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Sliding Mode Control Based V/F Speed Control of a Squirrel Cage Induction Motor

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Abstract

The scalar speed control of a 3-phase squirrel cage induction motor (3-phase SCIM) is one of the simple speed control techniques that can be employed for low-performance applications like air blowers, fans, pumps, …etc. The performance of (the V/F) method can be improved by employing robust control methods to improve the transient response and enhance system stability at various operating conditions for high-performance applications. In this paper, the speed of the 3-phase SCIM has been regulated by the exponential sliding mode control (E-SMC) method. The motor parameters are estimated based on the manufactured datasheet of a 10 hp 7.5 kW 3-phase SCIM made by "Mez Mohelnice Czechoslovakia". The result of speed control is compared with a traditional PI controller. The system is tested through several operating conditions like system startup, change in the speed set point during a constant load, change of load torque throughout a constant rotational speed, and system performance during flickers in the supply voltage. The proposed system is simulated by MATLAB SIMULINK. Overshoot and time to steady state in E-SMC is 0.16 % and 0.09 s respectively whereas with PI controller the results are 53.22 % and 0.52s respectively. The speed of the motor has been controlled for a range of 15-120 % of the supply frequency.

Keywords*:* Exponential, Control, PI**,** SCIM**,** SMC Speed, V/F

INTRODUCTION

Due to the development in power electronics, the adjustable speed of induction motor drives is improved to obtain smoothness for a wide variation of continuous speed [1]. For many years, induction motors had been employed in a wide range of domestic and industrial applications due to the robust design that enables them to work in various environments, durability, and high efficiency [2]. In the case of its supply, there are many types of induction motors either single-phase or three-phase. Single-phase types are used for low-power applications. Three-phase types are used for different kinds of applications with a higher level of power [3]. It is well known that the three-phase induction motors are either wound rotor or squirrel cage type. In many applications, the 3-phase squirrel cage induction motor (3-phase SCIM) would be the preferred selection of motors kinds since it does not require slip-rings, no windings in its rotor part, able to work in normal, dusty, or greasy environments [4]. If a 3-phase SCIM is connected to a three-phase main supply, it will rotate at its rated speed. If the motor is exposed to high or low loads, its mechanical speed will decrease or increase respectively [5]. But, in many applications, the speed of the 3-phase SCIM have to be adjusted according to the work requirements [6]-[7]. The motor speed can be controlled by scalar or vector techniques [8]. The scalar technique is done by changing the supply voltage and frequency linearly. This technique is simple, low cost provides a good response in steady-state operating conditions with constant torque. The main drawback is the low performance during transients and the performance of it is poor at low-speed regions, i.e. below 15 % of the motor-rated speed. [9]. Vector techniques are utilized with applications that require high performance accompanied by better accuracy. The demerit of this technique is the complexity and high cost of the practical implementation [10]. In this field, there are many researchers who tried to regulate the speed of the 3-phase SCIM through various controlling methods. H. M. D. Habbi, et al. [11] had controlled the speed of a 3-phase SCIM in scalar and Indirect Field oriented control (IFOC) by using a modified PI controller. The motor drive with IFOC provides decoupling components of the stator current which makes torque and flux. Kibok Lee et al. had presented a universal scalar flying restart strategy for induction machines [12]. This method search for the frequency for rotor speed estimation. Then, it applies the correct voltage and frequency to reduce the inrush current throughout the restart operation. The algorithm of the restart operation provides a controllable dynamic restart, independent of the induction motor parameters. A. S. Abdel-Khalik et al. had proposed a control scheme for an asymmetrical six-phase induction machine based on simple scalar V/f control by a parameter-independent post-fault [13]. It can provide the most common post-fault situations used in this field like minimum copper loss modes and equal stator copper loss. Furthermore, the controller can be used either in open-loop or closed-loop speed control modes effectively. A real-time sliding mode control (SMC) speed control of induction motor is made by A. Bennassar et al. [14]. The performance of the system is tested experimentally by employing the dSPACE1104 controller board in two layers to reduce the chattering effect. A. Datta and G. Poddar had proposed an improved method of control to drive medium-voltage induction motors by hybrid inverter [15]. The inverter is a three-level high-voltage inverter working in quasi-square-wave mode. A series connection of high-frequency Low-voltage H-bridge cells with the three-level inverter to eliminate harmonic voltages generated by the inverter. The inverter can work at constant current through a wide range of frequencies changing from 5 to 50 Hz. A method for performance estimation of 3-phase SCIM is made by L. A. Pereira et al. through using of stator voltages and currents measurements which are acquired throughout a no-load startup test and without acquisition of its speed [16]. The work is done via two steps which are parameter estimation of single cage rotor while considering the leakage inductances and rotor resistance variable with the slip. In the 2nd step, the motor performance during steady-state conditions is estimated through the estimated parameters of the motor equivalent circuit. The estimated performance has been compared with the measurements obtained via standardized laboratory tests. G. -J. Jo and J. -W. Choi had presented a rotor field-oriented drive implementation based on (V/F) technique [17]. An oscillation suppression compensator novel design and stability analysis are performed with the numerical analysis of the stability surface and root locus. M. A. Awdaa et al. [18] had made a comparative study between IFOC and V/F techniques for 10 hp 3- phase SCIM. For both techniques, the speed of the motor is regulated by a PI controller where a space vector PWM is used to generate pulses for the 3-phase inverter. Z. Yang et al. had proposed a combination of a bearing-less induction motor with a sensor-less control strategy and a sliding mode observer with a phase-locked loop [19]. In the 1st step, the observation equation of the rotor flux is established where the stator current, in addition to the rotor flux, are two state variables. In the 2nd step, a reduction of the rotor chatter and speed tracking performance enhancement and detecting module of electrical flux angle is made based on the phase-locked loop structure that extracts the rotor electrical flux angle and the rotor speed through the flux component observation. In most of the previous works, speed control of the three-phase induction motor has been made in many ways based on the (V/F) scalar technique. Few of them are either hybrid with the scalar technique or based on field-oriented control (vector technique). Many researchers either had to develop a special inverter or measuring technique to perform speed control operations. In this paper, a combination of a low-cost, simple (scalar) technique, with a robust control method which is exponential sliding mode control (E-SMC) is used to regulate the speed of 3-phase SCIM. The speed of the motor is regulated through various operating conditions. This paper is arranged as follows: an introduction, description of system mechanism, Speed control of 3-phase SCIM by V/F method, Speed control methods, Results and Discussion, and Conclusions.

Description of System Mechanism

The system basically consists of a 3-phase SCIM, 3-phase inverter, and a speed controller, as shown in Figure 1. It is well known that the inner construction of the 3-phase SCIM rotor does not contain windings. Instead of that, the rotor section consists of a short-circuit rings assembled and held altogether by several steel bars. When mains power is supplied to the motor, the motor will start to operate and accelerate till reaching its rated speed, which depends on the loading conditions of the motor [20]. Then, in order to adjust the motor speed, the voltage level and frequency of its supplied voltage should be increased or decreased through a proper linear relationship [21]. The speed of the 3-phase SCIM can be changed based on the value of its supply frequency proportionally. In the construction of the current system, the 3-phase SCIM gets its supplied voltage from a three-phase inverter. The inverter is supplied by DC voltage either from batteries or through a rectified AC voltage. This inverter consists of three legs. Each branch (leg) has only two switches, mostly IGBTs or MOSFETs. These six switches require appropriate pulse widths from the controller. The responsibility of the controller is to provide the required pulse width modulation (PWM) for each switching device in order to obtain the required voltage level and frequency at the inverter's output terminals. Various PWM methods can be utilized to obtain the desired three-phase sinusoidal voltage [22-23]. In this work, the sinusoidal PWM or (SPWM) technique is used for this purpose.

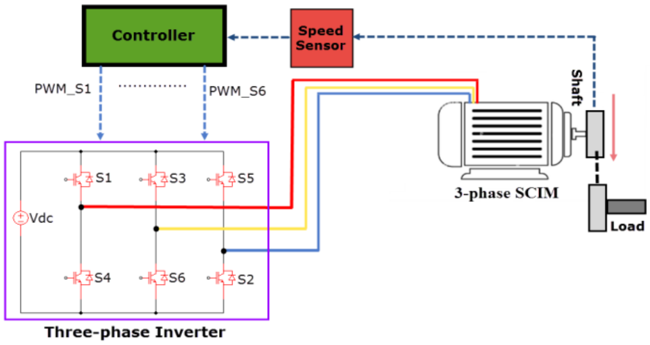

Figure 1 Speed control of 3-phase SCIM

1. Speed control of 3-phase SCIM by V/F method

By supplying the 3-phase SCIM with a three-phase source, it starts to rotate and then accelerate till the attainment of its rated speed. The rated speed of the 3-phase SCIM is less than its synchronous speed (n_s). The difference between $n_s$and the actual rotational speed of the motor (n_r) is denoted by slip (S) between its rotor and stator [24-25].

$$S = \frac{n_s - n_r}{n_s} \qquad (1)$$

$$n_s = \frac{120\,F}{P} \qquad (2)$$

Where F is the Supply frequency and P is the number of poles. In industrial and other applications, it is essential to regulate the motor speed according to a desired set-point. The 3-phase SCIM angular velocity (ω) is measured by:

$$\omega = \frac{2\pi n_r}{60} \qquad (3)$$

Speed control of the 3-phase SCIM is one of the essential requirements to prevent speed value decrease or increase due to an increase or decrease of the torque caused by a mechanical load on the motor shaft. Also, in a lot of industrial or electrical vehicle applications, it may be desirable to set the motor to rotate at a particular speed value. There are many ways to speed regulation of the 3-phase SCIM like changing its supply voltage level (V), changing its supply frequency (F), stator current control, and supply voltage and frequency control. To prevent air-gab saturation that may be caused due to the change in the frequency or stator voltage level individually, the speed of the motor can be regulated via a linear relationship by changing both the stator voltage level and frequency at the same time. This technique is known as (V/F) technique. The induced voltage in any magnetic circuit is proportional to the frequency and flux, the root mean square (RMS) of the value of air-gap flux is expressed by [26]:

$$V_a = k_m \omega \varphi \qquad (4)$$

or

$$\varphi = \frac{V_a}{k_m \omega} \qquad (5)$$

Where φ is the flux, V_a is the air-gap induced voltage, k_m is just a constant number and has relied on the amount of stator winding turns. From eq. (5), if the voltage level of the stator is reduced, the flux between stator and rotor (air-gap flux) and the torque T_e are decreased as well. Thus, by the (V/F) technique, the φ will be constant. If the stator voltage frequency is more than rated value, φ and T_e will decrease. In the case that the synchronous angular velocity analogous to the rated frequency value, it is referred as base speed ω_{base}, then at any other frequency, the angular synchronous speed ω_s at becomes:

$$\omega_s = \beta \ \omega_{base} \qquad (6)$$

Where β represents the ration between ω_s and ω_{base}. The maximum value of T_e becomes:

$$T_{e_{max}} = \frac{3}{2\ \omega_{base}(X_s + X_r')} \left(\frac{V_a}{\beta}\right)^2 \qquad (7)$$

Where the impedances X_s and X_r' are the stator rotor (referred to stator). The $T_{e_{max}}$ does not rely on frequency, and can be approximately become constant. Though, during high value of stator voltage frequency, the φ is decreased because the stator impedance drop. The voltage level of the stator section has to be increased to maintain the motor torque level [27]. The T_e/ω characteristics through (V/F) technique are shown in Figure 2.

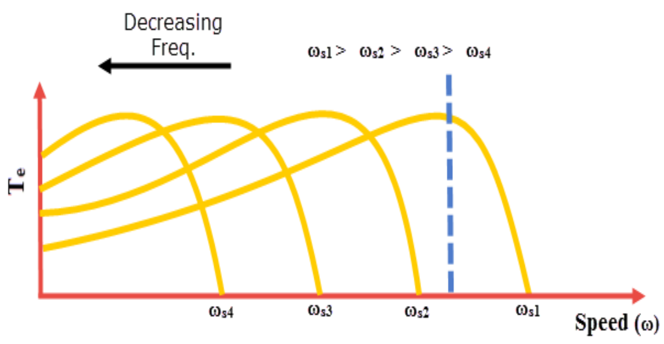

Figure 2 Speed /Torque characteristics of 3-phase SCIM by V/F technique

2. Speed control methods

It is desired to set the speed of the 3-phase SCIM at a specific set point. The aim of the controller is to reduce the error value (e) between the set point and the actual mechanical angular speed value (ω_m) where [28-29]:

$$e = set\ point - \omega_m \qquad (8)$$

Figure 3 shows the functional block diagram of how to control the speed of a 3-phase SCIM. A speed sensor takes the actual measurement of the motor speed ω_m. This value is compared with a set point to produce the e signal. The e is fed to a particular controller to reduce its value to zero, i.e. $\omega_m = set\ point$. The resulting control signal is divided into two signals to control the supply frequency and the stator voltage level through the modulation index value. In this paper, the modulation technique is sinusoidal pulse width modulation. There are six pulses are fed to each switching device of a three-phase inverter. The 3-phase SCIM is connected at the inverter terminals.

2.1 Speed control by Exponential sliding mode control

Basically, sliding mode control (SMC) is one of the most appropriate control methods for systems with variable structures [30]. It is one of the robust and nonlinear controllers. In the environment state-space control system, it can slide system state variables on a specific sliding surface. Many types of SMCs are invented and developed [30]. In this paper, the proposed control method of the 3-phase SCIM speed is by using exponential sliding mode control (E-SMC). In this method, the sliding surface is expressed by [31]:

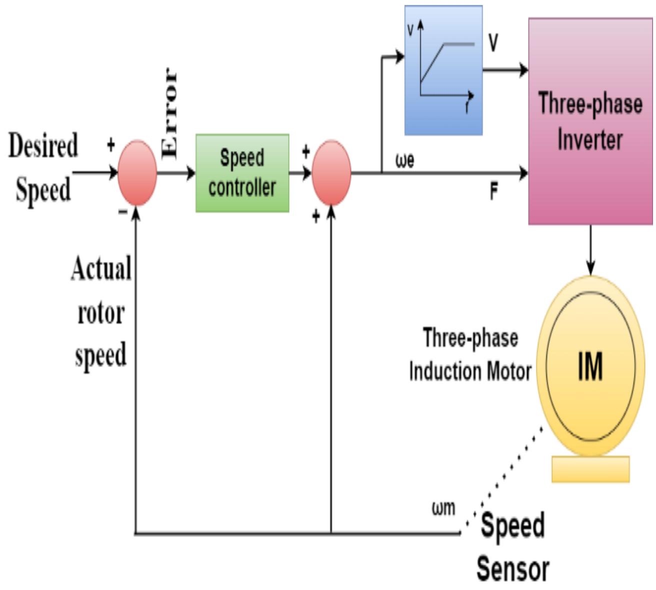

Figure 3 Block diagram of 3-phase SCIM speed control

$$\sigma = c\ e + \dot{e} \qquad (9)$$

where $c > 1$, The goal of SMC is to make σ reach zero. The reaching law (the controlling signal) is given by [32]:

$$u\ \frac{K}{N(\sigma)}\ sign(\sigma)\,, \qquad k > 0 \qquad (10)$$

and

$$N(\sigma) = \delta_0 + (1-\delta_0).e^{(-\alpha|\sigma|^p)} \quad (11)$$

where α is also strictly positive, p is positive integer, , and δ_0 is a strictly positive offset less than 1.

2.2 Speed control by Proportional – Integral (PI) controller

In this method, the e signal is forwarded to the PI controller. A controlling variable *u(t)* is generated and expressed mathematically by [33]:

$$u(t) = e(t) \times KP + \frac{KI}{TI} \int e(t)dt \quad (12)$$

where KI and KP are the integral and proportional gains of the PI controller. These gains can be set or tuned to get the required response of the system. In this paper, the performance of the motor speed control is compared between E-SMC and PI controller.

RESULTS AND DISCUSSION

The capacity of the 3-phase SCIM motor is 7.5 kW 10 hp based on the parameters taken from a manufactured datasheet of one motor with model number “132 M FECCL” of the “MEZ MOHELNICE CZECHOSLOVAKIA” company [34]. The manufactured data are listed in the Table 1. In “MATLAB SIMULINK” there is a parameters estimation tool equipped with the induction motor block [35-36]. By depending on the data in Table 1, then the estimated motor parameters are listed in the Table 2 which is for double cage SCIM. The speed of the motor is controlled by two methods which are the proposed E-SMC and compared with a traditional PI controller. To check the mechanism of speed control and system behavior, different simulation cases are made which are:

Table 1 Motor manufactured data (from datasheet)

Specifications	Data
Power	7500 W
Nominal Line-to-Line RMS voltage	400 V
Nominal Frequency	50 Hz
Nominal Full Load line current	15.4 A
Nominal Full Load mechanical torque	50.1 N.m.
Synchronous speed	1500 R.P.M.
Nominal full load (mechanical) speed	1430 R.P.M.
Starting current to nominal current ratio	6
Starting torque to full load torque ratio	2.1
Breakdown torque to nominal torque ratio	2.5
Nominal Power factor	0.84
Inertia	0.028 kg.m^2
Efficiency	85 %

Table 2 Estimated parameters of the motor

Parameter	Value
Nominal power	7500 W
Stator voltage	400 V
Frequency	50 Hz
Stator resistance	1.873 Ω
Stator Inductance	0.0007497 H
Cage1 resistance	0.7445 Ω
Cage 1 inductance	0.001003 H
Cage 2 resistance	4092 Ω
Cage 2 inductance	0.0007497 H
Mutual inductance	0.07493 H
No. of poles	4

1.System start-up

In this case, the desired speed set point is set at 1200 R.P.M and the motor is fully loaded as presented in figure (4). After the best tuning of the PI controller, the simulation results showed that the motor needed 0.85 s to reach the steady state case. Whereas in the case when Exponential SMC, only 0.09 s reaches the desired steady-state value. This means that there is a 0.76 s time span between the two controllers for the start-up condition. Also, the overshoot in speed value in the case of the PI controller is 14.15 % whereas its value in the case of E-SMC is 0.16 %. This means that E-SMC has a very fast response to get the steady-state condition with a very low overshoot percentage. Furthermore, there is 3.5 R.P.M steady state error of the actual motor speed when the PI controller is used, whereas in the case then the Exponential SMC this error is zero. The gains of the PI controller is 0.04 and 0.2 for KP and KI respectively.

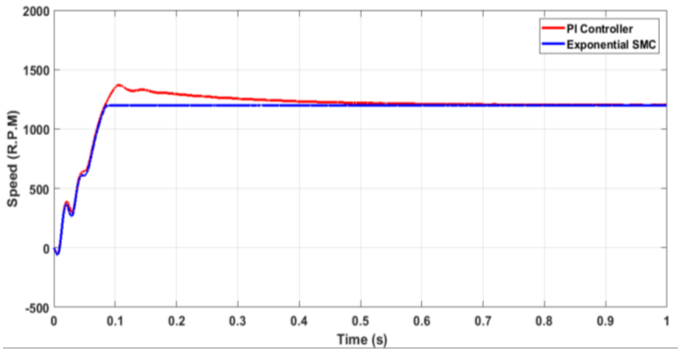

Figure 4 Speed of 3-phase SCIM at startup

For the E-SMC method, the system trajectory between the error (e) and change of error (Δe) are shown in figure 5. In this figure, it can be seen that the error value starts from 1200 till reaching the zero value when the desired speed is 1200 R.P.M. Δe generates high values but in phase with e to reach the steady state value. At steady state condition, both of e and Δe will have zero value.

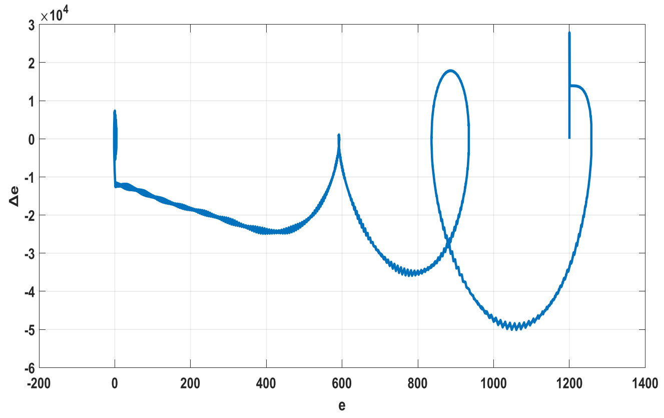

Figure 5 error versus change in error trajectory

One of the issues that most SMC methods suffer from is the "chattering effect". Due to the existence of a sign function with gives 1 if the value of the result is positive and -1 if the value of the result is negative. This will affect the controlling signal which in turn makes an unstable system while controlling the speed of the motor. So, there is one of the ways to reduce the chattering effect by replacing the sign function with the tan inverse or (tan^{-1}) function [37]. Because the (tan^{-1}) function takes a range of values above zero till +1 if the result is positive and a range of negative values less than zero till reaching -1 if the result is a negative value. Figure 6 shows the effect of chattering reduction if (tan^{-1}) is used instead of the sign function.

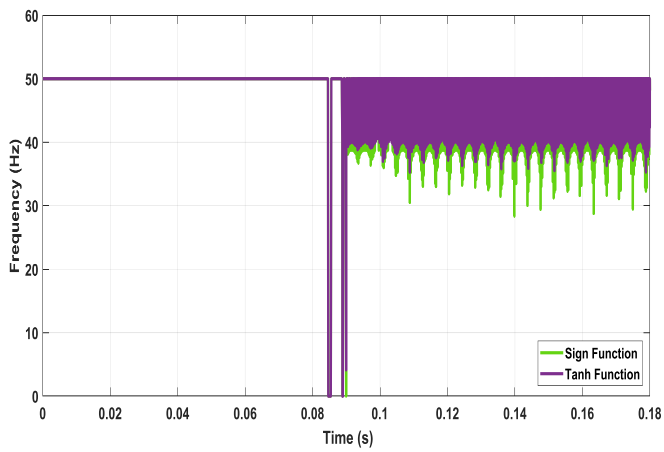

Figure 6 Chattering effect for frequency value

Since the speed of the motor is controlled via (V/F) technique, the estimated linear relationship can be obtained through making regression between the frequency and voltage for various values of them at different set points of the motor speed. Figure 7 shows the linear relationship of the 7.5 kW 3-phase SCIM by (V/F) technique. The estimated linear relationship is defined by the following equation where the correlation value between both of them is 0.9969 which is considered as strongly positively correlated.

$$Voltage = 4.9 + 7.53\,F \qquad (13)$$

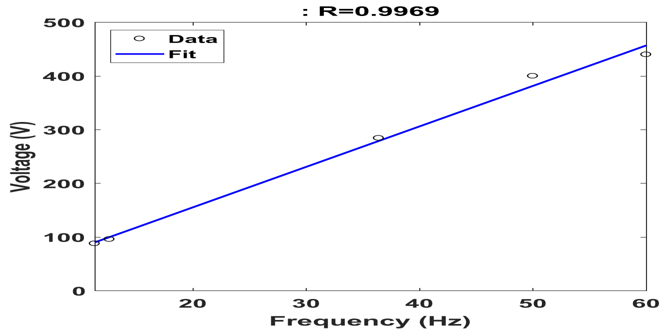

Figure 7 Linear regression relationship between voltage and frequency of the 7.5 kW 3-phase SCIM

2. Effect of speed change at full load

In this case, the motor is made at full load condition. The prior speed of the motor is set at 600 R.P.M. If simulation time exceeds one second, the set point is changed to 1300 R.P.M. If the PI controller is used, the motor need 0.26 s as a transient to reach the new steady state value as shown in figure (8). During this transient time, the T_e and stator current values are raised from their rated value to 170 N.m and 70.71 A respectively. At the end of the transient time, both T_e and stator current reach their steady-state value. In this figure, it can be noted the effect of (V/F) technique when the frequency of the stator current is increased while increasing the motor speed.

When E-SMC is used at the same operating condition of speed changing, the motor needs 0.07 s as a transient time to reach the new steady state value. During this transient time, T_e and stator current reach maximum values of 174 N.m. and 94.7 A respectively before returning to the new steady state condition as shown in Figure 9. The maximum values of T_e and stator current when E-SMC is used are higher than when the PI controller is used. This is due to the rapid change that happened to the motor speed during employing the E-SMC speed control method.

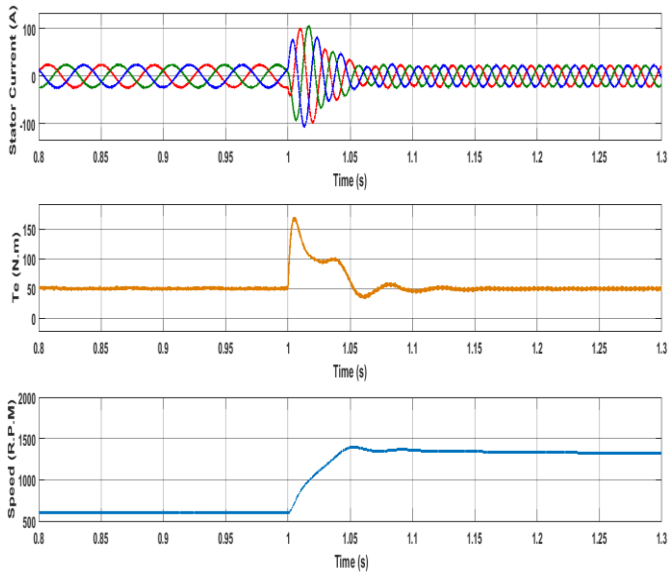

Figure 8 effect of speed Change when PI controller is used

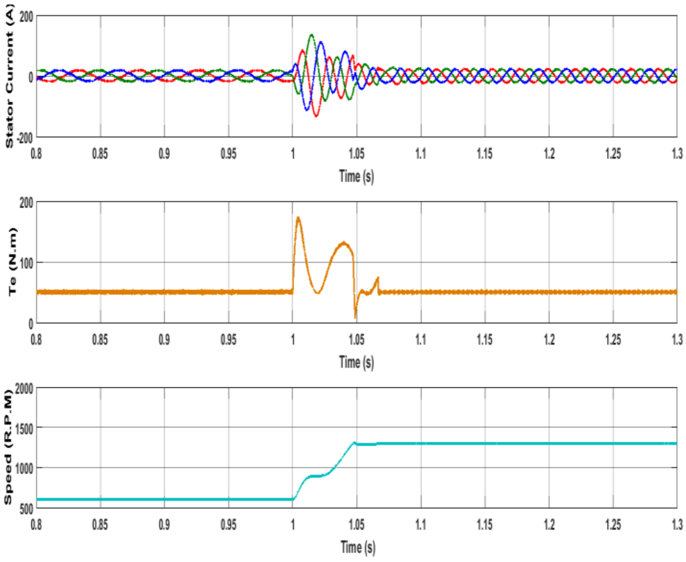

Figure 9 effect of speed Change when E-SMC controller is used

5.3 Effect of load change at constant speed

In this operating condition, the motor speed is fixed at 1300 R.P.M. The mechanical load is changed from the rated value to 25 N.m. i.e. half of the rated value. The load value is changed when simulation time is 0.7 s. When PI controllers is used, the transient time for speed value to return its steady state value is 0.16 s where the maximum change in speed value reaches 1425 R.P.M. as shown in Figure 10. The dip in T_e value during the transient time 14 N.m.

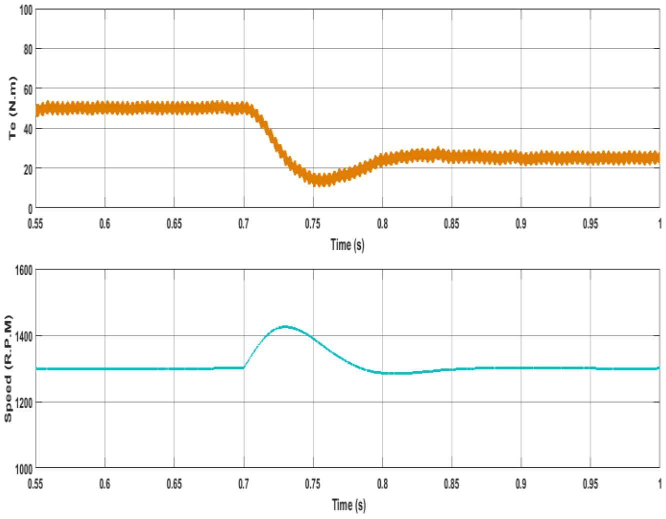

Figure 10 Effect of sudden load Change when E-SMC is used

When the E-SMC speed control method is used, the transient time for the speed value to return to its steady state value is 0 s which means no change in the motor speed value as shown in figure (11). The dip in T_e value during the transient time is 7 N.m. which is lower than the case when the PI controller is used due to the fast and instant change in the motor speed value during the transient time.

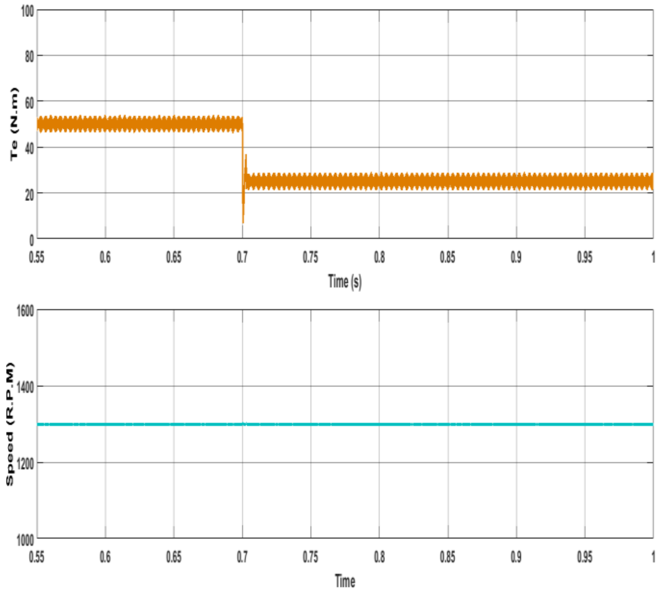

Figure 11 effect of sudden load Change when E-SMC is used

5.4 Effect of changes in the inverter DC voltage

The system is tested in one of the uncertainty occasions which is the voltage flicker and check the robustness against such condition. In this operating condition, the DC input voltage is changed from the rated value which is 566 V then flicks to (590 to 525) V in short period of time. If the PI controller is used, Figure (12) shows the fluctuations in speed and T_e values. Which means, for unstable power supply, the control of the motor speed may not be done properly. Figure (13) shows the results of speed and T_e if E-SMC is used. In this figure, it can be seen that during DC voltage flickering, there is none sensible or may be a slight change in the motor speed and T_e values. This means that the E-SMC can be considered one of the robust methods to control the speed of the 3-phase SCIM.

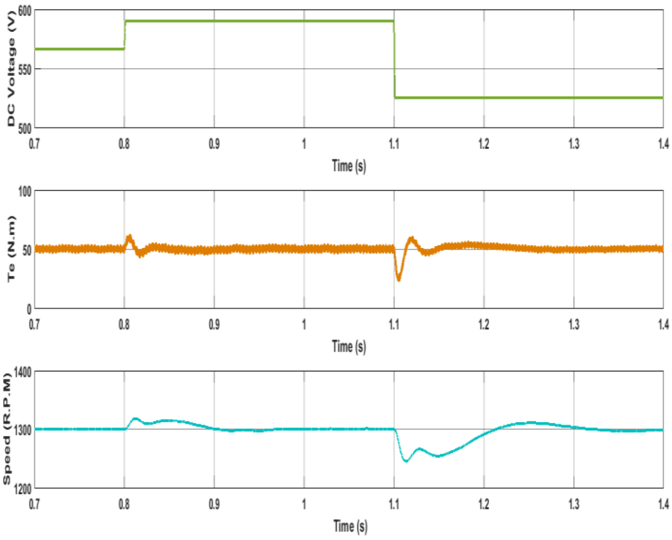

Figure 12 effect of variation in DC supply when PI controller is used

Table 3 represents a comparison among the most the works that implemented by V/F techniques that are mentioned in the literature review and the present work. The present work is the fastest among them with a high degree to overcome the uncertainty changes.

CONCLUSIONS

The V/f technique is used in this study to regulate the speed of a 3-phase 7.5 kW SCIM. The reference speed command is translated into the corresponding frequency. The used speed controllers are the PI controller and the E-SMC which are tested with various reference speed values, as well as different operating conditions. The results of a rapid and accurate performance of the E-SMC method are obtained and presented where its start-up response is faster by 0.43 s than the PI controller. Also, the system's robustness is also tested in different loads where the system takes 0s to return to its speed after sudden load application. The chattering effect is reduced in a great way to enhance system stability. Also, the utilization of the E-SMC method had regained the system to deal with the uncertainties with a linear speed regulation for 15-120 % at full load. The simulation results demonstrated excellent dynamic performance. The E-SMC control method is simple to implement and low-cost, and it can be used in a variety of industrial applications.

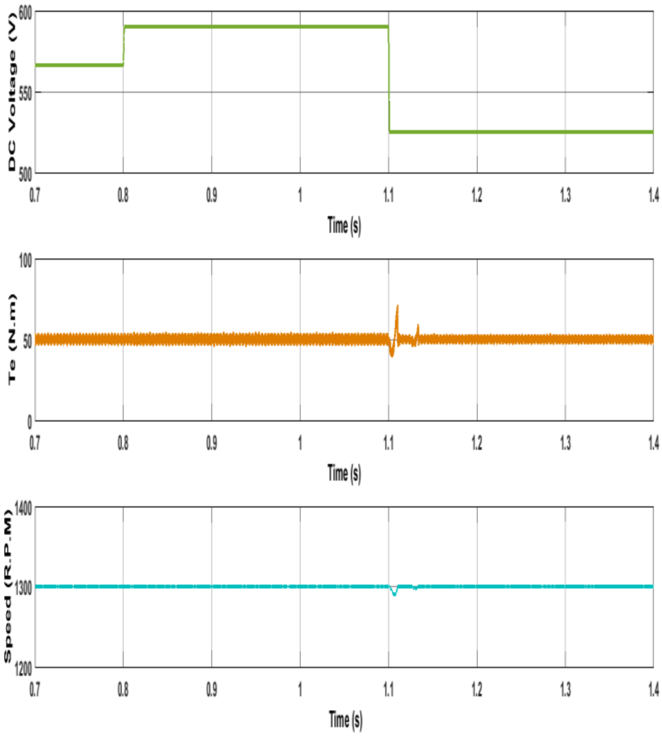

Figure 13 Effect of variation in DC supply when E-SMC is used Motor manufactured data

Table (3) Comparison of the present work with previous researches

Ref. No.	Motor Type	Controlling method	Response to speed change	Response for uncertainties
[11]	3-phase SCIM	PI	High overshoot	Not specified
[12]	3-phase SCIM	Integrator	Slow response	Not specified
[13]	3-phase IM	PR	Slow response	Not specified
[14]	3-phase SCIM	Special Algorithm	Good response	Not specified
[15]	3-phase SCIM	Special Algorithm	Low THD	Not specified
[18]	3-phase SCIM	PI	High overshoot	Not specified
Proposed work	3-phase SCIM	E-SMC	Rapid Response with low chattering effect	Rigid and stable for uncertainties

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