Journal of
Engineering Sciences
Faculty of Engineering
Assiut University
JES
مجلة
العلوم الهندسية
كلية الهندسة
جامعة أسيوط
journal homepage: http://jesaun.journals.ekb.eg

New Improved Nonsingular Fast Terminal Sliding Mode Control (NFTSMC) for Current Control of Three Phase Induction Motor

Received 25 July 2024; Revised 30 November 2024; Accepted 30 November 2024

Ashraf Hagras[1]
Ahmed Alaa Mahfouz[2]

Keywords
Nonsingular Fast Terminal Sliding Mode Control (NFTSMC); Three Phase Induction Motor (TPIM); current control; hysteresis controller.

Abstract: This paper proposes new improved Nonsingular Fast Terminal Sliding Mode Control (NFTSMC) technique for current control of Three Phase Induction Motor (TPIM). This technique adds more advantages to the conventional terminal sliding mode control theory to speed and smooth the torque and speed response under varying conditions. The proposed new improved nonsingular fast terminal sliding mode control technique overcomes the traditional demerits of Terminal Sliding Mode Control (TSMC) theory like the limited values of its constraints and its state differentiation and avoids the complexity of its following versions. This supports the simplicity of controller design and its easy adaptability to achieve its targets. The stability of the proposed method was analyzed and guaranteed using Lypunov stability theory. Therefore, this technique was compared with nonlinear hysteresis controller using MATLAB/SIMULINK to validate its design and show its faster starting torque, speed response, with small torque effect at step load change compared to the hysteresis controller and for constant flux operation at different inertia. Besides that, it offers strong robust performance against electrical, mechanical parameters uncertainties and external load disturbances.

1. Introduction

Three phase induction motor has very complex dynamics due to the coupling between their model equations. These couplings imposed complex nonlinearities. Therefore, it can’t be controlled easily with fixed gains PI and PID controllers especially under special conditions. These conditions range from motor parameters changes under the effect of temperature changes, sudden changes of applied loads and speed requirements due to the different industrial applications. Advanced nonlinear control like backstepping and sliding mode control was motivated to be the popular methods to conquer these nonlinearities and compensate the motor control errors under the effect of its parameters’ uncertainties due to temperature effects and step load disturbances [1-4]. But, SMC was be the best method to

[1]Assist. Prof., Dept. of Engineering and Scientific Apparatus, Egyptian Atomic Energy Authority, Egypt. ashrafa1973@yahoo.com
[2] Professor, Department of Electrical Power and Machines, Cairo University, Egypt. aelkousy@yahoo.com

https://doi.org/10.21608/jesaun.2024.307104.1357

control the highly nonlinear and strong coupling machines and systems because of fast response, high accuracy, free of complexities of calculations, and model errors, fast convergent time and strong robust performance against parameters uncertainties under large ranges [5]. Also, in [6, 15]; Adaptive TSMC proved superior transient and steady state performance compared to adaptive backstepping SMC and adaptive integral backstepping SMC.

However, Nonsingular Terminal SMC had fast convergence time besides chattering free compared to other types of SMC [7- 9]. In [5], the terminal sliding mode surface consists of linear sliding mode part and another nonlinear sliding mode part to converge more quickly to the equilibrium point in more accurate manner. The authors of [10] used TSMC to provide the reference for predictive controller to make it more robust and decrease the torque oscillations. In [11-12] the fast terminal sliding mode controller required adaptive law or adaptive barrier function to compensate the effect of disturbances upper bounds while [13] added integral terminal SMC law to the main integral type SMC to solve the problem of unknown disturbance and uncertainties bounds. Ref. [14] used design of two approaches; TSMC and Active Disturbance Rejection Control (ADRC) using extended state observer to strengthen the robustness of the system against model uncertainties of unknown bounds and disturbances. While [15] used the terminal SMC as the equivalent control in the total control and super twisting algorithm with adaptive gains as the discontinuous control in the total control to decrease the convergence time and optimize the steady state and transient performance of all its terms for Wind Energy Conversion System (WECS) besides Low Voltage Ride Through (LVRT) capability. Therefore, although the main control in the previous literature was TSMC and it was supported by adaptive law, another function or algorithm, our paper didn’t have these functions or algorithms to give more simple control law free of complexities to reduce the computational burden of the processor.

Since the observer design was spread to compensate any external disturbances, mismatched parameters changes or unmodeled dynamics and due to the advantages of TSMC; fast convergence, accurate tracking and maintaining the system on the sliding surface without oscillations, it was designed to build load torque observer in [17] to add advantages like fast transient response and accurate tracking of the sliding surface to the traditional PI controller. So, Ref. [18] designed the disturbance observer based on Adaptive TSMC to compensate any unknown disturbance, its bounds or mismatched parameters changes. While Ref. [19-21] designed TSMC based extended state observer or disturbance observer to compensate all disturbances whether external, due to the internal process, estimating the system states or permit to decrease the gain of the switching control.

Not only TSMC was used for observer design or the main control for highly nonlinear systems, but it was developed to overcome the demerits of traditional TSMC and its versions. In Ref. [22], the sliding mode surface doesn’t include only the differentiation of the error but also, the switching control include the integral of the sign function which made the system free chattering and the gain of the switching control include the bounds of the differentiation to compensate all types of disturbances. Ref. [23] present continuous TSMC by inserting sign function of the error and another function of the error differentiated resulting in a new proposed sliding mode surface and new continuous TSMC which can compensate unknown effects under various operating conditions. Ref. [24] proposed new second order sliding mode control by proposing new second order sliding mode surface which speeded and smoothed the transient response. While [25] designed new full order terminal sliding mode control characterized by bi-limit homogeneous property to obtain fast transient response resulting in new continuous terminal sliding mode control which made the system more stable. Therefore, TSMC theory was developed or changed in effective manner to add more advantages to adopt with the new plant dynamics but at the expense of added complicated laws.

As shown in the previous literature, TSMC was supported with additional algorithms or functions [17-21] or its theory was developed [22-25] but in our paper the theory became free of any constraints or complexities like additional functions or complicated laws. Therefore, the TSMC theory was applied in this paper in simple and new form based on simple error of the *d-q* currents. It achieved the targets of compensating external disturbance, motor parameters uncertainties in addition to regulating the speed and torque with ripples minimization and smooth response because it attains its power fast reaching inherited in the sliding surface without limited constraints and eliminated the differentiation of the error.

The major contribution of this paper is as follows:

1) Novel design of new improved Nonsingular Fast Terminal Sliding Mode Control (NFTSMC) technique for current control of three phase induction motor.
2) Fast convergent time, fast reaching phase and faster transient response compared to hysteresis controller because it is based on simple form of TSMC theory without developments [22-25] and is free of the constraints of the conventional theory.
3) Control laws are free of complexities of calculations [5], another law or function [11, 12, 17-21] or another algorithm or strategy [13-15] which reduce the computation burden of the processor.

The paper was organized as follows: The Three Phase Induction Motor (TPIM) was modeled in section 2. Design of the NFTSMC and its stability proof was introduced in section 3 and 4. The simulation results were given in section 5 and conclusions were drawn in section 6.

2. Mathematical Modeling of Three Phase Induction Motor

The three-phase induction motor can be modeled using the following equations in the synchronous reference frame:

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \quad (2)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_{slip}\psi_{qr} \tag{3}$$

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_{slip}\psi_{dr} \tag{4}$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \quad , \psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{5}$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \quad , \psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{6}$$

V_{ds} and V_{qs} are the *d*- and *q*- components of stator voltage, V_{dr} and V_{qr} are the *d* and *q*- components of rotor voltage, ψ_{ds} *and* ψ_{qs} are the *d*- and *q*- components of stator flux linkage, ψ_{dr} *and* ψ_{qr} are the *d*- and *q*- components of rotor flux linkage, i_{dr} *and* i_{qr} *are* the *d*- and *q*- components of rotor current, i_{ds} *and* i_{qs} *are* the *d*- and *q*- components of stator current, ω_e, ω_r and ($\omega_{slip}= \omega_e-\omega_r$) are the synchronous rotating frequency, the electrical rotor speed and the slip speed respectively. R_s, R_r, L_s and L_r are the stator phase resistance, rotor phase resistance, stator phase inductance and rotor phase inductance respectively.

Setting the synchronous reference frame in the rotor reference frame and the rotor field aligned with the *d*-axis, i.e.

$$\psi_{qr} = 0 \; and \; \dot{\psi}_{qr} = 0 \tag{7}$$

Setting $V_{dr} = V_{qr} = 0$ and manipulating Eqs. (1-6) results the following control equations of the stator voltage in the *d* and *q* axis:

$$V_{ds} = \sigma L_s \frac{d}{dt} i_{ds} + i_{ds}\left[R_s + R_r \frac{L_m^2}{L_r^2}\right] - \omega_e i_{qs} - R_r \frac{L_m}{L_r^2}\psi_{dr} - \omega_r \frac{L_m}{L_r}\psi_{qr} \tag{8}$$

$$V_{qs} = \sigma L_s \frac{d}{dt} i_{qs} + i_{qs}\left[R_s + R_r \frac{L_m^2}{L_r^2}\right] + \omega_e i_{ds} + \omega_r \frac{L_m}{L_r}\psi_{dr} - R_r \frac{L_m}{L_r^2}\psi_{qr} \tag{9}$$

Taking care of the conditions of field orientation control and manipulating Eqs. (3) and (5) results: $\dot{\psi}_{dr} = -\frac{R_r}{L_r}\psi_{dr} + \frac{R_r L_m}{L_r} i_{ds}$, for steady state operation $\dot{\psi}_{dr} = 0$ results:

$$\psi_{dr} = L_m i_{ds} \tag{10}$$

The electromagnetic torque can be obtained as follows:

$$T_e = \frac{3P}{4}\frac{L_m}{L_r}\psi_{dr}, \text{therefore } i_{qs}^{ref} = \frac{4P}{3}\frac{L_r}{L_m}\frac{T_e}{\psi_{dr}} \tag{11}$$

Manipulating Eqs. (4) and (6) results:

$$\omega_{slip} = \frac{4P}{3}\frac{L_m}{\tau_r}\frac{i_{qs}}{\psi_{dr}} = \omega_e - \omega_r \quad , where \; \tau_r = \frac{L_r}{R_r} \tag{12}$$

Therefore, $i_{ds}^* , i_{qs}^* \; and \; \theta_e$ can be calculated as expressed in Eqs. (10), (11) and (12). Fig. 1 shows the block diagram of conventional vector control of three phase induction motor. The hysteresis controller was implemented in *a-b-c* frame while the NFTSMC was implemented in the *d-q* frame as shown in Fig. 2.

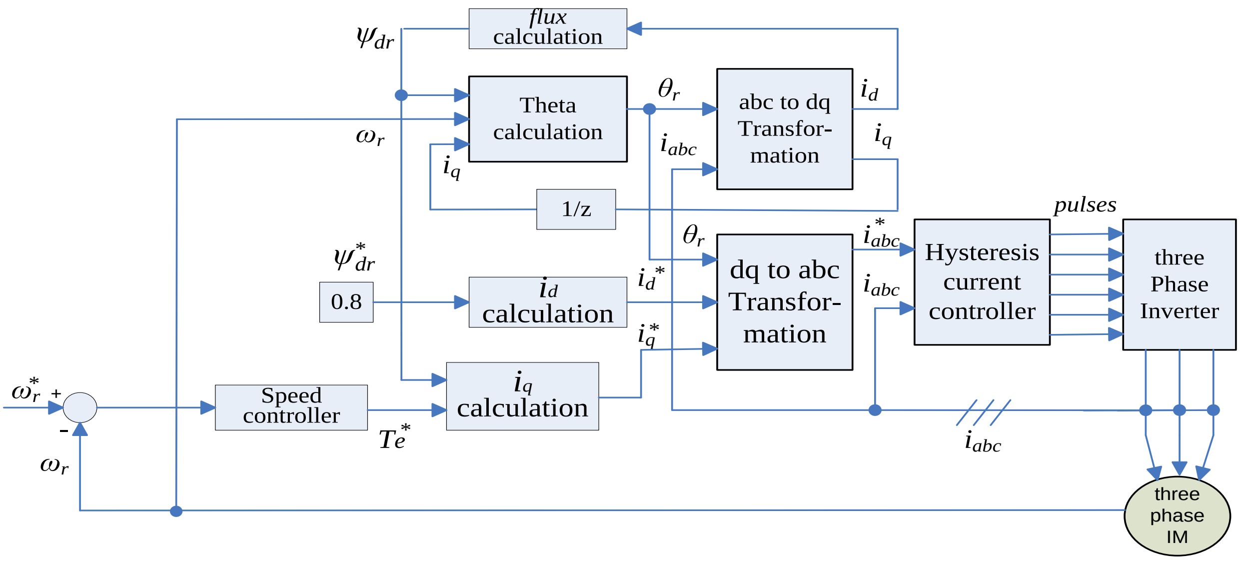

Fig. 1 Block diagram of the conventional Hysteresis Controller (HC) based vector control of IM

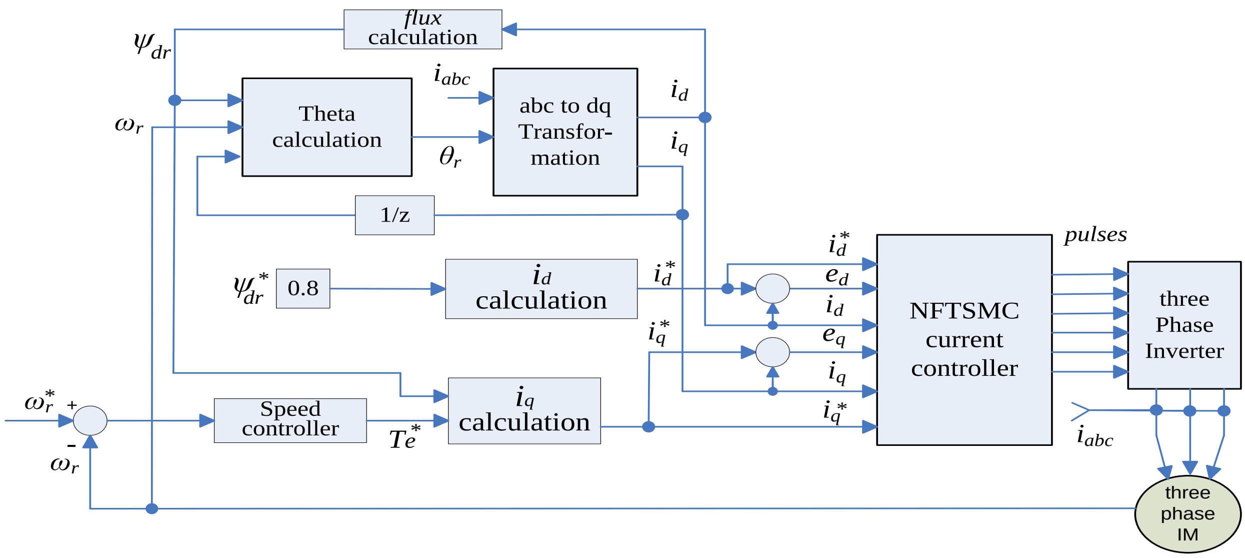

Fig. 2 Block diagram of the new improved NFTSMC based vector control of IM

3. Design of the proposed New Improved Nonsingular Fast Terminal Sliding Mode Current Controller (NFTSMCC)

Using Eq. (8), the error of the *d*-axis stator current can be expressed as follows:

$$e_d = i_{ds}^* - i_{ds}$$

Then, the error can be differentiated as follows:

$$\dot{e}_d = \dot{i}_{ds}^* - \dot{i}_{ds} = \dot{i}_{ds}^* - \frac{d}{dt} i_{ds}$$

$$= \dot{i}_{ds}^* - V_{ds}/\sigma L_s + (i_{ds}/\sigma L_s)\left[R_s + R_r \frac{L_m^2}{L_r^2}\right] - \omega_e i_{qs} - R_r \frac{L_m}{\sigma L_s L_r^2} \psi_{dr}$$

$$\dot{e}_d = \dot{i}_{ds}^* - V_{ds}/\sigma L_s + a i_{ds} - \omega_e i_{qs} - b\psi_{dr} \tag{13}$$

With the same way, the error of the q-axis stator current can be obtained:

$$\dot{e}_q = \dot{i}^*_{qs} - \dot{i}_{qs} = \dot{i}^*_{qs} - \frac{d}{dt} i_{qs}$$

$$= i^*_{qs} - V_{qs}/\sigma L_s + (i_{qs}/\sigma L_s)\left[R_s + R_r \frac{L_m^2}{L_r^2}\right] + \omega_e i_{ds} + \omega_r \frac{L_m}{\sigma L_s L_r} \psi_{dr}$$

$$\dot{e}_q = i^*_{qs} - V_{qs}/\sigma L_s + a i_{qs} + \omega_e i_{ds} + c\psi_{dr} \quad (14)$$

Where $= (1/\sigma L_s)\left[R_s + R_r \frac{L_m^2}{L_r^2}\right]$, $b = R_r \frac{L_m}{\sigma L_s L_r^2}$, $c = \omega_r \frac{L_m}{\sigma L_s L_r}$

Taking into account the uncertainties of parameters and time varying parameters, the eqs. (13) and (14) become:

$$\dot{e}_d = i^*_{ds} - V_{ds}/\sigma L_s + (a + \Delta a) i_{ds} - \omega_e i_{qs} - (b + \Delta b)\psi_{dr}$$

$$\dot{e}_d = i^*_{ds} - V_{ds}/\sigma L_s + a i_{ds} - \omega_e i_{qs} - b\psi_{dr} + \sigma_1(t) \quad (15)$$

$$\dot{e}_q = i^*_{qs} - V_{qs}/\sigma L_s + (a + \Delta a) i_{qs} + \omega_e i_{ds} + (c + \Delta c)\psi_{dr}$$

$$\dot{e}_q = i^*_{qs} - V_{qs}/\sigma L_s + a i_{qs} + \omega_e i_{ds} + c\psi_{dr} + \sigma_2(t) \quad (16)$$

Where $\sigma_1(t) = \Delta a i_{ds} + \Delta b \psi_{dr}$ and $\sigma_2(t) = \Delta a i_{qs} + \Delta c \psi_{dr}$

Proposing the new improved Nonsingular Fast Terminal Sliding Mode Control (NTSMC) surface as follows [26]:

$$S = x_1 + \int x_2^{(\frac{p}{q}+1)}$$ Where p and q are any value between 1 and 2 (16)

Differentiating the sliding mode surface:

$$\dot{S} = \dot{e} + e^{p/q}$$

Let x_1=e and replacing it in the above equations; the differential errors of the d and q-axis in Eqs ((1٥)-(1٦)) results: In the two axis; d-axis and q-axis, the d-axis error will converge to the zero state quickly with the following conventional switching law:

$$\dot{S}_d = \dot{e}_d + e_d^{p/q} = -Ksign\,(e_d)$$

$$\dot{S}_q = \dot{e}_q + e_q^{p/q} = -Ksign\,(e_q)$$

$$\dot{S} = \dot{e}_d + e_d^{p/q} = i^*_{ds} - \frac{V_{ds}}{\sigma L_s + a i_{ds}} - \omega_e i_{qs} - b\psi_{dr} + e_d^{\frac{p}{q}} = -Ksign\,(e) \quad (18)$$

In order to make the system converges to the desired state in a finite time and maintaining the system on it without oscillations, the following condition should be verified:

$$\dot{S} = \dot{e}_d + e_d^{p/q} = -Ksign\,(e_d) = 0$$

Then, the control inputs can be expressed as:

$$V_{ds-c} = \sigma L_s (i^*_{ds} + a i_{ds} - \omega_e i_{qs} - b\psi_{dr} + e_d^{\frac{p}{q}} + Ksign\,(e_d)) \quad (19)$$

$$V_{qs-c} = \sigma L_s(i_{qs}^{*} + a i_{qs} + \omega_e i_{ds} + c\psi_{dr} + e_q^{\frac{p}{q}} + Ksign\left(e_q\right)) \quad (20)$$

4. Stability Analysis

Lyapunov theory has two conditions to verify the proposed sliding mode control technique. The first condition guarantees the system will be maintained on the sliding mode surface regardless of uncertainties and external disturbances. Therefore, the equivalent control will support that by setting the first condition, $\dot{S} = S = 0$ as obtained from Eq. (18).
The second condition should verify the reaching condition of the proposed control law, therefore the Lyapunov candidate chosen as follows:
Choosing the Lypunov function as follows:

$$V = (1/2)S^2$$

Differentiating the Lypunov function as follows:

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

Substituting Eqs. (17) and (18) results:

$$\dot{V} = S\dot{S} = S\left(i_{ds}^{*} - V_{ds}\left(\frac{1}{\sigma L_s}\right) + a i_{ds} - \omega_e i_{qs} - b\psi_{dr} + \sigma_1(t) + e_d^{\frac{p}{q}}\right) = S(-Ksign(e_d)) < 0$$

Therefore, if $K > 0$, the reaching condition will be verified and ensures the stability of the closed loop system.

5. Simulation Results

The robust performance of the proposed method, its design and stability were validated by implementing it through MATLAB Package (2018). The simulation results proved the strong robust performance of the proposed new improved NFTSMC against step load change, step speed change, long range of parameters uncertainties and faster speed and torque transient response. The hysteresis controller has nonlinear structure, simple implementation and design, no multiple gains and doesn't need fine tuning resulting in faster response.
Therefore, these advantages compared to the efficient nonlinear hysteresis controller were highlighted through the following comparisons which done during four conditions as follows:

1- Normal operation
2- Uncertain stator parameters (100%) operation
3- Uncertain stator parameters (-75%) operation
4- Uncertain moment of inertia (200%) operation

The parameters of TPIM are as follows: R_s=1.287 ohm, L_s=0.8e-3 H, R_r=1.228 ohm, L_r=3.8e-3 H, J=0.162 Kg.m^2, B=0001 N.m.s and P=2. Fig. 3 shows the block diagram of the proposed system using MATLAB and Fig. 4 shows the block diagram of the proposed NFTSMC using MATLAB.

5.1 Normal steady state operation

Fig. 5 shows the steady state operation of three phase induction motor using the proposed method under step change of torque at t= 1s and step speed change at t= 1.5s during normal operation. As shown in this figure, the speed reaches its reference (100r/s) in less than (0.2٢ s) and changes smoothly and fast to another reference value (120 r/s). The step speed change has small torque effect (53 N.m). The load torque recovers to the steady state (30 N.m) in about 0.2s.

Fig. 6 shows the steady state operation of three phase induction motor using the hysteresis method under step change of torque at t= 1s and step speed change at t= 1.5s. As shown, the speed reaches its reference (100 r/s) in less than (0.18 s) and changes smoothly to another reference value (120 r/s). The step speed change has large torque effect (about 140 N.m) compared to the proposed improved NFTSMC (53 N.m) as shown in Fig. 5. But, the load torque recovers to the steady state (30 N.m) after 0.05s.

Therefore, the proposed method has strong robust performance against step speed change with small torque effect compared to the conventional hysteresis method. The two methods have robust speed performance against step load change and faster response but the hysteresis method is little faster in this case.

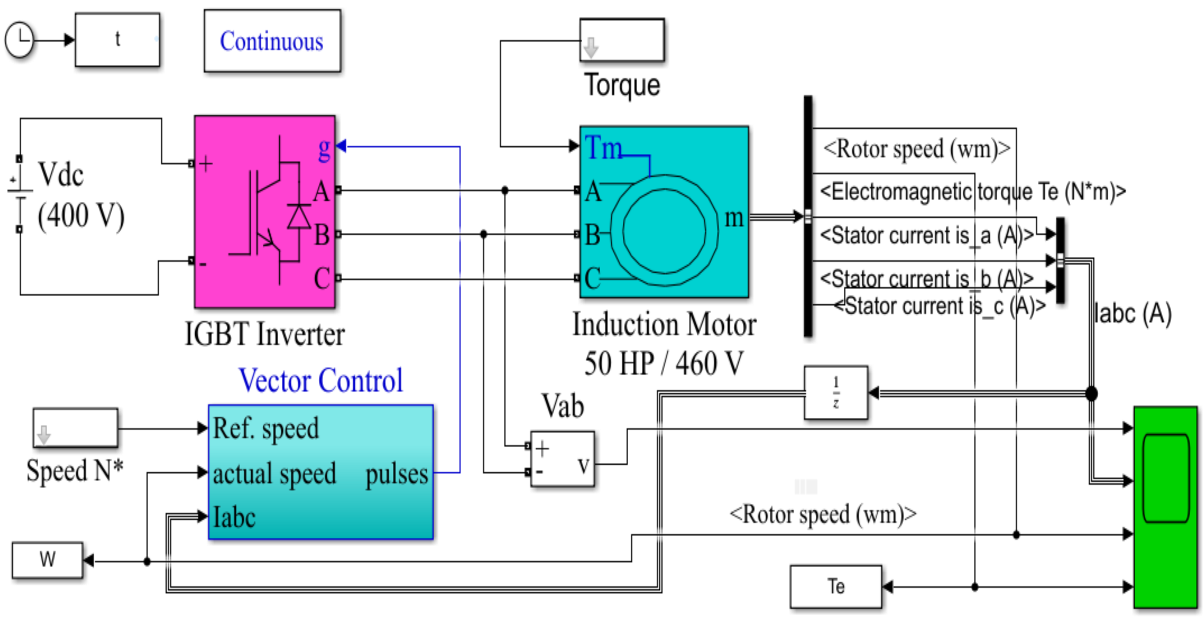

Fig. 3 The block diagram of the proposed system using MATLAB

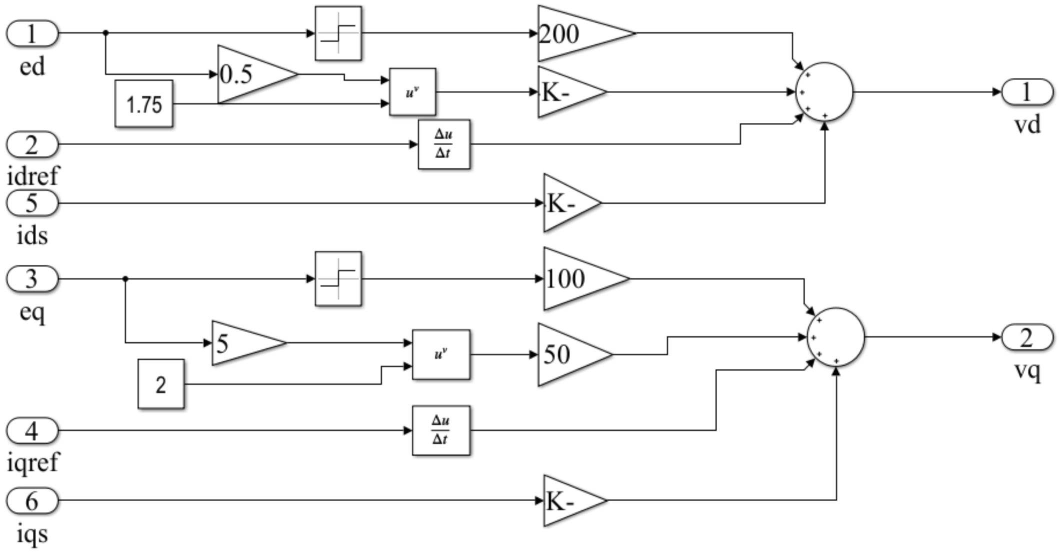

Fig. 4 The block diagram of the proposed NFTSMC using MATLAB

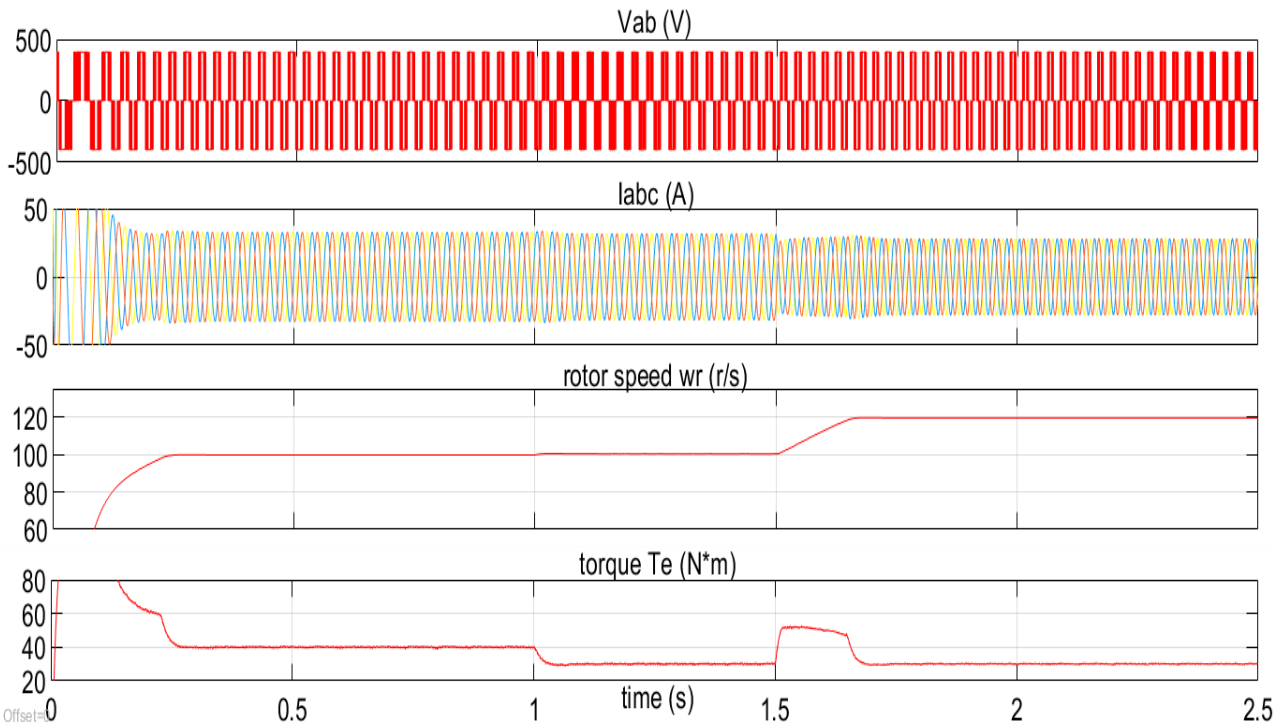

Fig. 5 The normal operation of the proposed new improved NFTSMC method

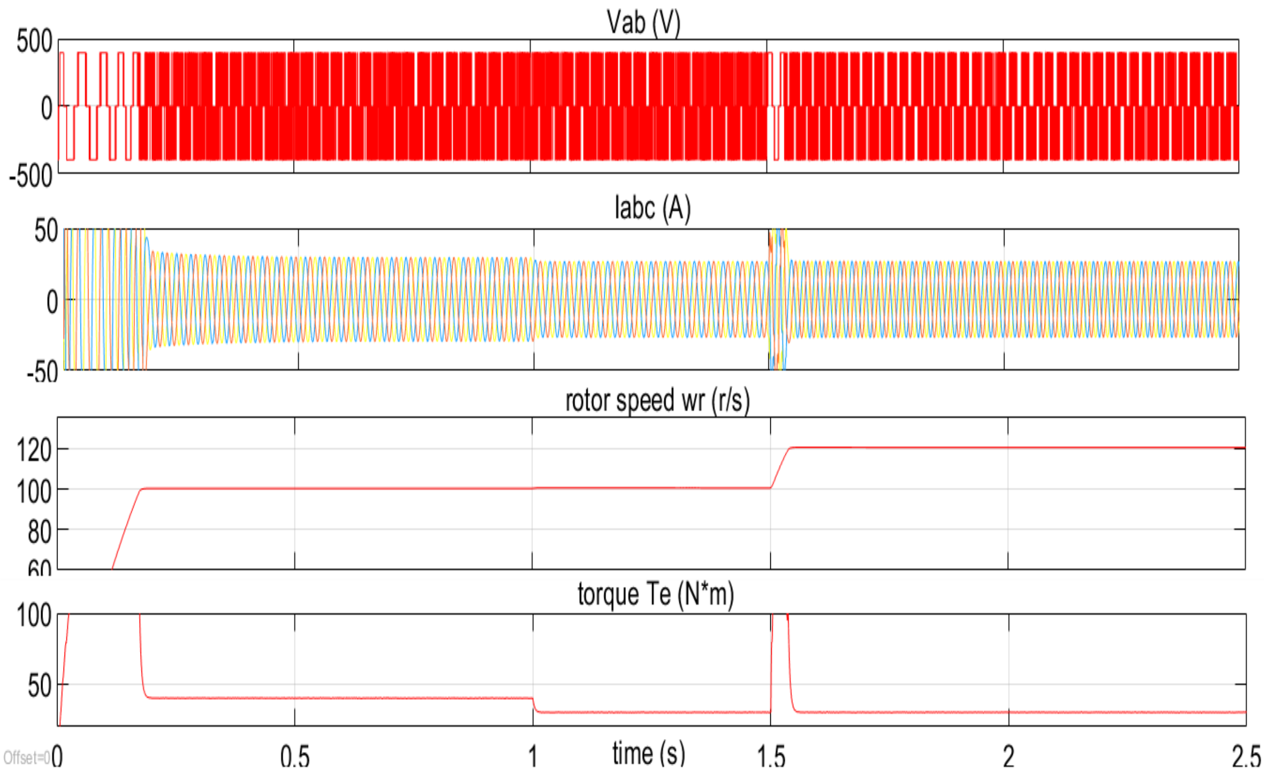

Fig. 6 The normal steady state operation of the conventional hysteresis method

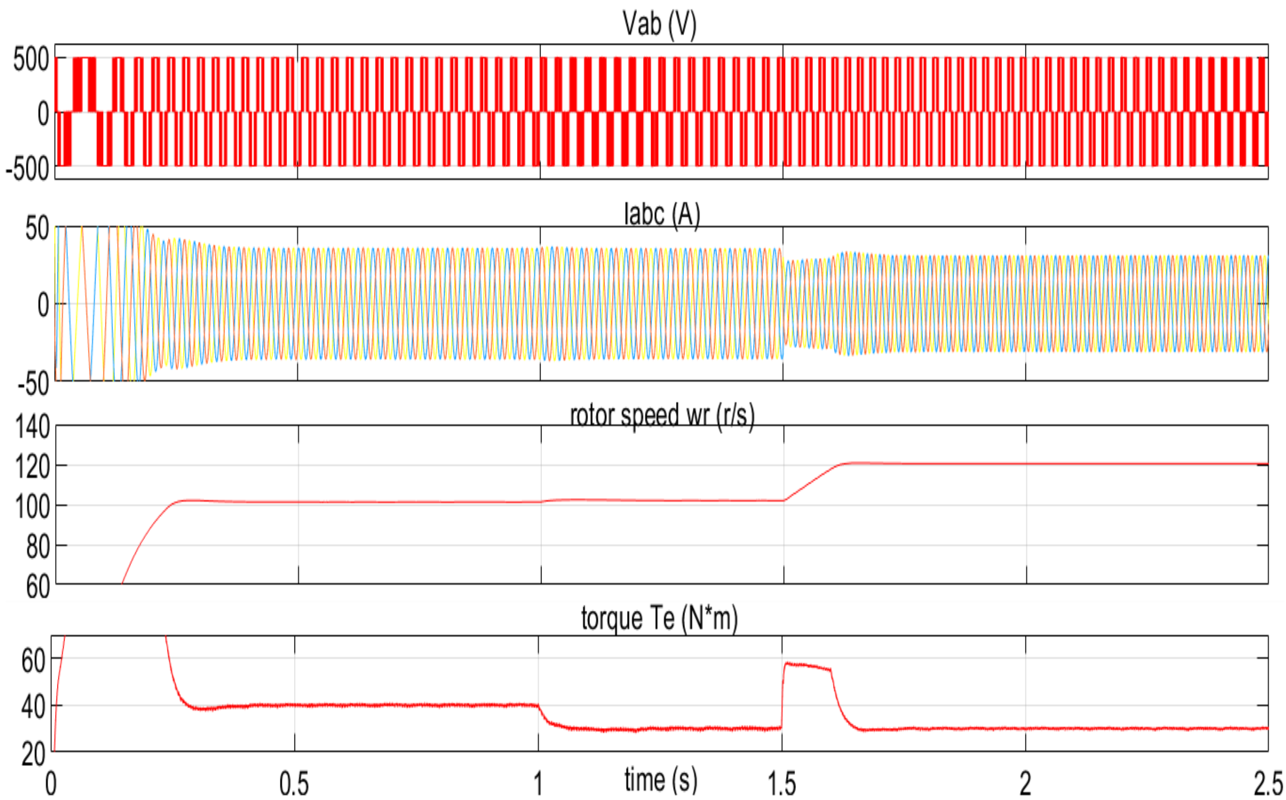

Fig. 7 The steady state operation of the proposed Improved NFTSMC method at 100% uncertain stator parameters

5.2 Uncertain stator parameters (100%) operation

The proposed method was tested against 100% stator resistance and leakage inductance. Fig. 7 displays the rotor speed response when it changed at t=1.5 s and the torque which step decreased at t=1 s. The speed rise time was 0.2١ s and the speed rises to 120 r/s smoothly in 0.1s. The step speed change has little effect on the torque which doesn't increase more than 60 N.m in 0.15 s. The step load torque has no effect on the speed.

Fig. 8 exhibits the operation of the induction motor using the hysteresis method. The motor was exposed to the same conditions like step changing the torque at t=1s and speed at t=1.5s. The speed starting response was fast but slower than the proposed method and its normal operation (0.3١ s). The motor exhibits slower torque response than its normal operation at the starting (0.35 s). The step speed has large effect on the torque (about 126 N.m) in 0.05 s compared to the proposed NFTSMC (about 60 N.m).

Therefore, for uncertain (100%) stator parameters operation, the proposed method has faster starting speed and torque response and strong robust performance against step speed change and load change compared to the hysteresis controller. In addition, the proposed method displayed comparable faster speed and torque response with smaller torque effect than the nonlinear hysteresis controller at step speed change attaining high starting torque and faster response characteristic of induction motor. Therefore, the proposed method proved their superiority due to more degrees of freedom imposed by their control terms in the controller structure.

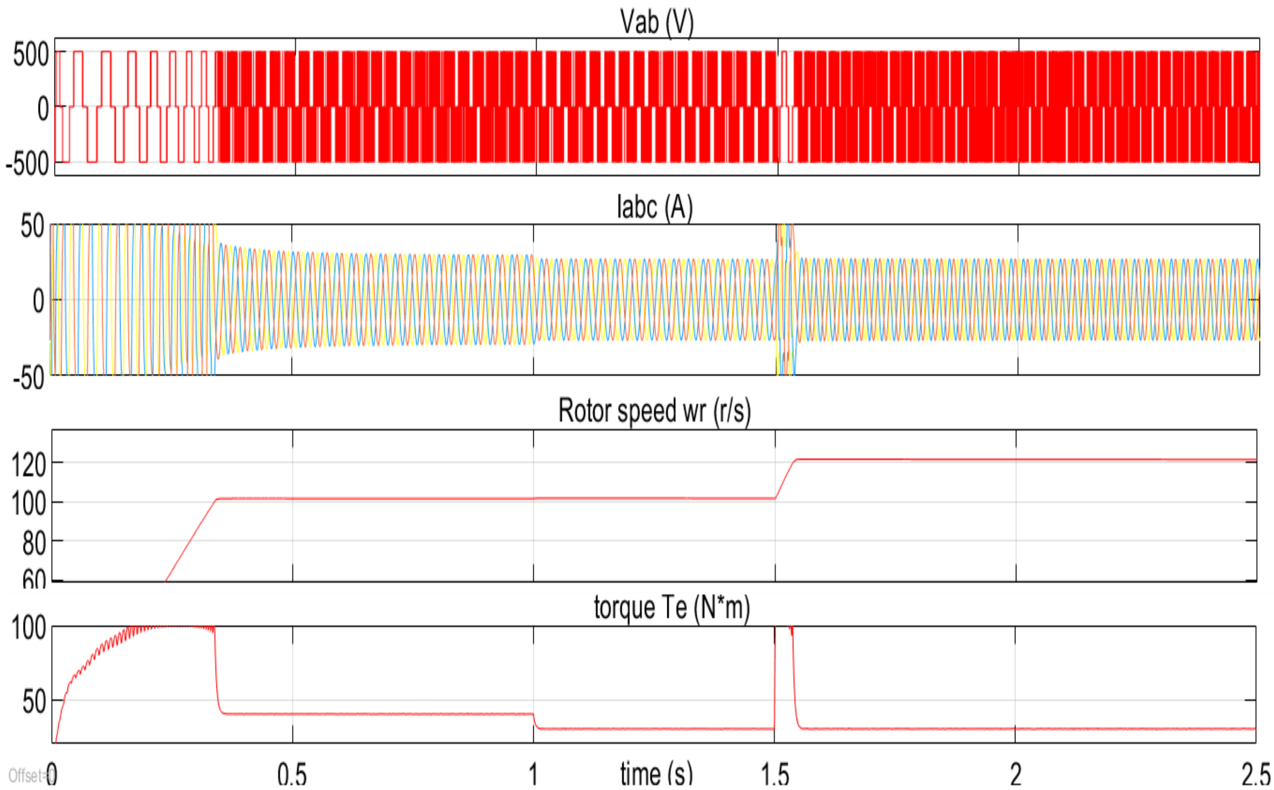

Fig. 8 The steady state operation of the hysteresis method at 100% uncertain stator parameters

5.3 Uncertain motor (-75%) parameters operation

Fig. 9 displays the voltage, current, torque and speed response of the proposed controller for -75% uncertainties of stator resistance and inductance. The speed response doesn't affected due to step load change at t= 1 s. It changes smoothly to another speed reference value at t= 1.5 s. Also, the hysteresis controller displays the same smooth speed response due to load change at t= 1 s in Fig. 10.

However, the torque response of the new improved NFTSMC has small torque effect (64 N.m) compared to the hysteresis controller (270 N.m) due to speed change at t=1.5 s as shown in Fig. 11. Fig. 12 depicts the high starting torque and faster torque response of the IM using the proposed controller (570 N.m) compared to the conventional hysteresis controller (265 N.m).

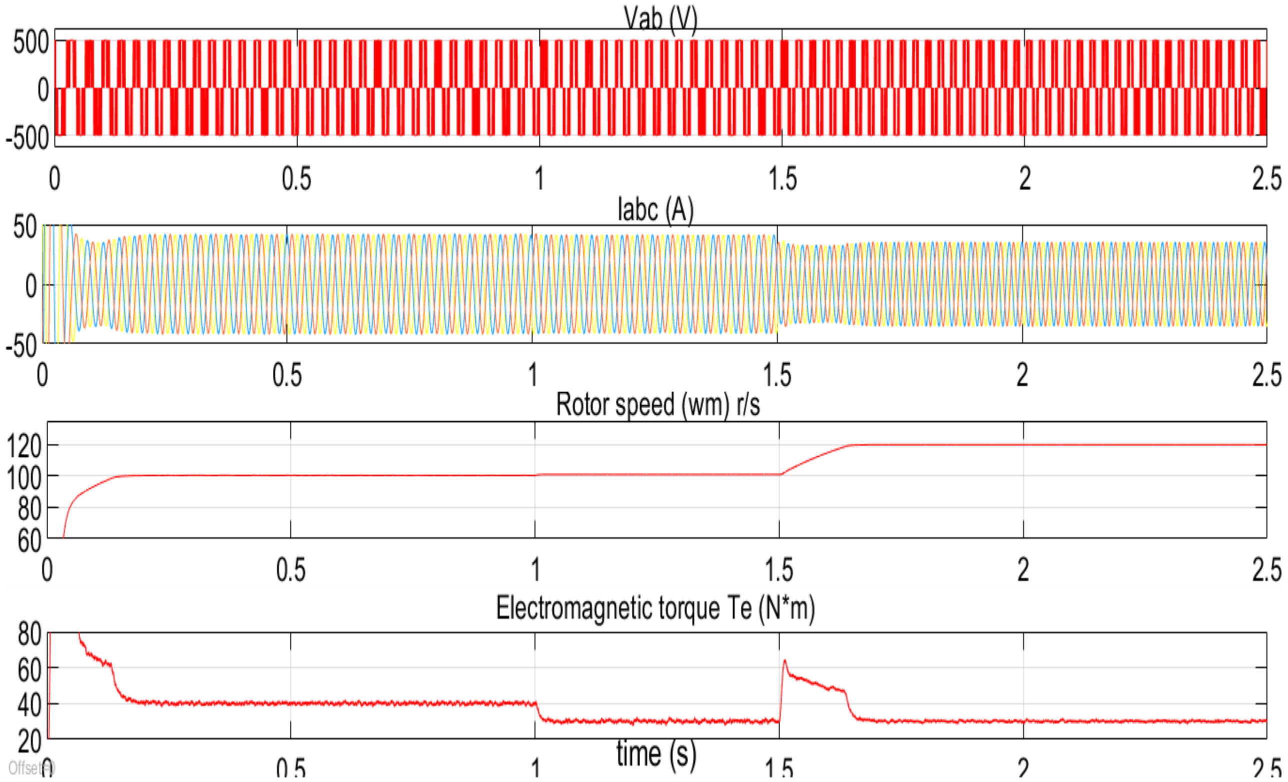

Fig. 9 The new improved NFTSMC response at -75% uncertain stator parameters

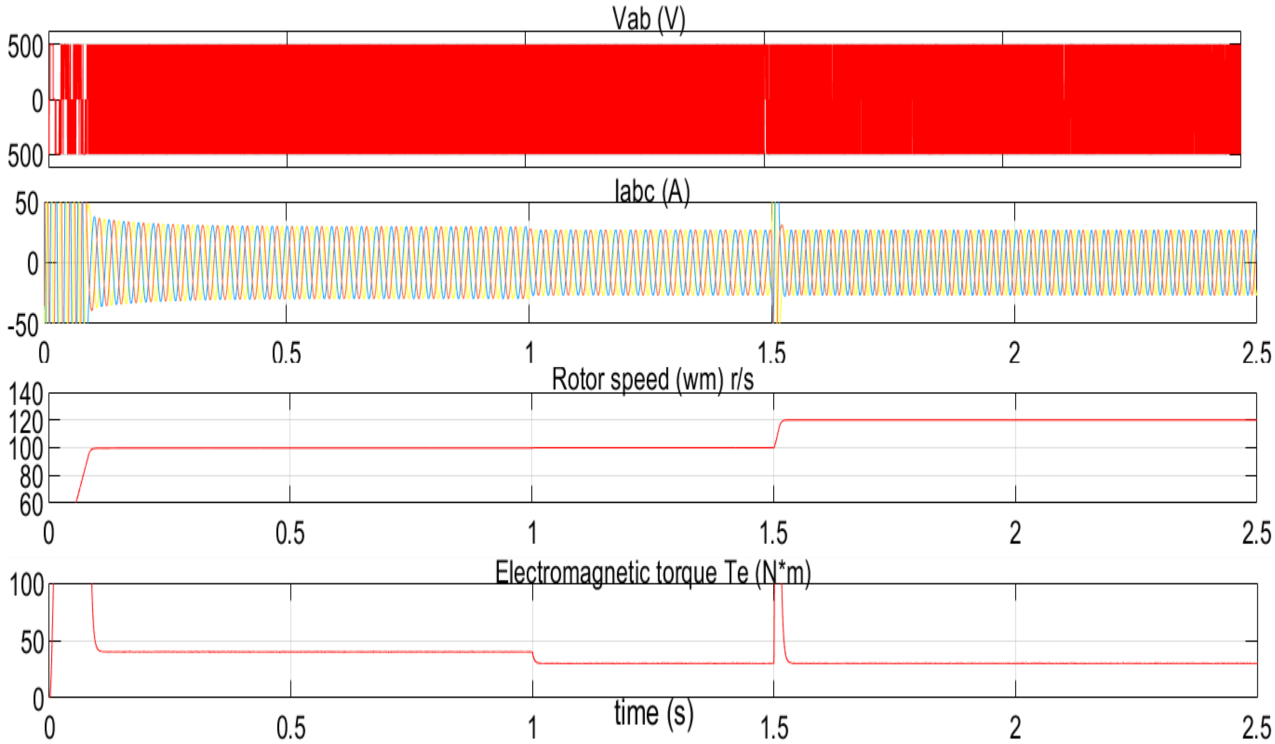

Fig. 10 The steady state operation of the hysteresis method at -75% uncertain stator parameters

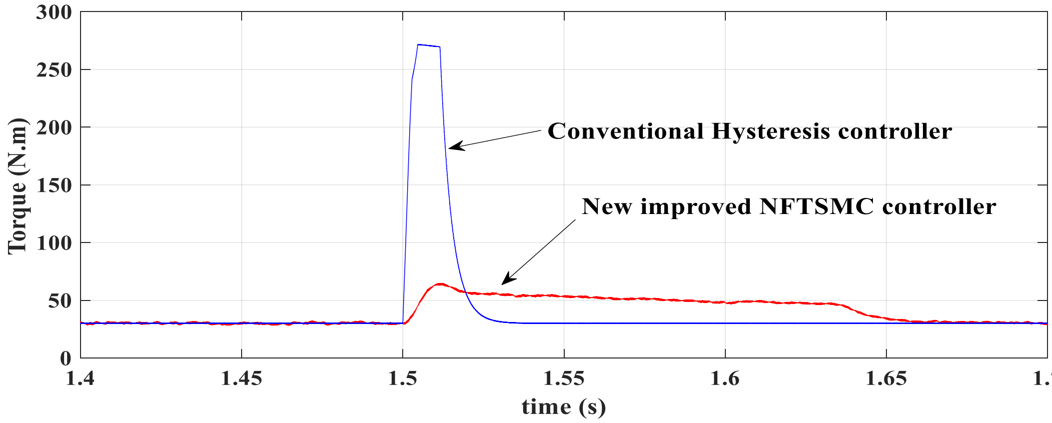

Fig. 11 The torque response due to speed change at t= 1.5 s for -0.75% uncertain parameters

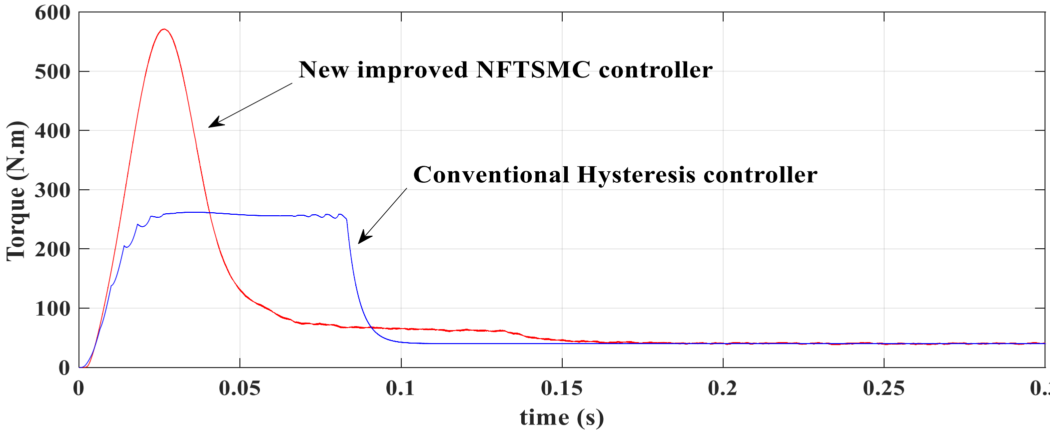

Fig. 12 The starting torque response of both controllers for -0.75% uncertain parameters

Therefore, the proposed controller attained its superior adaptive capability against step load and speed change during normal conditions, under the effect of 100% stator parameters uncertainties and under the effect -75% electrical parameters uncertainties. Besides that, it displayed faster torque and speed response at starting added to smooth speed transient response at step speed change. In addition, the proposed method offered comparable torque and speed response with smaller torque effect at step speed change compared to large torque effect of the hysteresis controller. Both controllers had strong robust speed performance against step load change.

5.4 Uncertain moment of inertia (200%) operation

In this operation, the moment of inertia was increased to two times its value to test both controllers. As shown in Fig. 13 which show the voltage, current, speed and torque response of the proposed method, the rotor speed rises to its reference 100 r/s in about 0.3 s and changed smoothly to another reference 120 r/s at t= 1.5s like its response in normal conditions.

Fig. 14 displays the voltage, current, speed and torque response of the conventional hysteresis method under the condition of two times of the motor inertia. As shown in fig. 14, the rotor speed and torque response retain its normal response but with increased speed and torque rise time about 0.24 s and 0.28 s respectively compared to the normal conditions. Also, its torque response still had larger change effect (about 210 N.m.) compared to the proposed method (70 N.m) due to the step speed at t= 1.5 s as displayed in Fig. 15. The speed response of the two methods were not affected due to two step load change at t= 1 s as displayed in Fig. 16.

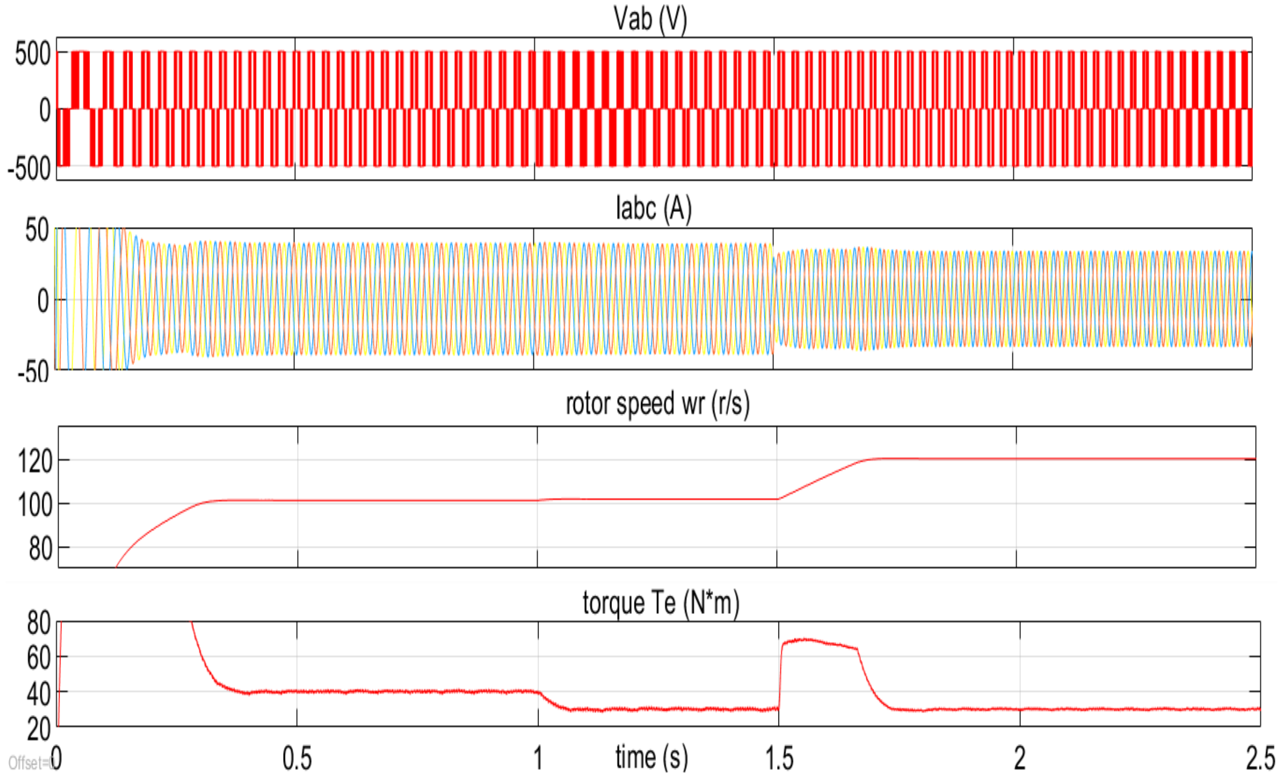

Fig. 13 The steady state operation of the proposed method at 200% uncertain (J)

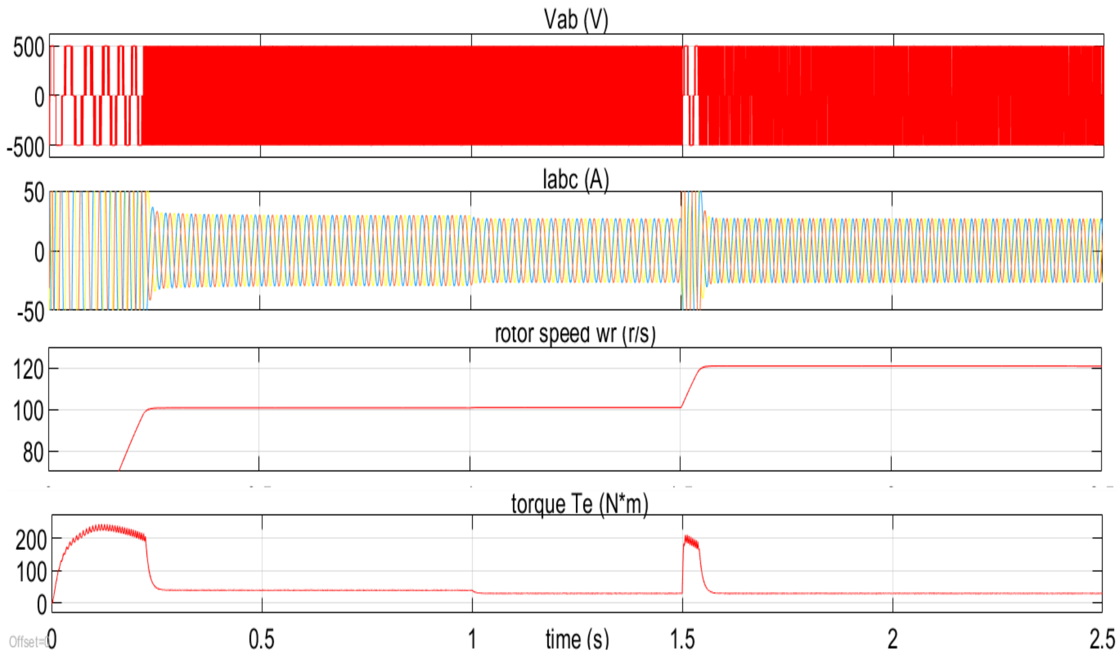

Fig. 14 The steady state performance of hysteresis method at 200% uncertain moment of inertia (J)

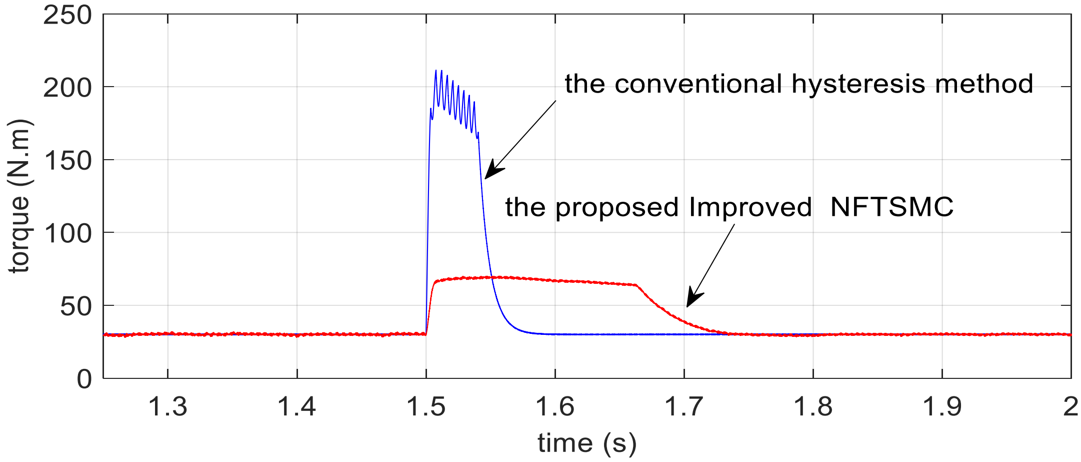

Fig. 15 The transient torque response due to step speed change for uncertain (J) operation

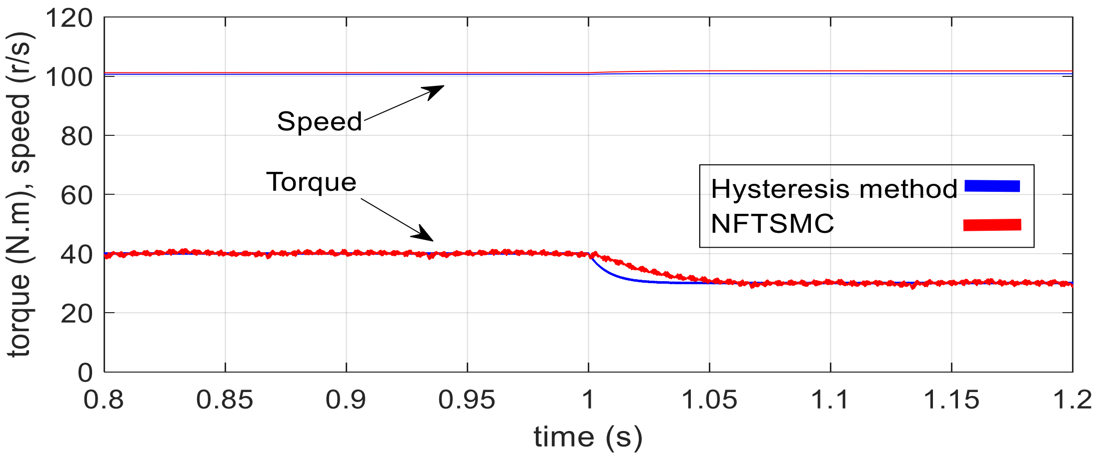

Fig. 16 The speed and torque response due to step load change for uncertain (J) operation

6. Conclusions

Novel design and application of new improved NFTSMC was proved through comparison with the nonlinear hysteresis controller for three phase induction motor. The proposed method proved their adaptive capability during normal operation, against long ranges of uncertainties and time varying electrical and mechanical parameters. The proposed method proved its strong robust capability during transient state attaining faster response, high starting torque compared to the hysteresis controller. Also, it proved its adaptive capability during steady state against step change of speed and torque with smaller torque effect and with the least speed and torque ripples. These achievements are thanks to more degrees of freedom imposed by the efficient control terms in the new improved NFTSMC structure.

References

[1] Thanh N. Truong, Anh T. Vo and Hee-Jun Kang,” A Backstepping Global Fast Terminal Sliding Mode Control for Trajectory Tracking Control of Industrial Robotic Manipulators”, IEEE Access, 2021, Vol. 9, pp. 31921-31931.

[2] Muhammad M. Islam, Syed A. Siffat, Iftikhar Ahmed, Muwahida Liaquat and Safdar A. Khan, “Adaptive Nonlinear Control of Unified Model of Fuel Cell, Battery, Ultracapacitor and Induction Motor Based Hybrid Electric Vehicles”, IEEE Access, 2021, Vol. 9, pp. 57486-57509.

[3] Tong Li, Xudong Liu and Haisheng Yu,” Backstepping Nonsingular Terminal Sliding Mode Control for PMSM With Finite-Time Disturbance Observer”, IEEE Access, 2021, Vol. 9, pp. 135496-135507.

[4] Eluri N.V.D.V. Prasad, Mrutyunjaya Sahani, P.K. Dash,” A new adaptive integral back stepping fractional order sliding mode control approach for PV and wind with battery system based DC microgrid”, Sustainable Energy Technologies and Assessments Vol. 52, 2022, pp. 102261-102281.

[5] Zebin Yang, Dan Zhang, Xiaodong Sun, Weiming Sun and Lin Chen,” Nonsingular Fast Terminal Sliding Mode Control for a Bearingless Induction Motor”, IEEE Access, 2017, Vol. 9, pp. 16656-16664.

[6] Hafiz Muhammad Salman Yaseen, Syed Ahmad Siffat, Iftikhar Ahmad, Ali Shafiq Malik,” Nonlinear adaptive control of magnetic levitation system using terminal sliding mode and integral backstepping sliding mode controllers”, ISA Transactions, Vol. 126, 2022, pp.121–133.

[7] Yashar Mousavi, Geraint Bevan, Ibrahim Beklan Kucukdemiral, Afef Fekih,” Sliding mode control of wind energy conversion systems: Trends and Applications”, Renewable and Sustainable Energy Reviews, Vol. 167, 2022, pp. 112734-112761.

[8] Ke Shao, Jinchuan Zheng, Hai Wang, Feng Xu, Xueqian Wang, Bin Liang,” Recursive sliding mode control with adaptive disturbance observer for a linear motor positioner”, Mechanical Systems and Signal Processing, Vol. 146, 2021, pp. 107014-107025.

[9] Minghao Zhou, Yong Feng, Chen Xue, Fengling Han,” Deep convolutional neural network based fractional-order terminal sliding-mode control for robotic manipulators”, Neurocomputing, Vol. 416, 2020, pp. 143–151.

[10] Sajad Saberi, Behrooz Rezaie,” Robust adaptive direct speed control of PMSG-based airborne wind energy system using FCS-MPC method”, ISA Transactions, Vol. 131, Dec. 2022, pp. 43-60.

[11] ZHENGHAO WANG AND YONGHUI LIU, ” Adaptive Terminal Sliding Mode Based Load Frequency Control for Multi-Area Interconnected Power Systems with PV and Energy Storage”, IEEE Access, Vol. 9, 2021, pp. 120185-120192.

[12] Mohammadreza Askari Sepestanaki, Mojtaba Hadi Barhaghtalab, Saleh Mobayen, Abolfazl Jalilvand, Afef Fekih and Pawe Skruch,”Chattering-Free Terminal Sliding Mode Control Based on Adaptive Barrier Function for Chaotic Systems With Unknown Uncertainties”, IEEE Access, Vol. 10, 2022, pp. 103469-103484.

[13] Omid Mofid, Saleh Mobayen and Afef Fekih," Adaptive Integral-Type Terminal Sliding Mode Control for Unmanned Aerial Vehicle Under Model Uncertainties and External Disturbances", IEEE Access, Vol. 9, 2021, pp. 53255-53265.

[14] Hamede Karami, Khalid A. Alattas, Saleh Mobayen and Afef Fekih, "Adaptive Integral-Type Terminal Sliding Mode Tracker Based on Active Disturbance Rejection for Uncertain Nonlinear Robotic Systems with Input Saturation", IEEE Access, Vol. 9, 2021, pp. 129528-129538.

[15] Mohamed Makhad, Khalida Zazi, Malika Zazi and Azeddine Loulijat,"Adaptive Super-twisting Terminal Sliding Mode Control and LVRT Capability for Switched Reluctance Generator based Wind Energy Conversion System", Electrical Power and Energy Systems, Vol. 141, 2022, pp. 108142

[16] Minghao Zhou; Siwei Cheng; Yong Feng; Wei Xu, Likun Wang and William Cai," Full-Order Terminal Sliding-Mode-Based Sensorless Control of Induction Motor With Gain Adaptation", IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 10, No. 2, April 2022, pp. 1978 – 1991.

[17] Bo Wang; Cheng Luo; Yong Yu; Gaolin Wang; Dianguo Xu," Anti-disturbance Speed Control for Induction Machine Drives Using High-Order Fast Terminal Sliding-Mode Load Torque Observer", IEEE Transactions on Power Electronics, Vol. 33, No. 9, Sept. 2018, pp. 7927 – 7937.

[18] Wei Liu; Siyi Chen; Huixian Huang," Adaptive Nonsingular Fast Terminal Sliding Mode Control for Permanent Magnet Synchronous Motor Based on Disturbance Observer", IEEE Access, Vol. 9, 2019, pp. 153791 – 153798.

[19] YI LONG and YAJUN PENG3," Extended State Observer-Based Nonlinear Terminal Sliding Mode Control With Feedforward Compensation for Lower Extremity Exoskeleton", IEEE Access, Vol. 10, 2022, pp. 8643-8652.

[20] Linjie Ren, Guopin Lin, Yuanzhe Zhao, Zhiming Liao and Fei Peng," Adaptive Nonsingular Finite-Time Terminal Sliding Mode Control for Synchronous Reluctance Motor", IEEE Access, Vol. 9, 2021, pp. 51283-51293.

[21] Wei Xu, Abdul Khalique Junejo, Yi Liu and Md. Rabiul Islam, "Improved Continuous Fast Terminal Sliding Mode Control with Extended State Observer for Speed Regulation of PMSM Drive System", IEEE Transactions on Vehicular Technology, Vol. 68, No. 11, Nov. 2019, pp. 10465 – 10476.

[22] Minghao Zhou, Hongyu Su, Haoyu Zhou, Likun Wang, Yi Liu and Haofan Yu," Full-Order Terminal Sliding-Mode Control for Soft Open Point", Energies 2022, pp. 1-18.

[23] Prashant Kumar, Devara Vijaya Bhaskar, Ranjan Kumar Behera and Utkal Ranjan Muduli, "Continuous Fast Terminal Sliding Surface Based Sensorless Speed Control of PMBLDCM Drive", IEEE Transactions on Industrial Electronics, Vol. 70, No. 10, 2023, pp. 9786 – 9798.

[24] Bo Wang; Tianqing Wang; Yong Yu; Dianguo Xu," Second-Order Terminal Sliding-Mode Speed Controller for Induction Motor Drives with Nonlinear Control Gain", IEEE Transactions on Industrial Electronics, Vol. 70, No. 11, Nov. 2023, pp. 10923 – 10934.

[25] Huazhou Hou; Xinghuo Yu; Long Xu; Kamal Rsetam and Zhenwei Cao," Finite-Time Continuous Terminal Sliding Mode Control of Servo Motor Systems", IEEE Transactions on Industrial Electronics, Vol. 67, No. 7, July 2020, pp. 5647 – 5656.

[26] Ashraf Hagras and Ahmed Alaa Mahfouz," Speed Control of Single phase Induction Motor Using New Improved Nonsingular Fast Terminal Sliding Mode Control", 2022 23rd IEEE International Middle East Power system Conference (MEPCON), 13-15 Dec., 2022, Cairo Egypt.