# Comparative Study of Different Drive Controller for a Traction System

Yamen Yhya, R. Sharkawy and M. Hamouda



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Yamen Wahid Yhya
*Electrical Engineering Department*
*Arab Academy for Science, Technology and Maritime Transport*
Cairo, Egypt
yamen_waheed@hotmail.com

R. M. Sharkawy
*Electrical Engineering Department*
*Arab Academy for Science, Technology and Maritime Transport*
Cairo, Egypt
Rania.m.elsharkawy@aast.edu

M. R.Hamouda
*Electrical and Computer Engineering Department, University of Waterloo*
Ontario, Canada
On leave from Future University, Cairo
M2hamouda@uwaterloo.ca

***Abstract*— The electrical traction locomotive often uses an induction motor due to the fact that it has many advantages; it has a simple construction robustness, high reliability, low maintenance cost besides it is the cheapest. This motor can be easily controlled by different techniques. This paper compares between four different types of control techniques that are used to control the motor speed. These methods are the field-oriented control using space vector modulation (FOC-SVM), the field-oriented control using hysteresis (FOC-hy), the direct torque control using hysteresis (DTC-hy) and the direct torque control using space vector modulation (DTC-SVM). MATLAB SIMULINK is used to conduct this study to show the behavior of the induction motor (IM) under these different control techniques. A comparison between the different control techniques is obtained for a train journey between two stations. The results of the study show the motor stator voltage, stator current, input and output power consumption, input and output energy, electromagnetic torque and motor speed in the time domain for the motor under study.**

***Keywords*— *space vector modulation, FOC-SVM, FOC-hy, DTC-hy, DTC-SVM, IM, MATLAB SIMULINK, electrical traction locomotive***

## I. INTRODUCTION

Several techniques have been developed to control the speed of the IM. Recently due to the advanced technology in the power electronics, this motor is nominated to be the best motor to be used in traction system because of its simple control, rigidity, low maintenance need and lower cost compared with DC motor [1]. The Egyptian metro line I uses DC motor fed from 1500 VDC system. All new lines in Egyptian metro will use Induction motors fed from 750 VDC and inverters. Normally, in the electric locomotive there are three inverters, one of them to drive the front wheel, the second is to drive the rear wheel and the last one is to feed the auxiliary devices in locomotive and charge the emergency battery.

The IM confronting a theoretically challenging control problem since the dynamic system is nonlinear, the electric rotor variables are not measurable, while physical parameters are mostly inaccurate [2]. Unlike the traditional industrial setting, in which the IM operates mostly at steady state, the electric train applications require proper control to achieve fast transient response and energy efficiency. Important characteristics of an electric train (ET) motor include good drive control and fault tolerance, as well as low noise with high efficiency. The control of the induction motor for ET has attracted much attention in the past five years[2].

The main electrical element in traction electrical system is variable frequency driver (VFD). This element is responsible for controlling motor speed. Using efficient VFD will result in improving the overall performance of the traction system. This means: fast response, generating maximum electromagnetic torque with a wide range of speed control, low ripple and robustness are required as proposed in [3].

The most recent control technique used for VFD is the scalar control using space vector modulation. This technique is the most popular and simple one. It does not produce a high performance because the IM has nonlinear relation between flux and electromagnetic torque. Early seventies, K. Hasse proposed the field oriented control (FOC) [4]. It is known now as an indirect FOC (IFOC). F. Blascke presented the direct FOC (DFOC) in [6]. These two techniques are used widely in industry. Although, this way can control flux and electromagnetic torque separately, it cannot change the flux, but still constant since the IM equation is still nonlinear. Recently, new techniques are designed to control flux and torque by using different algorithms [3].

Another method known as feedback linearization control (FLC) introduced a new nonlinear transformation of the IM state variables, so that in the new coordination, the speed and rotor flux amplitude are combined by feedback [6, 7].

A method based on the variation theory and energy shaping has been investigated recently, and is called passivity based control (PBC) [8]. In this method, the induction motor is described in terms of the Euler-Lagrange equations expressed in generalized coordinates. I.Takahashi and T. Noguchi suggested the new way to control directly electromagnetic torque in 1986 [9]. That was called direct torque control (DTC) while M.Depenbrock suggested the direct self-control (DSC) [10, 11, 12]. It is based on FOC strategies where, the current hysteresis switches are used. This method is known as classical DTC. The main advantages of this technique is that it is suitable for modern power electronic inverter with simple utmost behavior; yet, it has some disadvantages such as variable time switching as shown in references [3, 13,14].

References [1,13,15,16] have indicated that space vector modulation (SVM) is the best techniques in pulse width modulation (PWM) techniques. This technique can regulate the voltage magnitude and the phase angle. Furthermore, it eliminates the harmonics in current and voltage in the stator of the IM. This makes it suitable for open and closed loop control due to low current ripples and reduced switching time. It is easy to program this technique in Digital Signal Processing DSP and microcontrollers. Recently, from the classical DTC methods a new control technique called Direct Torque Control – Space Vector Modulated (DTC-SVM) has been developed. In this new method disadvantages of the classical DTC are eliminated.

This paper compares between four different control techniques are used for speed control of the induction motor. SIMULINK MATLAB is used for this study showing the best behavior of the Induction Motor (IM) with the chosen different control techniques. A comparison between the different control techniques is obtained to show stator voltage, stator current, input and output power consumption, input and output energy, electromagnetic torque and motor speed in the time domain during one train journey between two stations.

## II. TRAIN MATHEMATICAL MODEL

The railway dynamics equations are derived directly from Newton's second low of motion [17]:

$$F_t = F_{in} - F_{ex} = m^* a \quad (1)$$

where, $F_t$ is the resultant force acting to the train;

$F_{in}$ is the force produced from the train motors;

$F_{ex}$ is the total resistive force on the train;

m* is the train effective mass; and

a is the acceleration;

$$F_{ex} = F_r + F_{gr} + F_c \quad (2)$$

where $F_r$ is fraction force and given by:

$$F_r = A + Bv(t) + Cv(t)^2 \quad (3)$$

where, v(t) is the train velocity in Km/h.

The gradient force $F_{gr}$ is obtained from:

$$F_{gr} = \alpha\, 10^{-3} mg \quad (4)$$

where **α** is the gradient coefficient.

m is real train mass;

α is the gradient coefficient; and

g is the gravity

The friction force due to the curves $F_c$ is given by:

$$F_c = \frac{k_e}{r_c} 10^{-3} \quad (5)$$

where $k_e$ the track gauge coefficient and $r_c$ is the radius of the track curve. The rotating angular speed $\omega_m$ is used to calculate the linear speed and the distance from:

$$v(t) = \frac{r\omega_m}{\mu_t} \quad (6)$$

The distance can be obtained from the linear speed by:

$$D = \int v(t)dt \quad (7)$$

where $\mu_t$ is the gear ratio.

The load torque for one motor is calculated from the following equation [18]:

$$T_L = \frac{rF_t}{\mu_t n} \quad (8)$$

where n is the number of motors in all train. The electric train data is provided in Appendix A.

The mechanical system block diagram of the train is shown in Fig.1.

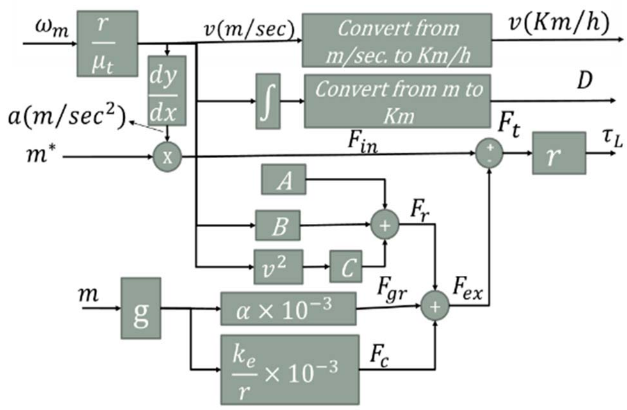


Fig. 1 Locomotive mechanical model

## III. MATLAB SIMULINK MODEL

Simulations of the four different control strategies have been carried out using MATLAB SIMULINK. Figure 2 shows the block diagram of the system under study. The AC power supply is connected to rectifier. The DC output of rectifier is injected into breaking chopper. The output of the chopper circuit feeds 3 phase inverter. Finally the output of the inverter is applied to a 3 phase IM. The speed reference and motor speed are the main input to PI speed controller. The input to the control technique block is the speed error, the voltage and current of motor and the braking chopper. The outputs of the control block provides the gates status for 3 phase inverter. In the study, the train journey is 2 Km and it's supposed that the time will take 136 Sec. with speed not exceeding 60 Km/h.

The electric traction locomotive is controlled by a special reference speed signal shown Figure 3. The electrical and mechanical data for motor is given in appendix B.

The control techniques mostly used in the VFD's is vector-based controller type. This study is a comparison among the most significant vector-based control methods.

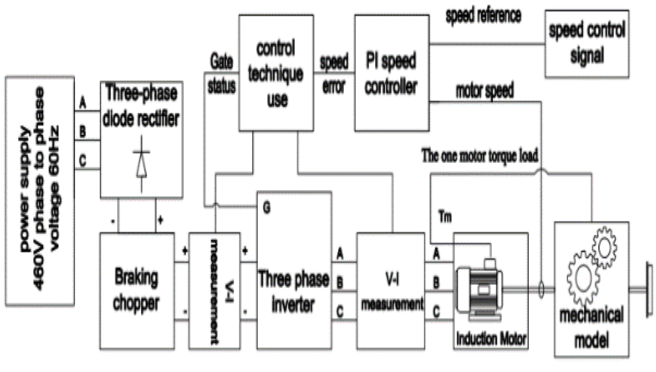


Figure 2 Block diagram of the overall system model

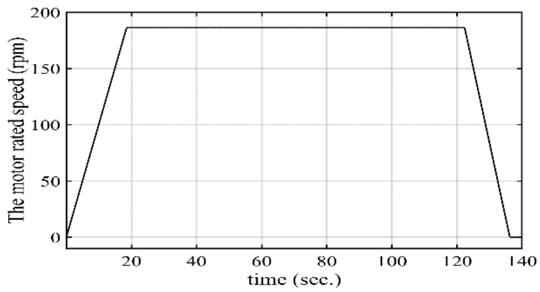

Fig. 3 speed signal reference

### A. Field-oriented control with Hysteresis(FOC-hy)

The FOC-hy is controlled in the IM flux and torque separately. The algorithm control has been carried out on basis of simplified regulators as PI regulators. In case of IM, it's possible control torque and flux each separately if the system is connected in coordination with the rotor flux vector. The FOC-hy has two methods. Firstly, the system convert the stator current ( $i_a$, $i_b$ and $i_c$) into artificial ($i_d$ and $i_q$) currents by using Park's transformation. Then, the produced current components are used to identify rotor flux and electromagnetic torque in IM. The other method is to use the rotor angel as constant value between the stator reference and rotor reference. The block diagram of these methods is shown in Fig. 4[3].

### B. Field-oriented control with SVM (FOC-SVM)

The FOC-SVM is similar the FOC-hy. The major difference between them uses the SVM instead of the hysteresis current modulation [2]. As shown Fig. 5, the FOC-SVM contains the same components as that of the FOC-hy. This is the main difference between the two methods. It is current modulation technique. When, the system calculates the $i_d$ and $i_q$ for IM stator.it compared with its references and injected to PI. The PI output inject to α and β transformer. It is output going to SVM current modulator.

### C. Direct Torque Control using hysteresis (DTC-hy)

The DTC is extremely varying from FOC in view of torque control; where FOC has series detect as regards to relatively poor response due to depending on parameter of IM. The DTC has many advantages as low time response, low effect due to changes of parameters, low leakage current due to control loops and part of sensorless operation [18]. The DTC has some disadvantages such as: has difficulty in starting, high ripple in current and torque and switching time rate is different, accordingly it has high noise. The ultimate aim of this method is to use the stator voltage and current so as to find the flux and torque value instantaneously. The DTC-hy estimates flux and torque then proceed to find the gate statues for inverter by hysteresis. The motor speed compared with the reference speed for electrical train to find speed error. The speed error to inject PI controller to find the estimated torque, next to use the stator voltage and current to get the estimated flux value [19]. Fig. 6 gives the global configuration of a DTC.

### D. Direct Torque Control using SVM (DTC-SVM)

The SVM technique has become the most advanced PWM methods due to the fast improving in microprocessor and DSP techniques. That resulted in: the control systems become more linear, less harmonic, quick response and easy implementation [19]. In Fig.7 the block diagram of DTC-SVM control scheme. This method is divided into four sections. The first section evaluates the torque, flux and phase angle from the stator voltage and current. The second section evaluates the estimated value for flux and torque. in the third section the system compares between calculated and estimated values. The result is the error values. It is injected into PI controller to find the $V_d$ and $V_q$ voltages. The third section converted the $V_d$ and $V_q$ to $V_\alpha$ and $V_\beta$ by use the phase angle calculated from section one. Last section uses SVM unit to find gate statues for VSI.

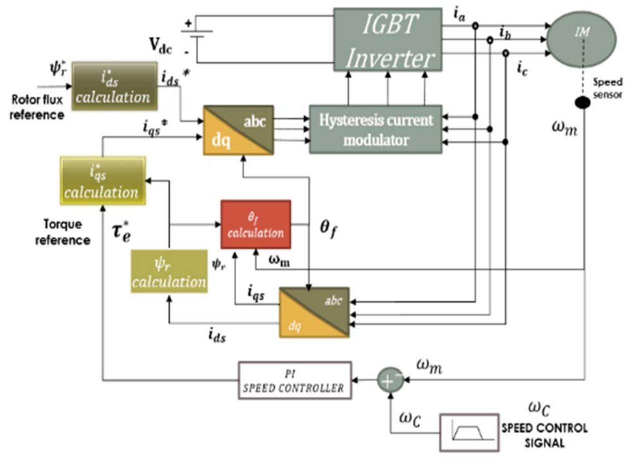

Fig. 4 The block diagram for FOC-hy

V

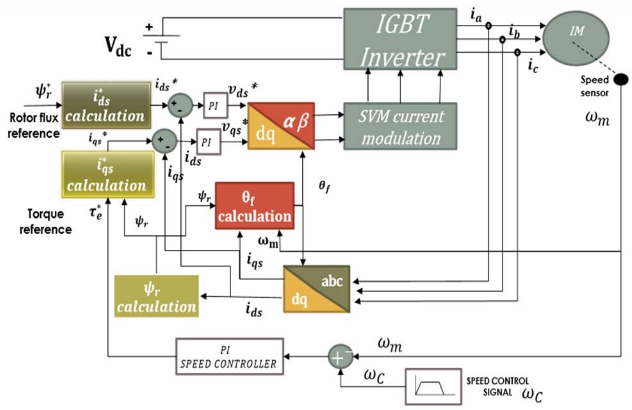

Fig. 5 The block diagram for FOC-SVM

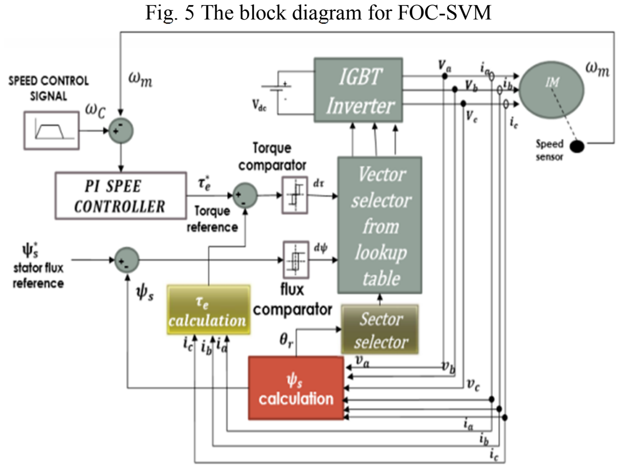

Fig. 6 The block diagram for DTC-hy

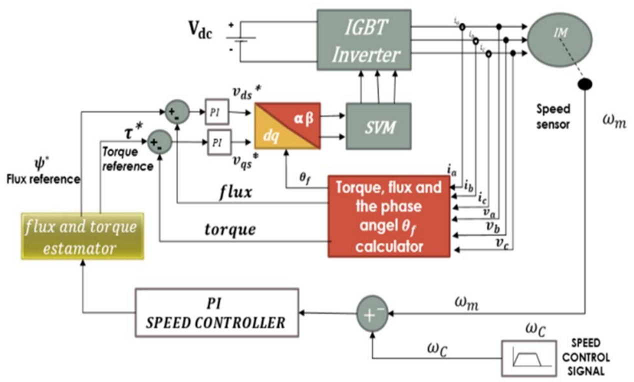


Fig. 7 the block diagram for DTC-SVM

## IV. Simulation and Results

Simulink files are prepared to study different scenarios after adding all measuring equipment. Discrete simulation is used to conduct this study with very low time step equal to 2 µs. Fast Fourier transform is used to get the components of the voltage applied to the induction motor and the stator current as well. The train mechanical model is simulated in details with a pre specified speed reference signal shown in Fig. 3. The outputs from the simulation are: the output voltage from the inverter, the motor stator current; the input and out current; and the input and out energy during the train journey. Moreover, the motor electromagnetic torque is obtained and displayed

### A. *Inverter output voltage*

Fig. 8 shows the effective phase voltage out from the inverter and applied to the IM for the four different control techniques. It is clear that there are high frequency components during the period from zero until the motor reach constant speed and also during the slowdown period for all techniques. Table 1 shows the rms voltage, the THD and the main frequency components that appear in the voltage wave for all control techniques. It is clear that the FOC-SVC is the best from the point of view of harmonic contents. Four cycles from the voltage wave during steady state of all control techniques are illustrated in Fig. 10.

### B. *IM stator current*

Fig. 9 shows the effective value of the stator line current for the four different control techniques. It is clear that there are high frequency components during the period from zero until the motor reach constant speed and also during the slowdown period for all techniques. The average value starts from a low value and reach a value of approximately 130 A for the four control techniques. Table 2 shows the rms current at steady state, the THD and the main frequency components that appear in the voltage wave for all control techniques. Once more the FOC-SVC is the best from the point of view of harmonic contents. Four cycles from the current wave during steady state of all control techniques are illustrated in Fig. 10.

### C. *Power and Energy during journey*

The input power from the AC source and the output power during the journey for all control techniques are calculated. It looks like there is small difference in the amount of input power for the different techniques. The input and output energy for all techniques are calculated. There is a minor difference in energy efficiency of the different control techniques. The energy efficiency is 94.5% in FOC-hy, 94.86% in FOC-SVM, 94.0% in DTC-hy and 93.77% in DTC-SVM. Table.3 Compares between the power dissipated and energy efficiency of the different controllers.

### D. *Electromagnetic torque*

In Fig. 11, The electromagnetic torque when use FOC-hy is stable and smooth at all stages, FOC-SVM begins with high ripple with low speed and goes to smooth. DTC-hy has high ripple for all stages while DTC-SVM performance is smooth and stable for all stages.
Moreover, the following tables summarize these simulations:

TABLE I. STATOR VOLTAGE COMPONENTS DURING STEADY STATE

| Aspects | *FOC-hy* | *FOC-SVM* | *DTC-hy* | *DTC-SVM* |
|---|---|---|---|---|
| Vrms | 209.5V | 209.5V | 196.5V | 196.4V |
| THD | 0.28% | 0.21% | 0.58% | 0.52% |
| dc | 0.04% | 0.03% | 0.1% | 0.04% |
| 30Hz | 0.12% | 0.11% | 0.24% | 0.1% |
| 90Hz | 0.19% | 0.17% | 0.32% | 0.32% |
| 120Hz ( 2nd Har.) | 0.14% | 0.08% | 0.14% | 0.26% |
| 150Hz | 0.1% | 0.07% | 0.21% | 0.30% |
| 180Hz ( 3rd Har.) | 0.1% | 0.06% | 0.41% | 0.11% |
| voltage at staring and stop | Not fast | Fast with large value of high frequencies | Fast with low value of high frequencies | Fast and smooth |

TABLE II. STATOR CURRENT COMPONENTS DURING STEADY STATE

| Aspects | FOC-hy | FOC-SVM | DTC-hy | DTC-SVM |
|---|---|---|---|---|
| Irms | 229.7A | 229.7A. | 246.2A. | 246.6A |
| THD | 0.21% | 0.20% | 0.46% | 0.68% |
| dc | 0.01% | 0.02% | 0.07% | 0.06% |
| 30Hz | 0.11% | 0.12% | 0.23% | 0.41% |
| 90Hz | 0.18% | 0.16% | 0.28% | 0.23% |
| 120Hz ( 2nd Har.) | 0.08% | 0.08% | 0.28% | 0.45% |
| 150Hz | 0.07% | 0.06% | 0.09% | 0.43% |
| 180Hz ( 3rd Har.) | 0.07% | 0.05% | 0.21% | 0.15% |
| current at start and stop | with high frequency | with high frequency | with high frequency | Fast and smooth |

TABLE III. COMPARISON BETWEEN THE DIFFERENT CONTROLLERS AT THE POWER DISSIPATED AND ENERGY EFFICIENCY AND THE RESPONSE OF ELECTROMAGNETIC TORQUE

| Aspects | FOC-hy | FOC-SVM | DTC-hy | DTC-SVM |
|---|---|---|---|---|
| Pi(Kwatt) at 25 sec.(S.S) | 130.0893 | 129.6457 | 130.9291 | 131.0902 |
| Po(Kwatt) at 25 sec.(S.S) | 123.0382 | 123.0382 | 123.0386 | 123.0378 |
| Pd(Kwatt) at 25 sec.(S.S) | 7.0511 | 6.6075 | 7.8905 | 8.0524 |
| $\xi_E$ all journey | 94.54% | 94.86% | 94% | 93.77% |
| Torque ripples in % at transient | 0.55% | 2.48% | 5.46% | 1.23% |
| Torque ripples in % at S.S. | 0.40% | 1.09% | 5.51% | 0.72% |
| Torque response | Smooth all speed values | High transient ripples at low speeds | Have high ripple at all speed values | Smooth at all speed values and the overall lowest in the comparison |

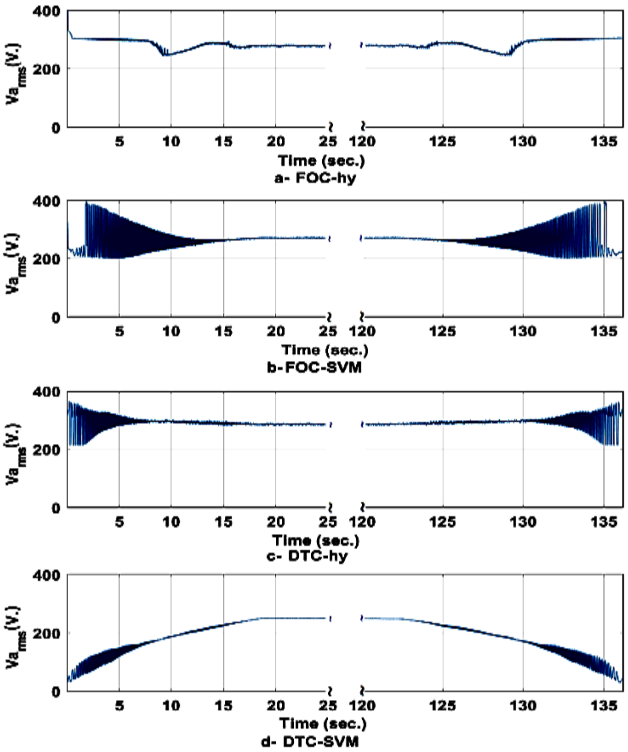


Fig. 8 inverter effective output phase voltage

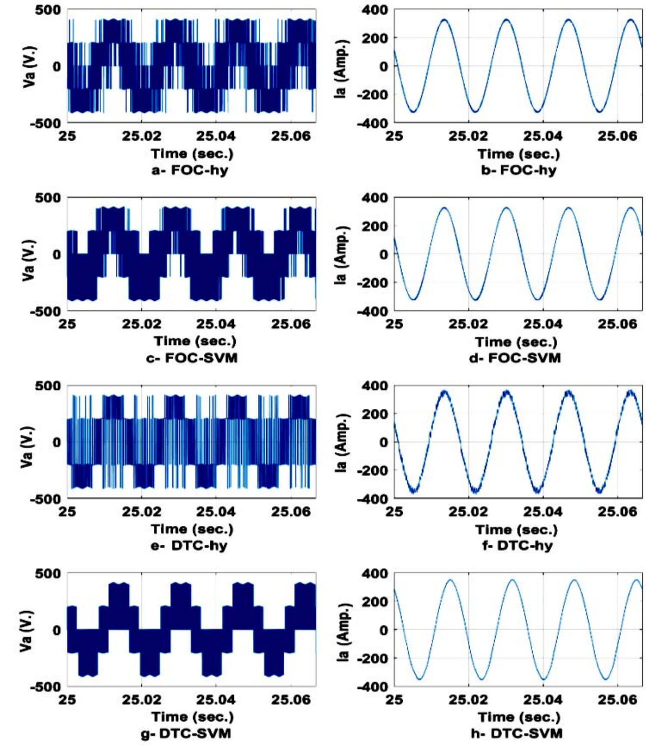


Fig. 10 Motor voltage and current wave in steady state

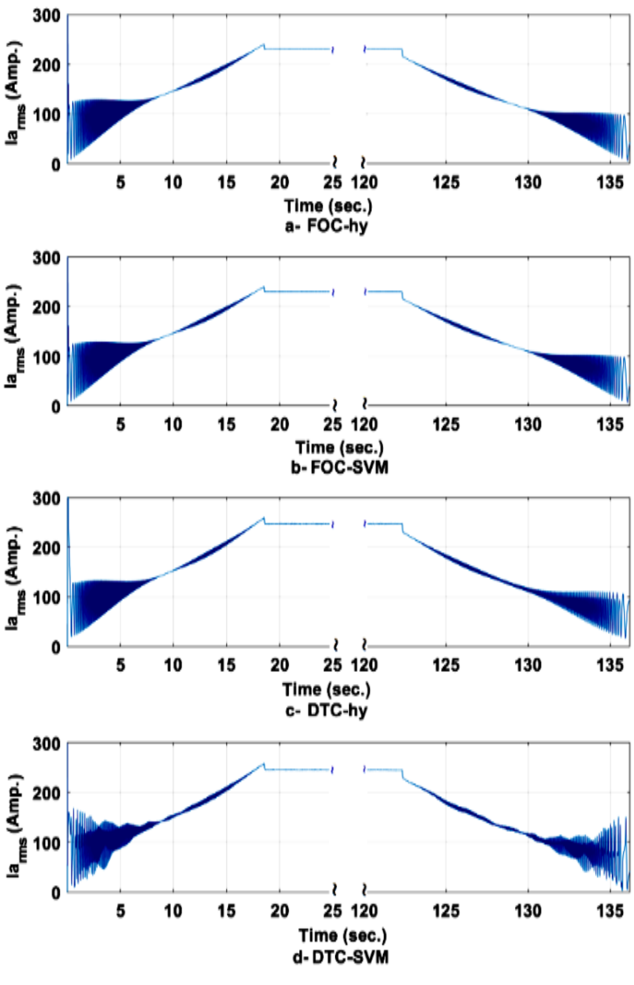


Fig. 9 Effective motor input current

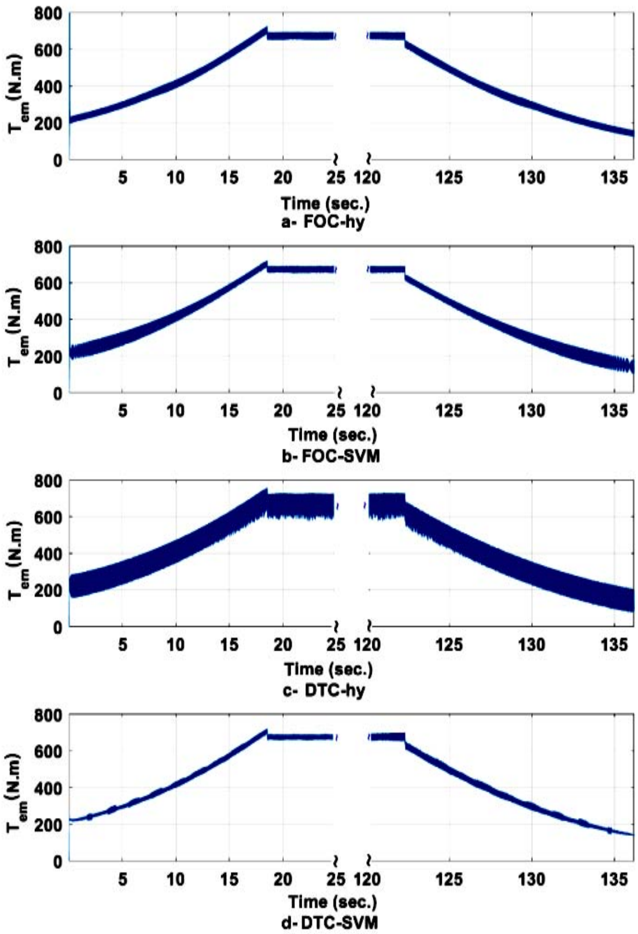


Fig. 11 Electromagnetic torque under different control techniques

## V. CONCLUSION

A comparison between four different control techniques usually used to control the induction motor mainly FOC-hy, FOC-SVM, DTC-hy and DTC-SVM is carried out. This comparison shows that the FOC-SVM is the best regarding speed control and fast response. The DTC-SVM is the best regarding the torque response in view of the stress on the shaft of the motor. The traction application needs fast response at torque variation with fixed speed motor. Furthermore, The DTC-SVM control can achieve the complete de-coupled control of torque and flux and significant torque ripple reduction. It has low torque ripple, low current distortion and high-performance dynamic characteristics. The results indicate that the DTC-SVM technique is the best to control the induction motor in traction application during transients but it has low performance at the steady state. The FOC-SVM is the most compatible under all circumstances except for the torque. The differences between FOC-SVM and DTC-SVM are not significant. Yet, the torque response is superior for traction.

## VI. APPENDICES:

Appendix A

| | |
|---|---|
| Train weight (not including rotating coefficient) | 668.9 ton |
| Train weight (including rotating coefficient) | 714.7 ton |
| Maximum acceleration | 0.9m/sec.2 |
| Maximum deceleration | 1.2m/sec.2 |
| Running resistance | $R = \overbrace{18.3153}^{A} + \overbrace{0.35218}^{B} \times \upsilon \underbrace{0.007308}_{C} \times \upsilon^2$ |
| Maximum speed | 60 Km/h |
| r (wheel radius) | 0.4925 meter |
| $k_e$(the track gauge coefficient) | 1435 |
| **α** (the gradient coefficient) | 4% |

Appendix B

| | |
|---|---|
| Nominal power P: | 149.2 KVA |
| Voltage line to line $V_{rms}$: | 460 V |
| Nominal frequency f: | 60Hz |
| Stator resistance $R_s$ and inductance $L_s$ | 14.85 mΩ & 302 µH |
| Rotor resistance $R_r$ and inductance $L_r$ | 9.295 mΩ & 302µH |
| Mutual inductance $L_m$: | 10.46 mH |
| Inertial J: | 3.1 Kg.m2 |
| Friction factor F: | 0.08 N.m.sec |
| Number of pairs poles p: | 2 |

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