International Journal of Systems Engineering
2022; 6(2): 46-58
http://www.sciencepublishinggroup.com/j/ijse
doi: 10.11648/j.ijse.20220602.11
ISSN: 2640-4222 (Print); ISSN: 2640-4230 (Online)

Permanent Magnet Synchronous Motor (PMSM) Speed Response Correction Using Fuzzy-PID Self-Tuning Controller Under Sudden and Gradual Load Variation

Vahid Teymoori[1, *], Nima Arish[1], Mehdi Moradi[2], Pedram Ghalebani[3]

[1]Electrical and Electronics Faculty, Stellenbosch University, Stellenbosch, South Africa
[2]Electrical and Electronics Faculty, Cape Town University, Cape Town, South Africa
[3]Electrical and Electronics Faculty, Semnan University, Semnan, Iran

Email address:

Teymoorivahid@yahoo.com (Vahid Teymoori), nima.arishh@gmail.com (Nima Arish), mehdiimmoradi@gmail.com (Mehdi Moradi)
[*]Corresponding author

To cite this article:

Vahid Teymoori, Nima Arish, Mehdi Moradi, Pedram Ghalebani. Permanent Magnet Synchronous Motor (PMSM) Speed Response Correction Using Fuzzy-PID Self-Tuning Controller Under Sudden and Gradual Load Variation. *International Journal of Systems Engineering*. Vol. 6, No. 2, 2022, pp. 46-58. doi: 10.11648/j.ijse.20220602.11

Received: November 1, 2022; **Accepted**: February 1, 2023; **Published**: February 9, 2023

Abstract: The development and improvement of the control of electric motors has drawn the researchers' attention to the implementation of all types of controllers in motors, especially the permanent magnets, because of advantages such as high-power density in lower volumes, lower losses, higher efficiency, high speed performance range and etc. in comparison with other motors, as well as extensive use in the industries including robotics, military, medical, and so on. These motors are a suitable replacement for popular motors, such as induction and reluctance, due to their good characteristics. Permanent magnet motors are subject to considerable disturbance during sudden load removal; irrespective of the type of controller implemented, the gradual load variation in the system in comparison with sudden changes, introduces less disturbance to the system. In this research, a thorough investigation of the performance of a permanent magnet synchronous motor (PMSM) under different load conditions is presented. In order to improve the motor's behavior using two types of self-adjusting FPID and NFPID controllers and PID controllers, performance quality is compared with each other in different load conditions. The simulation results show that the unpleasant behavior created during the sudden change of the FPID controller has been improved.

Keywords: Permanent Magnet Motors, PID Controller, Fuzzy Controller, Self-Tuning

1. Introduction

The discovery of magnetic materials and their creation with high energy density led to the development of machines with a PM excitation field in the 1950s. In this type of machine, magnetic materials are used instead of the coil in the rotor. On the other hand, the advancement of the semiconductor and rectifier switches in the early 1990s led to the replacement of electrical commutators instead of mechanical commutators. These two developments led to the development of permanent magnetism [1]. Magnet motors are permanent electrical machines that are widely used in low-power motor control applications such as robotics, military applications, adjustable speed drives, and medical devices [2, 3]. Permanent magnet motors have better performance in higher efficiency conditions, higher torque at lower speeds, higher power density, lower maintenance, and lower noise compared to other motors [4, 5]. The most important problem with permanent magnet motors is that they require a sophisticated control system. This causes sensitivity of the system parameters of the permanent magnet synchronous motor drives in different applications with load variations. Since these changes are an undesirable characteristic in the excitation system of permanent magnet motors, accuracy in controlling speed or position, against parametric changes or load disturbances is important. Regarding this problem, the parameters of the controller should be changed instantly and continuously [6]. There are two methods for implementation of different models of controlling permanent magnet motors including vector control and direct torque control (DTC) [7]. In the vector control strategy, the responses of the permanent state and the transient state are controlled. In direct torque control, the goal is precise control of the torque, the speed control as well as the transient state control are less studied [8]. Figure 1 shows the speed control of the permanent magnet motor. Hall Effect sensors determine switching at any moment with taking into account the position of the rotor, the speed and winding current error, as well as maintaining the reference speed constant even at the moment of load change and oscillation [9]. Permanent magnet motors usually have an internal or external position sensor to detect the position of the rotor. In the drive of the permanent magnet motors, there is a three-phase inverter, a position sensor and a speed controller. The motor position detection sensors are used to obtain the most suitable switching modes by the vector control method to illuminate the semiconductors in the inverter circuit [10]. In recent years, advanced control techniques such as adaptive control, sliding mode control and self-regulating PID controllers have been used to solve the problem of proper control in transient conditions [11]. Designing and implementing of all these control methods require an accurate mathematical model of the stimulation system, which is actually a very difficult task to achieve. The use of intelligent computing methods, such as fuzzy control, is an attractive solution in controlling the speed of drivers [12, 13]. In some methods [14], a fuzzy Q scheme is proposed in which the fuzzy rule database consists of 8 rules. For fuzzy inputs, only two linguistic attributes, far and near, are considered. According to the material in this study, fuzzy logic is used to control the speed of a permanent magnet motor, whose rotor position is used by Hall Effect sensors mounted on the stator Figure 1.

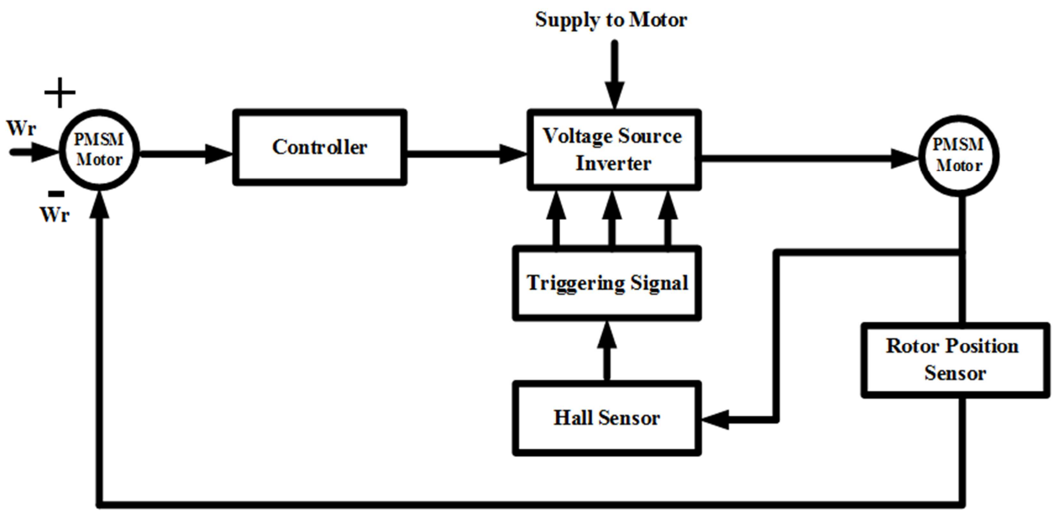


Figure 1. *Speed control scheme for permanent magnet synchronous motor.*

2. The Mathematical Model of Permanent Magnet Synchronous Motor

In the modeling of permanent magnet motor, core saturation and coil leakage inductance, vortex flow and hysteresis losses are neglected, and the magnetic potential in the air gap is distributed uniformly sinusoidal [15]:

Voltage Equations:

$$V_q = R_s I_q + \omega_r \lambda_d + \rho \lambda_q \tag{1}$$

$$V_d = R_s I_d - \omega_r \lambda_d + \rho \lambda_d \tag{2}$$

Flux linkage Equations:

$$\lambda_q = L_q I_q \quad \omega_m = (\int \frac{T_e - T_L + B\omega_m}{J})dt \tag{3}$$

$$\lambda_d = L_d I_d + \lambda_f f \tag{4}$$

Replacing equations 3 and 4 in equations 1 and 2:

$$V_q = R_s I_q - \omega_r (L_d I_d + \lambda_f) + \rho L_q I_q \tag{5}$$

$$V_d = R_s I_d - \omega_r L_q I_q + \rho (L_d I_d + \lambda_f) \tag{6}$$

The combination of equations 5 and 6 in the form of a matrix:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \tag{7}$$

Electric torque equation:

$$T_e = \frac{3}{2}(\frac{P}{2})(\lambda_d I_q - \lambda_q I_d) \tag{8}$$

Mechanical torque equation:

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

The relationship between base and rotor speeds:

$$\omega_m = \omega_r(\frac{2}{P}) \quad (10)$$

In the equations, ω_r is the rotor's base speed and ω_m is the speed of the rotor.

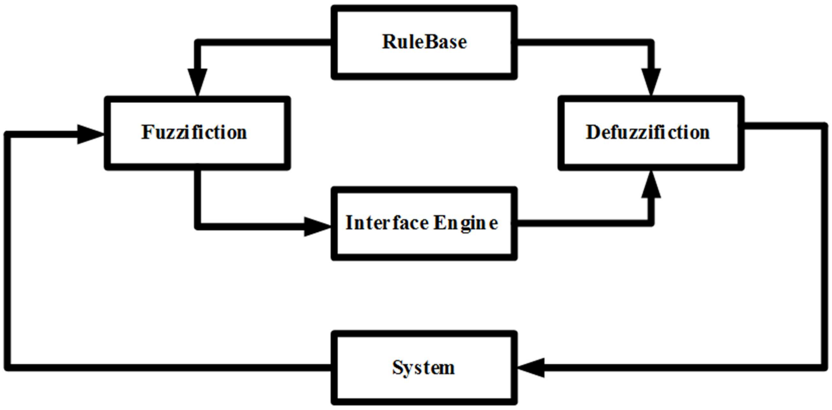


Figure 2. *Block diagram of a system under a fuzzy controller.*

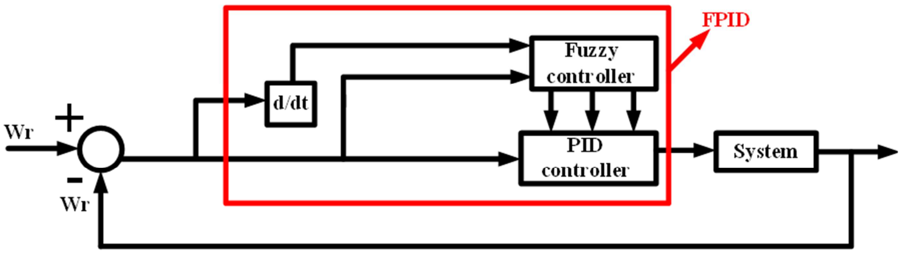


Figure 3. *The block of FPID Controller Diagram.*

3. Controller

A. PID controller

Using a PID controller is a good way to correct the error between the measured variable and the reference value. The optimum control system has a small rise time, a small settling time, a small overshoot time, and little steady state failure. The equation of this control is as the equation (12) [16]:

$$H(s) = P + I + D = K_p + \frac{K_i}{S} + K_d \quad (11)$$

Where K_p is the factor of proportionally, K_i is the integral coefficient and K_d is the derivative coefficient.

B. Fuzzy-PID Controller

Fuzzy logic is a suitable tool for solving various problems in the real world to tolerate errors and noise in data, which are unavoidable in real-world problems. The fuzzy controllers are divided into four sections, two of which perform the transformation process: fuzzification, database, deductive motor, defuzzification Figure 2 [17]. The fuzzy system is used to set the K_p, K_i, and K_d coefficients to control the PID during changing the system parameters. Fuzzy-PID controller inputs are error and error derivative or error variation (d/dt) which is shown in Figure 3. A nonlinear transformation of error and error derivative for PID coefficients is made by fuzzy inference system and the values of PID coefficients are obtained by the fuzzy system [18].

Fuzzy control changes the three coefficients of K_p, K_i and K_d to achieve the appropriate conditions. Fuzzy *membership functions* have two inputs and three outputs, their values are classified into seven ranges (NB, NM NS, Z, PS, PB, PM) [12]. The fuzzy membership functions in the fuzzy editor toolbox is shown in Figure 4. According to a set of rules, the relationship between input and output of fuzzy control can be illustrated using the knowledge available in designing control systems. The proper choice of rules and the number of possible states play an important and essential role in the controller response, and in the absence of the correct selection, they are not only improved, but also the responses are much less favorable. These rules are chosen in Table 1.

The output of the fuzzy rules is the speed and angle of rotation of the motor. For fuzzy inference, Sugeno fuzzy inference engine is used [19]. Therefore, we use equation 13 to estimate the speed:

$$S = \frac{\sum_i a_i s_i}{\sum_i a_i} \quad (12)$$

In equation 13, $a_i$is the rate of fire of rule i.

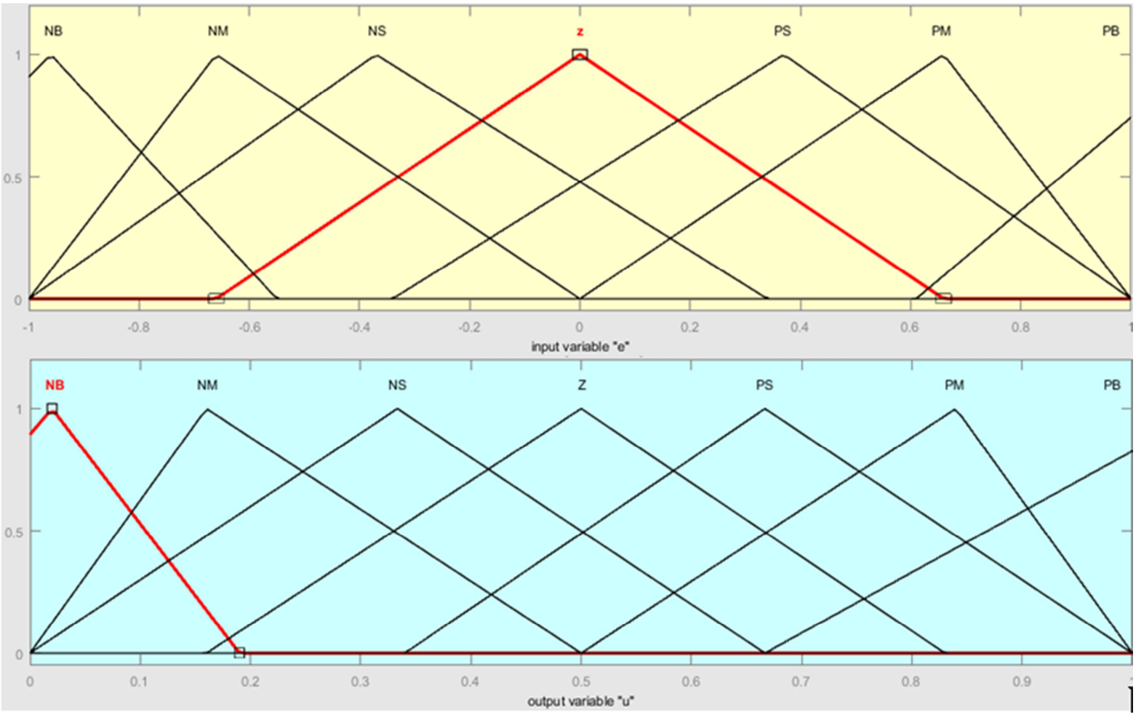


Figure 4. *Fuzzy Membership.*

Table 1. *Fuzzy Rules.*

CE \ E	NB	NL	NS	Z	PS	PL	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NL	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
Z	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PL	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

4. Modeling

More detailed models for checking the performance of the motor in a sudden and gradual load with PID control and FPID are shown in Figures 5 and 6. The speed of the motor is compared by sending feedback paths at the reference speed with the help of the comparator linked to the PID and the FPID. The output of the control outputs the required command to determine the status of the inverter keys. the inverter keys are switched on according to the command signal and based on the vector control method. The output of the inverter circuit feeds the motor. The electromagnetic torque parameters and the rotor speed are measured from the motor output. Simulation has been carried out under various operating conditions, including the moment of launching and loading and removing it.

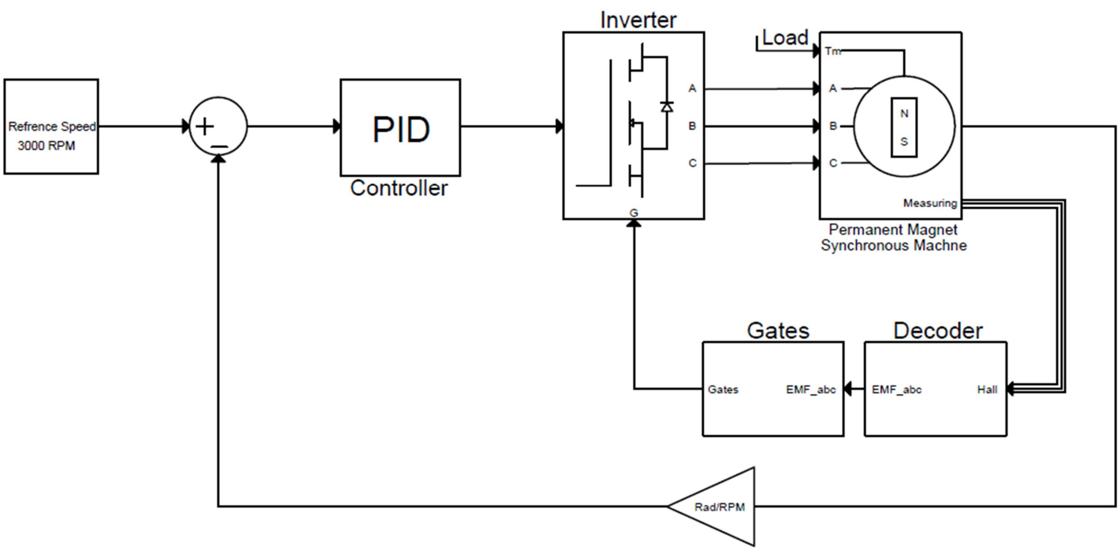


Figure 5. *Block diagram of the PID controller for PMSM motor.*

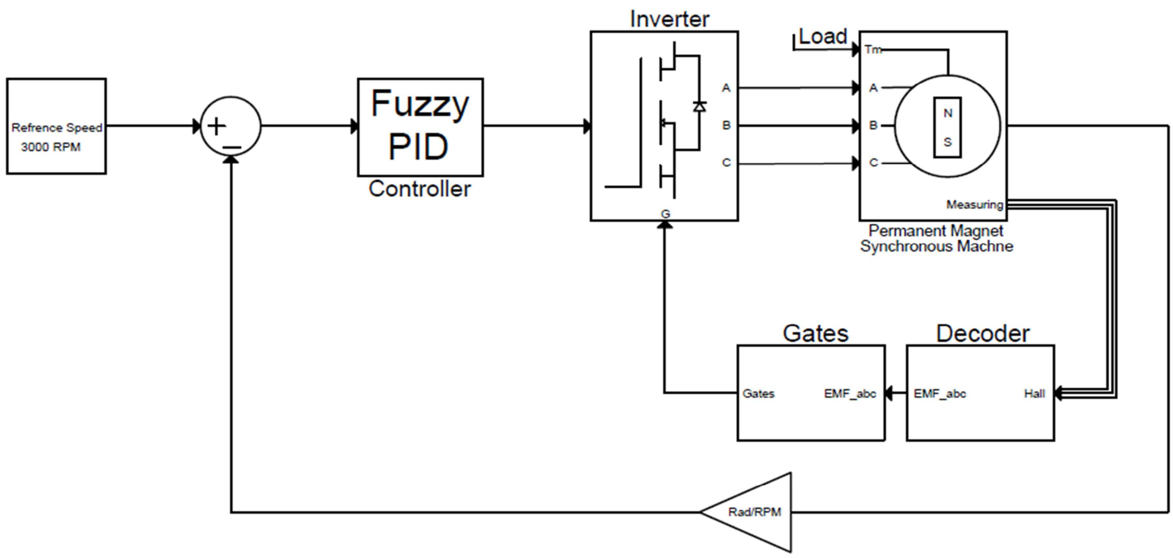


Figure 6. *Block diagram of the FPID controller for PMSM motor.*

5. Setting PID Coefficients

Many controllers of permanent magnet synchronous motors in industrial applications have adopted the constant coefficients method for PID, which works well under certain operating conditions, but its performance degrades in other conditions. Additionally, proper PID coefficients are usually obtained by using time-consuming test and error methods. For this system, the proper coefficients are obtained by using the Ziegler–Nichols open-loop method and have more favorable transient response compared to other methods.

6. Simulation Result with FPID

Simulation has been carried out in two cases of sudden load removal and gradual load removal. Thus, at the time t = 0 to t = 0.1 seconds, the motor starts at idle conditions. With a sudden change in torque of 3Nm at time t = 0.1 seconds and sudden removal at t = 0.4 seconds, while in gradual load change from t = 0.1 to t = 0.2, the load torque increased linearly from 0Nm to 3Nm and then the load is held constant at 3Nm during t = 0.2 to t = 0.3. Additionally, from t = 0.3 to t = 0.4, the load eases from 3Nm to zero. The response curves with PID control for sudden and gradual load change are shown in Figures 7 and 8 respectively, and the response curves with FPID control for sudden and gradual load change are shown in Figures 9 and 10, respectively.

Table 2. *Results of the response speed for the sudden and gradual load with PID controller.*

Load Variation	Characteristics	Time Interval (s)	Overshoot%	Peak Time (s)	Rise Time (s)	Settling Time (s)	Steady state Error
Sudden Load Variation	Starting	0-0.1	8.42	0.0204	0.013	0.0946	0 rpm
	Load Application	0.1-0.4	-4.54	0.0073	_	0.085	2 rpm
	Load Removal	0.4(s)	4.54	0.007	_	0.082	0 rpm
Gradual Load Variation	Starting	0-0.1	8.42	0.0204	0.013	0.0946	0 rpm
	Load Application	0.1-0.2	-0.57	0.0196	_	0.065	2 rpm
	Load Application	0.2-0.3	0.143	0.019	_	0.054	0 rpm
	Load Application	0.3-0.4	0.57	0.0196	_	0.07	14 rpm
	Load Removal	0.4(s)	_	_	_	0.051	0 rpm

Table 3. *Results of the response speed for the sudden and gradual load with FPID controller.*

Load Variation	Characteristics	Time Interval (s)	Overshoot%	Peak Time (s)	Rise Time (s)	Settling Time (s)	Steady state Error
Sudden Load Variation	Starting	0-0.1	2.82	0.039	0.0218	0.096	0 rpm
	Load Application	0.1-0.4	-5.35	0.009	_	0.066	0 rpm
	Load Removal	0.4(s)	5.37	0.0096	_	0.096	0 rpm
Gradual Load Variation	Starting	0-0.1	2.82	0.039	0.0218	0.096	0 rpm
	Load Application	0.1-0.2	-0.987	0.029	_	0.058	2 rpm
	Load Application	0.2-0.3	0	0	_	0.025	0 rpm
	Load Application	0.3-0.4	0.976	0.032	_	0.056	2 rpm
	Load Removal	0.4(s)	_	_	_	0.052	0rpm

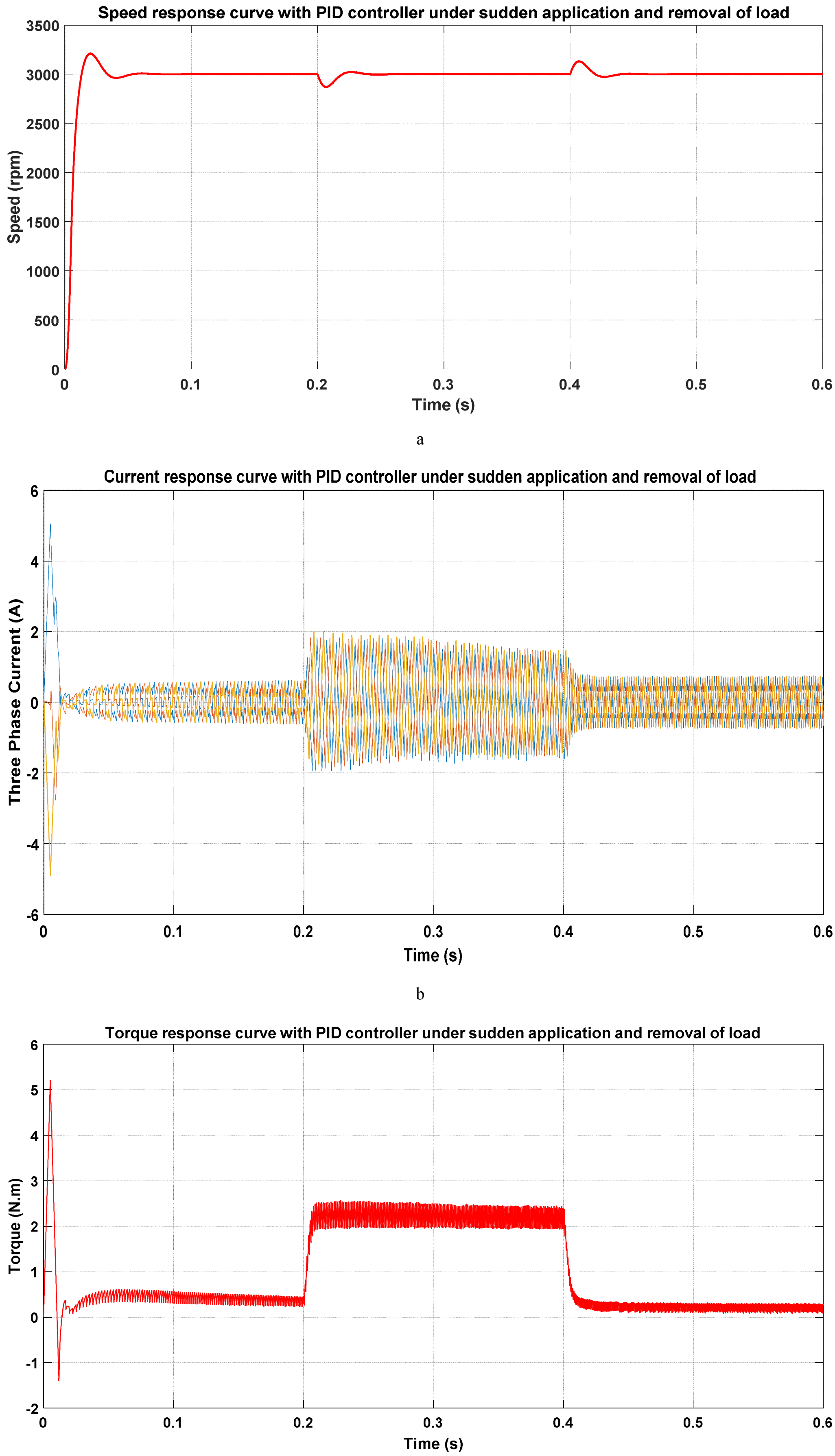
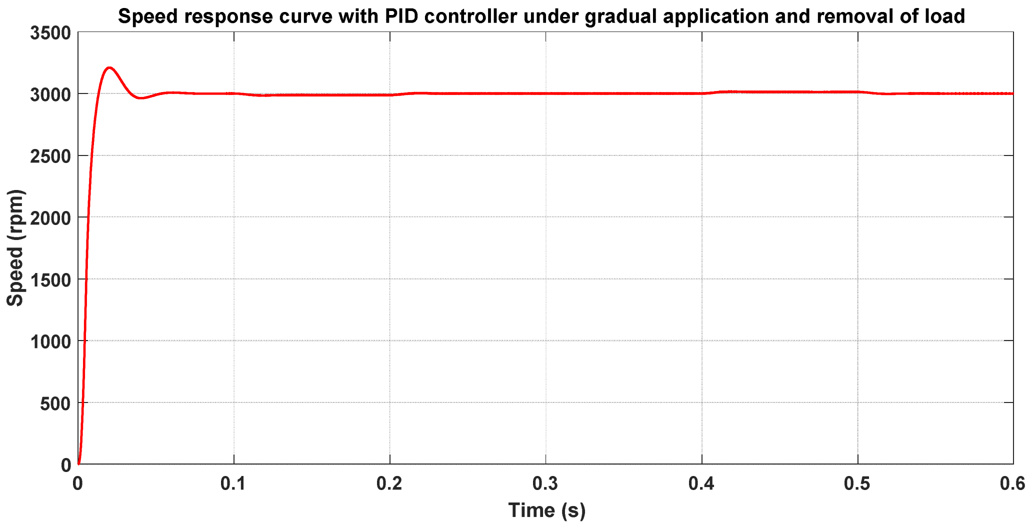
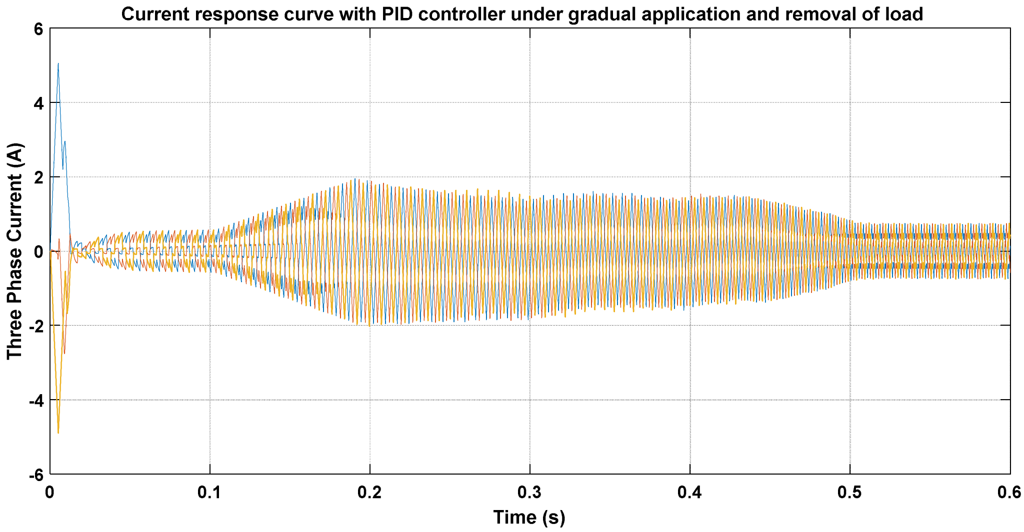


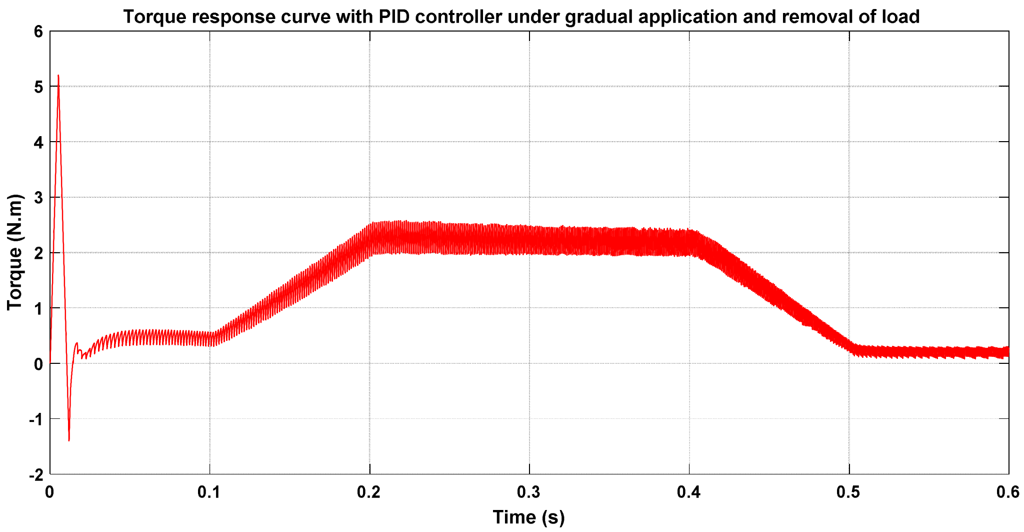
Figure 7. *System specification with PID controller under sudden load conditions. a) speed Response, b) three-phase flow response, c) torque Response.*



a

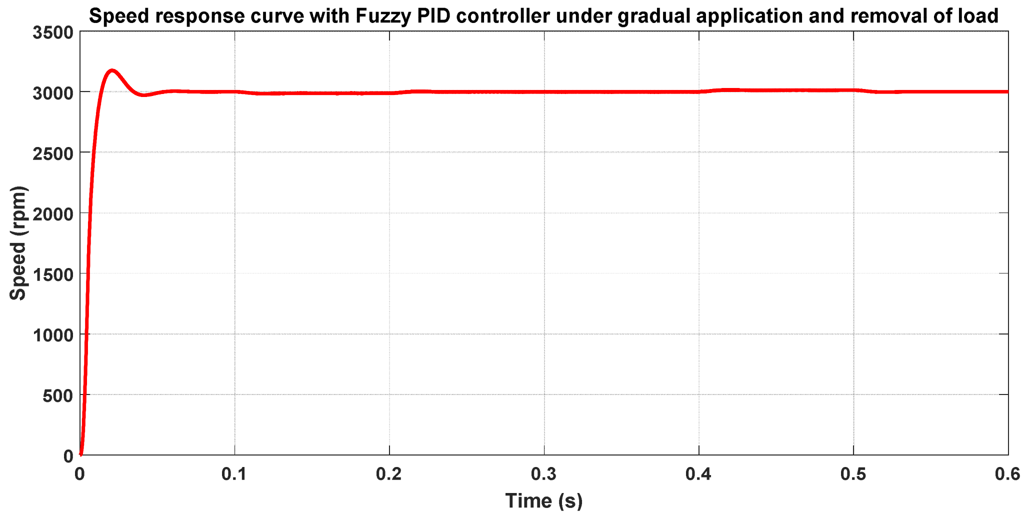


b

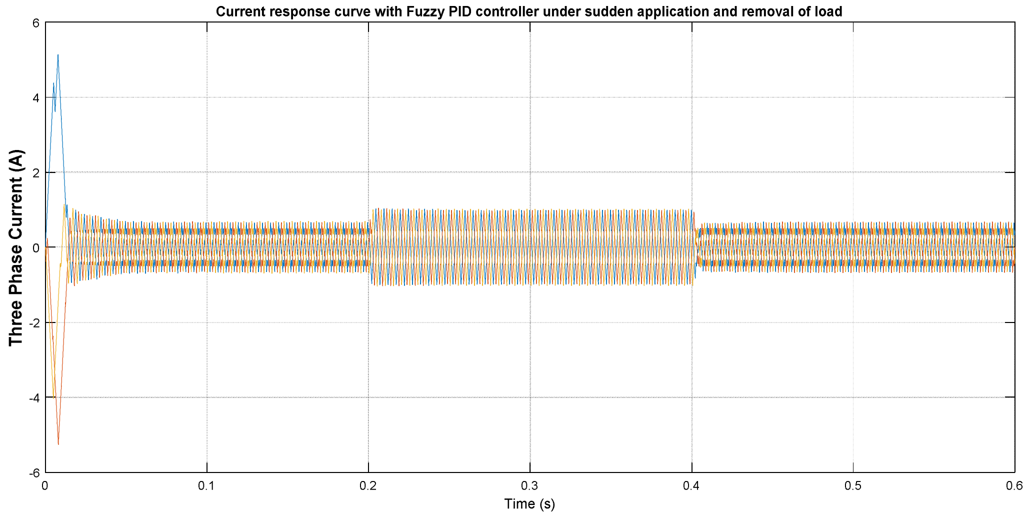


c

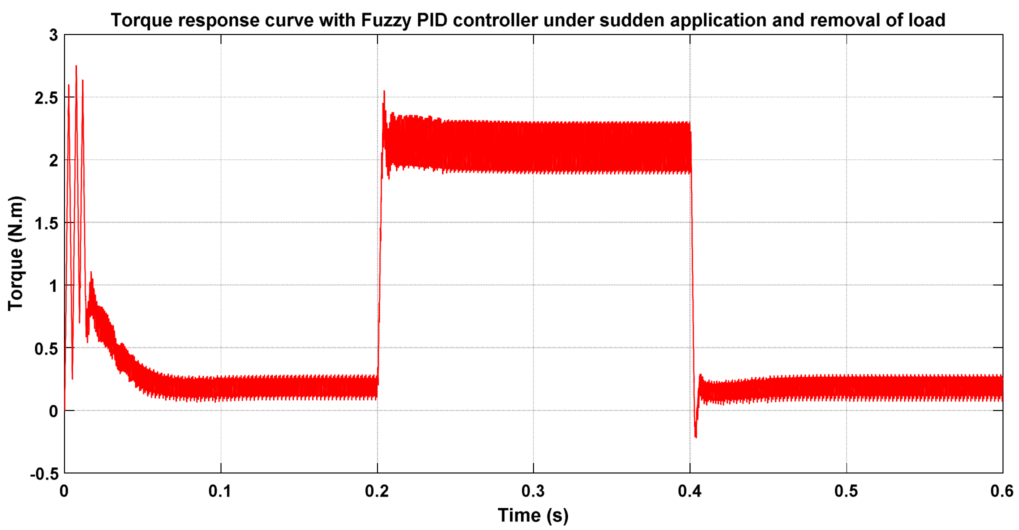
Figure 8. *System specifications with PID controller under gradual load conditions. a) speed Response, b) three-phase flow response, c) torque Response.*



a

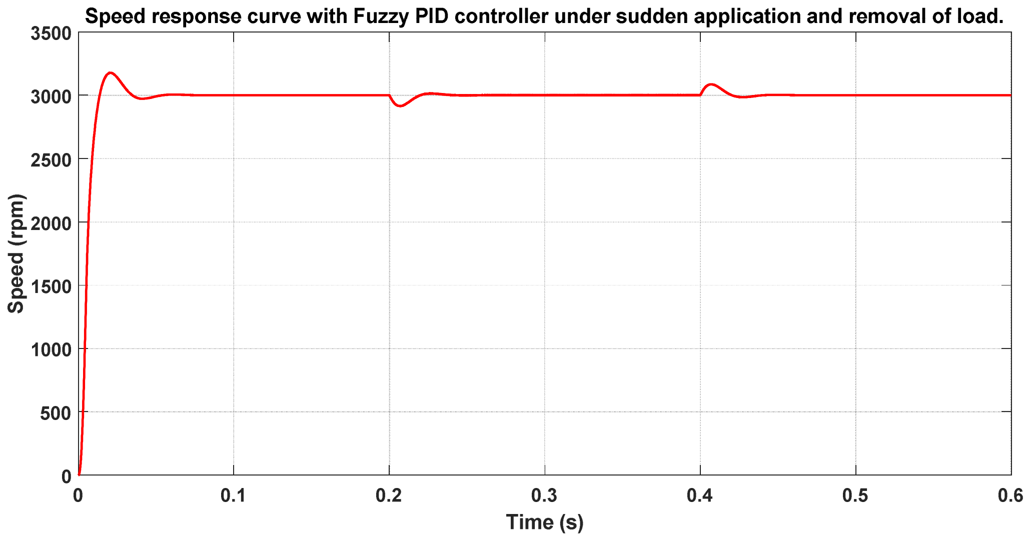


b

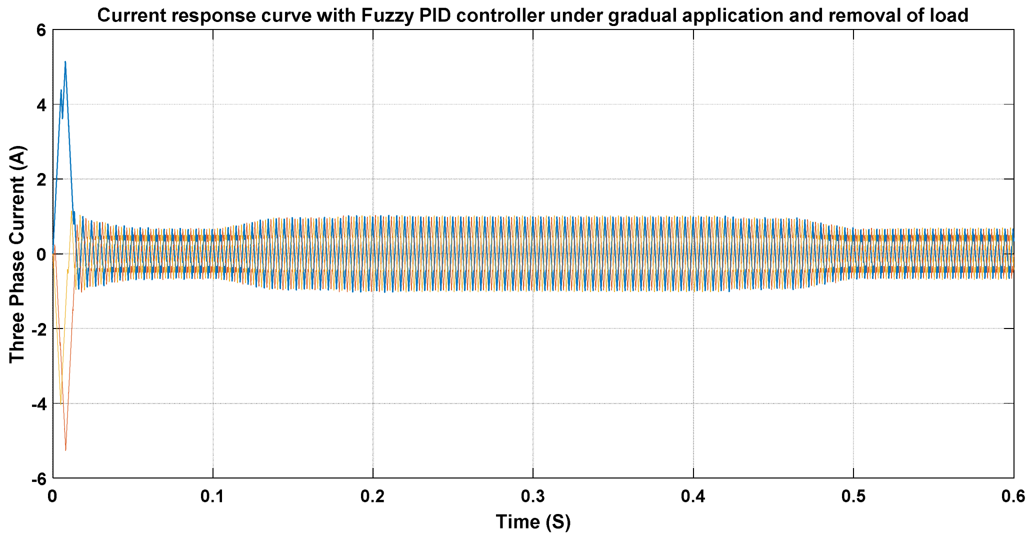


c

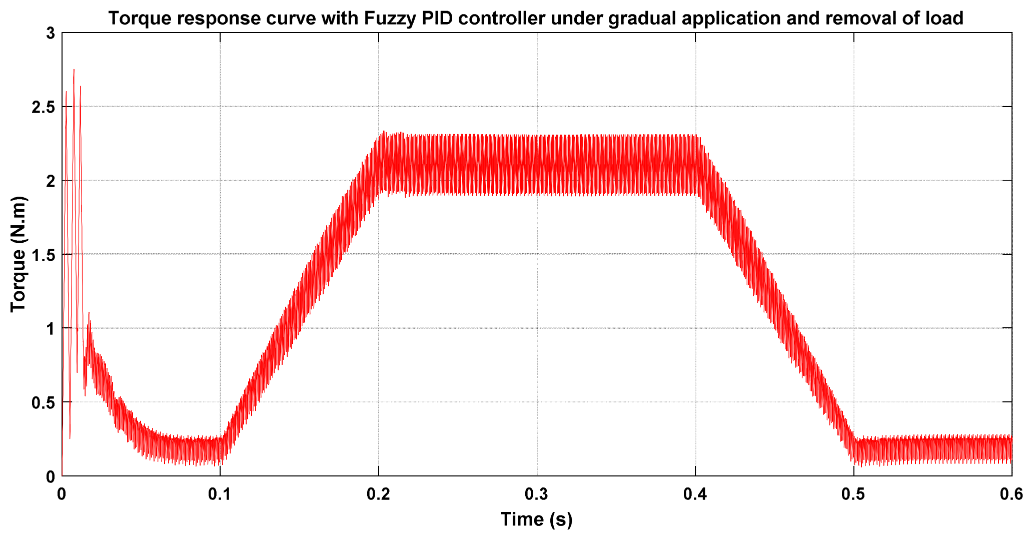
Figure 9. *System Specifications with FPID controller under sudden load conditions. a) Speed Response, b) three-phase flow response, c) torque Response.*



a



b



c

Figure 10. *System specifications with FPID controller under gradual load conditions. a) speed Response, b) three-phase flow response, c) torque Response.*

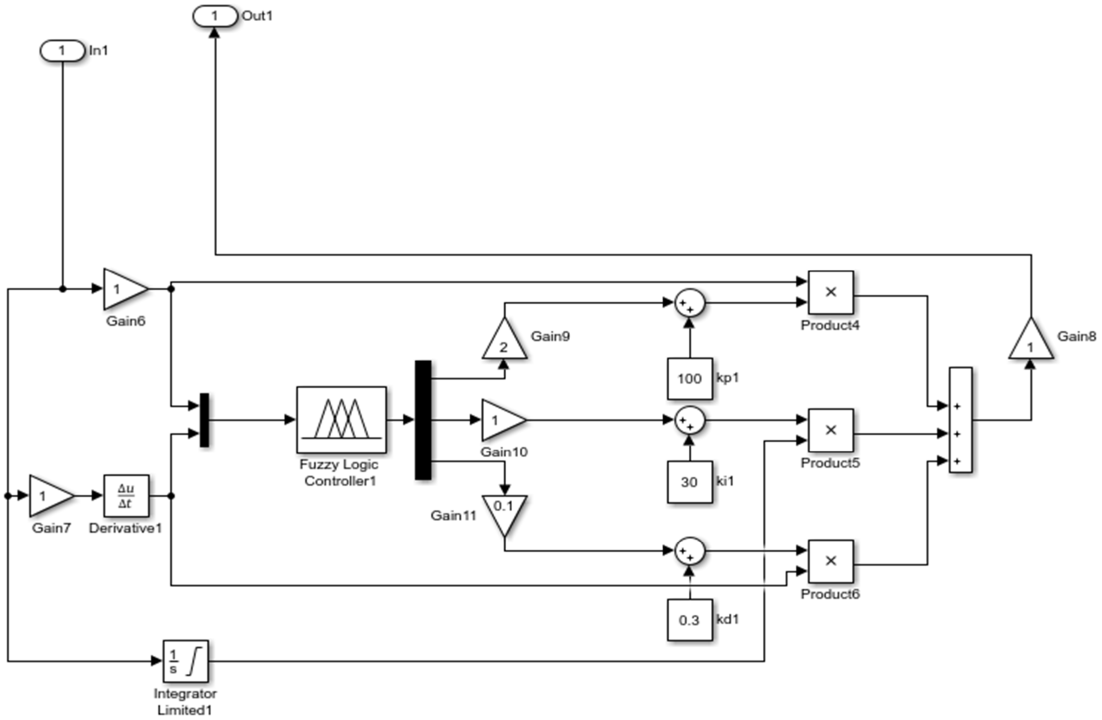


Figure 11. *Block diagram of RBF Fuzzy-Q learning with Sugeno.*

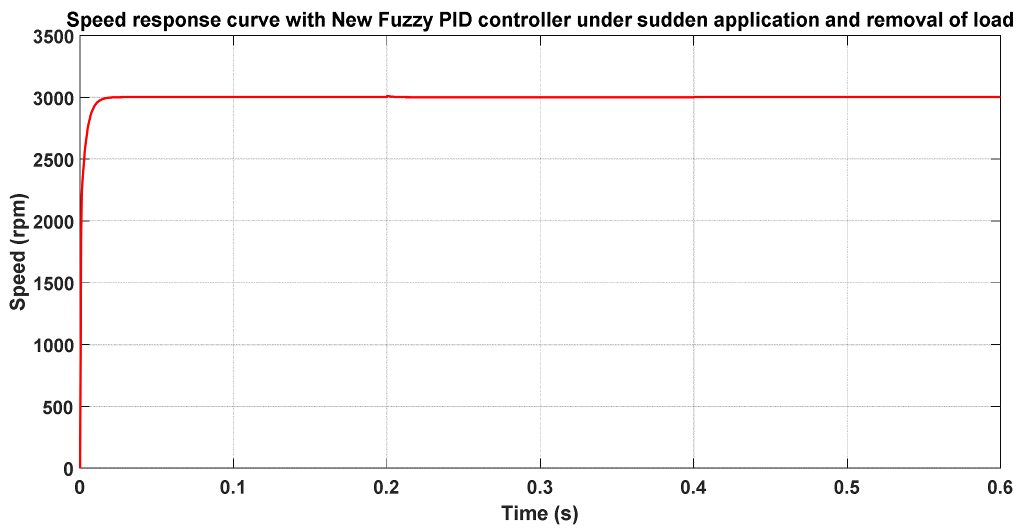
Simulation Result with NFPID

In this simulation, the Ziegler–Nichols PID control coefficients which are shown Figure 11 is optimized and applied to the system. The response curves with the NFPDI controller for the sudden load and gradual load changes are shown in Figures 12 and 13, respectively.

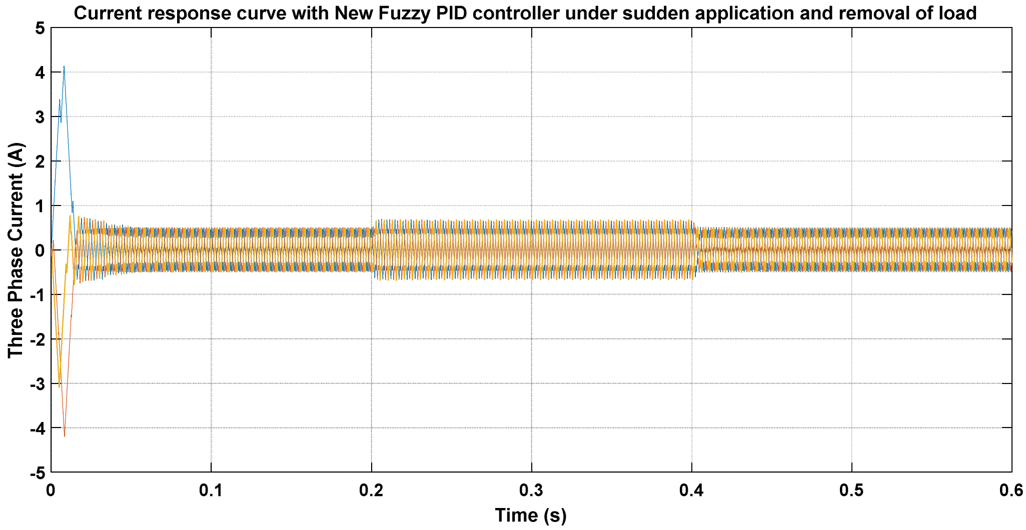
Force and thrust force for the proposed and prototype vernier PM machines, respectively.

Table 4. *Results of the response speed for the sudden and gradual load with NFPID learning controller.*

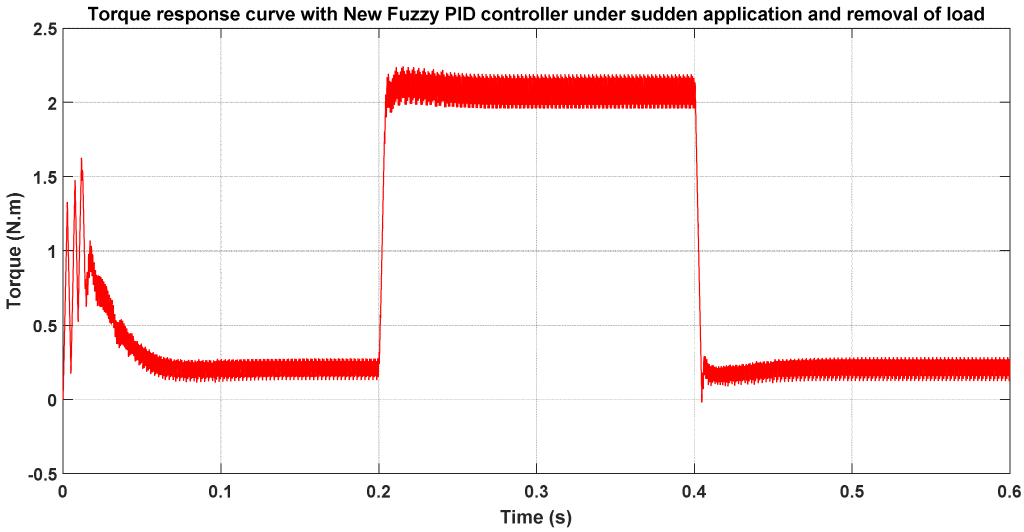
Load Variation	Characteristics	Time Interval (s)	Overshoot%	Peak Time (s)	Rise Time (s)	Settling Time (s)	Steady state Error
Sudden Load Variation	Starting	0-0.1	2.76	0.028	0.0210	0.089	0 rpm
	Load Application	0.1-0.4	-5.25	0.007	_	0.057	0 rpm
	Load Removal	0.4(s)	5.31	0.0094	_	0.089	0 rpm
Gradual Load Variation	Starting	0-0.1	2.54	0.028	0.0210	0.088	0 rpm
	Load Application	0.1-0.2	-0.977	0.027	_	0.054	2 rpm
	Load Application	0.2-0.3	0	0	_	0.023	0 rpm
	Load Application	0.3-0.4	0.958	0.031	_	0.051	2 rpm



a

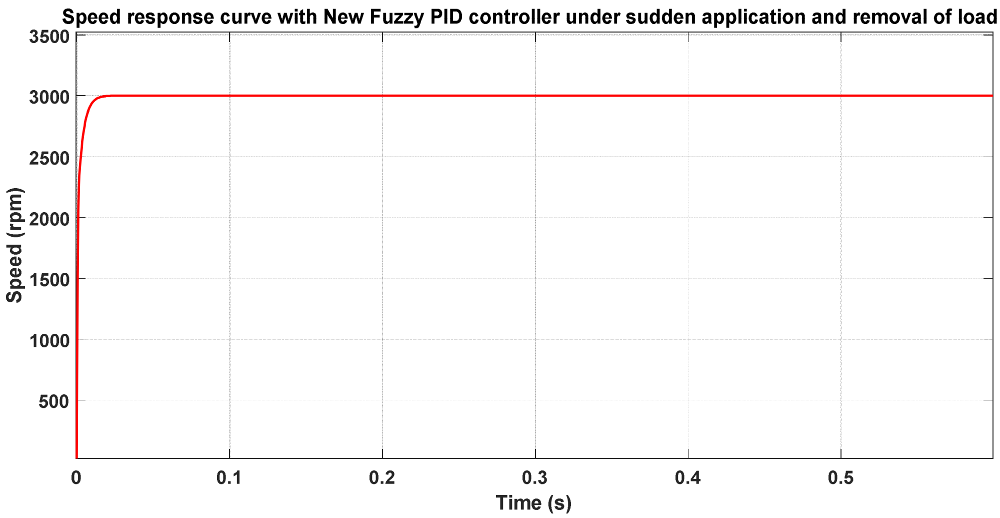


b

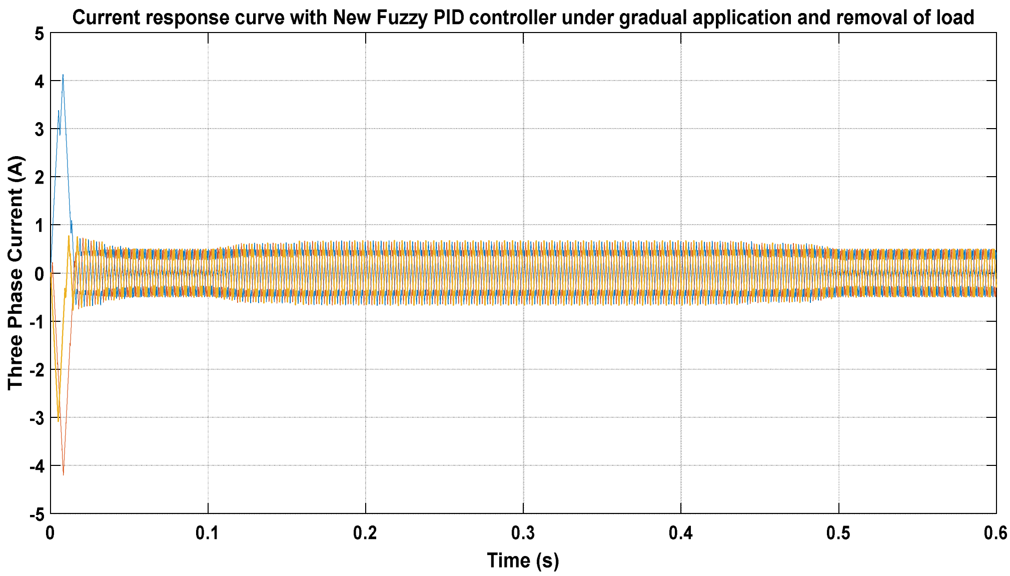


c

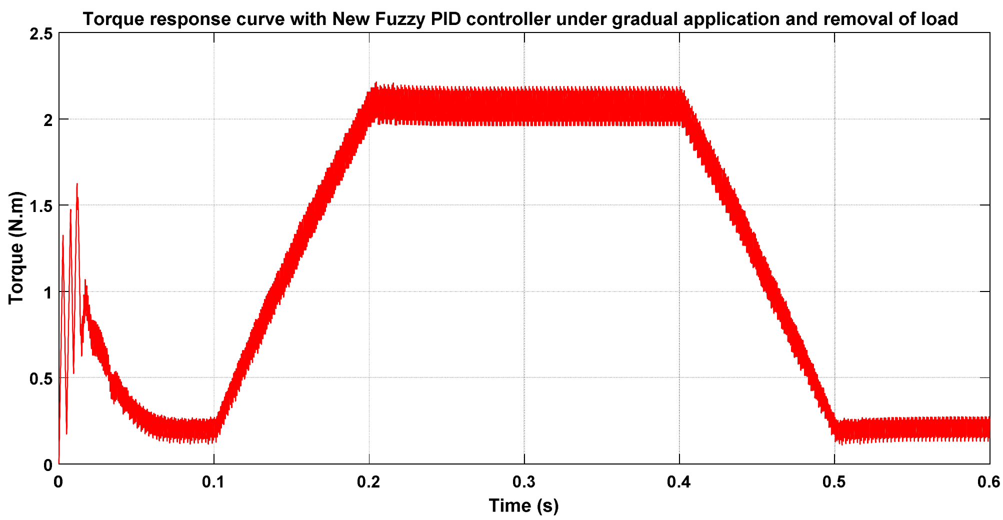
Figure 12. *System Specifications with RBF Fuzzy-Q learning controller under sudden load conditions. a) speed Response, b) three-phase flow response, c) torque Response.*



a



b



c

Figure 13. *System specifications with RBF Fuzzy-Q learning controller under gradual load conditions. a) speed Response, b) three-phase flow response, c) torque Response.*

7. Conclusion

In this paper, suitable membership functions for the use of fuzzy controller for controlling the speed of the permanent magnet synchronous motor engine were proposed for two different methods, and the results were presented and for comparison and analysis of the motor with FPID and NFPID learning controllers when the engine is exposed to sudden load changes, as well as gradual load variations with constant velocity, have been investigated. Based on the data of tables 2, 3 and 4 on the time parameters of the deposition, the rate of heave and overshoot in the case of sudden load changes in both FPID controllers has been improved and there is no change in the permanent mode response of the system. Additionally, it performs better in terms of gradually removing load. Therefore, the behavior and characteristics of the motor are improved with the NFPID controller.

References

[1] Deng, Hui, et al. "A sensorless vector strategy for the PMSM using improved sliding mode observe and fuzzy PI speed controller". Power Electronics Systems and Applications (PESA), International Conference on. IEEE, 2015.

[2] N. Arish and V. Teymoori, “Development of Linear Vernier Hybrid Permanent Magnet Machine for Wave Energy Converter,” Int. J. Eng., 2020.

[3] N. Arish, V. Teymoori, H. Yaghobi, and M. Moradi, “Design of New Linear Vernier Machine with Skew and Halbach Permanent Magnet for Wave Energy Converters,” in 34th International Power System Conference, PSC 2019, 2019.

[4] N. Arish, M. Ardestani, and V. Teymoori, “Comparison of Dual Stator Consequent-pole Linear Permanent Magnet Vernier Machine with Toroidal and Concentrated Winding,” in 2020 11th Power Electronics, Drive Systems, and Technologies Conference, PEDSTC 2020, 2020.

[5] N C. C. Chan, K. T. Chau, J. Z. Jiang, W. Xia, M. Zhu and R. Zhang, "Novel permanent magnet motor drives for electric vehicles," in IEEE Transactions on Industrial Electronics, vol. 43, no. 2, pp. 331-339, April 1996, doi: 10.1109/41.491357.

[6] Yang, Mahinda. Rahman, M. “Implementation of an Artificial-Neural-Network-Based Real Time Adaptive Controller for an Interior Permanent-Magnet Motor Drive,” IEEE Transactions on Energy Conversion, vol. 2, pp. 96-104, 2003.

[7] Rahideh A, Karimi M, Shakeri A, Azadi M. "High Performance Direct Torque Control of a PMSM using Fuzzy Logicand Genetic Algorithm", IEEE Int. Conference Electric Machines Drives Syst., pp. 932-937, 2007.

[8] Cao X, Fan L. "Vector Controlled Permanent Magnet Synchronous Motor Drive Based on Neural Network and Multi Fuzzy Controllers", IEEE Fifth International Conference on Fuzzy Systems and Knowledge Discovery, pp. 254-258, 2008.

[9] Rahimi, A., Bavafa, F., Aghababaei, S., Khooban, M. H., & Naghavi, S. V. "The online parameter identification of chaotic behavior in permanent magnet synchronous motor by Self-Adaptive Learning Bat-inspired algorithm". International Journal of Electrical Power & Energy Systems, 78, 285-291, 2008.

[10] Wang J, Liu H. "Novel Intelligent Sensorless Control of Permanent Magnet Synchronous Motor Driv", IEEE Ninth Int Conference Electronic Measure. Instruments, pp. 953-958.

[11] Pillay, P., Krishnan, R., 1989. Modelling, "simulation and analysis of permanent magnet motor drives", part-I: the Brushless Dc motor drives. IEEE Trans. Ind. Appl. 25 (March/April), 274-279, 2009.

[12] Dorf, C., Richard, C., Robert Bishop, H. "Modern control systems", 9th ed. Prentice Hall Inc., New Jersey-07458, USA, Chapters 1, 5, pp. 1-23, pp. 173-206, 2001.

[13] V. Teymoori, N. Eskandaria, N. Arish and A. Khalili, "Design of permanent magnetic motor speed controller drive with power supply inverter based on a new switching method," *2019 International Power System Conference (PSC)*, pp. 453-458, 2019.

[14] Yen, Chih-Ta & Cheng, Ming-Feng. (2018). A study of fuzzy control with ant colony algorithm used in mobile robot for shortest path planning and obstacle avoidance. Microsystem Technologies. 24. 10.1007/s00542-016-3192-9.

[15] Yongjuan, Zhao, Yutitan, Pan. "The Design and Simulation of Fuzzy PID Controller", International Forum on Information Technology and Applications, Kunming, China, pp. 95-98, 16-18 July, 2010.

[16] M. C. Harke, G. D. Donato, F. G. Capponi, T. R. Tesch, and R. D. Lorenz, "Implementation issues and performance evaluation of sinusoidal, surface-mounted pm machine drives with Hall-effect positionsensors and a vector-tracking observer". *IEEE Trans*. *Ind*. *Appl*., vol. 26, no. 3, pp. 161-173, Jan./Feb, 2008.

[17] Diab, A. M., et al., Enhanced Active Disturbance Rejection Current Controller for Permanent Magnet Synchronous Machines Operated at Low Sampling Time Ratio. IEEE Journal of Emerging and Selected Topics in Industrial Electronics, 2021.

[18] Samadi Gharajeh, M. and Jond, H., An intelligent approach for autonomous mobile robots path planning based on adaptive neuro-fuzzy inference system. Ain Shams Engineering Journal, 2021.

[19] Rajurkar, S. D., & Verma, N. K. Developing deep fuzzy network with Takagi Sugeno fuzzy inference system. IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), 2017.