 8 bit AVR microcontroller that has high capability and low power consumption, has a memory capacity of 16 Kbyte, 512 bytes EEPROM, 32 I / O channels, 32 registers, internal and external interruption units, and USART port for serial communication.

The microcontroller will process the input data to determine the output signal in the form as a control signal (PD) to further determine the amount of PWM in the ESC.ESC is a component that acts as a motor rotation controller BLDC. The size of an ESC is calculated in units of Ampere (A), where size is related to BLDC motor requirements. ESC will convert PWM into three-phase sinusoidal wave, which then rotate BLDC motor. The magnitude of PWM signals entering the ESC affects the amplitude and frequency of the sinusoidal wave that will enter the motor.

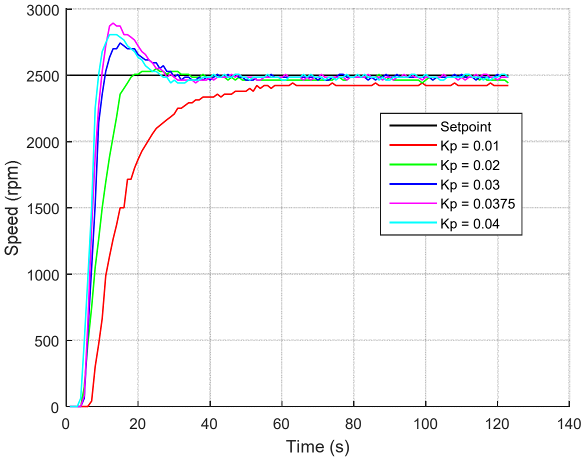
The rotary encoder sensor produces a pulse when the motor rotates,which is then fed back to the microcontroller. Microcontroller then performs its function as enumerator and converts the enumeration result into a speed scale that is rpm.The rotary encoder sensor is one of the hall speed sensors. This sensor is mounted with a disk encoder that gives 0 or 1 outputs according to the speed of the BLDC motor.The read speed the rotary motor of BLDC requires an additional filter to read sensor data. The designed filter is a low-pass filter typefor noise removal due to the location of the sensor next to the motor.

C. *Controller Design*

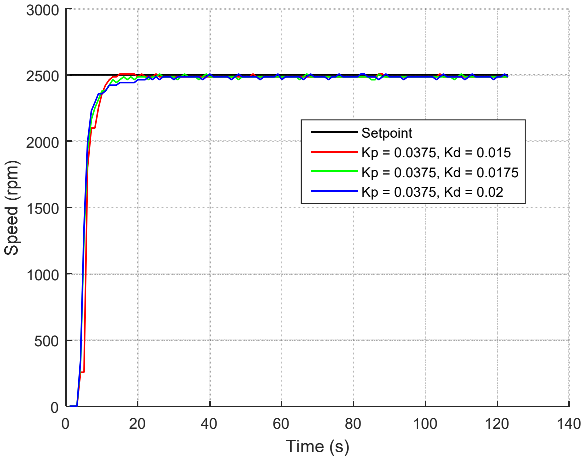
The controller design consists of two stages. The first step is to find the best fixed parameter value of Kp and Kd at the maximum control speed (2500 rpm). Based on the effect on the PD gain shown in Table I, the selected Kp and Kd produced by trial and error to control the BLDC motor with a speed of 2500 rpm is Kp = 0.0375 and Kd = 0.015. The transient response is shown in Fig.4.Table I indicated effects of PD gains on the dynamic performances, such as rising time, overshoot, settling time, and steady-state error when the value of each gain increases [7].

Variation of Kp values used to find the selected value by try and error to rotate the motor at speed 2500 rpm is 0.01, 0.02, 0.03, 0.0375, 0.04. Using Kp 0.0375 is the best choice compared to other Kp variations, when used variations of Kp values of 0.01 the system is very slow to reach the set point while using Kp of 0.04 produces to overshoot on the system response.

The system response at Kp = 0.0375 actually still produced to overshoot.Therefore, it takes the correct value of Kd parameter to improve the system response.The Kd variations used as a comparison in the try and error tuning are 0.015, 0.175 and 0.2. Addition of Kd parameter of 0.015 could eliminate the overshoot that happened with time to reach the set point which also remain fast.The graph of the Kp and Kd tuning response by try and error is shown in Fig.3. Effect of PD gain is presented in Table I.



a. Variations of Kp



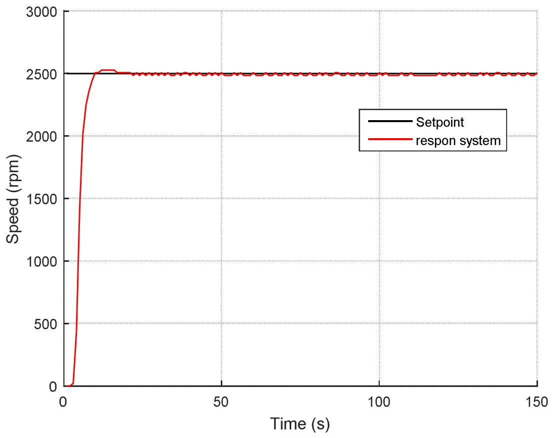
b. Variations of Kd

Fig. 3. Response system of tuning kp and kd by trial and error.

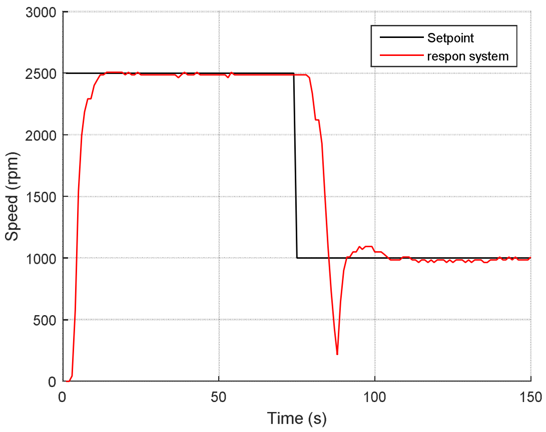
TABLE I. EFFECTOF PD GAINS

Gain	**Response of System**			
	Rising time	***Overshoot***	***Settling time***	***Steady state error***
Kp	Decrease	Increase	Slight decrease	Decrease
Kd	Slightly decrease	Decrease	Decrease	No effect

The best value of Kp and Kd at speed 2500 rpm turns out to produce fewer good parameters to overcome the change of speed down which produce undershoot big enough as shown Fig. 4.



a. Contant set point at 2500 rpm.



b. Change set point at 2500 rpm to 100 rpm.

Fig. 4. Response system used Kp=0.0375 and Kd=0.015.

Undershoot that occurs when the reference speed is lowered can be overcome by decreasing the Kp gain and increasing the Kd gain. It is necessary to do second stage design that is creating fuzzy logic to correct parameter setting appropriate reference of speed given.

The input set of fuzzy logic is the set of error and delta error as in Fig. 5 and Fig. 6 is divided into 5 labels, namely negative big (NB), negative (N), zero (Z), positive(P) and positive big (PB).

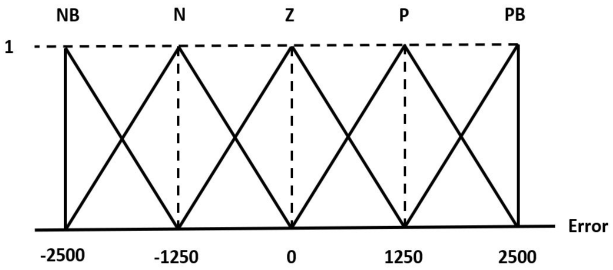


Fig. 5. Membership function for error.

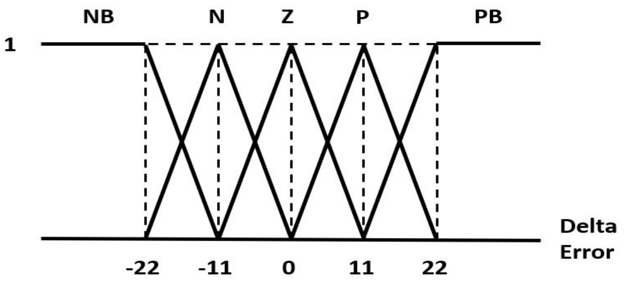


Fig. 6. Membership function for delta error.

The membership function of output is shown in Fig.7 and Fig. 8. The output membership set for Kp and Kd is also divided into 5 labels, i.e., negative big (NB), negative (N), zero (Z), positive (PM) and positive big (PB).

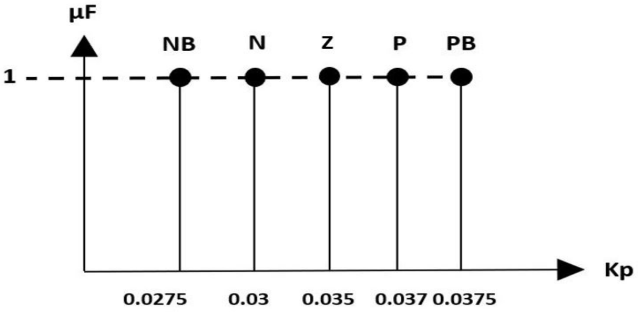


Fig. 7. Membership function for Kp.

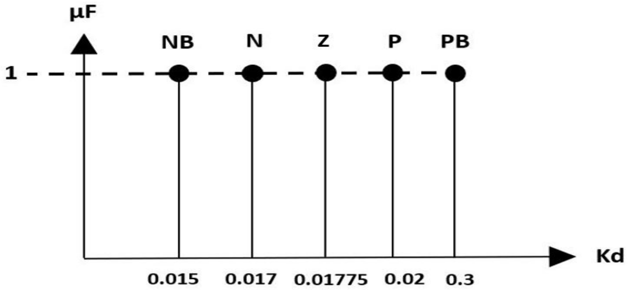


Fig. 8. Membership function for Kd.

The rule base is created according to the desired output as enter the PD controller. The rule base is divided into 2, the rule basis for Kp and Kd values as shown by Table II and Table III, while the inference system used is the minimum inference system.

TABLE II. RULE BASE OF KP

e\de	NB	N	Z	P	PB
NB	-	NB	N	P	-
N	-	NB	Z	P	-
Z	-	N	Z	P	PB
P	-	N	Z	P	-
PB	-	N	P	P	-

TABLE III. RULE BASE OF KD

e\de	NB	N	Z	P	PB
NB	-	PB	P	N	-
N	-	PB	Z	N	-
Z	-	P	Z	N	NB
P	-	P	Z	N	-
PB	-	P	N	N	-

The fuzzy method used is the Sugeno method where the deffuzification stage by weighted average. This method by finding the mean value for all the output values of each rule. The result from this defuzzification process is a value of Kp and Kd, then the numerical output of Kp andKd gains is next included into the calculation of the PD controller.

III. RESULTS AND DISCUSSION

The STR PD controller test using the self-tuning regulator PD is performed by providing fixed reference velocity value, upto reference changes, down reference changes, and testing of system responses to momentary disturbances. This discussion is a comparison with the performance of the controller carried out the test response to the plant using PID controller. Test results from PD controller by using Kp and Kd values remain, i.e., Kp = 0.0375 and Kd = 0.015 used to compare the performance of the self-tuning regulator PD controller.

A. Fixed Reference

Tests on fixed references are tests performed on inputs with specific reference speeds. The speed of reference is 2000 rpm.Self tuning regulator PD controller is expected to make BLDC motor rotates at 2000 rpm with stable speed with steady-state errors below 5% and has tr and ts are small or can also be said the system has a fast response. Transient response graph for the 2000 rpm speed is shown in Fig. 9.

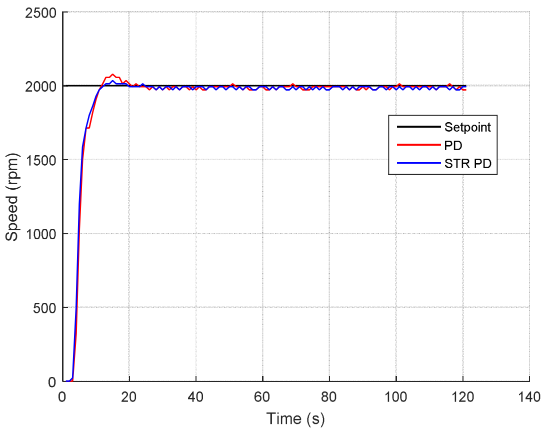


Fig. 9. Response system of controllers at 2000 rpm.

Self tuning regulator PD has the system response; rise time 2.438s, peak time 3.047s, settling time 4.266s, overshoot 1.79%, error of steady state 1.42 %, whereas in the PD controller, the plant has a transient response of rise time 2.235s, peak time 3.047s, settling time 4.266s, and overshoot 3.93%, and steady-state error 1.42 %. Based on the response data obtained can be seen that the PD controller produces rise time faster than the response on the self-tuning controller PD regulator, peak time, settling time and error steady states are same but the self-tuning PD controller has a smaller Mp.

B. Reference Change Up

This test is performed to determine the ability of the system in following the reference change up.Input speed increased by 1500 rpm, i.e., from the speed of 1000 rpm to 2500 rpm as shown in Fig. 10.

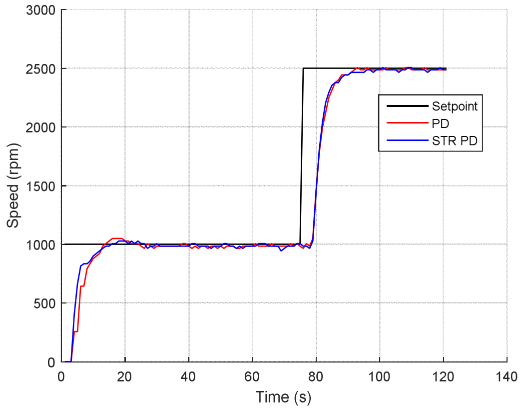


Fig. 10. Response system of self tuning regulator PD controller for reference change up.

Fig. 10 shows the system response using STR PD with rise time 5.484 s, time rise 5.758, with no overshoot and error of steady state 1.716 %. The transient response to the reference change up from 1000 rpm to 2500 rpm, using the PD controller has rise time 3.859 s, rise time 4.062 s, no overshoot, and error of steady state 0.856 %.

Compared to the self-tuning regulator PD controller with the PD controller, the PD controller has a better response parameter than the self-tuning regulator PD controller because it produces faster rise time and settling time with the same overshoot and steady-state erroris smaller.

C. Reference Change Down

This test is done by lowering the speed of the maximum speed of control that is 2500 rpm to the minimum speed of control that is 1000 rpm. The system response of controllers is shown in Fig. 11. This test is performed to determine the ability of the system in following the changing of reference down.

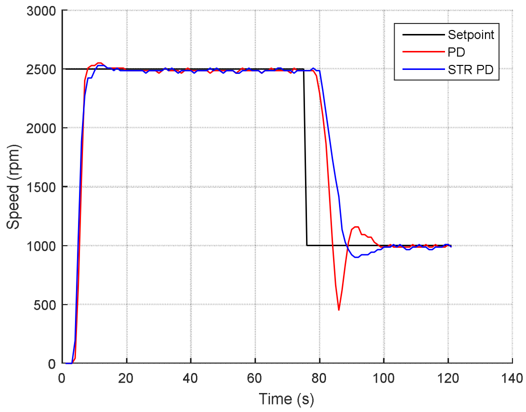


Fig. 11. Response system of self tuning regulator PD controller for reference change down.

Response system of self-tuning like as Fig.12 shows that system has rise time 3.047 s, settling time 5.891 s, no overshoot, undershoot 9.9 % and error of steady state 4.28 % when reference change down from maximum speed 2500 rpm go to minimum speed 1000 rpm. The value of transient response parameters from the use of PD controller that is rise time 2.069 s, settling time 4.875 s, undershoot 55 % and overshoot 15.72 %, error of steady state 2.14 %.

In both the reference, testing is changed down it is using the STR PD controller and the PD controller. The system response result of the self-tuning regulator PD controller can minimize to undershoot in the PD controller from 55% to 9.9% even with the slower rise time and settling time.

D. *Testing of Memontary Disturbance*

The interruption is to provide a momentary braking on the BLDC motor so that the motor speed BLDC dropped dramatically. Provision of interference is made when the system has reached a stable state in according toits reference. This test is to determine the performance of PID self-tuning controller with fuzzy logic against outside interference at speed 2000 rpm.The test results using the STR PD controllers and PD controllers are respectively shown by Fig. 12.

BLDC motor speed drops to 1028.6rpm from seconds of 14.016 decrease speed for 1.016 seconds, after 1.016-second control of regulatory self-tuning PD tries to return system output to the setpoint by giving greater PWM. The control system that gives the finer PWM causes an overshoot of 10.365% that reaches the speed of 2207.3 rpm, and the system starts to get the steady state again at 18.282 seconds.

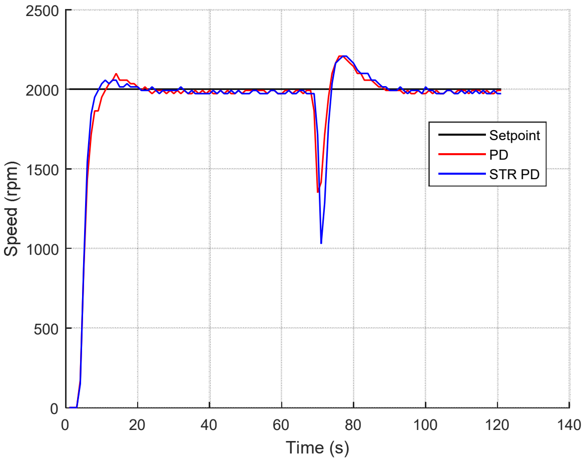


Fig. 12. Response system of self tuning regulator PD controller for momentary disturbance.

The same disturbance is also given to test the system's response to the PD controller at the same time. This temporary braking disturbance on the PD controller causes the motor speed to drop to 1350.1 rpm for 0.884 seconds, then recovery at 15,096 seconds and raises the overshoot by 10.365%. The system reaches the steady-state again at 18.078 seconds. Both controller STR PD controller and PD controller have been able to overcome the momentary disturbance that arises from outside the system in the form of instantaneous braking.This disturbance causes the motor speed down and raises to overshoot because the controller tries to give greater PWM value to restore the motor state according to a set point which is desired.

IV. CONCLUSION

This paper presents comparison results of STR PD controller and conventional PD controller for the speed control of BLDC Motor. In conventional PD control, it is not necessary to change the control parameters due to changes in reference speed. With results obtained from test directly in real time, clearly for the same operation condition, the BLDC speed control using STR PD controller technique had better performance than the conventional PD controller, mainly when the motor was working at speed reference change down, it can minimize to undershoot that caused by PD controller from 55 % become to 9.9 %. In addition, the STR PD controller also can follow fixed reference faster than PD controller with rise time 2.438 s, peak time 3.047 s, settling time 4.266 s, overshoot 1.79%, error of steady-state 1.42 %. It can follow speed reference change up and overcome the interference from the outside of a momentary disturbance.

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