# CONTROL OF BRUSHLESS DC MOTOR USING SINGLE-INPUT FUZZY PROPORTIONAL-INTEGRAL CONTROLLER

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MAY 2018

*To my family for their ever loving support over the years*

*To my friends for their never ending encouragement and support*

# ACKNOWLEDGEMENTS


Alhamdulillah, first, I would like to convey my deepest gratitude to my supervisor, Dr Shahrin Md Ayob for his guidance and supervision until the completion of my thesis.

Special thanks for my parents (Baharudin Idris and Rosnah Bustamam) as well as my siblings (Rashidah, Atiqah, Hanisah and Fadhilah) who have been patient and tolerant towards me throughout my study period. Thanks for their encouragement and supports that I manage to complete this thesis after more than three years. Also, a special thanks to my co- supervisor, Assoc. Prof. Dr Junaidi Abdul Aziz who has been helpful and generous especially during my supervisor absent.

Last but not least, I wish to express my appreciation to Assoc. Prof. Dr Nik Rumzi Nik Idris, my lab mates (Dr Ibrahim, Dr Ali, Dr Low, Akmal, Akram and Sajad) and my colleagues (Rozana, Farhanah, Atika, Baizura, Farhana and Fatihah) for their advice and idea in improving this project and thesis. Not forgotten, my high school friends (Nazihah, Rabiatul, Syafiqah, Syikin, Amira Z, Nabila, Idurrah, Ilyana, Sri, Nazirah, Aqilah, Amira K, Ain, Atiqah, Hazwani, Shafa, Zuriana, Isma and Munirah) who have been really motivational and supportive in all these years we have known each other.

I am so grateful to all individual who have involved directly or indirectly in completion of my thesis. Once again, thank you very much.

## ABSTRACT

Over the years, development in control industry has brought a hybrid controller, Fuzzy Proportional-Integral (PI) Controller (FPIC) as Brushless DC (BLDC) motor speed regulator with as good performance as PI controller. The FPIC suffers from lengthy design time due to the large number of rules and parameter tuning. Thus, this thesis proposes a newly developed Single-Input Fuzzy PI Controller (SIFPIC) to be used as the BLDC motor speed controller. SIFPIC is a simplified version of FPIC with one input variable derived using signed distance method. SIFPIC gives a speed performance comparable to the FPIC but with much faster computing time and simpler tuning process. The motor performance with SIFPIC is evaluated through simulation and experimental approach in terms of speed, current and torque response under several test conditions. The performance is then compared with the motor performance with discrete PI and FPIC speed controller. FPIC is excluded from the comparison in the experiment due to the limitation of DS1104 Digital Signal Processor. From the simulation conducted, SIFPIC produced a comparable performance as FPIC in speed response where both controllers eliminated undershoot and oscillation problems. Under constant speed and changing speed conditions, SIFPIC also showed it superiority from discrete PI controller with average of 36.3% and 11.7% lower ripples than discrete PI controller, respectively. The simulation findings have been verified by the experimental results.

## ABSTRAK

Selama bertahun-tahun, pembangunan dalam industri kawalan telah membawa pengawal hibrid iaitu pengawal kabur kadar kamir (FPIC) sebagai pengawal kelajuan motor arus terus tanpa berus (BLDC) dengan prestasi sebaik pengawal kamiran-berkadaran (PI). Namun, pengawal FPIC yang dihasilkan mempunyai masalah iaitu memerlukan masa yang panjang untuk mereka-bentuk pengawal kerana mempunyai jumlah parameter talaan dan peraturan kawalan yang banyak. Oleh itu, tesis ini mencadangkan Pengawal Kadar Kabur Kamir Masukan Tunggal (SIFPIC) untuk digunakan sebagai pengawal kelajuan untuk sistem motor BLDC. Pengawal SIFPIC adalah versi yang dipermudahkan daripada FPIC yang mempunyai masukan tunggal yang diterbitkan menggunakna kaedah jarak bertanda. Pengawal SIFPIC memberikan prestasi kelajuan setanding dengan pengawal FPIC tetapi dengan masa pengiraan yang lebih cepat dan proses penalaan yang lebih mudah. Prestasi motor BLDC dengan SIFPIC dinilai melalui pendekatan simulasi dan ujikaji tindak balas kelajuan,motor, arus dan daya kilas di bawah beberapa keadaan ujian. Seterusnya, prestasi motor akan dibandingkan dengan prestasi motor yang dikawal oleh pengawal PI diskrit dan pengawal FPIC. FPIC dikecualikan daripada kajian perbandingan disebabkan oleh kekangan memproses isyarat digital DS1104. Daripada hasil simulasi, pengawal SIFPIC menghasilkan prestasi setanding FPIC dalam tindak balas kelajuan motor dimana kedua-dua pengawal menghapuskan masalah lajakan turun dan ayunan. Dibawah keadaan kelajuan tetap dan berubah, SIFPIC menunjukkan keunggulan berbanding pengawal PI diskrit dengan purata 36.3% dan 11.7% riak yang lebih kecil untuk arus dan daya kilas. Penemuan simulasi telah disahkan oleh hasil eksperimen.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $B$ | – | Damping factor |
| $ce$ | – | Change of error |
| $d, d(k)$ | – | Signed distance input |
| $d_{bp}$ | – | Breakpoint distance |
| $d_o$ | – | Distance from random point to origin line |
| $d_{sn}$ | – | Distance from sliding surface to random point |
| $e_a,\ e_b,\ e_c$ | – | Back EMF of phase a, b and c |
| $e, e(k)$ | – | Error signal |
| $e_p, e_p(k)$ | – | Scaled error signal |
| $\dot{e}, \dot{e}(k)$ | – | Change of error signal |
| $\dot{e}_p, \dot{e}_p(k)$ | – | Scaled of change of error signal |
| $f_c$ | – | Cross-over frequency |
| $f_s$ | – | Switching frequency |
| $f_a(\theta), f_b(\theta), f_c(\theta)$ | – | Rotor angle function for phase a, b and c |
| $i_a, i_b, i_c$ | – | Motor phase current |
| $i_{ref}$ | – | Current reference |
| $J$ | – | Moment of inertia |
| $k_b/k_e$ | – | Back EMF constant |
| $k_e$ | – | Input scaling factor for error signal |
| $k_{\dot{e}}$ | – | Input scaling factor for change of error signal |
| $k_d$ | – | Derivative gain |
| $k_i$ | – | Integral gain |
| $k_p$ | – | Proportional gain |
| $k_t$ | – | Torque constant |
| $k_u$ | – | Ultimate gain for Ziegler-Nichols tuning |
| $L_s$ | – | Stator inductance |

| | | |
|---|---|---|
| $m, n$ | – | Gain parameter for SIFPIC |
| $R_k$ | – | $k^{th}$ rule of FLC |
| $R_s$ | – | Stator resistance |
| $T$ | – | Period |
| $T_e$ | – | Electromagnetic torque |
| $T_d$ | – | Derivation period for Ziegler-Nichols |
| $T_i$ | – | Integral period for Ziegler-Nichols |
| $T_L$ | – | Load torque |
| $T_s$ | – | Sampling time |
| $T_{s1}, T_{s2}$ | – | Sampling time for inner and outer loop |
| $T_u$ | – | Period of oscillation for Ziegler-Nichols |
| $u, u(k)$ | – | Actual control output |
| $\dot{u}, \dot{u}(k)$ | – | Change of actual control output |
| $\dot{u}_o, \dot{u}_o(k)$ | – | Control output from lookup table |
| $v_a, v_b, v_c$ | – | Motor voltage for phase a, b and c |
| $w_o, w_m$ | – | Output/motor speed |
| $w_{ref}$ | – | Speed reference |
| $x_1, x_2$ | – | Crisp data |
| $x$ | – | Input state variable |
| $\dot{x}$ | – | Change of input state variable |
| $z^{-1}$ | – | Unit delay |
| $\alpha_{ss}, \alpha_{ls}$ | – | Slope for small and large signal disturbance |
| $r$ | – | Scaling factor |
| $p$ | – | Fuzzification level |
| $q$ | – | Number of input |
| $\mu$ | – | Degree of membership function |
| $\omega_n$ | – | Natural frequency |
| $\psi$ | – | Control surface |
| $\zeta$ | – | Damping ratio |

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AC | – | Alternating Current |
| ADC | – | Analogue to Digital Converter |
| BLDC | – | Brushless DC |
| BoA | – | Bisector of Area |
| CoG | – | Centre of Gravity |
| CoGS | – | Centre of Gravity Singleton |
| DAC | – | Digital to Analogue Converter |
| DC | – | Direct Current |
| DSP | – | Digital Signal Processor |
| EMF | – | Electromagnetic Force |
| EMI | – | Electromagnetic Interferemce |
| FLC | – | Fuzzy Logic Control |
| FPIC | – | Fuzzy PI Controller |
| FSMC | – | Fuzzy Sliding Mode Control |
| IGBT | – | Insulate Gate-Bipolar Transistor |
| MoM | – | Mean of Maxima |
| NB | – | Negative Big |
| NS | – | Negative Small |
| PB | – | Positive Big |
| PD | – | Proportional Derivative |
| PI | – | Proportional Integral |
| PID | – | Proportional Derivative Integral |
| PS | – | Positive Small |
| PWM | – | Pulse Width Modulation |
| RTI | – | Real-Time Interface |
| SIFLC | – | Single-Input Fuzzy Logic Controller |
| SIFPIC | – | Single-Input Fuzzy PI Controller |

| | | |
|---|---|---|
| SMC | – | Sliding Mode Control |
| SW | – | Switch |
| UoD | – | Universe of Discourse |
| Z | – | Zero |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Energy exists in variety of forms: kinetic, electrical, mechanical, chemical and potential energy. In power electronic and electric drive field, energy is mainly in either electrical or mechanical energy depends on the application requirements. There are also applications that use both form of energy known as electro mechanics such as traffic light and washing machine. Electromechanical devices involve energy conversion either an electrical signal creating mechanical movement or mechanical movement creating the electrical signal with the aid of converters [1]. Those devices are more known as electric machines. The machine is said to act as a motor when conversing electrical energy into mechanical energy and as a generator when conversion is vice-versa.

Electric motor is the prime movers of the electrical drive which is applied for a system with motion control requirement. Most electric motors are used in constant speed operation that do not need to be controlled unless for starting, stopping and protection [1, 2]. However, at some point there is need for the motor to be controlled where speed and torque must support the mechanical load demand. The electric motor is categorized into two classes: Direct Current (DC) and Alternating Current (AC) motor. DC motor can be controller over a wide range of speed by using either a variable voltage supply or by changing strength of field winding current. The AC motor operates with two rotating or moving magnetic fields on the rotor and stator respectively [2]. Two main types of AC motor are induction and synchronous motor. The induction motor always relies on slip speed to induce the rotor AC current while synchronous motor uses either permanent magnet, salient poles or independent excited rotor winding.

In this work, a permanent magnet Brushless DC (BLDC) motor is used for the drive system. BLDC motor is a three-phase synchronous motor which received AC current converted from DC power supply by power inverter. The BLDC motor is made up of permanent magnet rotor and stator winding with rectangular stator current that produces trapezoidal back electromotive force (EMF) and a constant torque [3]. Thus in order to obtain variable speed operation, the motor requires a drive system operates in electromechanical system that includes an electronic motor controller and a rotor position feedback sensor. BLDC motor has the ability to develop high torque with good speed response which is appealing in motion control industry [3, 4]. Besides that, BLDC motor has excellent efficiency, higher power density and a simple control scheme.

Since the 1990's, the Proportional-Integral (PI) controller is widely known and used in electric drive field due to its fast and efficient response [5]. PI controller is a linear controller that implements a well-established design procedure such as bode-plot technique, Nyquist and etc. In addition, the performance of this type of controller is easy to analyze using several mathematical and computer tools that have been established. PI controller has a few disadvantages and the most known is its limitation of operating well in one point. Thus, as it is desirable to have variable-speed operation in a non-linear system, PI controller may not be the best option. Other than that, PI controller also has slow computation, oscillation and overshoot problems and complicated mathematical model [5, 6]. Non-model based method such as Neural Network and Fuzzy Logic can help get rid of the problem in deriving the mathematical model of a system.

Fuzzy Logic Controller (FLC) is commonly more familiar in drive control industry than Neural Network and other Artificial-Intelligence method. FLC basically uses an algorithm to systematically convert the linguistic rules into an automatic control scheme [7]. This type of controller has a few advantages over PI controller such as auto-tuning technology where it can be set manually by the researcher; it can be used for a broad range of operating condition and produces a precise control performance. However, despite all the benefits offered, FLC still suffers from lengthy period of design procedure due to many parameters and number of rules to tune. In addition, it does not have any standard design procedure which means the design still based on heuristic method [8].

Experimental approach in purpose to analyze the comparison between FLC and PI speed response in high-performance AC drives has been done and recorded in [9]. The study concluded that FLC does not necessarily superior over PI controller except in case of load transient rejection; FLC is indeed always superior. Some researchers have implemented a new kind of controller where both FLC and PI controller is combined, namely a hybrid controller as way to overcome the issues of both controllers. The hybrid Fuzzy PI Controller (FPIC) gives control performance with shorter settling time, better robustness and stability [10]. The fuzzy part of this controller can be structured as its PI counterpart in small signal disturbance in where the control surface exhibits a linear surface. One main drawback of FPIC is that it is not a mathematical-based controller which means it cannot avoid heuristic design approach and make it still suffers from lengthy designing time.

In this research, Single-Input Fuzzy PI Controller (SIFPIC) is proposed as the speed controller instead of the conventional FPIC for the BLDC motor drive system. SIFPIC introduced a new variable called distance, $d$ as the sole-input to the controller which has been previously derived by [11] through signed-distance method. SIFPIC has simple generation and tuning process but still able to provide a control response comparable to the conventional controller response but with much shorter computing time.

## 1.2 Objective of Research

The objectives of this research are:

(i) To design the SIFPIC as speed controller for BLDC motor drive system.

(ii) To construct and develop a prototype of BLDC motor drive system with SIFPIC as the speed controller.

(iii) To evaluate the speed, current and torque performance of SIFPIC through simulation and experimental approach.

## 1.3 Scope of Research

This research will cover a comprehensive and inclusive review of control method for motor drive especially for BLDC motor drive. Previous related work on motor drive are reviewed and analyzed critically. The purpose of the review is to propose a simple control method for the drive system. This work proposed SIFPIC as the speed controller for the BLDC motor drive system which has been developed in previous study for a converter regulation. The modeling design of SIFPIC and simulation works are done using software MATLAB/Simulink. The evaluation of the SIFPIC is evaluated through comparison with discrete PI controller and FPIC in form of speed, current and torque response. This work will also implement a hardware prototype to validate the simulation findings through experimental approach.

## 1.4 Importance of Research

It is believed that the conventional Fuzzy PI controller has solved the small signal disturbance issues, yet for large signal disturbance, the complication of heuristic tuning and the lengthy design time cycle is still become great obstacle. In addition to that, consistent response is somewhat difficult to achieve as the system has to consider large number of rules and parameters to tune. These problems can be solved by implementing SIFPIC as proposed. SIFPIC used single variable as its input which called signed-distance, $d$ derived from signed-distance method. SIFPIC reducing the number of rules that needed to tune make it a simpler control scheme. The computation time of the system is expected to become very fast and SIFPIC can easily behaves as discrete PI controller in small signal disturbance with approximately equivalent response.

## 1.5 Organization of Thesis

This thesis is organized into five chapters. Their contents is outlined as follows:

(i) Chapter 2 provides a comprehensive literature review of control method on regulating the speed of BLDC motor. The review includes for both linear and non-linear system. The advantages and disadvantages of all methods are all listed.

(ii) Chapter 3 proposes the SIFPIC as the simpler version of the conventional Fuzzy PI controller. The controller introduced a concept of Signed-distance method in order to shorten the computation time. A relationship with discrete PI controller is established with discussion on the control surface of fuzzy controller is presented.

(iii) Chapter 4 presents the design procedures of closed loop BLDC motor drive system in MATLAB/Simulink. System simulation and performance evaluation is done under several conditions and were compared with the performance of discrete PI controller and FPIC. This chapter also presents the complete procedure of hardware implementation of the controller on drive system..

(iv) Chapter 5 presents the results from both simulation and experimental approach. A discrete PI controller and FPIC have been developed for comparison purpose. However, FPIC does not included in experimental approach due to difficulty in processing the rule inference in the actual system. This chapter also provides the detail analysis on the response.

(v) Chapter 6 concludes the research on the proposed method for the motor drive system. The conclusion is made through the analysis of the control response from both simulation and experimental approach.

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