Power performance of boundary technique on FOSMC based induction motor drives

A W Aditya[1], R M Utomo[1], Hilmansyah[1], E Purwanto[2], M R Rusli[2], B Praharsena[3]

[1] Department of Electrical Technology, Politeknik Negeri Balikpapan, Jalan Soekarno Hatta, Balikpapan, Indonesia
[2] Department of Industrial Electrical Engineering, Politeknik Elektronika Negeri Surabaya, Jalan Raya ITS, Surabaya, Indonesia
[3] Department of Electrical Engineering, Politeknik Negeri Madura, Jalan Raya Taddan, Sampang, Jawa Timur, Indonesia

E-mail: angga.wahyu@poltekba.ac.id

Abstract. Power analysis of induction motor (IM) consists of active, reactive and apparent power. Those power related to power factor (PF) which indicate the performance of IM. This paper presented the power analysis and power factor of IM using IFOC system (part of vector control). However, IFOC only provides speed regulation but not the robustness under disturbance. In one hand, FOSMC proposed the robustness against disturbance and stability of the systems. In another hand, FOSMC has the disadvantages in chattering phenomenon which increase power consumption. Boundary technique (BT) designed in FOSMC using sat(.) function to reduce the power consumption. As the results, the BT decreases stator current consumption, active, reactive and apparent power. active power has an average decrease of 13.02 percent in the variable of torque load, reactive power has an average decrease of 10.46 percent and apparent power has 12.11 percent. The stator current has an average decrease of 12.53 percent. At no-load conditions, the average decrease in power consumption is 30.05 percent. This value decreases when the torque load increases.

1. Introduction

In the industrial world, IM has been used because of its reliability and low price[1, 2]. But the speed of IM is very difficult to control due to its complex mathematical model. The vector control method is the most popular method due to its high efficiency and performance[3, 4]. Indirect Field Oriented Control (IFOC) which part of vector control is easy to use in industrial application due to its simple and inexpensive implementation [5]. IFOC system represents the IM mathematical model to DC motor [6]. it facilitates variable speed regulation of IM. In the last decades, many papers discuss IFOC and its implementation. Speed regulation of IFOC based on real-time control system designed to optimized transient speed response [7]. Backstepping as speed controller in IFOC for fast response three-phase IM [8]. Fault-tolerant control of IFOC based on IM drives to compensate for the failure in current sensors [9]. IFOC applied in linear IM based on optimized slip frequency [10].

The power correction consists of active, reactive, apparent power consumption and power factor. The parameter performance of IM control can be calculated from power consumption, decreasing reactive power and power factor quality. Active power represents the power consumption in the system, the reactive power represents the power loss and the apparent power can be expressed as total power consumption. Power factor can be expressed as power consumption quality from IM control.

Sliding Mode Control (SMC) is one of the popular robust controllers because of its robustness and stability [11]. A recent study of SMC on electric machines have been carried out. First Order SMC (FOSMC) and High Order SMC (HOSMC) on Permanent Magnet Synchronous Motor (PMSM) has been designed to analyze the chattering phenomenon [12]. FOSMC applied to the current regulator of IFOC for IM to get better performance in direct and quadrature stator current [13]. FOSMC of IM using designed in the speed controller to give a robust response in speed [14]. This paper using sign(.) function which makes a chattering phenomenon. In one hand, increase the order of SMC (Second Order SMC (SOSMC)) can decrease the chattering phenomenon [15]. In another hand, it hard to do because of the complexity. SMC uses a modeling system and Lyapunov function to achieves robustness and stability. Ordinary SMC or FOSMC using sign(.) function to guarantee the robustness. This discontinues control input makes the chattering phenomenon. It consumes more power to a standstill the robustness. The BT using sat(.) function designed to reduced chattering phenomenon [16, 17]. This chattering phenomenon reduction in power consumption [18]. This paper proposes the BT using sat (.) function to reduce the chattering phenomenon. The power consumption (active, reactive and apparent) by IM analysis in stator current and voltage in direct-quadrature axis [19].

2. Induction motor equation

A mechanical model of dynamic IM modeling consists of a rotor speed equation or electromagnetic torque. The speed equation of IM shown in Equation (1) :

$$\frac{d\omega_r}{dt} = \frac{L_m}{J\,L_r}(\phi_{rd}\, i_{sq} - \phi_{rq}\, i_{sd}) - \frac{1}{J}m_o \tag{1}$$

where :

ϕ_{rd}	= Rotor flux in Direct axis	L_m	= Mutual Inductance
ϕ_{rq}	= Rotor flux in Quadrature axis	m_o	= Torque load (TL)
L_r	= Rotor Inductance	J	= Moment of inertia
		ω_r	= Speed

3. Indirect field oriented control

The IFOC concept for an IM shown in Figure 1. IFOC needs electromagnetic torque (T_e) and rotor flux for an input. The input can be controlled separately by direct-axis stator current (i_{sd}) and quadrature-axis stator current (i_{sq}).

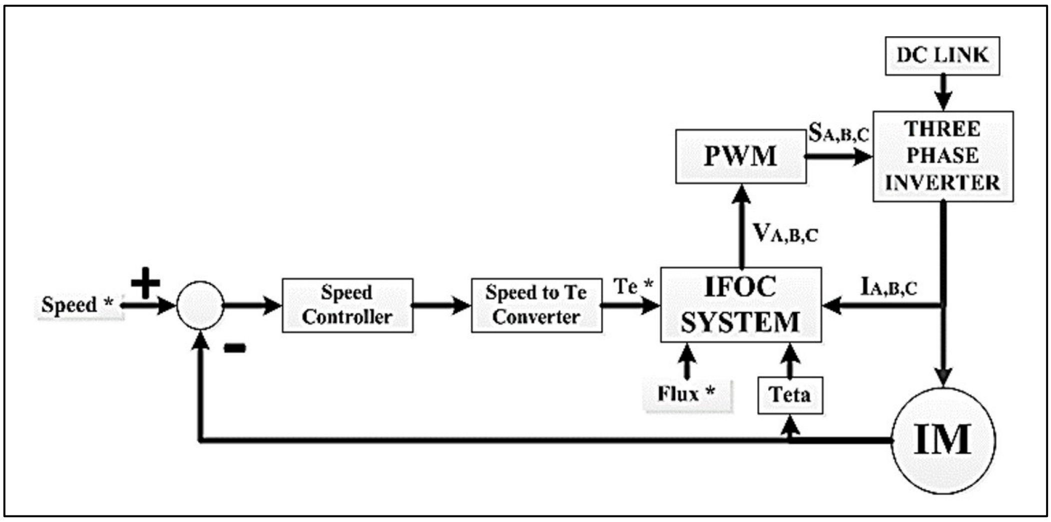

Figure 1. Diagram block of IFOC for an IM.

By giving constant rotor flux in (1), the equation of IFOC for IM are [3, 6, 20]:
The equation of speed become:

$$\frac{d\omega_r}{dt} = \frac{L_m}{J\, L_r}\, \phi_r\, i_{sq} - \frac{1}{J}\, m_o$$

The electromagnetic torque equation is:

$$T_e = \frac{3}{2}\, P\, \frac{L_m}{L_r}\, \phi_r\, i_{sq}$$

where : T_e = Electromagnetic torque
P = Number of pole pairs

The electromagnetic torque equation representation in the speed of IFOC for IM is:

$$\frac{d\omega_r}{dt} = \frac{2}{3\,J}\, P\, T_e - \frac{1}{J}\, m_o$$

The flux vector position angle is:

$$\theta = \int_0^t (P\omega_r + \omega_{sl})\, dt$$

4. Sliding Mode Control

The FOSMC design based on the sliding surface and the Lyapunov stability theory. The sliding surface is:

$$S(e;t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \qquad (2)$$

where: n = Sliding surface degree
e = X_{desire} - x is an error
λ = Positive constant

The FOSMC controller design follows:

$$U_{SMC} = U_{eq} + U_n$$

where: U_{SMC} = The SMC controller
U_{eq} = The controller from modeling system (Equivalent Control)
U_n = Added to guarantee the attractiveness of sliding surface in (2).

The Lyapunov function follows:

$$V = {}^{1}\!/_{2}\, S^2$$

The derivative of (2) is:

$$\dot{V} = S\,\dot{S}$$

The derivative of a Lyapunov function should be zero to get the equivalent control signal (U_{eq}) of FOSMC.

$$U_{eq} = \dot{V} = 0 \quad Or \quad 0 = S\,\dot{S} \qquad (3)$$

From electromagnetic torque equation represents in the speed of IFOC, (2) and (3), the FOSMC controller of speed is:

$$U_{eq}\,(T_e) = \frac{3J}{2}\left[\dot{\omega}_r^{*} + \frac{1}{J}\, m_o\right]$$

$$U_n = K\left[S_{\omega_r}(e,t)\right] + \beta\, sign\left[S_{\omega_r}(e,t)\right]$$

Where $S_x(e,t) = \lambda\, e_x$ and K and β is a positive constant gain.

The BT designed using sat(.) function to reduce chattering phenomenon in FOSMC cause of sign(.) function. Chattering phenomenon consumes more power to hold the robustness. Thin boundary layer restricts the discontinuous input. But, the robustness and stability of the system in the boundary area cannot be guaranteed. The boundary equation shown in Equation 4 [18].

$$sat(S) = \begin{cases} Sign(S) & for\ |S| > \beta_l \\ \frac{S}{\beta_l} & for\ |S| \leq \beta_l \end{cases} \tag{4}$$

where: β_l = boundary layer constant.

By Equation 4 to the speed controller in FOSMC design of IFOC system, the speed controller using bondary technique is:

$$U_{eq}\,(T_e) = \frac{3\,J}{2}\left[\dot{\omega_r}^* + \frac{1}{J}\,m_o\right]$$
$$U_n = K\left[S_{\omega_r}(e,t)\right] + \beta_l\, sat\left[S_{\omega_r}(e,t)\right]$$

5. Results and discussion

This paper proposes stator current, power (active, reactive and apparent) and power factor analysis of IFOC system for IM. FOSMC used as a robust controller which is designed in the speed controller. Rotor speed reference which is used in this paper is 1000 rpm. Active power consumption calculates using Equation 5 and Apparent power can be calculated using power triangle. The power factor of IM can be calculated using Equation 6.

$$P = \frac{3}{2}\left[(U_{ds}i_{ds}) + (U_{qs}i_{qs})\right] \tag{5}$$

$$Power\ Factor = {}^{P}/_{S} \tag{6}$$

where : P = Active power
Q = Reactive power
$S = P^2 + Q^2$ = Apparent power

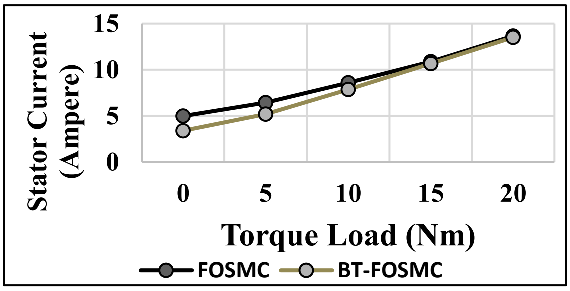

Figure 2. Stator current response in various TL (RMS).

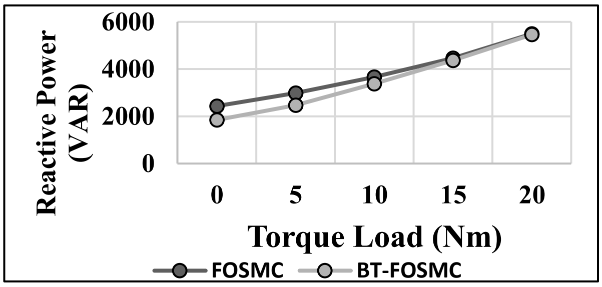

Figure 4. Reactive power response in various TL (RMS).

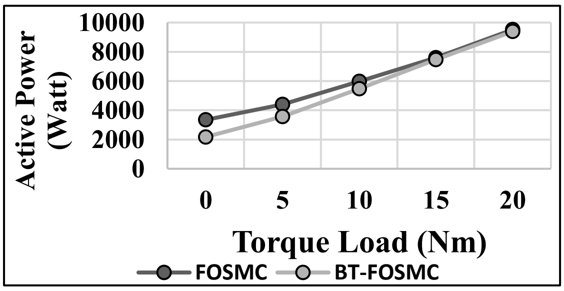

Figure 3. Active power response in various TL (RMS).

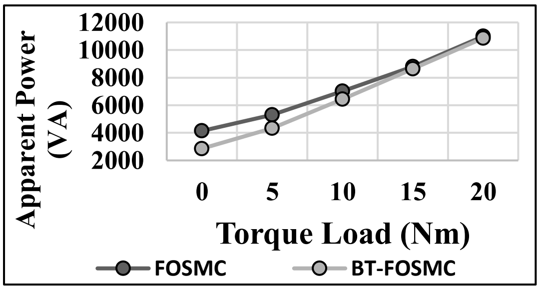

Figure 5. Apparent power response in various TL (RMS).

Table 1. Percentage reduction value in various TL.

	TL (Nm)				
	0	5	10	15	20
Stator Current	31.93 %	19.25 %	8.51 %	1.84 %	1.10 %
Active Power	35.00 %	18.70 %	8.24 %	1.83 %	1.33 %
Reactive Power	24.12 %	17.36 %	7.96 %	2.24 %	0.62 %
Apparent Power	31.03 %	18.27 %	8.15 %	1.94 %	1.18 %
Power Factor	6.17 %	1.20 %	0.00 %	0.00 %	1.15 %

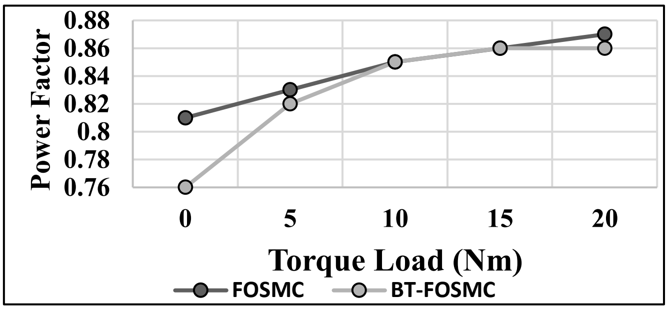

Figure 6. Power Factor response in various TL

Figure 2 shows stator current performance of FOSMC with and without the BT in various TL. Various TL test used to show the performance of BT in a specific value. Based on Figure 2 and Table 1, BT designed in FOSMC (BT-FOSMC) reduced current consumption 31.93 % in 0 Nm, 19.25 % in 5 Nm, 8.51 % in 10 Nm, 1.84 % in 15 Nm and 1.10 % in 20 Nm of TL. Figure 3 shown the comparison of active power response using FOSMC and BT-FOSMC. The result shows BT-FOSMC decrease 35.00 % of active power consumption in 0 Nm, 18.70 % in 5 Nm, 8.24 % in 10 Nm, 1.83 % in 15 Nm and 1.33 % in 20 Nm of TL. Figure 4 shown reactive power consumption of IFOC-IM using FOSMC. It represents losses in power analysis. The BT-FOSMC decreases reactive power consumption in all various torque load. In TL = 0 Nm decreases 587 VAR, TL = 5 Nm decreases 519 VAR, TL = 10 Nm decreases 292 VAR, TL = 15 Nm decrease 34 VAR. This value is decreasing exponantially because BT-FOSMC decreaseing chattering phenomenon in no load condition. In under disturbance, BT-FOSMC can't standstill the robustness. Figure 5 shown apparent power response. FOSMC response decrease 31.03 % (1284 VA) in TL = 0 Nm, 18.27 % (971 VA) in TL = 5 Nm, 8.15 % (571 VA) in TL 10 Nm, 1.94 % (171 VA) in TL = 15 Nm and 1.18 % (130 VA) in TL = 20 Nm. The power factor value of BT-FOSMC in 0 Nm is 0.76. This value is lower than FOSMC in 0.81 shown in Figure 6. This condition continues in 5 Nm of TL (BT-FOSMC = 0.82 and FOSMC = 0.83) and 20 Nm of TL (BT-FOSMC = 0.86 and FOSMC = 0.87). In TL = 10 and 15 Nm, BT-FOSMC has the same value as FOSMC (0.85 in 10 Nm of TL and 0.86 in 15 Nm of TL). The percentage of decreasing value in FOSMC with and without BT shown in Figure 7. The data shows an exponential decline in all parameter (stator current, active power, reactive power, apparent power and power factor) because of BT does not guarantee the robustness in boundary area. So, when the disturbance given in the boundary area, the respon returns to the robustness region.

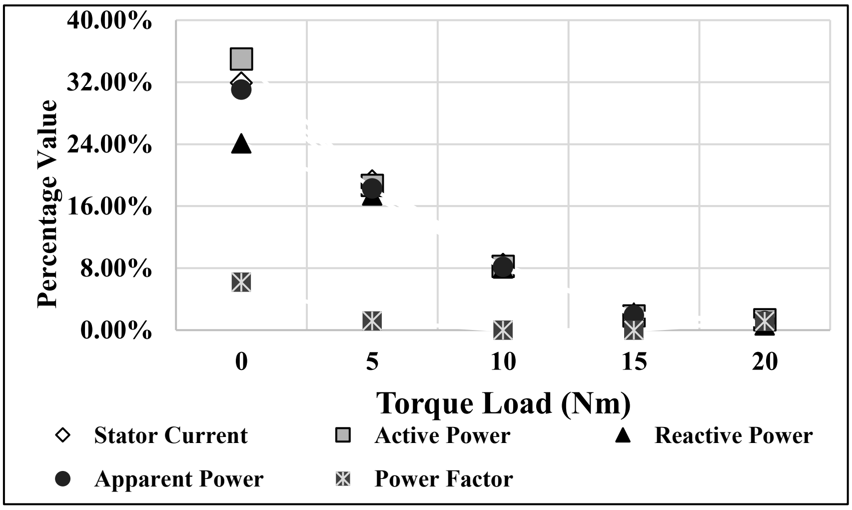

Figure 7. Percentage reduction response in various TL.

6. Conclusions

The paper presents BT applied in FOSMC designed for speed controller on IM using IFOC method. The chattering phenomenon in rotor speed response due to discontinuous control input reduced by BT. It makes stator current and power consumption (active, reactive and apparent power) reduce in no-load condition but increases exponentially in under disturbance. But the power factor response in most variations of torque load is reduced. In one hand, BT-FOSMC has advantages of reducing the chattering, current and power consumption. In another hand, BT-FOSMC does not guarantee the robustness in the boundary area and in under disturbance the reduction of power consumption decrease exponentially.

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