

STATE SPACE MODELLING AND SIMULATION OF CSI FED INDUCTION MOTOR DRIVE SYSTEM WITH A SIMPLIFIED PROGRAM

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ABSTRACT

This paper present the modelling and simulation of three phase PWM Current Source Inverter fed Induction Motor (CSI-IM) drive systems using state space representation and its implementation by means of Matlab/Simulink simulation software. Combining these powerful models with some matlab functions it is possible to obtain the ideal simulation platform for these systems. The main features of this type of simulation program are simplicity, accuracy and efficiency in terms of computation time. This simulation program can be used to verify the system design, to study system dynamic behavior and to investigate steady state waveforms of the drive system. In order to simplify the simulation process, different algorithms are developed for the simulation of different sections in the drive system. The feasibility, high reliability of the system and the validity of the control method are proved by the simulation results.

Keywords: *CSI, Matlab, S-functions, Simulink, State space.*

1. INTRODUCTION

Compared with voltage source inverter fed drives, the CSI drive has the features of simple structure, reliable short circuit protection, four quadrant operation capability and nearly sinusoidal output voltage and current waveforms. In addition, the switching device (symmetrical

GTO) used in the CSI can be easily connected in series, which makes the CSI drive particularly suitable for implementation at medium high voltage (4160V and up) levels. Therefore a block diagram of the GTO CSI-IM drive system is shown in Fig. 1. It is replacing the conventional Current Source Inverter drive in high power applications [1]-[2].

To date, most simulation work for this type of drive system is carried out on a steady state basis [3-6]. It is difficult to use general purpose simulation programs such as EMTP (Electromagnetic Transient Program) and SPICE (Simulation Program with Integrated Circuit Emphasis) to simulate the dynamic performance of the drive system due to the special PWM techniques employed in the inverter and the

complicated induction machine model. However the matlabsimulink software simulation tool is specially conceived for the development of continuous and discrete control systems. The main disadvantage of matlabsimulink software is the one of not being specific software for power electronic systems and, therefore, the designer must develop his own models for electronic systems. A toolbox of simulink named power system blockset is especially dedicated to the power electronic systems, although for a fixed structure is not as versatile as user defined models (s-functions). Nevertheless, the power stages topologies are fixed and well defined as opposed to the great amount of possibilities of control that offers a digital system (DSP), for a same power stage. In this paper, a computer simulation program specially designed for the PWM GTO CSI-IM drive system is introduced and it is implemented by means of Matlab / Simulink simulation software.

In this simulation program, the drive system is divided into three sections: (1) Rectifier section, (2) Inverter-machine section and (3) Control section. In general, the switching of the thyristors and GTO's

in the power circuit increases the complexity for simulation. In order to simplify the simulation process, different simulation algorithms are developed for different sections.

2. RECTIFIER SECTION

A computer subroutine for the rectifier is developed. The parameters passed to the subroutine are the RMS value of the line voltage V_{AB} , the time instant, the delay angle α and the dclink current i_{dc} . The subroutine brings back the instantaneous value of the dc link voltage v_{dc} .

As an example, a set of typical waveforms of the rectifier with a continuous dc link current at the delay angles $\alpha = 0^\circ$ and $\alpha = 30^\circ$ are illustrated in Fig. 3, v_{dc} is the dc link voltage.

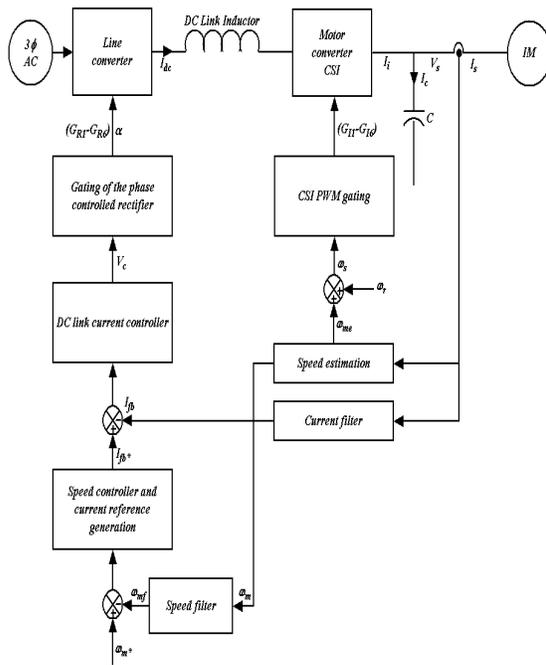


Fig. 1 Block diagram of the GTO CSI-IM drive system.

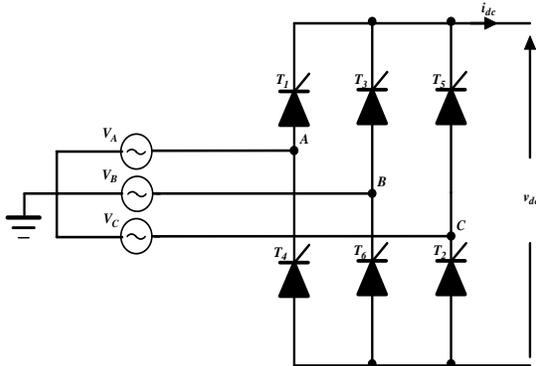
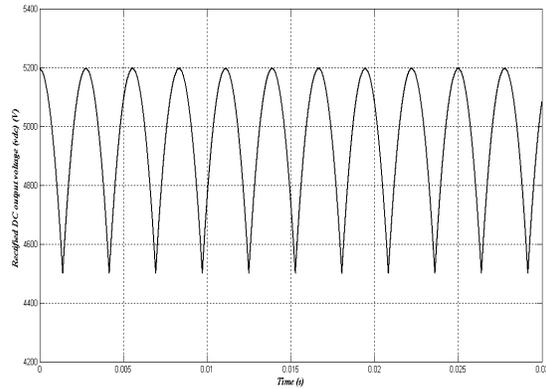
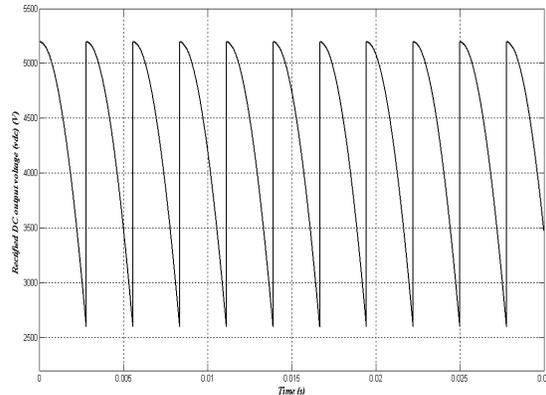


Fig. 2 Simplified circuit diagram of the thyristor rectifier



(a)



(b)

Fig. 3 Typical rectifier waveforms (a) at $\alpha = 0^\circ$ (b) at $\alpha = 30^\circ$

3. STATE SPACE MODELLING

The state space or internal representation of a dynamic system is an effective path to model linear systems. One is based on the state concept that is the set of variables (state variables) that store the system information. The value of the state variables at a certain moment determines the exact state of the system at that moment.

The systems in the state space are described by means of the “(1)” and “(2)”.

$$\dot{\bar{x}}(t) = \bar{A} \cdot \bar{x}(t) + \bar{B} \cdot \bar{u}(t) \quad (1)$$

$$\bar{y}(t) = \bar{C} \cdot \bar{x}(t) + \bar{D} \cdot \bar{u}(t) \quad (2)$$

Where \bar{x} the set of state vector is, \bar{y} is the outputs vector, \bar{u} is the inputs vector of the system and $\dot{\bar{x}}$ is the derivatives vector. The switching converters state space models are obtained combining the models obtained by the different states from possible switches.

4. STATE SPACE MODEL OF A CSI-IM SECTION

A circuit diagram for the inverter-motor section is depicted in Fig. 4. This section includes a dc link inductor, a GTO current source inverter, a three-phase output capacitor and an induction motor. Two commonly used modulation techniques, the trapezoidal pulse width modulation (TPWM) and the selected harmonic elimination (SHE) techniques, are considered in the program. According to the modulation patterns produced by these techniques, six distinct states can be defined.

The equivalent circuit for the inverter, capacitor and induction motor in a stator reference frame is shown in Fig. 5. The corresponding state equation (differential equations) with motor flux linkages as variables is derived and given by

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}\bar{u} \quad (3)$$

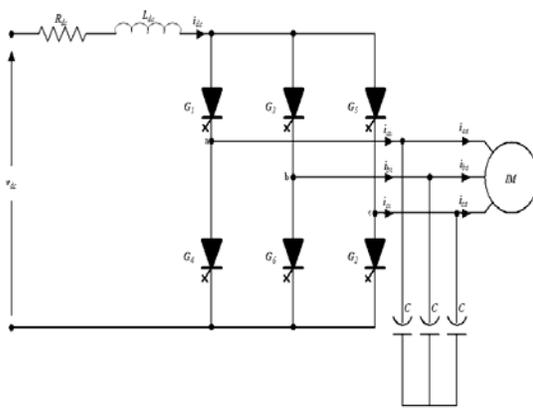


Fig. 4 Circuit diagram for the inverter-motor section

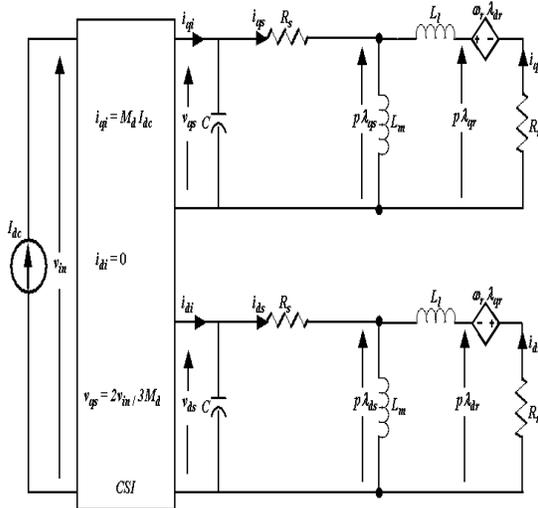


Fig. 5 Equivalent circuit of inverter and machine

Where

$$\dot{\bar{x}} = \frac{d\bar{x}}{dt}$$

$$\bar{A} = \begin{bmatrix} -\frac{R_s}{\sigma_m L_m} & 0 & \frac{R_s}{L_l} & 0 & 1 & 0 & 0 & 0 \\ 0 & -\frac{R_s}{\sigma_m L_m} & 0 & \frac{R_s}{L_l} & 0 & 1 & 0 & 0 \\ \frac{R_r}{L_l} & 0 & -\frac{R_r}{L_l} & \omega_{me} & 0 & 0 & 0 & 0 \\ 0 & \frac{R_r}{L_l} & -\omega_{me} & -\frac{R_r}{L_l} & 0 & 0 & 0 & 0 \\ -\frac{1}{\sigma_m L_m C} & 0 & \frac{1}{L_l C} & 0 & 0 & 0 & K(1) & 0 \\ 0 & -\frac{1}{\sigma_m L_m C} & 0 & \frac{1}{L_l C} & 0 & 0 & K(2) & 0 \\ 0 & 0 & 0 & 0 & K(3) & K(4) & -\frac{R_{dc}}{L_{dc}} & 0 \\ K_{iq} \lambda_{dr} & -K_{iq} \lambda_{qr} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\bar{x} = [\lambda_{qs} \quad \lambda_{ds} \quad \lambda_{qr} \quad \lambda_{dr} \quad v_{qs} \quad v_{ds} \quad i_{dc} \quad \omega_{me}]^t$$

$$\bar{B} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{dc}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{P}{2J} \end{bmatrix}^t$$

$$\bar{u} = [v_{dc} \quad T_{ql}]^t$$

This state equation has been arranged in such way that it is valid for all states. For different states, only the coefficients $K(1)$ to $K(4)$ in the equation need to be modified. Therefore, the simulation complexity is substantially reduced. Furthermore, this state equation is already expressed in a stator reference frame, and thus the time domain waveforms can be directly obtained by using any numerical integration methods without further transformations.

With the application of the TPWM and SHE techniques, the operation of the inverter can be divided into six distinct states. Each state corresponds to a unique pair of GTO's which are turned on. The definition of each state is given as follows.

TABLE I
Switching States

State	On-state GTO's
1	$G_1 \& G_2$
2	$G_2 \& G_3$
3	$G_3 \& G_4$
4	$G_4 \& G_5$
5	$G_5 \& G_6$
6	$G_6 \& G_1$

For example in state 5, G_5 and G_6 are turned on, and the following equations can be obtained

$$i_{ai} = 0 \quad (4)$$

$$i_{bi} = -i_{dc} \quad (5)$$

$$i_{ci} = i_{dc} \quad (6)$$

$$v_{cb} = v_{cs} - v_{bs} \quad (7)$$

Applying the abc to $dq0$ transformation matrix [10] to “(4)” – “(7)” gives

$$v_{cb} = \sqrt{3}v_{ds} \quad (8)$$

$$i_{qi} = 0 \quad (9)$$

$$i_{di} = \frac{2}{\sqrt{3}}i_{dc} \quad (10)$$

Also, the dc link voltage can be expressed as

$$v_{dc} = L_{dc} \frac{di_{dc}}{dt} + R_{dc}i_{dc} + v_{cb} \quad (11)$$

Substitute “(8)” into “(11)” gives

$$\frac{di_{dc}}{dt} = \frac{R_{dc}}{L_{dc}}i_{dc} - \frac{\sqrt{3}}{L_{dc}}v_{ds} + \frac{1}{L_{dc}}v_{dc} \quad (12)$$

Substitute “(9)” and “(10)” into “(1)” and combining “(12)” with “(1)” in which the coefficient K is given by

$$K(1) = 0, K(2) = \frac{2}{\sqrt{3}C}, K(3) = 0, K(4) = \frac{\sqrt{3}}{L_{dc}}$$

The coefficients $K(1)$ to $K(4)$ for different states are summarized in Table II.

Stat e	$K(1)$	$K(2)$	$K(3)$	$K(4)$
1	$\frac{1}{C}$	$-\frac{1}{\sqrt{3}C}$	$-\frac{3}{2L_{dc}}$	$\frac{\sqrt{3}}{2L_{dc}}$
2	0	$-\frac{2}{\sqrt{3}C}$	0	$\frac{\sqrt{3}}{L_{dc}}$
3	$-\frac{1}{C}$	$-\frac{1}{\sqrt{3}C}$	$\frac{3}{2L_{dc}}$	$\frac{\sqrt{3}}{2L_{dc}}$
4	$-\frac{1}{C}$	$\frac{1}{\sqrt{3}C}$	$\frac{3}{2L_{dc}}$	$-\frac{\sqrt{3}}{2L_{dc}}$
5	0	$\frac{2}{\sqrt{3}C}$	0	$-\frac{\sqrt{3}}{L_{dc}}$
6	$\frac{1}{C}$	$\frac{1}{\sqrt{3}C}$	$\frac{3}{2L_{dc}}$	$-\frac{\sqrt{3}}{2L_{dc}}$

5. CONTROL SECTION

The simulation for the control circuit is relatively simple. The dynamic behaviour of any control schemes can be described by a set of differential equations. These equations can be solved numerically.

As an example, consider the control circuit of the drive shown in Fig. 1. It is assumed that both compensators are of PI type, that is,

$$V_{\alpha} = \left(K_i + \frac{K_i}{\tau_{is}}\right)(I_f^* - I_f) = K_i(I_f^* - I_f) + V_{pii} \quad (13)$$

Where

$$V_{pii} = \frac{K_i}{\tau_{is}}(I_f^* - I_f) \quad (14)$$

and

$$\begin{aligned} I_f^* &= \left(K_s + \frac{K_s}{\tau_{sS}}\right)(\omega_m^* - \omega_{mf}) \\ &= K_s(\omega_m^* - \omega_{mf}) + I_{pis} \end{aligned} \quad (15)$$

Where

$$I_{pis} = \frac{K_s}{\tau_{sS}}(\omega_m^* - \omega_{mf}) \quad (16)$$

The outputs of the current and speed feedback filters can be expressed as

$$I_f = \frac{K_{cs}}{1+\tau_{ifs}}I_s \quad (17)$$

and

$$\omega_{mf} = \frac{K_{ss}}{1+\tau_{sfs}}\omega_m \quad (18)$$

Equation (14) and “(16)” to “(18)” can be expressed in a matrix form:

$$p \begin{bmatrix} v_{pii} \\ i_f \\ i_{pis} \\ \omega_{mf} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{K_i}{\tau_i} & \frac{K_i}{\tau_i} & -\frac{K_i K_s}{\tau_i} \\ 0 & -\frac{1}{\tau_{if}} & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_s}{\tau_s} \\ 0 & 0 & 0 & -\frac{1}{\tau_{sf}} \end{bmatrix} \begin{bmatrix} v_{pii} \\ i_f \\ i_{pis} \\ \omega_{mf} \end{bmatrix} + \begin{bmatrix} \frac{K_i K_s}{\tau_i} \omega_m^* \\ \frac{K_{cs}}{\tau_{if}} i_s \\ \frac{K_s}{\tau_s} \omega_m^* \\ \frac{K_{ss}}{\tau_{sf}} \omega_m \end{bmatrix}$$

The input parameters passed to the simulation program for the control circuit are the speed reference ω_m^* , the actual machine speed ω_m and stator current i_s . The output parameters brought back to the power circuit are the delay angle α and stator frequency ω_s which is the sum of the motor speed and rotor (slip) frequency ω_r . This rotor frequency is set at the rated value of the induction motor.

6. MODEL IMPLEMENTATION AND SIMULATION USING MATLAB/SIMULINK

Use For the implementation of the state space equations of a system model, Matlab Simulink has the denominated user defined functions or s-functions. In these blocks the code that defines the model in state equations can be written. In this code so much is defined the number of inputs and outputs, like the states and the state space equations of the system.

For the case of CSI-IM section shown in Fig. 5 can be modeled by means of s-function is defined. Next are the most important parts of the code:

- o (Flag = 0) Initialization and definition of: number of continuous states, discrete status, inputs and outputs and initial condition of the state variables.
- o (Flag = 1) Solve the state equation, calculus of derivatives for continuous states.
- o (Flag = 3) Solve the output equation.

The s-function can be called from a matlabsimulink function block. In figure Fig. 7 one is the Simulink block diagram where “CSI-IM model” is the sfunction that call’s the defined function. The inputs are multiplexed in a bus can be demultiplexed, and the same occurs for the outputs. This s-function will correspond to a block with the inputs, outputs and parameters shown in figure Fig. 6.

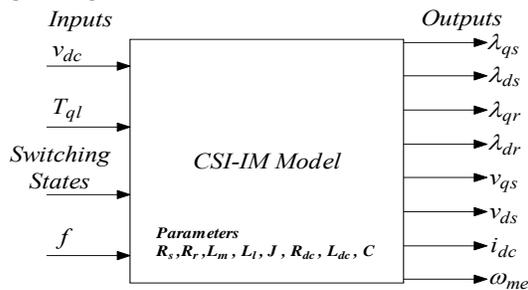


Fig. 6 Current Source Inverter-Induction Motor model block

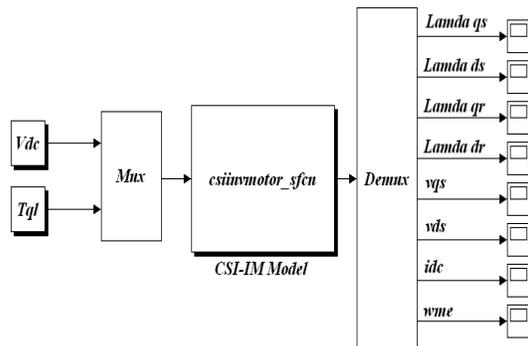


Fig. 7 Simulink implementation

The following Matlab Simulink models allow the simulation of the pulse width modulated current source inverter fed induction motor drive for variable frequency drive and have been used for the design of a real system.

Fig. 8 shows the Matlab Simulink block diagram of the PWM CSI-IM variable frequency drive system. The outer feedback control loop is used to generate the firing angle α for the rectifier section and the inner feedback control loop is determined the desired stator frequency for PWM pulse generation to the CSI.

7. SIMULATION PROCEDURE

The A simplified simulation procedure is summarized as follows.

1. Initialization.
2. Call rectifier subroutine.
3. Determine current state according to the switching pattern.
4. Select coefficient K from Table 2.
5. Solve state equation (3) for the inverter-motor section.
6. Calculate the stator frequency $\omega_s = \omega_r + \omega_{me}^*$
7. Solve equations for the control circuit.
8. Calculate the delay angle α
9. Go back to Step 2 if the required ending time for simulation is not reached.

8. SIMULATION RESULTS

The drive architectures of Fig. 7 and Fig. 8 have been completely implemented and assessed in the Matlab-Simulink environment along with their respective control systems. The simulation is based on the parameters shown in Table III.

A simulation study based on the model shown in Fig. 8 is carried out to compare open loop and closed loop control modes. The following figures show the steady state and dynamic waveforms of the drive system at two different stator frequencies. By using the selected harmonic elimination techniques, the 5th and 7th harmonics in the inverter output current are eliminated.

The Fig. 9(a) shows the behavior of the drive system operated at the stator frequency of 60 Hz in open loop control, specifically in response to a 20 NM step command of the motor torque at a step time of 32 seconds. Due to this step command there is a dip in motor speed at 32 seconds, after 2 to 3 seconds the motor speed raise to its reference speed.

Fig. 9(b) shows the behavior of the drive system operated at the stator frequency of 60 Hz in closed loop control, for the 20 NM step command of the motor torque at a step time of 32 seconds.

TABLE III

Machine and Drive Parameters

Machine Parameters	
800 hp, 4000 V, 101 A and 1750 rpm	
Stator resistance	$R_s = 0.275 \Omega$
Rotor resistance	$R_r = 0.195 \Omega$
Magnetizing inductance	$L_m = 0.265 H$
Total leakage inductance	$L_l = 0.0145 H$
Total moment of inertia	$J = 99.8 \text{ kg.m}^2$
Drive System Parameters	
Resistance of dc link inductor	$R_{dc} = 0.1 \Omega$
DC link inductance	$L_{dc} = 0.04 H$
Output filter capacitor	$C = 69 \mu F$

In this mode of control operation 50% of the torque and speed ripples (pulsations) are reduced compared to the open loop control mode of operation. The Fig. 10(a) shows the steady state waveforms of the motor currents when the drive system operating at the stator frequency of 60 Hz in open loop control has more switching transients results high torque pulsations. In Fig. 10(b) due to closed loop control the motor current waveforms are almost sinusoidal nature, the switching transients are almost eliminated. The Fig. 11(a) and Fig. 11 (b) shows the behavior of the drive system operating at the stator frequency of 30 Hz in open loop control and closed loop control, specifically in response to a 20 NM step command of the motor torque at a step time of 25 seconds and 32 seconds respectively. Due to this step commands there is a dip in motor speed, after 2 to 3 seconds the motor speed raise to its reference speed. In closed mode of control operation 25% of the torque and speed ripples (pulsations) are reduced compared to the open loop control mode of operation. Fig. 12 shows the motor current waveforms which are in sinusoidal nature at 30 Hz operating frequency in closed loop control. Fig. 13 shows the behavior of the drive system operating at the stator frequency of 30 Hz in closed loop control, for the -20 NM step command of the motor torque at a step time of 25 seconds. The developed electromagnetic torque follows the -ve torque command.

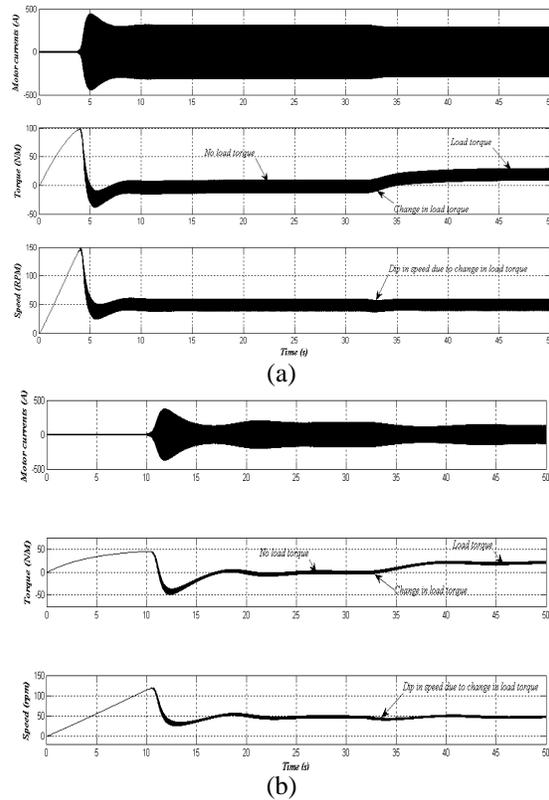


Fig. 9 Simulated dynamics for PWM CSI-IM drive at $f_s = 60 \text{ Hz}$. (a) Open loop Control. (b) Closed loop control.

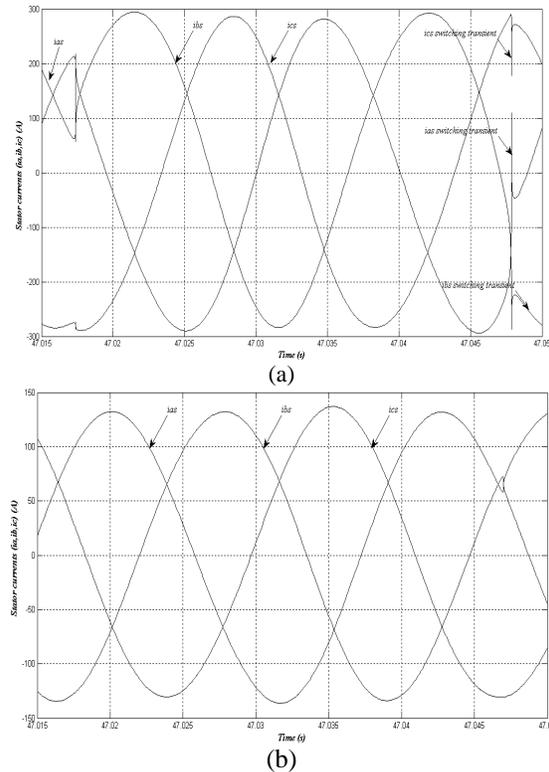
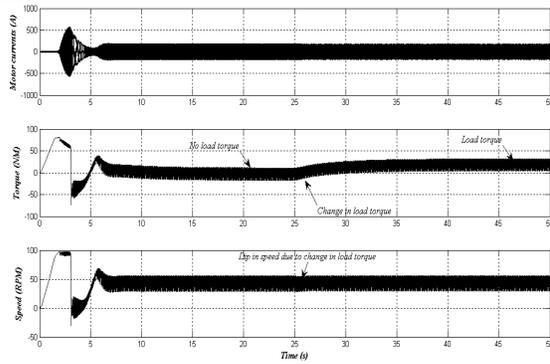
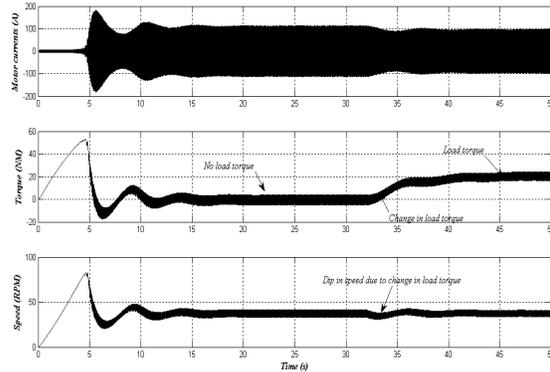


Fig. 10 Simulated steady state waveforms of the motor currents at $f_s = 60 \text{ Hz}$. (a) Open loop Control. (b) Closed loop control.



(a)



(b)

Fig. 11 Simulated dynamics for PWM CSI-IM drive at $f_s = 30 \text{ Hz}$. (a) Open loop Control. (b) Closed loop control.

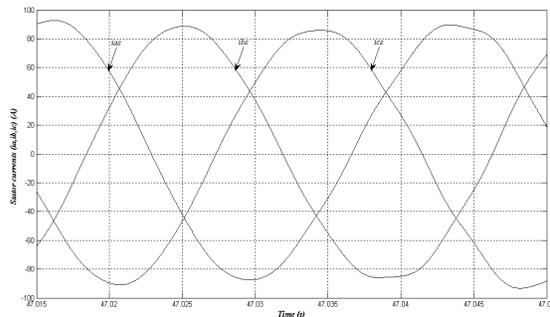


Fig. 12 Simulated steady state closed loop stator currents waveform at $f_s = 30 \text{ Hz}$.

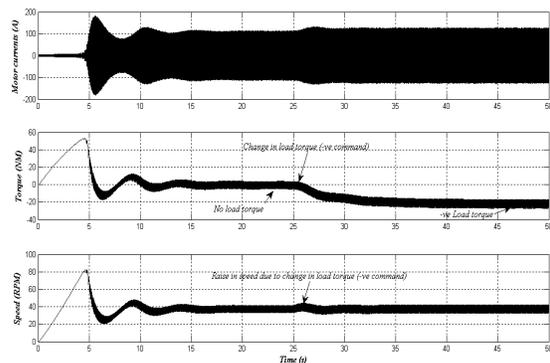


Fig. 13 Simulated dynamics for PWM CSI-IM drive with $-ve$ torque command closed loop control at $f_s = 30 \text{ Hz}$.

9. CONCLUSION

The use of Matlab Simulink for the power electronics systems models simulation allows taking advantage of the high benefits that this simulation software offers in the control systems design. The state space models of the power stages are directly implemented on user defined functions in a simple form. Designing by means of s-functions and state space equations the models of the power stages allows to the total control on the model and all its variables, being able at any moment to be modified if outside necessary. In this paper a simple, accurate and efficient computer program is proposed for the simulation of the PWM GTO CSI induction motor drive system. In order to simplify the simulation process, different algorithms are developed for the simulation of different sections in the drive system. This program can be used to study both steady state and dynamic behaviour of the drive system. The proposed control algorithm verified using matlab simulations. The V/f control scheme is considered for use in the proposed drive not only because it does not require any motor parameters but also it is easy to implement. However, the V/f controlled CSI drive has inherent stability problem caused by LC resonances. The system stability can be substantially improved by introducing an active damping control.

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