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New model of electric traction drive based sliding mode controller in field-oriented control of induction motor fed by multilevel inverter

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ABSTRACT

This paper presents a new model of electric traction drive for electric vehicle. The sliding mode speed regulator incorporated into Field Oriented Control is used to control the induction motor fed by the five levels Neutral Point Clamped inverter (NPC). The simulation results showed the high performances dynamics and high robustness of the suggested model, that are reflected by faster startup and good speed tracking performances in terms of response time, oscillations and disturbance rejection. Also, a comparative study between different inverter topologies: two levels inverter, three levels NPC inverter and five levels NPC inverter has been carried out. From the spectral analysis, the five levels NPC inverter fed drive provides better dynamics of voltage and current with reduced total harmonic distortion (THD).

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1. INTRODUCTION

During long years, the electric vehicle has been constrained by lower autonomy, long loading time, and higher manufacturing cost, compared to the thermal vehicle. Nowadays, with the awareness of global warming and the depletion of fossil energy resources and the development of the lithium-ion battery, the electric vehicle has become an interesting object of study and is starting to be marketed to the general public [1-5]. The propulsion of the electric vehicle is ensured by an electric traction drive composed of electric motors and converters [6-9]. Despite the advantages of this electric traction drive such as fast acceleration, high efficiency of electric motors, it remains a lever for improvement to boost the performances of the torque and the speed control and further minimize the vibrations.

Researchers are constantly exploring the improved models of electric traction drives. The induction machine fed by two level inverters is widely used to propel an electric vehicle [10, 11]. However, this model poses some limitations such as: the voltage stresses experienced by the switches generated by the direct voltage and the generation of voltage waves with harmonic distortion, which causes increased motor harmonics distortion losses and acoustic noise during steady-state operation. In order to improve the performances of this electric traction drive model, the authors in [12] propose the use of the Direct Field Oriented Control (DFOC) of induction motor powered by the five levels neutral point inverter for electric locomotive. In [13], the authors suggest a comparative study of two inverter topologies: five levels and seven levels inverter feeding the induction machine. These studies show the efficiency of multilevel inverters to mitigate the oscillations of the torque and the harmoniques of the current without any improvement in some performances like response time.

In this paper, a new model of electric traction drive with high performances dynamics and high robustness is suggested. The sliding mode speed regulator [14-19] applied to the control chain of the field oriented control of the induction motor powered by the five levels Neutral Point Clamped (NPC) inverter. A comparative study of the five levels, the three levels NPC inverters and the conventional two levels inverter is presented [20-25].

This article is structured as follows: the field oriented control model is presented in the second paragraph. Paragraphs 3 and 4 present the theory of various inverters: two levels, three levels and five levels NPC inverters. The fifth paragraph introduces the sliding mode regulator. The simulation results will be dicussed and evaluated in the last paragraph.

2. FIELD-ORIENTED CONTROL

The asynchronous machine is difficult to control, given the non-linearity of its mathematical model and the complex coupling between the rotor and the stator. Field-Oriented Control (FOC) has been proposed in 1971 by Blashke as an appropriate solution for the coupling problem. This command has been made possible through the development of semiconductor technologies and calculation units (DSP).

The field oriented control consists of adjusting separately the field and the torque, based on the orientation of the field. The choice of orientation axes can be made according to one of the field directions of the machine, the stator field, the rotor field or the gap field. In this article, the Indirect Rotor-Field Oriented Control (IRFOC) applied to the electric power train of electric vehicle is studied. The concept of this drive is based on the orientation of the rotor field Φ_r on the direct axis of the Park reference frame (d, q). This concept is expressed by [15]:

$$\Phi_{rd} = \Phi_r \text{ and } \Phi_{rq} = 0 \tag{1}$$

So, according to the induction machine model and the (1), the expressions of the electromagnetic torque and the rotor field are:

$$\Phi_r = M i_{sd} \tag{2}$$

$$C_{em} = p\,\frac{M}{L_r}\Phi_r i_{sq} \tag{3}$$

The rotor field can therefore only be regulated by the direct component of the stator current i_{sd} and the torque by the quadrature component of the stator current i_{sq}, which are completely decoupled. Figure 1 shows a schematic representation of IRFOC applied to the electric power train of electric vehicle.

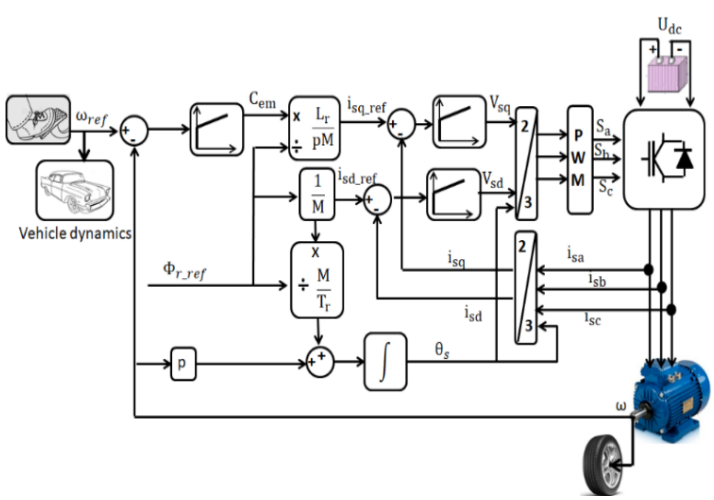

Figure 1. Schematic representation of IRFOC applied to the electric power train

3. CONVENTIONAL TWO LEVELS VOLTAGE SOURCE INVERTER

The two levels voltage inverter has been widely used in the area of AC induction motor drives. The schematic representation of the two levels inverter circuit is given by Figure 2. It consists of three arms (A, B, C), each composed of two IGBT and two antiparallel diodes. The control of the switches of one arm is complementary. Table 1 shows the different configurations of the switches, to which correspond the voltage vectors applied to the machine.

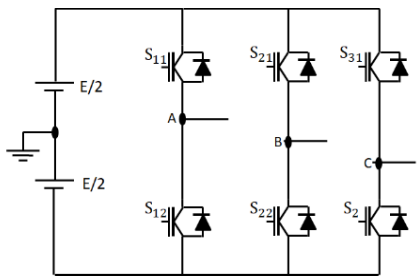

Figure 2. Schematic representation of the two levels inverter power circuit

Table 1. Switching states for two levels inverter

S_{j1}	S_{j2}	V_{ao}
On	Off	E/2
Off	On	-E/2

4. MULTILEVEL INVERTERS TOPOLOGIES

4.1. Three-levels inverter

The elementary concept of the three levels NPC inverter is to generate a three levels output voltage using two superimposed switches each fed by a separate DC voltage. The power circuit of the three levels NPC inverter (Figure 3) consists of three arms consitued of four switches connected in serie and two median diodes. Each switch consists of an IGBT and an antiparallel diode.

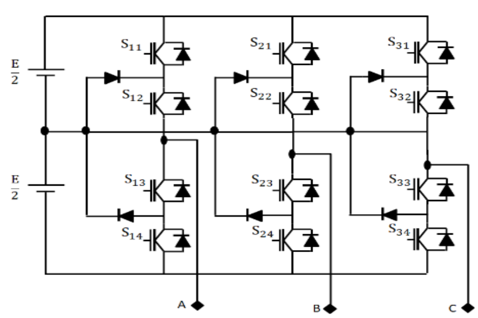

Figure 3. Schematic representation of the three levels NPC inverter power circuit

Table 2 shows the only possible sequence of switch commands that makes the system fully controllable at three levels and makes it possible to exploit the three possible levels of the output voltage ($\frac{-E}{2}$; 0 ; $\frac{E}{2}$).

Table 2. Switching states for three levels voltage inverter

S_{j1}	S_{j2}	S_{j3}	S_{j4}	V_{ao}
On	On	Off	Off	E/2
Off	On	On	Off	0
Off	Off	On	On	-E/2

4.2 Five-levels inverter

The three-phase five levels NPC inverter consists of three arms and four DC voltage sources. Each arm consitued of eight switches connected in series and six median diodes. Each switch consists of an IGBT and an antiparallel diode (Figure 4).

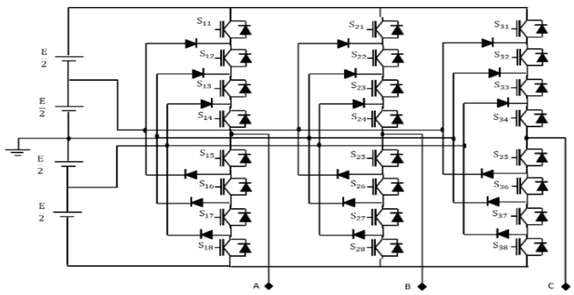

Figure 4. Schematic representation of the five levels NPC inverter power circuit

Table 3 shows the only possible sequence of switch commands that makes the system fully controllable at five levels and makes it possible to exploit the five possible levels of the output voltage ($\frac{-E}{2}$; $\frac{-E}{4}$; 0; $\frac{E}{4}$; $\frac{E}{2}$).

Table 3. Switching states for five levels inverter

S_{j1}	S_{j2}	S_{j3}	S_{j4}	S_{j5}	S_{j6}	S_{j7}	S_{j8}	V_{ao}
On	On	On	On	Off	Off	Off	Off	E/2
Off	On	On	On	On	Off	Off	Off	E/4
Off	Off	On	On	On	On	Off	Off	0
Off	Off	Off	On	On	On	On	Off	-E/4
Off	Off	Off	Off	On	On	On	On	-E/2

5. SLIDING MODE REGULATOR

Classical control laws of type PI are effective for controlling linear systems with constant parameters. However, these control laws are insufficient for nonlinear systems, having variable parameters or subject to disturbances. Sliding mode control of variable structure systems provides a solution to these problems. Its importance lies in: high precision, fast dynamic response, stability, simplicity of design and implementation and robustness to variation of internal or external parameters. The concept of the sliding mode regulator is to constrain the trajectories of the system to reach a given surface, sliding surface, and then remain there until equilibrium point. This drive is done in two steps: the convergence towards the surface and then the sliding along it.

The model of the induction motor used to calcul the sliding mode control [14, 15] (Figure 5) is:

$$\frac{di_{s\alpha}}{dt} = -\left(\frac{1}{\sigma T_s} + \frac{(1-\sigma)}{\sigma T_r}\right) i_{s\alpha} + \omega_s i_{s\beta} + \frac{(1-\sigma)}{\sigma M T_r}\phi_{r\alpha} + \frac{(1-\sigma)}{\sigma M}\omega\phi_{r\beta} + \frac{1}{\sigma L_s}V_{s\alpha} \tag{4}$$

$$\frac{di_{s\beta}}{dt} = -\omega_s i_{s\alpha} + \left(\frac{1}{\sigma T_s} + \frac{(1-\sigma)}{\sigma T_r}\right) i_{s\beta} - \frac{(1-\sigma)}{\sigma M}\omega\phi_{r\alpha} + \frac{(1-\sigma)}{\sigma M T_r}\omega\phi_{r\beta} + \frac{1}{\sigma L_s}V_{s\beta} \tag{5}$$

$$\frac{d\phi_{r\alpha}}{dt} = \frac{M}{T_r} i_{s\alpha} - \frac{1}{T_r}\phi_{r\alpha} + (\omega_s - \omega)\phi_{r\beta} \tag{6}$$

$$\frac{d\phi_{r\beta}}{dt} = \frac{M}{T_r} i_{s\beta} - (\omega_s - \omega)\phi_{r\alpha} - \frac{1}{T_r}\phi_{r\beta} \tag{7}$$

$$C_{em} = \frac{pM}{L_r}\left(\phi_{r\alpha} i_{s\beta} - \phi_{r\beta} i_{s\alpha}\right) \tag{8}$$

The sliding surface and its derivative are defined as:

$$S(\omega) = \omega_{ref} - \omega \tag{9}$$

$$\frac{dS(\omega)}{dt} = \frac{d\omega_{ref}}{dt} - \frac{d\omega}{dt} \tag{10}$$

The expression of the speed is substituted in (10) :

$$\frac{dS(\omega)}{dt} = \frac{d\omega_{ref}}{dt} - \frac{d}{dt}\left(\frac{Mp}{JL_r}\Phi_r i_{sq} - \frac{f}{J}\omega_{ref} - \frac{1}{J}C_r\right) \tag{11}$$

By introducing the control current $i_{sq} = i_{sqeq} + i_{sqn}$ into (11), we obtain:

$$\frac{dS(\omega)}{dt} = \frac{d\omega_{ref}}{dt} - \frac{d}{dt}\left(\frac{Mp}{JL_r}\Phi_r i_{sqeq} + \frac{Mp}{JL_r}\Phi_r i_{sqn} - \frac{f}{J}\omega_{ref} - \frac{1}{J}C_r\right) \tag{12}$$

With:
i_{sqeq}: Equivalent command (equivalent current), it is a continuous function that is used to hold the variable on the sliding surface. It is obtained from the invariance conditions of the surface.
i_{sqn}: Discontinuous command (discontinuous current), which forces the trajectories of the system to converge towards the sliding surface.

Therefore, the equivalent cuurent is deducted from the invariance conditions of the surface (S(ω) = 0, $\frac{dS(\omega)}{dt} = 0$ and $i_{sqn} = 0$) : .

$$i_{sqeq} = \frac{JL_r}{pM\Phi_r}\left(\frac{f}{J}\omega_{ref} + \frac{1}{J}C_r\right) \tag{13}$$

The discontinuous current is deducted from the convergence condition $\frac{dS(\omega)}{dt}S(\omega) < 0$:

$$i_{sqn} = K_{\omega}\mathrm{Sign}(S(\omega)) \tag{14}$$

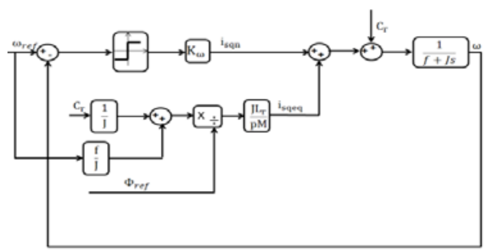

Figure 5. Schematic representation of the sliding mode speed regulator

6. SIMULATION RESULTS AND ANALYSIS

To examine the effectiveness of the suggested model of electric traction drive using the sliding mode speed regulator in IRFOC to drive the asynchronous motor supplied by the five levels NPC inverter, a series of simulations has been performed using Matlab/Simulink. A frequency carrier of 1000 Hz is chosen. The DC voltage source is 600 V. The total harmonic distortion (THD) values are measured using the Powergui FFT block. A comparative analysis between the suggested model and the conventional model using the PI speed regulator in IRFOC to drive the asynchronous machine supplied by two levels inverter is presented. At startup, a reference speed (REF) corresponding to the nominal speed (147 rad/s) of the induction machine has been applied, and at the moment t=4s, the resistive torque has been increased, followed by a change in the direction of rotation of the induction machine at t=8s.

As shown in Figure 6 to Figure 8, the suggested model using the sliding mode regulator in IRFOC with the five levels NPC inverter power supply presents the good speed tracking performances in terms of response time, oscillations and disturbance rejection. As shown in Table 4, the response time, the starting current and the torque are significantly reduced with the suggested model compared to the conventional model. So, it can be concluded that the suggested electric traction drive of the electric vehicle provides faster startup with reduced torque and current (Figure 9 to Figure 12). This model is a promising solution to overcome the problem of energy consumption of the electric vehicle at startup. In addition, the use of the sliding mode regulator makes it possible to reject perfectly the disturbances, which is suitable to ensure the road safety.

On the other hand, a comparative analysis between the various structures of the inverters applied to IRFOC using the sliding mode regulator in terms of the harmonic distortion has been carried out. Figure 13 to Figure15 show the phase voltage supplying the asynchronous motor. Thus, it is seen that by incrementing the level of the inverter, the phase voltage V_{an} becomes approximately sinusoidal.

From the spectral analysis of the stator current waveforms, it is found that by incrementing the level of the inverter, the resulting total harmonic distortion (THD) decreases. It can therefore be inferred that the five levels inverter powering the motor provides better voltage and current waveforms with reduced THD compared to the conventional two levels and three levels inverters (Figure 16 to Figure 18).

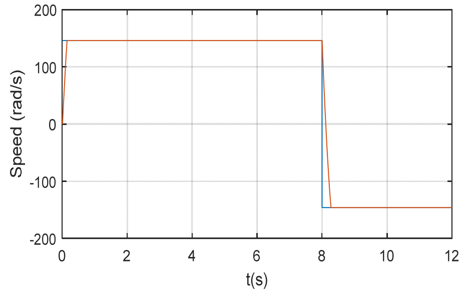

Figure 6. Speed response of electric traction drive model using sliding mode regulator in IRFOC of asynchronous motor supplied by five levels NPC inverter

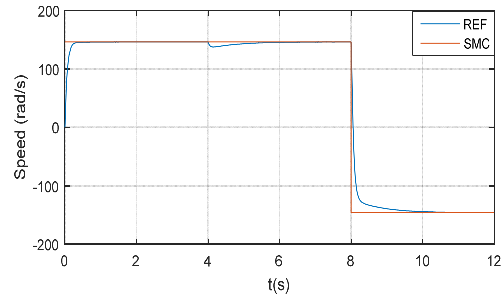

Figure 7. Speed response of electric traction drive model using PI regulator in IRFOC supplied by conventional two levels inverter

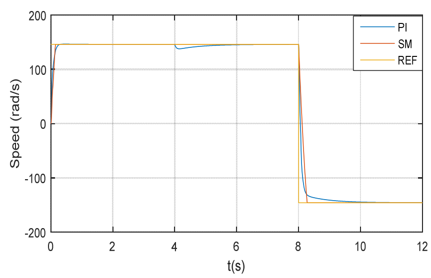

Figure 8. Comparison of speed response of two electric traction drive models : (a) IRFOC using sliding mode regulator with five levels NPC inverter, (b) IRFOC using PI regulator with the conventional two levels inverter.

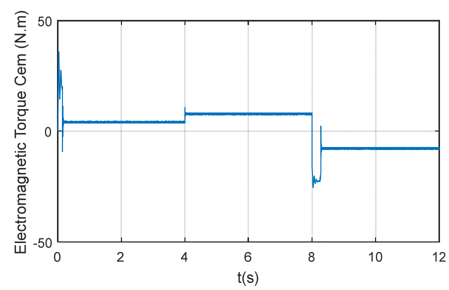

Figure 9. Electromagnetic torque response of electric traction drive model using sliding mode regulator in IRFOC of asynchronous motor supplied by five levels NPC inverter

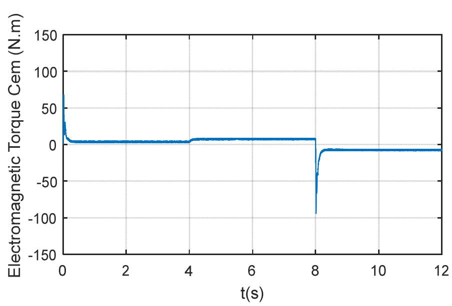

Figure 10. Electromagnetic torque response of electric traction drive model using PI regulator in IRFOC of asynchronous motor supplied by the conventional two levels inverter

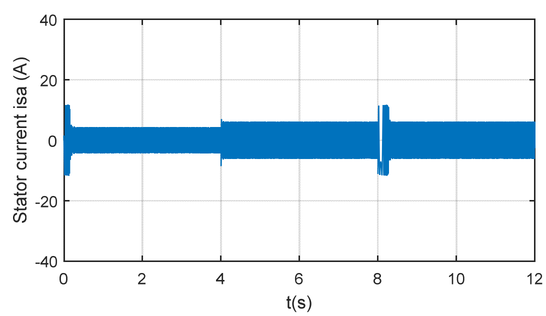

Figure 11. Stator current response of electric traction drive model using sliding mode regulator in IRFOC of asynchronous motor supplied by five levels NPC inverter

Also, comparing the responses of the stator current and the torque of different models using the sliding mode regulator in IRFOC of asynchronous motor supplied by different inverters topologies: the conventional two levels inverter, the three levels NPC inverter and the five levels NPC inverter, it is observed from the Figure 9 to Figure 12 that by using the five levels inverter the torque and current ripples are reduced.

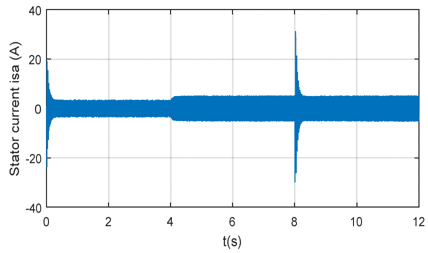

Figure 12. Stator current response of electric traction drive model using PI regulator in IRFOC of asynchronous motor supplied by the conventional two levels inverter

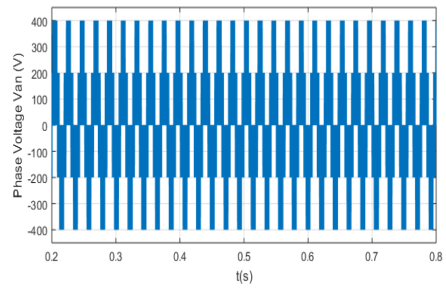

Figure 13. Phase voltage of the conventional two levels inverter

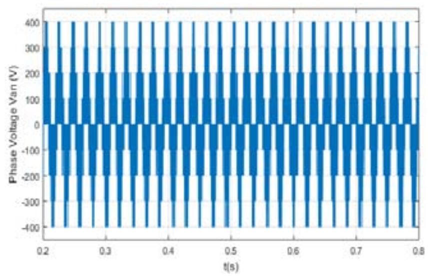

Figure 14. Phase voltage of the three levels NPC inverter

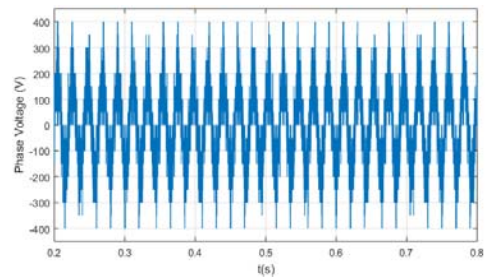

Figure 15. Phase voltage of the five levels NPC inverter

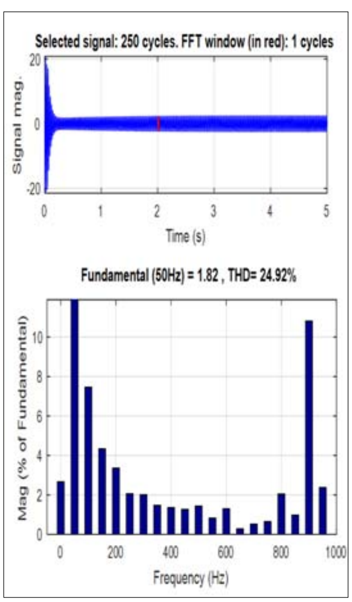

Figure 16. The harmonic spectrum of the stator current with the conventional two levels inverter

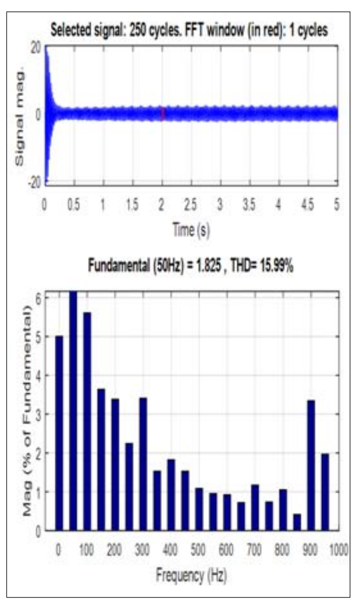

Figure 17. The harmonic spectrum of the stator current with the three levels NPC inverter

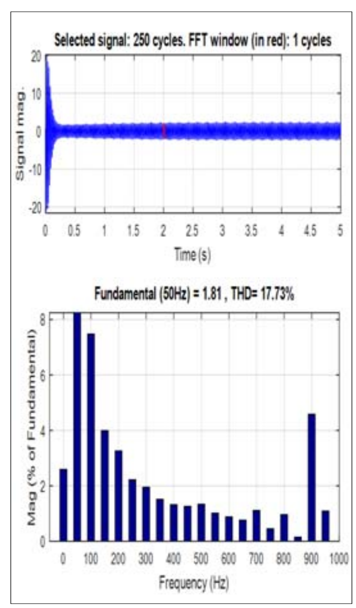

Figure 18. The harmonic spectrum of the stator current with the five levels NPC inverter

Table 4. Performance comparison of two models: (a) IRFOC using sliding mode regulator with five levels NPC inverter, (b) IRFOC using PI regulator with the conventional two levels inverter

	IRFOC using Sliding mode regulator and Five level NPC inverter	IRFOC using PI regulator and the conventional two level inverter
Response time to attaint 146 rad/s	0.17 s	0.6 s
Response time to attaint -146 rad/s	8.28 s	11.25 s
Electromagnetic torque at startup	36 N.m	68.58 N.m
Electromagnetic torque at the change of the direction of rotation of the motor	-25.62 N.m	-94.18 N.m
Stator current at startup		
Stator current at the change of the direction of rotation of the motor	11.61 A	19.06 A

7. CONCLUSION

This article suggests a new model of electric traction drive of electric vehicle using sliding mode speed regulator applied to IRFOC of asynchronous motor powered by the five levels neutral point clamped (NPC) inverter. This model has been compared with the conventional model using the conventional PI regulator applied to IRFOC of asynchronous motor powered by the conventional two levels inverter. In addition, a comparative study between different inverters topologies has been made. From the simulation results, the suggested model showed high performances in terms of response time, oscillations and disturbance rejection. The use of the five levels NPC inverter provides current and voltage waveforms with a reduced total harmonic distortion.

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