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Field Oriented Control Design of Inset Rotor PMSM Drive

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Abstract. The main challenge of PMSM implementation in the adjustable-speed drives especially in automotive industry is to attain the optimal PMSM drive performance. Vector control is proved to be the best method in controlling synchronous machine such as PMSM. This paper objective is to design a speed control system for the manufactured inset rotor PMSM, which integrates the interleaved DC-DC boost converter, inverter, and sinusoidal pulse width modulation and fed by the battery bank DC source. The proposed speed control in this paper employs FOC vector control technique with PI controller which control both converter and inverter independently. This paper investigates the effectiveness of the proposed speed control method for driving the manufactured inset rotor PMSM. To verify the effectiveness of the designed speed control system, computer simulation is conducted. The motor performances are observed in operating condition with disturbance in form of sudden change of load torque. The simulation results show that the control method is stable but the rotor speed still affected by the given disturbance.

INTRODUCTION

The quality of permanent magnet (PM) material has improved and attracted considerably contribution in the development of permanent magnet AC (PMAC) motors [1]. PMAC motor with sinusoidal back emf known as permanent magnet synchronous motor (PMSM) is commonly applied in industrial application. It can be further categorized into surface mounted rotor magnet (SPMSM), inset rotor magnet, and interior PMSM (IPMSM). Due to its simple structures, high efficiency, low inertia, and high power density, PMSM is implemented as adjustable-speed drives in automotive industry and several application such as robotics and aircrafts. But, to attain the optimal drive performance, the design of PMSM requires matched drive that leads to become attractive topic to the researchers [2]. The nonlinearity coupling among its winding current and rotor speed [3] complicates the design of motor drive.

Generally, control techniques for PMSM especially in adjustable-speed drives of the automotive application can be divided into scalar control which adjusts only magnitude and vector control which adjusts both magnitude and instantaneous position. The differential quadrature dq-axis current control are the important parameters in vector control technique [4]. Field oriented control (FOC) is the vector control technique that employs the coordinate transformation of motor equation in dq-axis frame which synchronously rotates with PM flux [5]. It controls motor stator currents in the form of space vector [6]. Due to its fast dynamic response, simple control structure, and energy efficient operation FOC is one of the best vector control technique for PMSM [7].

Speed control system for the manufactured and measured inset rotor PMSM parameters in [8,9] integrates DC-DC boost converter, inverter, and sinusoidal pulse width modulation (SPWM). Since the battery voltage in DC source of the speed control system is below the operating voltage of inset rotor PMSM, the converter boosts the battery output voltage feeding the inverter with rated DC bus voltage. The interleaved DC-DC boost converter topology avoids the system suffering from heat and large inductor size [10]. Precise rotor position information

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provided by sensors and sine wave generated by SPWM determine the switching of the inverter for driving the motor [11]. Both converter and inverter are controlled by proportional integral (PI) controller due to its simplicity, functional structure, and robust performance [12]. The controller is designed by defining the constant gain which performs correction to parameter error and disturbance of large load. However, tuning the PI constant needs high accuracy since the motor performance will be degraded due to time varying parameters [13].

This paper investigates the effectiveness of the proposed speed control method for driving inset rotor PMSM using FOC and PI controller. Computer simulation is conducted to simulate the designed speed control. The motor control performances are observed in operating condition with disturbance in the form of sudden change of load torque.

MODEL OF INSET ROTOR PMSM AND DRIVES TOPOLOGY

Mathematical Model of Inset Rotor PMSM

The two axis d-q model are used for modeling the inset rotor PMSM in the synchronously rotating rotor reference frames. The stator voltage equation in dq-axis frame are given in equation (1) and (2). The electromagnetic torque is expressed in equation (3) while the mechanical torque is expressed in equation (4).

$$U_d = R_s i_d + \frac{di_d}{dt} L_d - \omega_e L_q i_q \tag{1}$$

$$U_q = R_s i_q + \frac{di_q}{dt} L_q + \omega_e \left(\psi_p + L_d i_d\right) \tag{2}$$

$$T_{em} = \frac{3}{2} p\left[\psi_p i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{3}$$

$$T_{em} = T_L + J \frac{d\omega_m}{dt} \tag{4}$$

$$\omega_e = p\omega_m \tag{5}$$

where

U_d, U_q : d-axis and q-axis stator voltage
R_s : stator resistance
i_d, i_q : d-axis and q-axis stator current
L_d, L_q : d-axis and q-axis inductance
T_{em} : electromagnetic torque
T_L : load torque
J : inertia moment
ψ_p : permanent magnet flux
ω_e : rotor electrical speed
ω_m : rotor mechanical speed
B : friction coefficient
p : number of pole pairs

By modeling dq-axis motor stator voltage equations, the equivalent circuit of motor in dq-axis frame can be replaced by equivalent circuit as shown in Fig 1.

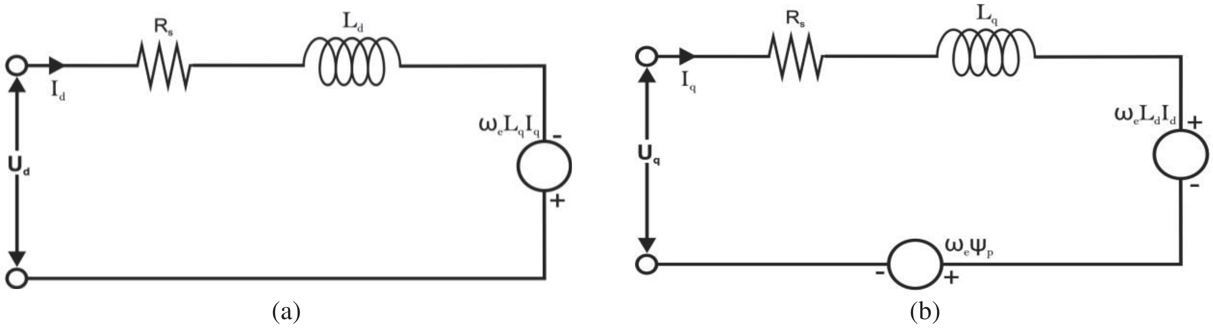

Figure 1. (a) d-axis equivalent circuit of inset rotor PMSM, (b) q-axis equivalent circuit of inset rotor PMSM

Drives Topology

The field oriented controller (FOC) structure of inset rotor PMSM drives in this paper can be divided into three parts, first is the control part, second is the power electronics and third is the plant of PMSM itself. Fig 2 shows the block diagram of the FOC used to drive the PMSM.

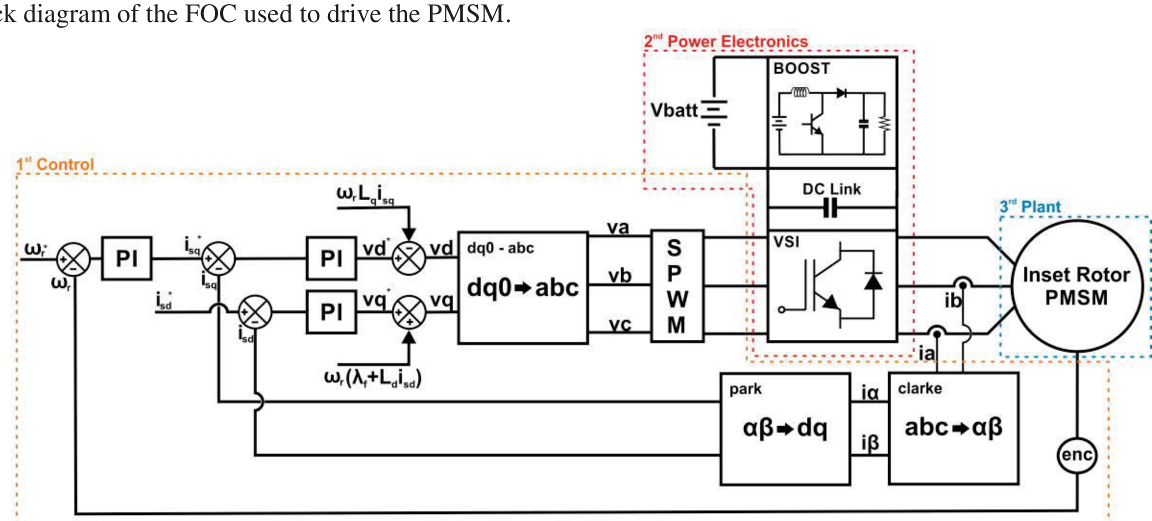

Figure 2. The block diagram of FOC structure of inset rotor PMSM

The first part, control part mainly designed to control the speed of inset rotor PMSM. The field oriented control (FOC) structure with combination of proportional-integral (PI) controller was utilized in this paper. By utilizing the FOC, the three phase system coordinates $\left(\bar{x} = \left[x_a\ x_b\ x_c\right]^T\right)$ can be transformed into the two phase synchronously rotating coordinates $\left(\bar{x} = \left[x_d\ x_q\right]^T\right)$ through the clarke and park transformation by using following equation (6)-(7).

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{7}$$

It then simplifies the control design process, because the transformed coordinates enable the decoupling control of direct-quadrature axis. Several control strategies are available after coordinates transformation such as constant torque angle (CTA), maximum torque per ampere (MTPA), unity power factor (UPF) and constant stator flux (CSF) [14]. In this paper CTA is used, the principle of CTA is to keep the constant angle between the stator current vector and the permanent magnet flux at an angle $\theta = 90^0$ (Fig 3). Therefore the d-axis stator current needs to be regulated at zero value $(i_d = 0)$. By utilizing the FOC and CTA strategies the PMSM machine can be controlled like a DC machine, the torque thus depends on i_q because $i_d = 0$ (equation (3)). Hence control problem is reduced by controlling the q-axis and regulating the d-axis to zero. PI controller is proposed to control the speed of inset rotor PMSM using FOC structure. There are three PI controllers in this part, the two controllers are used to control and regulate q-axis and d-axis respectively, while the other one is used to regulate the rotor speed in order to comply the desired speed (ω_{ref}). Furthermore, a compensator is added to eliminate the cross coupling in dq-axes (equation (1)-(2)). The voltage references resulted from PI current controller in dq-axes are then transformed back to three phase coordinates by using inverse clarke and inverse park transformation. Then these voltage references will be used to synthesize the input signals through sinusoidal pulse width modulation (SPWM) strategy.

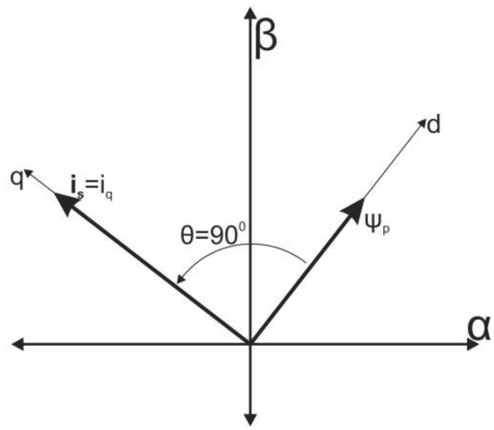

Figure 3. Constant torque angle strategy

The second part is the power electronic converters (PEC). The PEC is implemented to drive the inset rotor PMSM which can be seen in Fig 4. In this paper, the bidirectional PEC which consists of the interleaved boost converter connected with three phase voltage source inverter (VSI) via DC-Link is used. The interleaved boost converter steps up the battery pack voltage in order to comply the inset rotor PMSM voltage rating. The three stages interleaved boost converter method is chosen with the following reason: reducing the inductor size, reducing the stresses and losses of switching devices, and more compact due to the same switching device capacity.

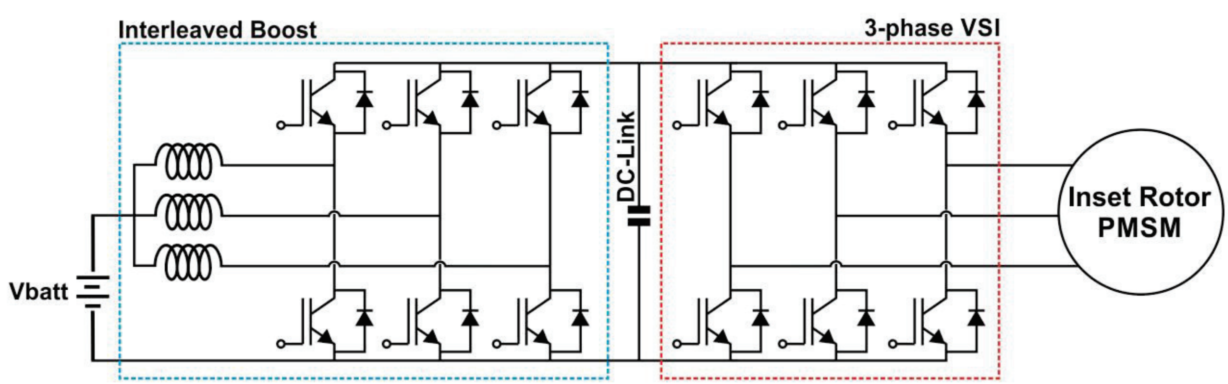

Figure 4. The used power electronic converter topology

The third part is the inset rotor PMSM that acts as the plant to be controlled. The mathematical model of PMSM in synchronous rotating dq coordinates has been descibed before and can be seen in equation (1)-(5). The motor parameters in table 1 which is used in the simulation was gained from the previous research [(8)]. Fig 5 shows the picture of the manufactured inset rotor PMSM.

TABLE 1. Inset rotor PMSM parameters

Parameters	Value	Units
Armature resistances	11.150e-03	Ohm
d-axis inductances	0.123e-03	Henry
q-axis inductances	0.142e-03	Henry
Permanent magnet flux	63.9e-03	Weber
Rotor inertia	4.177e-03	kg.m^2
Number of poles	6	-

Figure 5. The manufactured inset rotor PMSM

PI CONTROL DESIGN

Basic PID Controller

The proportional-integral-derivative (PID) is the well known controller for most engineer and practitioners. The simple yet robust structure make it to be the most popular controller among others. The block diagram of PID controller can be seen in Fig 6. This controller works by processing the error resulted from desired value and substracted by the actual value. The PID controller can be represented by the following equation:

$$\frac{U(s)}{E(s)} = K_p + K_i + K_d \tag{8}$$

where

$$K_i = \frac{K_p}{T_i s} \tag{9}$$

$$K_d = K_p T_d s \tag{10}$$

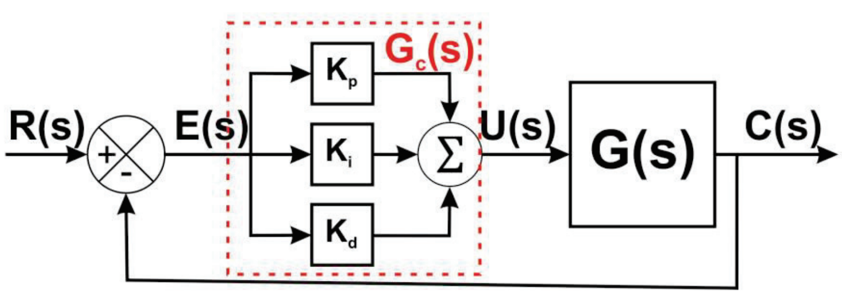

Figure 6. Block diagram of PID controller

By adjusting the defined three gains (K_p, K_i, K_d), the error can be used to synthesize the controller output for correcting the system error. Adjusting the aforementioned gains are frequently called controller tuning procedure. There are several developed methods to tune these gains. It can be classified by the analytical and practical method. The simplest practical method is by trial and error, this requires a little knowledge but it is a laborious effort. Another popular practical method is the Ziegler-Nichols (ZN) tuning which is used in this paper and will be briefly explained in the next.

Ziegler-Nichols Tuning

The Ziegler-Nichols (ZN) controller tuning is a simple but efficient method developed in the mid 19th by J.G.Ziegler and N.B Nichols. It provides a quick and structured gain adjustment. The ZN tuning rule is based on experimental step responses and the transient responses characteristics from the plant. Therefore, it is suitable for engineers to determine the parameters on site by experimenting on the plant. The procedure is to apply the proportional gain (K_p) until the plant exhibits oscillation. The critical gain (K_{cr}) can then be gained from the proportional gain that exhibits oscillation. From the plant oscillation, the critical period (P_{cr}) can be measured and used to calculate the integral and derivative time (T_i, T_d). The controller parameters can be tuned by using the formula shown in TABLE 2.

TABLE 2. Ziegler-Nichols tuning rule based on critical gain and critical period

Type of Controller	K_p	T_i	T_d
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$\frac{1}{1.2}P_{cr}$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

SIMULATION RESULTS

The simulation of inset rotor PMSM drive employing FOC and PI controller is conducted by using PSIM. The inset rotor PMSM motor parameter is given in TABLE 1. The PEC converter which consist of 3 stages interleaved boost converter along with the VSI switch are modeled as ideal switch for the sake of simplicity and evaluating only the performance of the controller. The interleaved boost converter, the speed and current control in the FOC structure are controlled independently. Therefore, there are 4 PI controllers here that are designed based on the ZN tuning procedure. In order to evaluate the controllers, the sudden change in the load torque T_L of the inset PMSM is applied. The load torque is initially at $T_L = 5Nm$, then it is changed at $t = 0.5s$ to $T_L = 35Nm$ as can be seen in Fig 7. It can be seen that the electromagnetic torque can follow the load torque even there are oscillation at the motor starting phase and at the sudden load torque change. The interleaved DC boost converter output is desired to be 170V to comply the inset rotor PMSM motor voltage. Fig 8 shows the performance of boost converter, the reference voltage $V_{ref\_boost} = 170V$ need to be kept constant at all time. However, because of high power consumption, an oscillation occured at the motor starting phase. Also when the load torque change suddenly at $t = 0.5s$, the boost converter output voltage experiences a second oscillation. On the other hand, the performance of speed controller behaves different. At the starting phase, the response to a step response is very good since there is no overshoot and oscillation. But, when the sudden load torque change as the disturbance is given, there is an oscillation and the steady state error still remains till the end as can be seen in Fig 9.

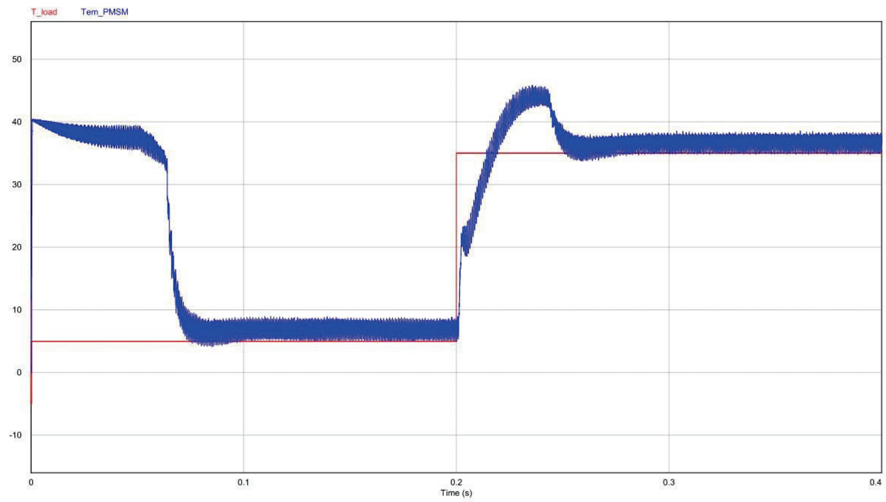

Figure 7. Load and electromagnetic torque

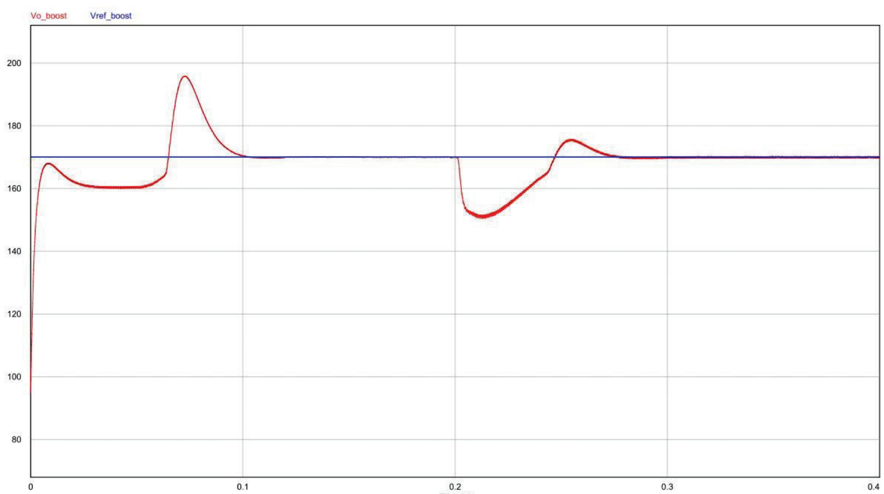

Figure 8. Boost converter voltage output

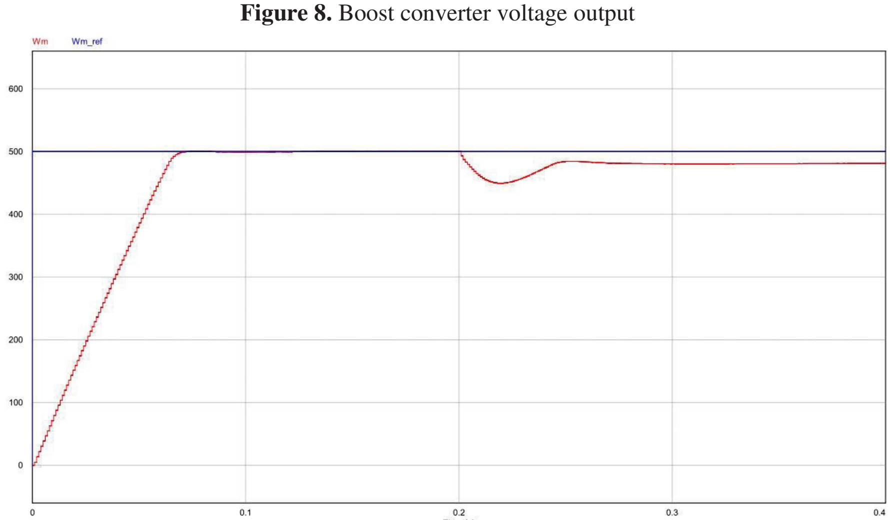

Figure 9. Performance of speed controller

CONCLUSION

The inset rotor PMSM speed controller and the interleaved boost converter works satisfactorily. The speed controller can follow the reference step input without oscillation at starting phase. But when the load torque changed abruptly, the speed response become oscillate and leaving a steady state error. The interleaved boost converter that controlled by independent PI controller also works well, the reference voltage can be followed with a slight oscillation at the starting phase and the sudden load torque change. Moreover, this PI controller on this drive can be refined either by using analytical tuning or by using adaptive gain, this will also be the future work plan.

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REFERENCES

1. F.F.M. El-Sousy, "Robust wavelet-neural-network sliding-mode control system for permanent magnet synchronous motor drive," in *IET Electric Power Application-2011*, IET Journals Vol. 5, Iss. 1. (The Institution of Engineering and Technology, United Kingdom, 2011), pp. 113-132.
2. S.K. Nayak and P. Dutta, "A comparative study of speed control of DC brushless motor using PI and fuzzy controller," in *International Conference on Electrical, Electronics, Signals, Communication and Optimization EESCO-2015*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, India, 2015), pp. 1-6.
3. M. Marufuzzaman, M.B.I. Reaz, and M.A.M. Ali, "FPGA Implementation of an intelligent current dq PI controller for FOC PMSM drive," in *International Conference on Computer Applications and Industrial Electronics ICCAIE-2010*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, Malaysia, 2010), pp. 602-605.
4. M. Konghirun and L. Xu, "A dq-axis current control technique for fast transient response in vector controlled drive of permanent magnet synchronous motor," in *The 4th International Power Electronics and Motion Control Conference IPEMC-2004*, IEEE Conference Publications Vol. 3. (The Institute of Electrical and Electronics Engineers, China, 2004), pp. 1316-1320.
5. S.K. Dwivedi, M. Laursen, and S. Hansen, "Voltage vector based control for PMSM in industry applications," in *International Symposium on Industrial Electronics ISIE-2010*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, Italy, 2010), pp. 3845-3850.
6. M. Marufuzzaman, M.B.I. Reaz, M.S. Rahman, and M.A.M. Ali, "Hardware prototyping of an intelligent current *dq* PI controller for FOC PMSM drive," in *International Conference on Electrical and Computer Engineering ICECE-2010*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, Bangladesh, 2010), pp. 86-88.
7. J. Espina, A. Arias, J. Balcells, and C. Ortega, "Speed anti-windup PI strategies review for field oriented control of permanent magnet synchronous machines," in *Compatibility and Power Electronics CPE-2009*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, Spain, 2009), pp. 279-285.
8. A. Muqorobin and P. Irasari, "Analisis respon motor magnet permanen pada saat pengukuran parameter elektrik," in *Jurnal Telaah-2013*, Jurnal Ilmu Pengetahuan dan Teknologi, Vol. 31. (Pusat Penelitian Fisika LIPI, Indonesia, 2013), pp. 123-131.
9. A. Muqorobin, P. Irasari, and Taufik, "Comparison of unmodulated current control characteristics of permanent magnet synchronous motor," in *Mechatronics, Electrical Power, and Vehicular Technology-2014*, MEV Journal Vol. 5. (Research Center for Electrical Power and Mechatronics LIPI, Indonesia, 2014), pp. 115-122.
10. A. Kumar and P. Gaur, "Bidirectional DC/DC converter for hybrid electric vehicle," in *International Conference on Advances in Computing, Communications and Informatics ICACCI-2014*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, India, 2014), pp. 839-843.

11. H. Mehta, V. Joshi, U. Thakar, M. Kuber, and P. Kurulkar, "Speed control of PMSM with Hall sensors using DSP TMS320F2812," in *The 11th International Conference on Power Electronics and Drive Systems PEDS-2015*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, Australia, 2015), pp. 295-300.
12. E. Celik, A. Dalcali, N. Ozturk, and R. Canbaz, "An adaptive PI controller schema based on fuzzy logic controller for speed control of permanent magnet synchronous motors," in *The 4th International Conference on Power Engineering, Energy and Electrical Drives POWERENG-2013*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, Turkey, 2013), pp. 715-720.
13. N. Noroozi-Varcheshme, A. Ranjbar-Noiey, and H. Karimi-Davijani, "Sensorless indirect field-oriented control of induction motor using PI controller," in *Universities Power Engineering Conference UPEC-2008*, IEEE Conference Publications. (The Institute of Electrical and Electronics Engineers, Italy, 2008), pp. 1-5.
14. D. Swierczynski, "Direct torque control with space vector modulation (DTC-SVM) of inverter-fed permanent magnet synchronous motor drive," Ph.D. thesis, Warsaw University of Technology, 2005.