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Comparison Analysis of Indirect FOC Induction Motor Drive using PI, Anti-Windup and Pre Filter Schemes

M.H.N Talib*, Z. Ibrahim, N. Abd. Rahim***, A.S.A. Hasim******
*,** Departement of Electrical Engineering, Universiti Teknikal Malaysia Melaka
*** UMPEDAC, Universiti Malaya, Kuala Lumpur, Malaysia
**** Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kuala Lumpur, Malay

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ABSTRACT

This paper presents the speed performance analysis of indirect Field Oriented Control (FOC) induction motor drive by applying Proportional Integral (PI) controller, PI with Anti-Windup (PIAW) and Pre- Filter (PF). The objective of this experiment is to have quantitative comparison between the controller strategies towards the performance of the motor in term of speed tracking and load rejection capability in low, medium and rated speed operation. In the first part, PI controller is applied to the FOC induction motor drive which the gain is obtained based on determined Induction Motor (IM) motor parameters. Secondly an AWPI strategy is added to the outer loop and finally, PF is added to the system. The Space Vector Pulse Width Modulation (SVPWM) technique is used to control the voltage source inverter and complete vector control scheme of the IM drive is tested by using a DSpace 1103 controller board. The analysis of the results shows that, the PI and AWPI controller schemes produce similar performance at low speed operation. However, for the medium and rated speed operation the AWPI scheme shown significant improvement in reducing the overshoot problem and improving the setting time. The PF scheme on the other hand, produces a slower speed and torque response for all tested speed operation. All schemes show similar performance for load disturbance rejection capability.

Corresponding Author:

M.H.N Talib,
Faculty of Electrical Engineering,
Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.
Email: hairulnizam@utem.edu

1. INTRODUCTION

Vector control or field oriented control (FOC) drive is one of the most popular choices of variable speed drive application industries. Since the advent of indirect FOC in 70's, the proportional integral (PI) controller scheme has been widely used in variable speed drive motor. However, there are several types of controller scheme such as PI control, fuzzy logic control, artificial intelligent control and variable structure controlled which can be utilized to get the best performance of the motor [1]-[7]. The main reason PI controller is well accepted is due to the simple structure which can be easily understood and implemented. This technique is able to independently control the torque and the flux-producing component of the stator current in a wide speed range.

However, in order to ensure the PI controller to work efficiently, the value of proportional gain (Kp) and integral gain (Ki) must be tuned correctly. The performance of the motor really depends on the gain of the PI controllers. However, in most cases, these gains are determined by a trial and error tuning technique which requires practical experience and may lead to time consumption. Even though, there are numbers of tuning technique such as Ziegler-Nichols methods and first order plus time delay method, certain knowledge of process control is required and even that will not ensure the best control performance [2], [3], [8]-[10]. On the other hand, the general second order method offers simpler technique and more mathematical formulation approached method. Thus, this method had been applied in getting all the PI values for the analysis in this paper.

Indirect FOC method itself faced a problem with parameter variation caused by the motor heating phenomenon and saturation [11]. This variation causes detuning problem in the decoupling operation and produce errors in the motor output values. Thus, a robust controller designed is necessary to adapt with the parameter variations and decoupling operation. In addition, it able to produce robust solution by applying the integral of time multiplied by the absolute of the error (ITAE) criterion method [2], [10]. Conventional or linear PI controller does not have output magnitude limiters, which could cause damage to the real system due to relatively large output value. Introducing integrator limiter and saturation limiter provide some protection to the system. However, this saturation limiter accumulates error, thus producing large overshoot, slow settling time and sometimes instability to the system [3], [4], [12]-[15]. Thus, PI controller with anti wind up was introduced. There are several Anti-Windup PI controllers to solve this wind up phenomenon such as AWPI with dead zone, AWPI condition, AWPI with tracking and many more. Most of the papers discuss on the anti wind up scheme in solving wind up phenomenon issue and its improvement. Based on the comparative study on the anti windup strategies, the AWPI condition technique found to be the most suitable for usual application due to the performance results, simple structure and less parameter controlled[3]-[4], [12]-[13], [16]. Most of the papers discussed only on the PI and Anti-windup performance at rated speed range. In this paper, the PF analysis is added in the analysis in various speed range demands. The pre filter scheme is able to get rid the unwanted zero in the closed loop system [3], [10].

In this project, the PI controller design is adopted based on the second order system design which has a simpler technique and direct mathematical formulation in comparison to the classical gain tuning method or symmetric optimum criterion[3], [9]-[10], [17]. The performance results of motor behaviors under wide speed range operation and load disturbance are analyzed based on the PI, Anti-Windup and Pre-Filter techniques. As far as the authors' knowledge, no work has been reported on analyzing the speed control motor performance based on this three control techniques together in different speed demand ranged quantitatively.

2. INDIRECT FIELD ORIENTED CONTROL DRIVE

The FOC imitates the concept of separately excited dc motor drive. Through this concept, the torque and the flux are controlled by two independent orthogonal variables known as the armature and field currents. Figure 1 shows the block diagram of indirect FOC scheme.

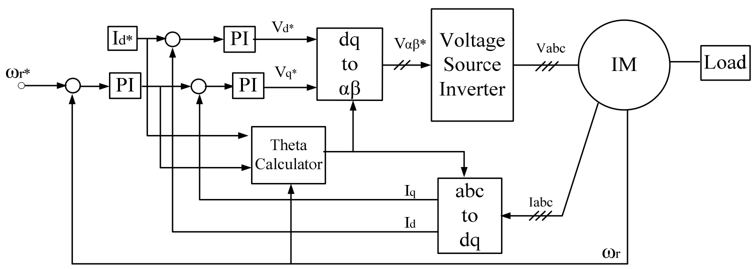


Figure 1. Indirect FOC block diagram

By applying space vector transformation to a three-phase system, the dynamic behavior of induction motor can be represented in mathematical equations as in (1)-(4) in synchronous rotating frame [18], [19].

Stator voltage equations:

$$\bar{V}_{ds} = R_s\bar{I}_{ds} + \frac{d\bar{\varphi}_{ds}}{dt} - \omega_s\bar{\varphi}_{qs}$$
$$\bar{V}_{qs} = R_s\bar{I}_{qs} + \frac{d\bar{\varphi}_{qs}}{dt} + \omega_s\bar{\varphi}_{ds} \quad (1)$$

Rotor Voltage equations:

$$\overline{V}_{dr} = 0 = R_r\overline{I}_{dr} + \frac{d\overline{\varphi}_{dr}}{dt} - (\omega_s - \omega_r)\overline{\varphi}_{qr}$$
$$\overline{V}_{qr} = 0 = R_r\overline{I}_{qr} + \frac{d\overline{\varphi}_{qr}}{dt} + (\omega_s - \omega_r)\overline{\varphi}_{dr} \quad (2)$$

Stator Flux equations:

$$\overline{\varphi}_{ds} = L_s\overline{I}_{ds} + L_m\overline{I}_{dr}$$
$$\overline{\varphi}_{qs} = L_s\overline{I}_{qs} + L_m\overline{I}_{qr} \quad (3)$$

Rotor Flux equations:

$$\overline{\varphi}_{dr} = L_m\overline{I}_{ds} + L_r\overline{I}_{dr}$$
$$\overline{\varphi}_{qr} = L_m\overline{I}_{qs} + L_r\overline{I}_{qr} \quad (4)$$

Where $\overline{V}$, $\overline{I}$, $\overline{\varphi}$, are the voltages, current and flux. Meanwhile subscript d, q represent the dq axis while s and r represent stator and rotor component. The stator and rotor resistance and inductance are denoted as Rs, Rr and Ls, Lr, whereas Lm is the mutual inductance. ωs and ωr represent the synchronous speed and mechanical speed respectively.

In the space vector approached, the electromagnetic torque, Te produced by the motor can be expressed in terms of flux and current as follows;

$$T_e = \frac{3}{2}\frac{P}{2}\left(\overline{\varphi}_{ds}\overline{I}_{qs} - \overline{\varphi}_{qs}\overline{I}_{ds}\right)$$
$$T_e - T_L = J\frac{d\omega_r}{dt} + B\omega_r \quad (5)$$

Where P, T_L, J and B denote the number of poles, external load, inertia and friction of the IM coupled with the permanent magnet dc-machine respectively.

In this system, the rotating coordinate reference frame having direct axis is aligned with the rotor flux vector that rotates at the stator frequency. If the q-component of the rotor flux is assume zero and the electromagnetic torque expression becomes:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r}\overline{I}_{sd}\overline{I}_{sq} \quad (6)$$

Based on the rotor voltage quadrature axis equation of IM, the rotor flux linkage can be estimated using this formula;

$$\hat{\psi}_r = \frac{L_m I_{ds}}{1 + \tau_r s} \quad (7)$$

Where, τ_r is the rotor time constant.

The slip frequency ω_{sl} is obtained from the rotor voltage direct axis equation by:

$$\omega_{sl} = \frac{L_m R_r I_{qs}}{\hat{\psi}_r L_r} \quad (8)$$

The rotor flux position, θ_e for coordinate transform is generated from the integration of rotor speed, ω_r and slip frequency, ω_{sl}.

$$\theta_e = \int \omega_r + \omega_{sl} \tag{9}$$

The FOC is composed of two inner current loops for flux and torque control. The outer speed loop is cascaded with the torque current loop. The output of this current loop regulate are transformed into stationary reference frame voltage by dq to αβ transformation. Then, these reference voltages are fed to SVPWM modulation process to generate pulse with modulation signal for inverter.

3. CONTROLLER DESIGN

Based on the mathematical model of the three phase IM, all the current loop and speed of PI controller are calculated by using a second order system for a step input. All the values for proportional (Kp) and integral (Ki) gains of the three PI controllers are determined by comparing the general second order system with the close loop block diagram transfer function.

3.1. PI Controller Scheme

Based on the motor Equation (1), in synchronous reference frame the block diagram of torque and flux component loop can be simplified as in Figure 2 and Figure 3.

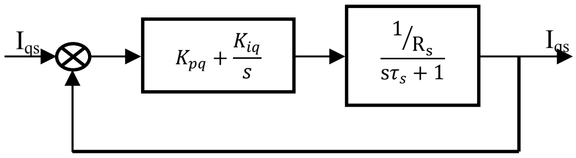


Figure 2. Simplified torque component current loop control

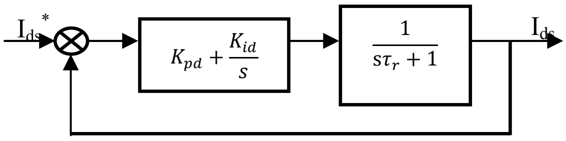


Figure 3. Simplified flux component current loop control

The closed loops equations for torque and flux component above are shown in Equation (10) and (11).

$$\frac{I_{qs}^*}{I_{qs}} = \frac{\left(K_{pq} + \frac{K_{iq}}{s}\right)\left(\frac{1/R_s}{s\tau_s + 1}\right)}{1 + \left(K_{pq} + \frac{K_{iq}}{s}\right)\left(\frac{1/R_s}{s\tau_s + 1}\right)} \tag{10}$$

$$\frac{I_{ds}^*}{I_{ds}} = \frac{\left(K_{pd} + \frac{K_{id}}{s}\right)\left(\frac{1}{s\tau_r + 1}\right)}{1 + \left(K_{pd} + \frac{K_{id}}{s}\right)\left(\frac{1}{s\tau_r + 1}\right)} \tag{11}$$

Where $\tau_s = \frac{L_s}{R_s}$ and $\tau_r = \frac{L_r}{R_r}$ is the stator and rotor time constant respectively. The speed loop block diagram is illustrated in Figure 4 is based on the mechanical motor equation.

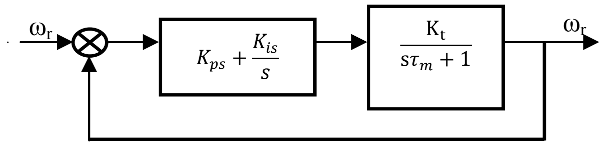


Figure 4. Simplified speed loop control

Where $\tau_m = \frac{J}{B}$ a is the motor mechanical time constant and torque constant, Kt is given as:

$$K_t = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_s}\bar{I}_{sd} \tag{12}$$

The speed closed loop transfer function is given as below:

$$\frac{\omega_r^*}{\omega_r} = \frac{\left(K_{ps} + \frac{K_{is}}{s}\right)\left(\frac{K_t}{s\tau_m + 1}\right)}{1 + \left(K_{ps} + \frac{K_{is}}{s}\right)\left(\frac{K_t}{s\tau_m + 1}\right)} \tag{13}$$

The denominator of the general second order system is governed by;

$$s^2 + 2\varsigma\omega_n + \omega_n^2 \tag{14}$$

Where ωn is the natural frequency of the closed-loop system and ς is the damping ratio. By comparing the denominator of the closed loop transfer function with Equation (14), the value of Kp and Ki can be determined. The gains of the PI controller are shown in Table 1. The values are obtain based on the equation above with ς is set at 1 and ωn is set at 100Hz, 10Hz and 1Hz for torque loop, flux loop and speed loop respectively.

Table 1. PI Controller Parameters

PI Controller	Kp	Ki
Speed Controller	0.13	0.4252
Flux Controller	4.65	8.94
Torque Controller	13.4	197.45

3.2. PI Controller with Anti-Wind Up Scheme

The main objective of the AW scheme is to avoid the over value or saturation value in integrator which causes high overshoot and long settling time. Large step change or large external load disturbance applied causes the PI controller saturate. This windup phenomenon results in inconsistency between the real plant input and the controller output. In order to overcome the wind up problem, the integral state is separately controlled [4], [15], [18]. Thus, additional integral control in added to justified on the PI controller output is saturated or not based on the anti-windup structure in Figure 5.

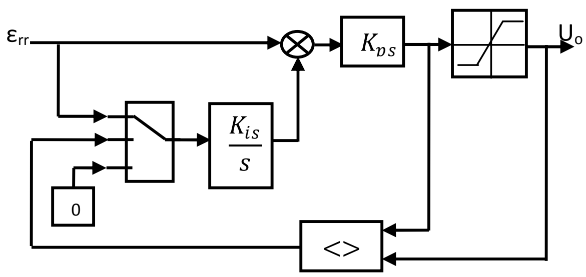


Figure 5. AWPI Conditional Integration Scheme

3.3. Anti Wind Up Scheme with Pre Filter

In order to have a pure second order system in the speed closed-loop, a pre-filter as shown in Equation (15) is added in series with the system [2], [3], [10].

$$G_{PF} = \frac{K_{is}}{k_{ps}S + K_{is}} \quad (15)$$

By inserting the pre-filter block, the behavior of the closed loop speed loop system is equal to the desired pure second order system. It is able to cancel the unwanted zero from the loop gain.

4. RESULTS AND DISCUSSION

The performance comparison between PI controller, PI controller with anti-windup and pre-filter schemes is conducted using Dspace1103 controller. A three parallel insulated bipolar transistor (IGBT) intelligent power module (SEMiX252GB126HDs) are used for the inverter. The parameters of a 1.5kW induction motor are shown in Table 2. The voltage supply is set at rated voltage 380 Vrms and the switching frequency is set at 8kHz. The sampling time is 50µs. The tests are conducted to evaluate the performance of the motor under various speed operation demands and load disturbance rejection. Figure 6 shows the hardware experimental setup for TLI and FLI drive system.

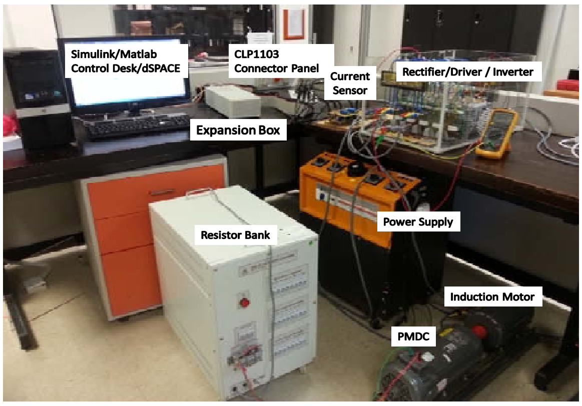


Figure 6. The hardware experimental setup

Table 2. Induction Motor Parameters

Motor Specifications	Value
Rated Voltage	380 V
Rated Frequency	50 Hz
Poles	4
Rated Speed	1430 rpm
Stator Resistance	3.45 Ω
Rotor Resistance	3.6141 Ω
Stator Inductance	0.3246 H
Rotor Inductance	0.3252 H
Magnetizing Inductance	0.3117 H
Inertia	$0.02kgm^2$
Viscous Friction	0.001 Nm/(rad/s)

4.1. Operation under Wide Speed Operation

This test is conducted during no load condition. For this experiment setup, 1.5kW Baldor three phase IM motor is coupled with 2.2kW Baldor permanent magnet DC machine. Incremental optical encoder is used to measure the shaft speed which has 500 pulses per revolution. For this test, the motor is required to operate at three different conditions which are standstill, forward direction and reverse direction at 500rpm, 1000rpm and 1400rpm operating speed. Every test is repeated for three times with different controllers' schemes. The first test is conducted using conventional proportional controller (PI) controller with limiters. Proportional controller with anti windup (AWPI) scheme for speed controller is applied for the second test condition. Then, the pre filter (PF) is added in cascade with the speed loop for the final experimental test.

Figure 7 shows the speed responses at 500rpm, 1000rpm and 1400rpm. The motor is required to operate from standstill to forward direction at 0.975s and reverse it direction at 4.226s. Based on the results, the motor tracks the command speed with almost zero speed error during steady state condition for all controllers. However, different transcient behaviours are notified such as rise time, percent overshoot and settling time. The details performance results from zero speed to forward direction are shown in Table 3 below:

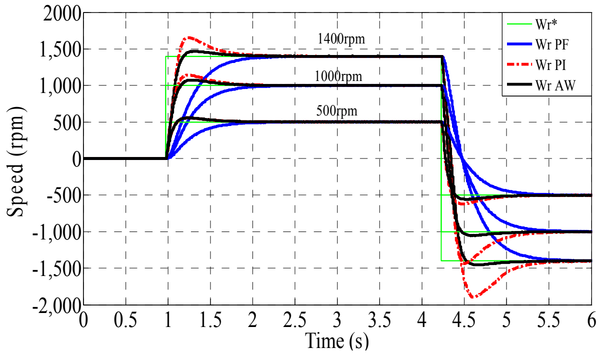


Figure 7. Speed response experiment results during standstill, forward and reverse direction at 500rpm, 1000rpm and 1400rpm speed operation (a) Overall performances (b) Closed up speed response at 500rpm (c) Closed up speed response at 1000rpm (d) Closed up speed response at 1400rpm

Table 3. Performance analysis of PF, PI and AW controller for forward Direction

Test Condition	Controller	%OS	Tr(s)	Ts(s)
500rpm	PI	11.6%	1.073	1.743
	AW	12.2%	1.077	1.718
	PF	0%	1.625	2.006
1000rpm	PI	14.3%	1.107	1.811
	AW	7.4%	1.091	1.727
	PF	0%	1.585	1.977
1400rpm	PI	18.3%	1.101	1.861
	AW	5.0%	1.130	1.640
	PF	0%	1.610	1.990

Meanwhile Table 4 shows the performance results from forward to reverse operation at 4.226s of the speed demand changed:

Table 4. Performance analysis of PF, PI and AW controller for reverse Direction

Test Condition	Controller	%OS	Tr(s)	Ts(s)
-500rpm	PI	24.2%	4.334	5.154
	AW	11.6%	4.362	5.022
	PF	0%	5.027	5.427
-1000rpm	PI	43.4%	4.383	5.333
	AW	5.3%	4.423	4.923
	PF	0%	5.041	5.411
-1400rpm	PI	35.64%	4.445	5.375
	AW	3.71%	4.447	4.897
	PF	0%	5.045	5.415

Based on the results, the AWPI and PI controller produced almost similar time rise response, Tr. Meanwhile, PF controller produces slower rise time response as well as the settling time. For the forward and reverse operations at 1400rpm demand, PI controller scheme recorded the highest percent overshoot with 18.3% and 35.64% respectively. No overshoot results from the pre filter controller for the demands changed. Meanwhile, the AWPI produce lower overshoot for those conditions at 5.0% and 3.71% respectively. The best characteristic of AWPI controller is it capabilities to produce lower percent overshoot while maintaining the rise time and improving the setting time. From the AWPI controller performance results, by increasing the speed range demand, the percent overshoot parameter is reduced compared to the conventional PI controller. In PI controller, a large step speed demand reference cause the output of the speed controller reaches the saturate limit of current, Iq. This anti-wind up phenomenon can be controlled by the AWPI scheme. The AWPI scheme control the integral parts from keep up integrating the error and the controller output from increased. The details analysis of the integral stage behaviors in PI and AWPI are explained based on the simulation results below.

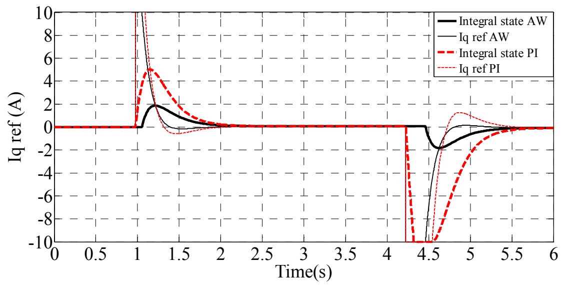
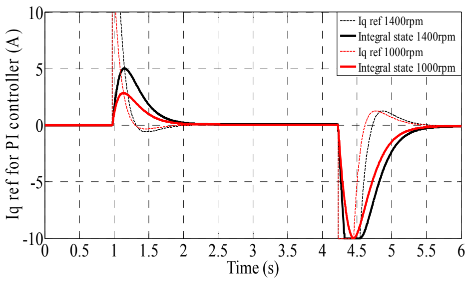
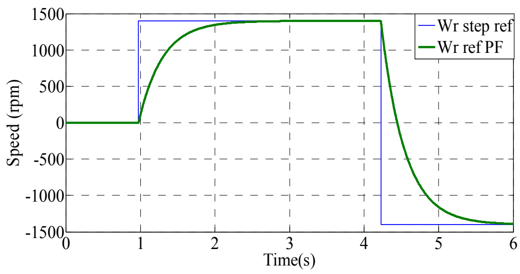


Figure 8. Simulation result comparing torque current response using PI and AWPI

Figure 8 shows the simulation results of current torque components response which compares between conventional PI and AWPI when a step function demand is applied from zero speed to 1400rpm in forward and reverse direction. Similar parameters, controllers and speed demand are used in this simulation and experiment. In the conventional PI scheme, the integral state becomes large at the start of linear region because it accumulates the speed error, even in saturation region. Thus, it produces excessive integral state results in a large overshoot. Meanwhile in the AWPI the integral state work only when the input and output saturation different is varnished. Therefore, it is able to reduce overshoot significantly and also maintains the rise time response, Tr results as PI controller. The speed control performance is much improved by AWPI scheme with regards to the large speed change.



(a)

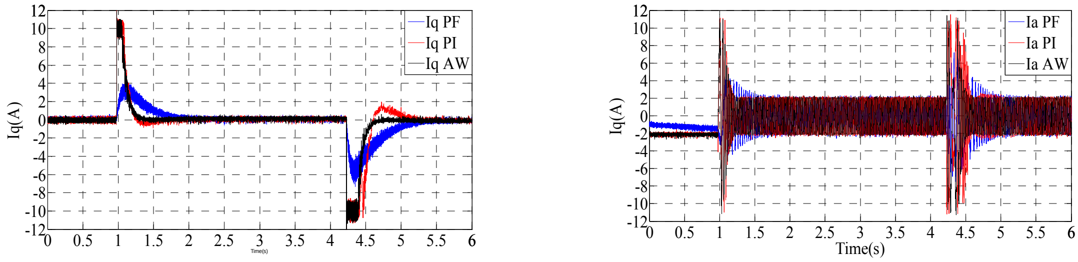


(b)

Figure 9. (a) Simulation result comparing torque current response using PI at 1000rpm and 1400rpm demand; (b) Reference step input demand and pre filter output demand

Figure 9(a) show the simulation results comparing torque current components for PI controller at 1000rpm and 1400rpm demand. During forward operation, the integral state output is 2.85A and 5A for 1000rpm and 1400rpm respectively. These results 14.3% and 18.3% of speed percent overshoot respectively. It means that, the higher changed of speed demand produce higher overshoot. However, during reverse operation, the percent of overshoot became 43.4% and 35.64% for 2000rpm and 2800rpm speed changed respectively. This result was affected by integral limiter integral limiter which is set at 10A. The integral state output is clamp at 10A for negative 1400rpm speed from 4.3s until 4.55s. This action, control the Iq reference demand from producing higher overshoot compared to negative 1000rpm demand change. As a result, lower percent overshoot with higher speed demand changes happened. The interesting part of the pre filter controller is it capabilities to maintain zero overshoot for all the speed demand range. Figure 9(b) shows the simulation comparison between step input reference and speed reference after the pre-filter process used as the reference signal in PF scheme. Due to the negative exponential speed reference demand by adding the PF, slower speed response results for PF scheme. This situation happened to all the step reference range demand and results no overshoot results but slower speed response.

Figure 10 show the torque current component, Iq and phase A current, Ia experiment results of the step response demands. From the stand still condition, the motor operated at 1400rpm in forward direction to 1400rpm reverse operation. Based on the result, almost similar torque current, Iq performance can be notify for PI and AWPI scheme. The torque current reach limited 10A set at the speed controller tremendously. PF scheme produce slower torque current response and only reach 4A amplitude during forward speed command. This also results in slower speed response of PF scheme. The similar results effect can be seen for the phase a stator current, Ia.



(a) (b)

Figure 10. Experiment results during standstill, forward and reverse direction at 1400rpm speed operation, (a) Torque current response (b) *Phase A current response*

4.2. Operation under Load Condition

The load rejection capabilities of the design were investigated with the nominal load disturbance applied during rated speed operation as shown in Figure 11. The load disturbance operation is accomplished by using a DC machine attached with the load bank. The armature terminals of the permanent magnet DC machine are connected to the resistor bank. The external resistor of the DC machines is set to produce rated current load of IM. The motor is operated at 1400rpm and sudden rated load disturbance is applied at 2.5s. From the results, the speed dropped about 180rpm and recover from the undershoot situation within 1s for the entire schemes. It proven that, all the schemes has same capability of load disturbance rejection during rated load. However, the speed change is not large enough to turn-on the saturation condition of the anti-windup system.

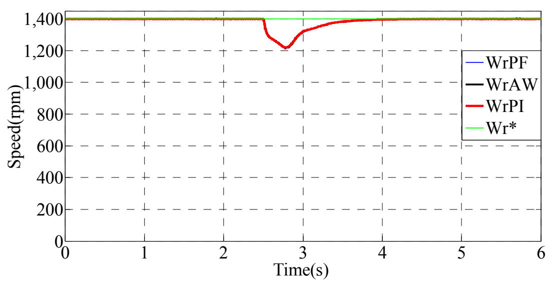


Figure 11. Experiment results with rated speed with nominal load dirstubunce

5. CONCLUSION

This paper presents the speed performance analysis of IFOC performance results between PI, AWPI and PF scheme control at low, medium and rated speed demand. All the three PI controller design are using second order system design approach. From the analysis, the AWPI is able to reduce overshoot problem by controlling the integral parts from keep up integrating the error at a set predetermine limiter. The result is more significant especially in term of percent overshoot reduction at the higher speed range demand. In addition, this great scheme is able to maintain the rise time and improving the setting time compared to the PI scheme. Meanwhile, PF scheme results slower speed and torque response performances. However, the PF is able to produce pure second order system in all speed range demands. It is able to get zero overshoot response with reasonable settling time response. Finally, for the load disturbance rejection ability, all schemes show similar performance capability to withstand the rated load disturbance.

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BIOGRAPHIES OF AUTHORS

Md Hairul Nizam Talib was born in Malaysia, in 1976. He received his B.S. in Electrical Engineering from the Universiti Teknologi Malaysia (UTM), Johor Bahru, Johor, Malaysia, in 1999, and his M.S. in Electrical Engineering from the University of Nottingham, Nottingham, UK, in 2005. He is currently working towards his Ph.D. at the Universiti Teknikal Malaysia Melaka (UTeM), Durian Tunggal, Melaka, Malaysia. He has been a lecturer at UTeM since 2002. His current research interests include power electronics, fuzzy logic control and motor drives.

Zulkifilie Ibrahim was born in 1966 in Malaysia. He received his B.Eng. degree from the University of Technology (UTM), Malaysia in 1989 and his PhD degree from the Liverpool John Moores University, UK in 1999. He is currently an Assoc. Professor at Universiti Teknikal Malaysia Melaka (UTeM), Malaysia since 2006. His main research interests are related to power electronics, fuzzy logic control, embedded system design and electric motor drives.

Nasrudin Abd. Rahim was born in Johor, Malaysia, in 1960. He received his B.S.(with Honors) and M.S. from the University of Strathclyde, Glasgow, U.K., and his Ph.D. from Heriot-Watt University, Edinburgh, U.K., in 1995. He is currently a Professor in the University of Malaya, Kuala Lumpur, Malaysia, where he is also the Director of the University of Malaya Power Energy Dedicated Advanced Centre (UMPEDAC). At present he is an Adjunct Professor at King Abdulaziz University, Jeddah, Saudi Arabia. Prof. Rahim is a Senior Member of IEEE, a Fellow of the Institution of Engineering and Technology, U.K., and a Fellow of the Academy of Sciences Malaysia. He is also a Chartered Engineer.

Ahmad Shukri Abu Hasim received his Diploma, Degree and Master in electrical engineering majoring in Power from Universiti Teknologi Mara Malaysia, in 2000, 2004 and 2008 respectively. He is a lecturer at Universiti Pertahanan Nasional Malaysia and currently pursuing his PhD at Universiti Teknikal Malaysia Melaka. His areas of interest are in power electronic and drive system.