Journal of Engineering Technology Vol. 5: 32-37, 2017
ISSN 2231-8798

Optimization of PI Parameter for Speed Controller of a Permanent Magnet Synchronous Motor

Lilik Jamilatul Awalin[1], Afifudin[2], Fadi Albatsh[3]& M. Khairil Rahmat[4]
[1]Electrical Engineering Section,
Universiti Kuala Lumpur British Malaysian Institute

Corresponding email: lilik@unikl.edu.my

Abstract: This paper present the estimation of Proportional and Integral (PI) gain to control the speed of permanent magnet of synchronous motor. Modelling of a Permanent Magnet Synchronous Motor (PMSM) drive system and installation of PI controller in the Matlab Simulink also will discuss in this paper. The simulation includes all realistic components of the system and simulated in Matlab Simulink workspace based on the mathematical model of the system devices including permanent magnet synchronous motor and inverter. Detail implementation of permanent magnet synchronous motor and inverter also explained. Determination gain is adopted from Ziegler Nichols tuning method considering Proportional Integral (PI) in order to control the speed controller of a Permanent Magnet Synchronous Motor (PMSM). Analysis of the stability of speed rotation of PMSM by considering PI controller will discussed in this paper. Based on the obtain result, the performance of the stability of the permanent magnet synchronous motor considering PI controller are achieved.

Keywords: Permanent Magnet Synchronous Motor (PMSM), Proportional Integral (PI) Speed Controller, Ziegler Nichols tuning method.

1.0 INTRODUCTION

Nowadays, many industrial applications are manufactured by different company. The parameters of the motors are unknown or not precise to guarantee the desired closed loop performance. So, it is necessary to estimate the motor parameters and determine the gains in order to achieve the desired performance.

Permanent magnet (PM) synchronous motors are mainly and widely used in low power and mid power system application such as computer peripheral devices, robotics, adjustable speed drives and electric vehicles [1]. A "permanent magnet synchronous motor" (PMSM) or "permanent magnet motor" (PMM) is a synchronous motor that uses permanent magnets rather than windings in the rotor that create constant magnetic field [2]. In paper [1] the authors have presented the detailed modelling of PMSM drive in Simulink workspace. The author's works also presented the speed control of PMSM considered a vector control approached and by used of state feedback (SFB) controller. Figure 1 shows permanent magnet synchronous motor diagram.

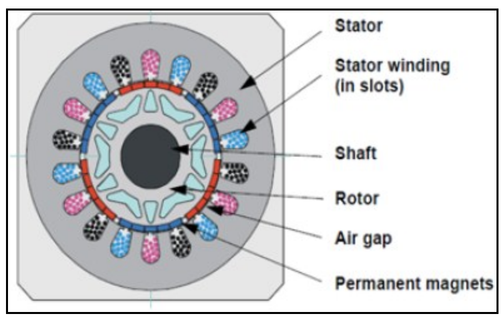

Figure 1: Permanent Magnet Synchronous Motor [2]

In so many ways, the PMSM offer more advantages that include high efficiency, high torque and small ripple which play as a main role in precision control. In high performance permanent magnet synchronous motor drive technology, field oriented control using coordinate transformation is commonly adopted [3]. The authors in paper [3] mentioned that the two parameters of the PI controller gain, K_p and K_i can be controlled online by self-tuning in the motor control system verification.

The PID controller calculates an "error" values as the difference between the measured process value and the desired set point [4]. The PID terms stands for the proportional, the integral and the derivative values. A proportional controller might not give steady state error

Journal of Engineering Technology Vol. 5: 32-37, 2017
ISSN 2231-8798

performance which is required in the system. An integral controller might give steady state performance but it will slows a system down. So the derivative controller helps to cure both of these problems.

However, the development in control systems are enabling new complexity in designing motor control which cause difficulties in programming. Usually, MATLAB/Simulink is one of the common software environment that used for modelling and simulation of electrochemical systems and their control applications before the realization step [5]. Therefore, paper [5] proposed MATLAB/Simulink model of a speed sensor field oriented control (FOC) of PMSM drive is developed because it is simple, easily to modify and economic that helps the experimental stage ran successfully.

The Ziegler Nichols tuning method is a method that related to the process parameters which are delay time, process gain and time constant, the controller parameter, controller gain and reset time.

2.0 ESTIMATION OF PI CONTROLLER CONSIDERING ZIEGLER NICHOLS TUNING METHODS.

A control system includes a speed feedback system, a motor, a controller, inverter and speed setting device. The speed control system allow to easily set and the speed of the motor can be adjusted. A system with designed feedback controller makes the system more reliable to disturbance and changes of parameters.

Figure 2 is illustrated rotating rotor of d-axis makes an angle θ_r with the fixed stator phase axis with the fixed stator phase axis, meanwhile the rotating stator mmf makes an angle α with the rotor d-axis. In the same time, the rotation of stator mmf is at the same speed as that of the rotor.

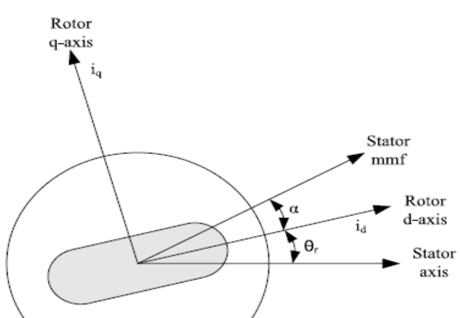

Figure 2: d-q motor axis [1]

The permanent magnet synchronous motor without damper winding has been developed on rotor reference frame using the assumption:

1. Saturation is neglected.
2. The induced EMF is sinusoidal.
3. Eddy current and hysteresis losses are negligible.
4. There are no field current dynamic.

A full speed range of permanent magnet synchronous motor drive system modelling includes a motor, inverter, and controller which include constant torque and flux weakening operation, reference current and PI controller. The system was simulated in Matlab Simulink workspace as shown in Figure 3.

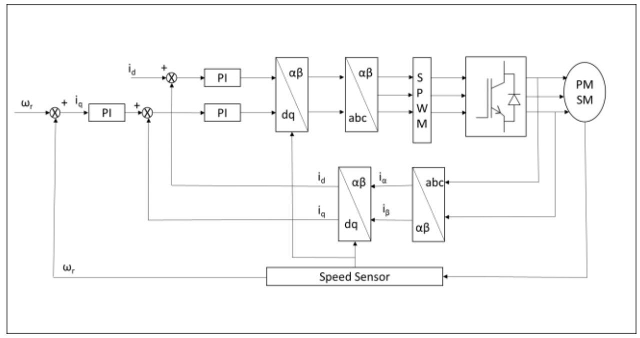

Figure 3: PMSM drive system modelling

The permanent magnet synchronous motor is fed by a current controller pulse width modulated (PWM) inverter. The motor currents are decomposed into i_d and i_q components which are respectively flux and torque components in the rotor based d-q coordinates system [6]. The motor model is defined with the following equations:
Voltage equations are given as below [7], [8]:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \quad (1)$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \quad (2)$$

Flux linkage are given as below [7], [8]:

$$\lambda_q = L_q i_q \quad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \quad (4)$$

Substitute equations (3) and (4) into (1) and (2) [7], [8]:

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho (L_q i_q) \quad (5)$$

$$V_d = R_s i_d - \omega_r (L_q i_q) + \rho (L_d i_d + \lambda_f) \quad (6)$$

Arranged equation in (5) and (6) in matrix form [7]:

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \quad (7)$$

The developed torque motor is being given by [7], [8]:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right) \quad (8)$$

Journal of Engineering Technology Vol. 5: 32-37, 2017
ISSN 2231-8798

The equation of mechanical torque is [7], [8]:

$$T_e = T_L B\omega_m + J\frac{d\omega_m}{dt} \quad (9)$$

Solving for the rotor mechanical speed form equation (9) [7]:

$$\omega_m = \int\left(\frac{T_e - T_L - B\omega_m}{J}\right)dt \quad (10)$$

And [7]:

$$\omega_m = \omega_r\left(\frac{2}{P}\right) \quad (11)$$

In the above equations ω_r is the rotor electrical speed while the ω_m is the rotor mechanical speed.

A. TRANSFORMATIONS BLOCK

Three phase machines are usually can be describe by voltage and current in a mathematical equations. The mathematical modelling of that kind of system would be complex since the induced voltages, flux linkages and current reform continuously as the electric circuit in a relative motion. As to be a complex system of electrical machine analysis, it could be common to use a mathematical equations of transformation to decouple variables and also to figure out the equations involving time varying quantities by referring all possible variables to a common frame of reference. Clarke and Park transformations are mainly used in vector control architectures related to permanent magnet synchronous machines (PMSM) and asynchronous machines [2].

For permanent magnet synchronous machines that related to vector control architecture, it is well known to use the park and Clarke transformation.

The following Figure 4 shows an example of reference frame of transformation block known as Park transformation. In park transformation, the abc_dq0 transformation block generate the direct axis, quadratic axis and zero sequences quantities in a two rotating reference frame for a three phase sinusoidal signal [8].

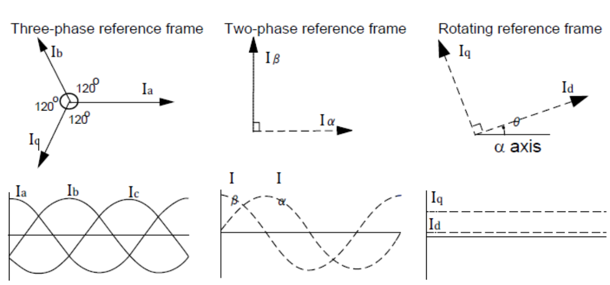

Figure 4: Reference frame of Park transformation [8]

B. PERMANENT MAGNET MOTORS

The permanent magnet synchronous motor is equivalent to the dc motor by decoupling control known as vector control or field oriented control. The vector control isolates any torque component of current and flux channels in the motor through the excitation stator.

The currents obtained are the stator currents that need to be transformed to the rotor reference frame with the rotor speed using Park transformation. Both q and d axis are constant in the rotor frames since α is a fixed given load torque. As for this fixed α, it is similar to the field current and armature current in the separately excited dc machine. The q axis is partially field current which it is distinctly equivalent to the armature current yet the other part is contributed by equivalent current source representing permanent magnet field. As far as it concern, d-axis is known as the flux producing component of the stator current while the q-axis is known as torque producing component of the stator current. The parameters of Permanent Magnet Motor Parameters are listed as shown in Table 1.

Table 1: Permanent Magnet Motor Parameters

Symbol	Name	Value
V_{LL}	Rated voltage	220 V
P	No. of Pole	4
ωm	Rated speed	1000 rpm
Rs	Stator resistance	0.2 ohm
L_q	q-axis inductance	8.5 mH
L_d	d-axis inductance	8.5 mH
J	Motor Inertia	0.089 kgm^2

C. SPEED CONTROLLER

The procedure of selecting control parameters, tuning method was popular method to stabilize the system. One of the tuning method is Ziegler and Nichols. They introduce the rules for tuning PID controller by setting the values of proportional gain Kp, integral time T_i, and derivative time T_d. Based on the experimental step responses or the value of Kp given, the outcome will lies in marginal stability when only proportional control action is used.

D. INVERTERS

The universal bridge block enable a universal three phase power converter that make up to six power switches that connected in a bridge configuration. The model block allows the simulation to converts using both naturally commutated or known as line commutated power electronics devices. The examples of power electronics devices are diodes, thyristors, GTO, IGBT and MOSFET. The number of bridge arms can be set to one or two to get a single phase for two or four switching devices. It also

Journal of Engineering Technology Vol. 5: 32-37, 2017
ISSN 2231-8798

can be set to three to get three phase converter for six switching devices.

The snubber resistance, *Rs* is a set of parameter to *inf* to eliminate the snubber from the model. On the other hand, the snubber capacitance, Cs is to set to 0 to eliminate the snubber or to *inf* to get the resistive snubber. Forward voltage, V_f is a parameter that available only when the power electronic devices selected to diodes or thyristors. The parameters are listed as shown in Table 2.

Table 2: Parameters for Converters and Inverters.

Name /Values	Converter (Rectifier)	Inverter (IGBT)
Snubber Resistance (Rs)	$10e^3$	$5e^3$
Snubber Capacitance (Cs)	$20e^9$	Inf
On-state resistance (ohm)	$1e^{-3}$	$1e^{-3}$
Forward Voltages (V)	1.3	0.8

E. ZIEGLER NICHOLS TUNING METHOD

The detail process of Ziegler Nichols tuning method are explain as follows:

1. Set Kd and Ki to zero.
2. Increase the Kp until the system start to oscillate i.e the dominant poles are at the imaginary axis. Called this gain as K_c, critical gain and find the ω_c, the critical frequency.
3. Set Kp = 0.45 Kc.
4. Then, depend on the controller structure, set the rest of the gain according to the Table 3 below.
5. Evaluate control parameter as prescribed by Ziegler and Nichols.

Table 2 is shows the formulation for each type of controller.

Table 3: Ziegler-Nichols tuning rule based on critical gain K_{cr} and critical period P_{cr}

Type of controller	K_p	T_i	T_d
P	0.5 K_{cr}	∞	0
PI	0.45 K_{cr}	0.45 K_{Cr}/W_C	0
PID	0.6 K_{cr}	1.2 K_{Cr}/W_C	0.3 $K_{Cr}W_C/4$

Where:
Kp= Proportional gain
Ti= Integral gain
Td= Derivative gain

3.0 RESULT AND DISCUSSION

A. SIMULATION OF THE SYSTEMS AT 300 RPM

The mathematical calculation to obtain the value of critical frequency, proportional gain and integral gain are as following and the simulation result as shown in Figure 5. Then, depend on the controller structure, set the rest of the gain according to the Ziegler Nichols tuning method. The following mathematical calculation are to obtain the values of K_p and K_i a simulation of 300 *rpm* as a parameters to set the new values of PI controller.

Set $K_p = 1$, $K_i = 0$

$$f = \frac{1}{T} = \frac{1}{0.575} = 1.7391 \quad (12)$$

$$\omega c = 2\pi f = 2\pi(1.7391) = 10.927 \quad (13)$$

$$K_p = 0.45K_c = 0.45(1) = 0.45 \quad (14)$$

$$K_i = \frac{0.45K_C}{\omega c} = \frac{0.45(1)}{10.927} = 0.411 \quad (15)$$

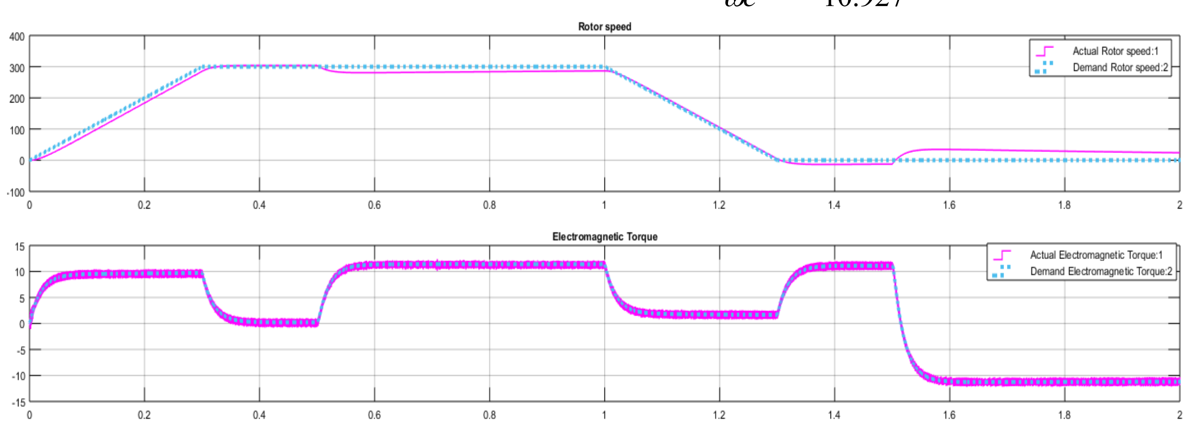

Figure 5: Simulation when K_d set to 0.45 and K_i are set to 0.411 value at 300 rpm

Journal of Engineering Technology Vol. 5: 32-37, 2017
ISSN 2231-8798

At an initial step, the speed set point is 300 rpm with the K_d set to 1 and K_i are set to zero value, the oscillation of the stator current also start at 0.5s and it generate a better oscillations. For rotor speed at this set point, the actual speed follow accurately at starting point of 0s and ramp up until hit the set point of 300 rpm and then the speed steadily at its speed until 0.5s. During 0.5s, a load of torque is applied to the motor and it can see clearly a small disturbance in the motor speed which is it stabilize quickly afterwards but not at the same pace with the set point of rotor speed.

At 1s, the speed set point is changed to 0 rpm as well as the actual point of rotor speed is descending accurately.

At 1.5s, the electromagnetic torque is moving downward and the motor speed ascending until it exceeding the set of speed limit. At this time, the oscillation of the stator current is not has a complete cycle.

The new simulation have been conducted after the values of the gain K_p = 0.45 and K_i = 0.411 were updated as calculated and the results as shown in Figure 5.

At the 0s of the starting point, the rotor speed ramp up at lower than the set point and stabilize a few second when hit its maximum amplitude. Then a disturbance occurred at 0.5s and did stabilize but the pace has a greater different which is lower than the set point of the speed. This rotation speed drag until 1s then the speed set point is changed to 0 rpm as well as the actual point of rotor speed is descending accurately.

Based on this Figure 6, the speed set point is 1000 rpm with K_d set to 0.45 and K_i are set to 0.0394. Based on this Figure 4.7, the speed set point is 1000 rpm with K_d set to 0.45 and K_i are set to 0.0394, the oscillation of the stator current started about 0.2s. At the 0s of the starting point, the rotor speed ramp up at lower than the set point and stabilize a few second when hit its maximum amplitude. Furthermore, disturbance occurred at 0.5s and achieved stability but the pace has a greater different which is lower than the set point of the speed.

This rotation speeds drag until at 1.5s then its overshoot a higher bit compared to the set point of speed rotation when the electromagnetic torque drop from 10Nm to -10Nm.

At 2s, the electromagnetic torque drop again until nearer to -19Nm and it was maintained up to 3.3s. During this time, the actual rotation speed steadily decreasing its speed even though it slower than the set value of speed rotation.

At 1.5s, the rotation speed overshoots from the set point when the electromagnetic torque descending to -10 Nm. Somehow, after completed the simulation by using implementation of Ziegler Nichols tuning method and the parameter of the PI speed controller have been set, yet the results of the simulation did not happened as expectation which there are still have disturbance at some points.

B. SIMULATION OF THE SYSTEM AT 1000 RPM

The simulation on the PI speed controller of the permanent magnet synchronous motor as the design shown in Figure 6. However, the time is changed to 4s to gives a better output of simulation. The following mathematical calculation are to obtain the values of K_p and K_i a simulation of 300 *rpm* as a parameters to set the new values of PI controller.

Set $K_p = 1$, $K_i = 0$

$$f = \frac{1}{T} = \frac{1}{0.55} = 1.8181 \quad (16)$$

$$\omega c = 2\pi f = 2\pi(1.8181) = 11.423 \quad (17)$$

$$K_p = 0.45K_c = 0.45(1) = 0.45 \quad (18)$$

$$K_i = \frac{0.45K_C}{\omega c} = \frac{0.45(1)}{10.927} = 0.0394 \quad (19)$$

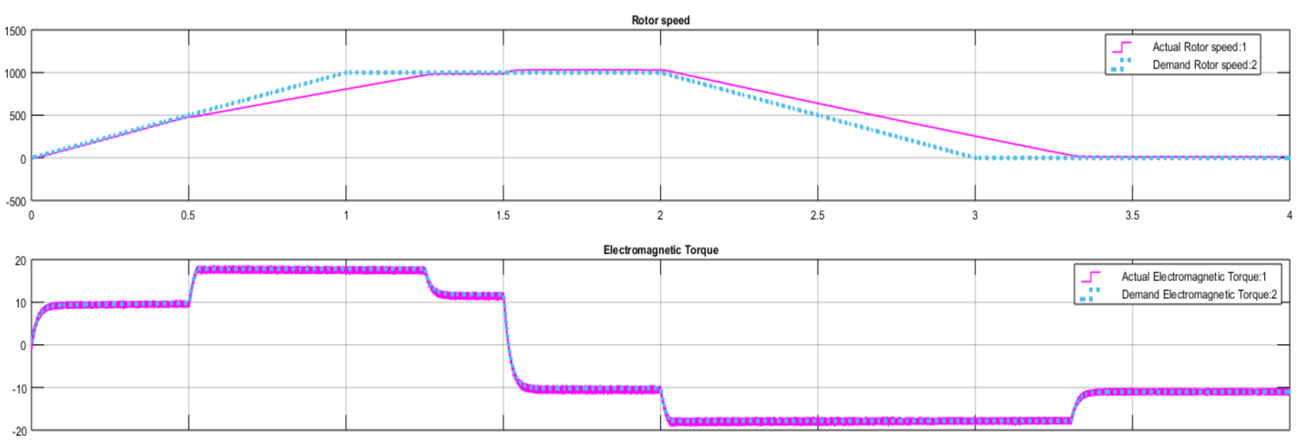

Figure 6: Simulation when K_d set to 0.45 and K_i are set to 0.0394 value at 1000 rpm

C. PERCENTAGE OF ERROR FOR BOTH SIMULATIONS

The percentage of error for both simulation were calculated and have been summarized into table form as shown in Table 4 below:

Table 4: Percentage of error for the speed

Simulation of motor speed (rpm)	Percentage of error (%) = [(Reference speed – Output speed) / (Reference Speed)]× 100
300	[(300-275) / (300)] × 100 = 8.33%
1000	[(1000 - 850) / (1000)] × 100 = 15%

Table 4 shows the percentage of error for 300 rpm which generate 8.33% of error. This condition is less compared to 1000 rpm. The error of 300 rpm is 8.33% can be assumed less because of the speed was not too fast. So, the PI controller can reduce the disturbance that occurred during the simulation. The percentage of error increased to 15% during 1000 rpm simulation, this can be caused by the disturbance occurrence have not been taken into account for this simulation.

4.0 CONCLUSION

This paper was successfully determined the parameter of gain by using the Ziegler Nichols tuning methods. The obtained parameter of gain was used to set the parameter of Kp and Ki. Based on setting of Kp and Ki, the speed rotation is optimized. Speed controller of the permanent magnet of synchronous motor has been successfully designed in order to analyse the results of the rotation speed in the systems. The gain of PI speed controller of permanent magnet synchronous motor was acceptable to stabilize the system.

REFERENCES

[1] Chakraborty, Ajoy Kumar, and Navonita Sharma. "Control of permanent magnet synchronous motor (pmsm) using vector control approach." *Transmission and Distribution Conference and Exposition (T&D), 2016 IEEE/PES*. IEEE, 2016.

[2] H. V. Deo and R. U. Shekokar, "Simulation of PMSM Speed Control System with Vector Control Method based on MAtlab," vol. 2, no. 6, pp. 354-359, June 2015.

[3] H. Y. Chung and S. L. LO, "Permanent Magnet Synchronous Motor Modeling and Control," *2014 International Conference on Fuzzy Theory and Its Application (iFUZZY2014),* pp. 65-70, 26-28 November 2014.

[4] M. L. Mhaisgawali and P. M. S., "Induction Motor Speed Control using PID Controller," vol. Vol 1(2), pp. 151-155.

[5] Kivanc, Omer Cihan, and Salih Baris Ozturk. "MATLAB function based approach to FOC of PMSM drive." *Modelling Symposium (EMS), 2015 IEEE European*. IEEE, 2015.

[6] Karakaya, Abdulhakim, and E. Karakas. "The speed control of permanent magnet synchronous motor using fuzzy logic and self tuning fuzzy PI controller." *Proc. ELECO'05* (2005).

[7] Pillay, Pragasen, and Ramu Krishnan. "Control characteristics and speed controller design for a high performance permanent magnet synchronous motor drive." *IEEE transactions on power electronics* 5.2 (1990): 151-159

[8] Utomo, Wahyu Mulyo, et al. "Speed Tracking of Field Oriented Control Permanent Magnet Synchronous Motor Using Neural Network." *International Journal of Power Electronics and Drive Systems* 4.3 (2014): 290.

[9] M. Corporation, *Park, Inverse Park and Clarke, Inverse Clarke Transformations MSS Software Implementation,* 2013, pp. 1-20.

[10] S. J. Chapman, "Electrical Machine Fundamental fourth edition," New York, McGraw, 2005, p. 380.

[11] Solea, Razvan, et al. "Nonlinear sliding-mode control for permanent magnet synchronous machine." *Optimization of Electrical and Electronic Equipment (OPTIM), 2014 International Conference on*. IEEE, 2014.

[12] Ogata, K. "Modern control engineering 5th edition. Lugar: Upper Saddle River, New Jersey 07458." *ed: Prentice Hall* (2009): 55.

[13] Umabharathi, M., and S. Vijayabaskar. "Speed Control of Permanent Magnet Synchronous Motor Using Evolutionary Fuzzy PID Controller." *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering* 9.12 (2016): 1485-1491.