Fuzzy-SMC-PI Flux and Speed Control for Induction Motors

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Abstract—**This paper presents the design and implementation of Fuzzy-SMC-PI methodology to control the flux and speed of an induction motor. The Fuzzy-SMC-PI is basically a combination of Sliding Mode Control (SMC) and PI control methodologies through fuzzy logic. In this strategy, SMC is responsive during transient state while PI control becomes fully active in the steady state area. This will ensure that the final controller will avoid SMC's inherent chattering problem in steady state and PI's sensitivity, overshoot, long settling time and rise time problems. The combination of both control strategies through fuzzy logic provides a mean to create a hybrid control strategy that produce minimum overshoot, faster settling time and an almost chatter free system. The resulting hybrid system operates by sliding between SMC and PI mode depending on the condition imposed by internal parameter perturbation and external factors such as load torque. Simulations of the proposed Fuzzy-SMC-PI strategy on the flux and speed controllers displayed diminished chatter, overshoot and significant reduction of settling time. One other significant result of applying Fuzzy-SMC-PI strategy on the flux component of the system is that optimum flux level is attained fairly quicker. This resulted in faster rise time and the motor reaching its targeted speed much earlier.**

Keywords—**sliding mode control, sliding control, Lyapunov stability design, induction motor flux and speed control**

I. INTRODUCTION

The Field Orientation Principle allows engineers to focus on developing more effective control strategy for the independent torque and flux controllers. One of these control strategies is sliding mode control (SMC) which is a very appealing control method as it is robust, easy to implement and able to create an high efficiency hardware. Being robust, it has low sensitivity to plant disturbances and plant parameter variations. Like other control strategy, SMC method is not an ideal control strategy. It has its fair share of inherent problems. One of these is the chattering issue. However, this phenomenon is addressable with various techniques such as the boundary layer method [1,2], equivalent control-based method [3-5], observer-based method [6], regular form method [7,8], disturbance rejection method [9-11] and intelligent control method [12-14]. In combination with these strategies, the overall performance of the SMC system is can be greatly enhanced although chattering is not fully removed.

The idea of applying SMC to asynchronous electric drives was first suggested by [15]. When it became feasible and realizable, it was explored more seriously in the eighties. It was the technological advancement that created conducive environment for both field orientation principle and sliding mode control strategy to move forward. The potential of sliding mode control methodologies was demonstrated in [16-18] for versatility of electric drives. In fact, several attempts have been made to apply SMC to control speed and rotor flux of induction motors but these approaches were not free from deficiencies such as the requirement of uncertainty bounds and the presence of chattering along the sliding surface.

As an attempt to solve these deficiencies, [19] used a low-pass filter with variable bandwidth to remove the chatter. The results of their work showed an affected transient response and an oscillating steady state response. Reference [20] used the same filter concept but determined the switching function using linear quadratic regulator design principle. In addition, the authors used adaptation methods to tune the switching plane.

Reference [21] used a boundary layer solution to remove the chatter at steady state. In addition to the limitations of the boundary layer solution, their method employed an additional observer to estimate the acceleration information of the motor because it had high frequency components and was difficult to measure. The same solution method is used by [22] but with torque observer to compensate external disturbances. In addition, sensorless direct torque method combined with space vector modulation was introduced in [23].

References [24,25] implemented a fuzzy logic controller to adjust the boundary layer width according to the speed error. The drawback of their controller is that it depends on the equivalent control which depends on the system parameters.

References [26-29] combined sliding mode control with adaptive backstepping control approach. They applied their controller to the torque and flux control of an induction motor. Their method utilized a model-following control technique to track a designed linear reference model so that the transient dynamics of the controlled torque and flux could be simply designed through a linear reference model.

Model reference concept was also used by [30]. They introduced a two-degree-of-freedom linear model-following controller design to meet the prescribed tracking and load regulation speed responses at nominal case to compensate variations from the nominal operating conditions. From the literature, this method can be considered as an integral sliding mode control [31].

The idea of utilizing these methods only complicates the design of speed controllers. Furthermore, using model reference strategies requires prior knowledge of the exact parameter values of the motor under control. Thus, new model references need to be redesigned when changing motors.

These reviewed control methods tried to solve the chattering problem but they result in the loss of implementation simplicity which sliding mode control systems offer. As an example, [32] criticized the work of [13,33] on eliminating the effect of reaching phases in sliding mode control. They stated that the drawback is the complicated design of a specific sliding curve and that this may lead to heavy computation burden or may lead to an increase in the switching frequency such that the system responses are still subjected to system uncertainties. However, their proposed method was already complex enough to cause the same drawbacks. One solution to these problems is an adaptive fuzzy sliding-mode control algorithm to combine SMC and proportional integral (PI) control [34-36]. References [34,35] combined PI and SMC through a fuzzy sliding controller but controlled only the speed of the motor but not the flux. This paper tackles both controls.

In conclusion, the boundary layer solution and equivalent control concept are the bases on which chattering removal solutions are developed for the speed control of induction motors using sliding mode control systems. The search for a robust and accurate method can lead to complicated design methods, some of which are limited in applications. Instead, this paper presents a method which is simple to implement and solves the chattering problem while maintaining the robustness of the system. The proposed method is based on using fuzzy logic control to combine the vector control's PI controller and the sliding mode speed controller. This method addresses both speed and flux control of the induction motor system.

II. FUZZY-SMC-PI CONTROL STRUCTURE

Fuzzy SMC-PI is basically a combination of SMC and PI through fuzzy logic. The advantage of such strategy is as follows. The SMC is responsive during transient state but it has an inherent chattering problem. This chattering phenomenon continuously created noise even under steady state. Thus zero steady state error is not attainable with control strategy using SMC methodology alone. On the other hand, with PI control strategy, zero steady state error is achievable but the PI control strategy is not all that ideal too. It has a significant overshoot problem and has a longer settling time and rise time. Comparatively, it is less responsive to SMC control strategy. The combination of both control strategies through fuzzy logic provides a mean to create a hybrid control strategy that produce minimum overshoot, faster settling time and an almost chatter free system. The resulting hybrid system operates by sliding between SMC and PI mode depending on the condition imposed by external factors such as load.

Fuzzy-SMC-PI strategy is developed by dividing the control region into three different regions as shown in Fig. 1 where e is the system's error. The first region involves pure SMC strategy. This region is responsible in bringing the system state to the targeted state as quickly as possible. This is followed by mixed strategy region which consists of SMC and PI strategies working in tandem through fuzzy logic to produce a single controller output. The objective of this region is to subdue any probable over-shoot prior to the steady state. The third and the final region is the pure PI strategy region. The output from this region serves to keep the steady error to a minimum or eliminates it totally.

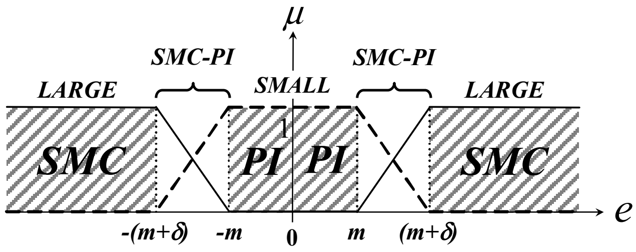

Figure 1. Fuzzy logic membership functions.

From the previous definition of the controller, it follows that the linguistic rules of the fuzzy logic supervisory controller should be defined as follows:

$$\begin{aligned} &Rule\ 1: \ IF \quad e \ \text{ is } SMALL \quad THEN \quad i = i_{PI} \\ &Rule\ 1: \ IF \quad e \ \text{ is } LARGE \quad THEN \quad i = i_{SMC} \end{aligned} \tag{1}$$

where e is the speed error and the input of the fuzzy logic controller and *SMALL* and *LARGE* are defined to be its membership functions, illustrated in Fig. 1, with parameters m and $m+\delta$, while μ is the degree of the memberships, and i_{PI} and i_{SMC} are the calculated control input commands of the PI and SMC controllers respectively and defined as follows:

$$\begin{aligned} i_{PI} &= k_p \cdot e + k_i \cdot \int e\,dt \\ i_{SMC} &= g \cdot sign(e) \end{aligned} \tag{2}$$

where g is the SMC constant control gain and *sign* is the signum function. Note that the proposed sliding surface is designed to be the system's error, i.e. $s = e$. Fig. 2 represents block diagram for implementation.

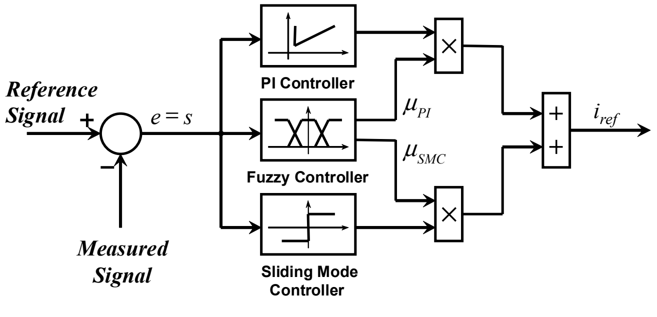

Figure 2. Implementation of the proposed Fuzzy-SMC-PI method.

III. INDUCTION MOTOR CONTROL DESIGN

In this paper, the field oriented control methodology, shown in Fig. 3, is adopted to implement the proposed Fuzzy-SMC-PI control method. Here, the field oriented speed and flux controllers are replaced by their respective Fuzzy-SMC-PI controllers.

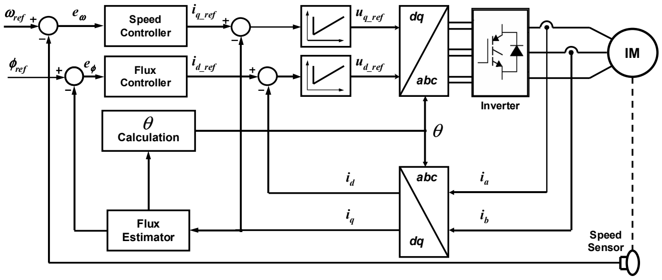

Figure 3. Field oriented control strategy.

However, to demonstrate the benefits of the new controller, the conventional SMC and PI controllers are designed and implemented in Fig. 3 as well. As PI is tuned using conventional methods, SMC needs to be designed to satisfy Lyapunov stability criterion.

A. *Conventional SMC Controllers*

As defined earlier, the sliding surface s of the speed ω and flux ϕ is simply the respective error signal. i.e.

$$\begin{aligned} s_\omega &= e_\omega = \omega_{ref} - \omega \\ s_\phi &= e_\phi = \phi_{ref} - \phi \end{aligned} \tag{3}$$

The discontinuous law to drive the state of the system to the reference state is:

$$\begin{aligned} i_{q\_ref} &= g_\omega \cdot sign(s_\omega) \\ i_{d\_ref} &= g_\phi \cdot sign(s_\phi) \end{aligned} \tag{4}$$

To obtain gain values g_ω and g_ϕ, design Lyaponov functions $V_\omega = 0.5{s_\omega}^2$ and $V_\phi = 0.5{s_\phi}^2$ then solve for g_ω and g_ϕ that satisfy Lyaponov stability conditions:

$$\begin{aligned} \dot{V}_\omega &= s_\omega \dot{s}_\omega < 0 \\ \dot{V}_\phi &= s_\phi \dot{s}_\phi < 0 \end{aligned} \tag{5}$$

To solve (5), use the induction motor's speed and flux differential equations in the direct and quadratic coordinates:

$$\begin{aligned} &\frac{d\phi_d}{dt} = -\eta\phi_d + \eta M i_d, \qquad \phi_q = 0 \\ &\frac{d\omega}{dt} = \frac{T - T_l}{J} = \alpha\phi_d i_q - \frac{T_l}{J} \end{aligned} \tag{6}$$

where $\eta = R_r/L_r$, $\alpha = NM/JL_r$, R_r is the rotor resistance, L_r is the rotor inductance, M is the mutual inductance, N is the number of pole pairs, J is the moment of inertia, and T_l is the load torque.

Evaluating (5) using (4) and (6) results in the following conditions for stable SMC speed and flux control:

$$\begin{aligned} g_\omega &> \frac{L_r}{NM}\frac{T_{l\_\max}}{\phi_d} \\ g_\phi &> \frac{\phi_{d\_\max}}{M} \end{aligned} \tag{7}$$

where the subscript *max* indicate the maximum value.

B. *Fuzzy-SMC-PI Controllers*

To obtain the design parameters of the controller, the PI controller is considered first when SMC is absent. By defining $v = \int s_\omega dt$, v_{ω_ref} as the reference value of v_ω, and $e_{v\omega}$ as the error of v_ω then:

$$\dot{E}_\omega = \begin{bmatrix} \dot{e}_{v\omega} \\ \dot{s}_\omega \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ \alpha\phi_d k_{i\omega} & -\alpha\phi_d k_{p\omega} \end{bmatrix} \begin{bmatrix} e_{v\omega} \\ s_\omega \end{bmatrix} = A_\omega E_\omega \tag{8}$$

Now define the Lyapunov function $V_{E_\omega} = 0.5{E_\omega}^T P_\omega E_\omega$ where $P = [p_{\omega 11} \;\; p_{\omega 12}; p_{\omega 21} \;\; p_{\omega 22}]$ is a symmetric positive definite matrix ($p_{\omega 11}, p_{\omega 22} > 0$ and $p_{\omega 12} = p_{\omega 21}$) satisfying the Lyapunov equation ${A_\omega}^T P_\omega + P_\omega A_\omega = -Q_\omega$ where Q_ω is a symmetric positive definite matrix.

As a necessity for the PI controller to be stable, the derivative of the Lyapunov function has to be definite negative, i.e. $\dot{V}_{E\omega} < 0$ which will result into:

$$\dot{V}_{E\omega} = p_{\omega 11} e_{v\omega} \dot{e}_{v\omega} + p_{\omega 12}\left(s_\omega \dot{e}_{v\omega} + \dot{s}_\omega e_{v\omega}\right) + p_{\omega 22} \dot{s}_\omega s_\omega \tag{9}$$

Once SMC is activated, two regions are considered; $|e| > m + \delta$ and $m \le |e| \le m + \delta$. In the first region, v_ω is constant and hence $\dot{e}_{v\omega} = 0$. On the other hand, v_ω is not constant in the second region and this results in $\dot{e}_{v\omega} = -s_\omega$. By taking into consideration these facts, the following conditions should be met to satisfy $\dot{V}_{E\omega} < 0$:

$$p_{\omega 22} > |p_{\omega 12}| \tag{10}$$

$$m_\omega + \delta_\omega > v_{\omega\_\max} \tag{11}$$

$$g_\omega > v_{\omega\_\max} k_{i\omega} + \frac{\left(p_{\omega 11} v_{\omega\_\max} + |p_{\omega 12}|(m_\omega + \delta_\omega)\right)}{\alpha\phi_d \; p_{\omega 22}} \tag{12}$$

$$m_\omega = v_{\omega\_\max} |p_{\omega 12}| \left(\varepsilon_\omega \phi_d \left(v_{\omega\_\max} k_{i\omega} + g_\omega\right)\right) / G_\omega \tag{13}$$

where $v_{\omega\_\max} = T_{l\_\max} / (J\alpha\phi_d \, k_{i\omega})$ and $G_\omega = p_{\omega 22}\alpha\phi_d (g_\omega - v_{\omega\_\max} k_{i\omega}) + p_{\omega 11} v_{\omega\_\max} + |p_{\omega 12}|(m_\omega + \delta_\omega)$

Similarly, the above steps can be followed to obtain the gain value of the flux controller g_ϕ. This is done by defining $v_\phi = \int s_\phi dt$, v_{ϕ_ref} as the reference value of v_ϕ, and $e_{v\phi}$ as the error of v_ϕ then the following can be written:

$$\dot{E}_\phi = \begin{bmatrix} \dot{e}_{v\phi} \\ \dot{s}_\phi \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ \eta M k_{i\phi} & -\eta M k_{p\phi} \end{bmatrix} \begin{bmatrix} e_{v\phi} \\ s\phi \end{bmatrix} = A_\phi E_\phi \qquad (14)$$

By assigning the Lyapunov function $V_{E_\phi} = 0.5 E_\phi{}^T P_\phi E_\phi$ and solving $\dot{V}_{E\phi} < 0$ for a stable system, the following conditions result:

$$p_{\phi 22} > |p_{\phi 12}| \qquad (15)$$

$$m_\phi + \delta_\phi > v_{\phi\_\max} \qquad (16)$$

$$g_\phi > v_{\phi\_\max} k_{i\phi} + \frac{p_{\phi 11} v_{\phi\_\max} + |p_{\phi 12}|(m_\phi + \delta_\phi)}{p_{\phi 22}\eta M} \qquad (17)$$

$$m = v_{\phi\_\max} |p_{\phi 12}| (\eta M (k_{i\phi} v_{\phi\_\max} + g_\phi)) / G_\phi \qquad (18)$$

where $v_{\phi\_\max} = \phi_{d\_\max} / (M k_{i\phi})$ and $G_\phi = p_{\phi 22}\eta M (g_\phi - v_{\phi\_\max} k_{i\phi}) - p_{\phi 11} v_{\phi\_\max} - |p_{\phi 12}|(m_\phi + \delta_\phi)$.

Therefore, to implement speed and flux controllers on the induction machine, conditions (10) to (13) and (15) to (18) has to be satisfied. With these conditions in hand, an iterative algorithm method can be used to tune further the two controllers without affecting the stability of the system.

IV. SIMULATIONS AND RESULTS

To verify the proposed controller, the following tests are carried out and the performance of the Fuzzy-SMC-PI controller is compared with the performance of the SMC and PI conventional controllers acting alone. The induction motor being used in this simulation is a three phase 50HP squirrel-cage induction motor. The parameters of the motor are indicated in Table I. The Simulink model represents Fig. 3.

A. *Activating the Flux controller*

In this simulation, the speed reference signal is set to 120 rad/s and the flux reference signal is set at 0.96 Wb. First, the simulation is performed without any control for the flux and then the flux controller is activated. The response for the flux is shown in Fig. 4 while the speed response for the three controllers are shown in Figs. 5 and 6 for passive and active flux control respectively.

Control schemes with active flux controller outperform passive flux controller schemes in areas such as rise time, start time over-shoot and settling time. Among the six control schemes configurations, SMC strategy with active flux controller, outshines other scheme in the aspect of rise time and settling time. The proposed Fuzzy-SMC-PI was consistently second best in overall performance. In fact, it displays the least start time over-shoot among the six different configurations. However, with respect to steady state error, Fuzzy-SMC-PI illustrated the best performance over all controllers.

TABLE I. PARAMETERS OF THE INDUCTION MOTOR

Parameter	Value
L_r	4.6 mH
R_r	0.39 Ω
M	4 mH
N	2 (4 poles)
J	0.0226 kg.m2

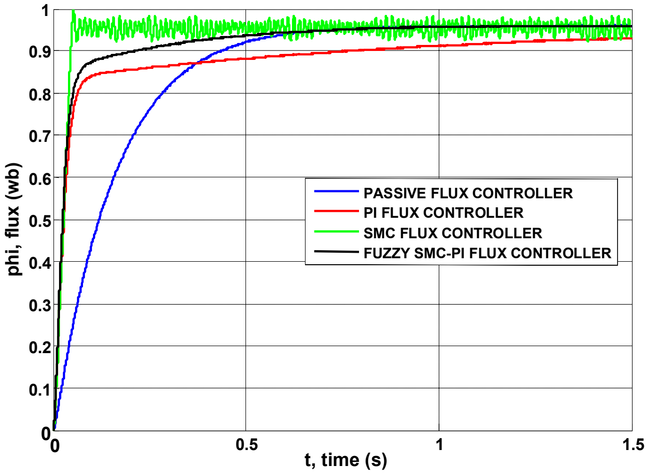

Figure 4. Passive and active flux control responses.

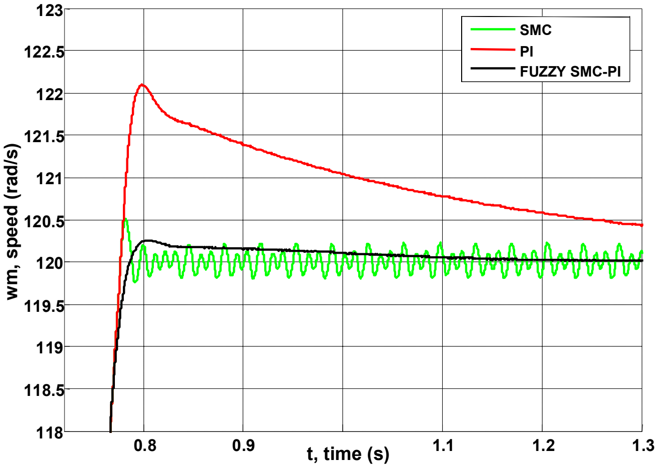

Figure 5. Speed response with passive flux control.

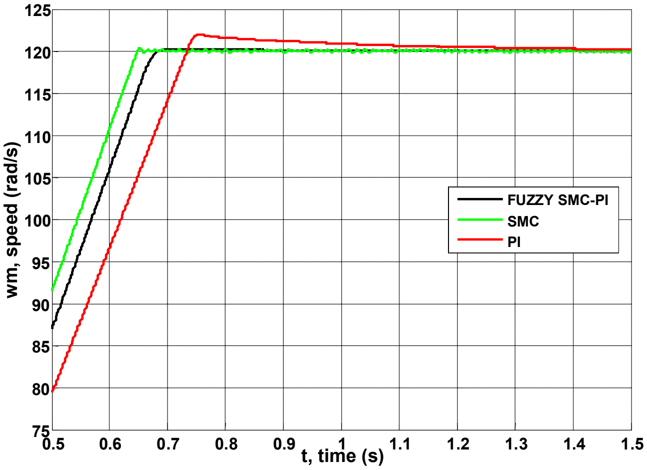

Figure 6. Speed response with active flux control.

B. *Load Torque disturbance response*

To check the disturbance rejection property of the proposed controller, a 500*Nm* load torque is applied to the shaft of the motor at *t* = 5*sec* and removed at *t* = 5.5*sec*. The results of the simulation are depicted in Fig. 7.

Under this perturbation of 500*Nm*, the SMC strategy outperforms Fuzzy-SMC-PI and PI strategies in the sense of speed of recovery. SMC strategy produced the least undershoots and overshoots. Under the SMC strategy, the speed is also restored fastest. However, as expected, the chattering phenomenon remains present in the SMC scheme.

In comparison with the PI controller, Fuzzy-SMC-PI strategy showed better response. It produced smaller undershoot. Also, there is virtually no overshoot by the Fuzzy-SMC-PI strategy unlike the PI strategy and the speed is restored relatively faster.

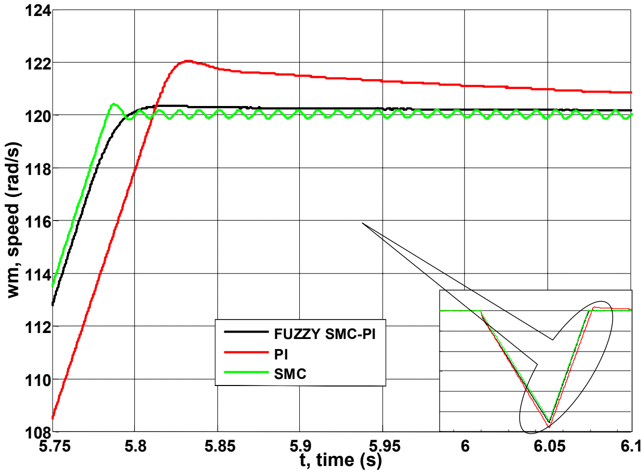

Figure 7. Speed response with applied 500 Nm Load Torque.

C. *Signal tracking*

Two different periodical reference signals are supplied to the system to verify the signal tracking property of the proposed controller. Fig. 8 shows the speed response for a sawtooth reference signal while Fig. 9 illustrates the speed response for a square wave reference signal.

It can be seen from the two figures that SMC control strategy exhibits the best overall tracking capability, while Fuzzy-SMC-PI outperformed PI strategy in tracking the given reference signal. In steady state area, SMC suffers from chattering that can be seen clearly from the figures.

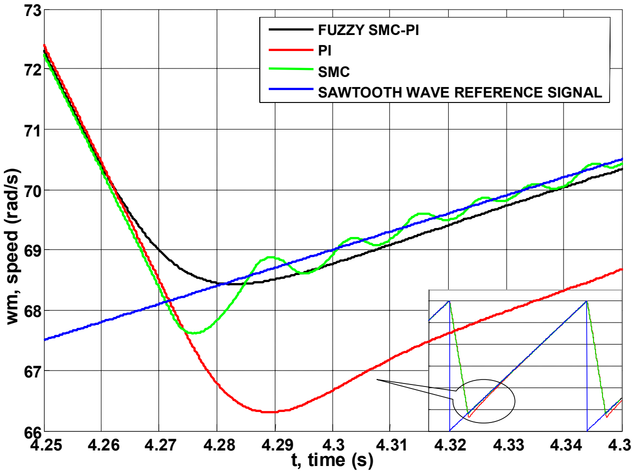

Figure 8. Speed response to a sawtooth reference signal.

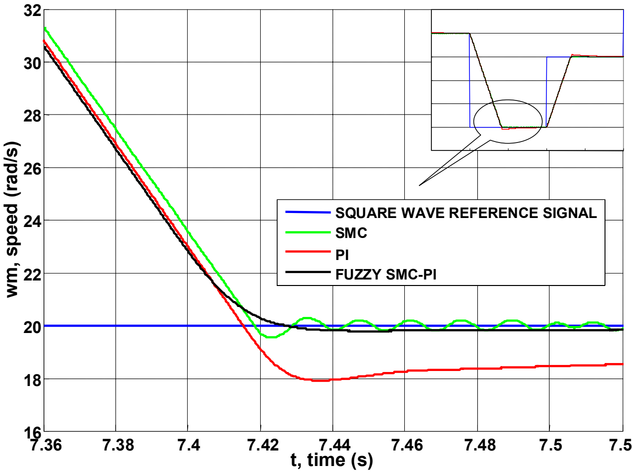

Figure 9. Speed response to a square reference signal.

V. CONCLUSION

This paper proposes a new design method to combine two controllers, PI and SMC, that posses high performances in different areas. SMC itself is a robust control strategy. However, due to the nature of its concept, it has an inherent chattering problem. This paper explores the use of fuzzy logic approach in combination with PI control strategy to remove chattering phenomena and retain the robustness of SMC control strategy. The proposed fuzzy controller is designed based on a Lyapunov stability function that both controllers share to achieve a stable controller.

The simulations are performed using the proposed Fuzzy-SMC-PI, SMC and PI schemes. Comparison is made with pure SMC or pure PI control strategies. The results indicate a promising future for the strategy. Depending on the tuning and the settings adopted, it is possible for the proposed Fuzzy-SMC-PI to have shorter rise time, faster recovery time and, minimum overshoot and undershoot. The benefits accrued to having active controller for flux is shorter rise time. In applications where there are lots of stops and starts operations such as robotic applications, it should contribute to smoother, more fluid motion and better responsive system.

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