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Learning improvement by using Matlab simulator in advanced electrical machinery laboratory

Seyed Zeinoabedin Moussavi [a] *, Morteza Fazly [a]

[a] *Shahid Rajaee Teacher Training University, Lavizan,Tehran, Iran*

Abstract

This paper deals with using simulators such as MATLAB/SIMULINK to work on complicated problems in electrical machines. Simulation of direct vector control of induction machine (IM) drive on the rotor flux direction with composite model flux observer can improve electrical machine learning's of graduate and under graduated students. In the indirect vector control of IM, current reference values are used for the estimation angle of the rotor flux space vector (ARFSV), however using current reference values instead of current real values can decrease accuracy of ARFSV. In the direct vector control, current real values (current feedback) estimate ARFSV. The ARFSV estimation can be performed by the current model flux observer and voltage model flux observer. These observers have some restrictions. But The composite model reduces disadvantages of every individual ones. In fact, Simulation of the composite model is applied to induction machines to get results compare to the classical current and voltage models. The interesting point is that the composite model approach shows great advantages over those classic ones, i.e. speed control over the wide range of motor operation with enough short settling time. All these remarkable benefits support the application of composite model in ARFSV.

Keywords: Learning Induction Machine (IM) Drive, Education of Composite Model Flux Observer, Estimation angle of the rotor flux space vector words;

1. Introduction

In engineering, compared to the pure theoretical sciences, normally we have this chance to predict the general behavior of diverse systems by the modeling phenomena. The simulator software plays very important rule in this story. Moreover, by simulation instead of doing experiments, which normally costs a lot and is time-taking, the behavior of different systems can be explored.

In this paper simulation of induction machine drive are investigated. Induction machines are the commonly used converters in home appliances. On the other hand, the vector control theory is nowadays usually applied in controlled drives with induction machines where high dynamic and static speed or position control performances are required. Regardless of chosen control strategy (direct or indirect vector control, acting on stator terminal voltages or currents, maintaining the modulus of stator, rotor, or air gap flux vector constant) rotor position or speed sensor is commonly applied. Recently, there has been a lot of research effort spent in order to exclude rotor position for speed

* Seyed Zeinoabedin Moussavi. Tel.: +98-21-2297-0006; fax: +98-21-2297-0006
E-mail address: smoussavi@srttu.edu

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control purpose. In our work, the stator current need to implement the feedback loops for induction motors speed control is applied as shown in Fig.1. The angle of the rotor flux space vector (ARFSV) is not measured but will be estimated. Accurate estimation of the rotor flux angle requires acceptable performance of Field Oriented Control (FOC), from that estimation also the frequency needed in the control law, ω1 would be derived. Meanwhile imperfect field-orientation introduces cross coupling as e.g. a voltage applied to affect only the current in the d-direction in reality affects both current components. Transformations between the coordinate systems of the rotor and stator are explicitly shown in Fig.1 as well as the fact that a three-phase Voltage Source Inverter (VSI) is used to generate the stator voltages. The observer block is hence used to indirectly estimate ARFSV(χ_r), via the already derived frequency ω1 is called Indirect Field-Orientation (IFO). It has been shown in [1] that the CM with IFO is quite robust to model errors with regards to stability. Imperfect parameter estimation by conventional current model leads to deteriorated system performance. The current model (CM) is sensitive to *Rr* and *Lm*. Note that also the estimate of *Lm* affects the performance with the IFO implementation of CM. By using so-called Direct Field-Orientation (DFO), χ_r is obtained by directly estimating the rotor flux. This estimator corresponds to a simulation of the rotor flux equation with the stator current as input. This model is therefore referred to as the CM. The current model may also be implemented by using the rotor flux equation in estimated rotor flux coordinates. By separating this equation into real and imaginary parts, we may hence estimate the derivative of the rotor flux angle as $\chi_{r.}$ where we approximated the rotor flux and the quadrature stator current component by their reference values (the estimated flux reference converges to its constant reference value and the current controllers make the current reference follow their reference values).

From the equivalent circuit diagram in induction machine model we may also express the rotor flux in terms of the stator voltage. We then obtain the so-called voltage model (VM), at high speeds; the voltage model gives an accurate stator flux estimate, since the back EMF dominates the stator voltage. However, at low and zero speed, the voltage model is well known to give non-satisfactory performance. This is due to sensitivity to the voltage drop across the stator resistance and to inherent signal integration problems at low excitation frequencies, see [2] and [3].

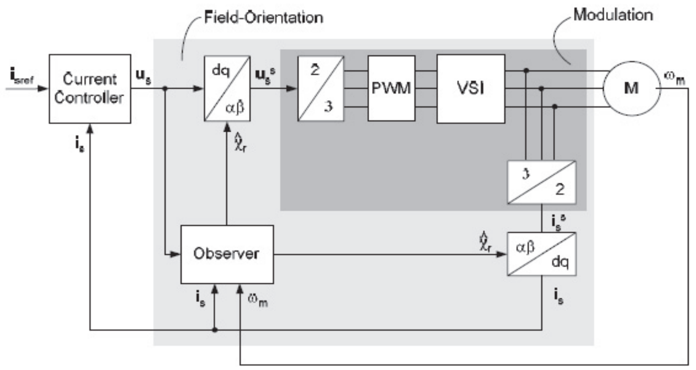


Figure.1 Illustration of current control where coordinate transformations are explicitly shown.

A further problem with stator flux estimation is that this equation cannot be directly used in practice as it contains a pure integration. This gives a marginally stable system due to the pole at the origin (this pole corresponds to a pole pair at ±jω1 in a real-valued representation in synchronous or polar coordinates). Also, integration may give integrator drift, see e.g. [4]. To solve the integration problem, the pure integration can be replaced by a low-pass filter. In this case also the static effect of the filter should be compensated for as is done with the Statically Compensated Voltage Model (SCVM), see [5]. Due to the problems with VM at low speeds, the rotor flux is here preferably estimated using the current model, while the voltage model is suitable at higher speeds, see e.g. [6], [7] and [8]. By combining CM and VM what is called Composite Model flux observer we tried to illustrate advantages of each individual at low and high speed performance using simulation in Matlab/Simulink. We conclude that this combination demonstrates more accurate rotor flux angle estimation (χ_r) over the entire motor speed range.

This simulation shows operation in base speed region. Simulation design is modeled in K-coordinate system with AB components, however rotor coordinate system with dq components as a special kind of K-coordinate is implemented.

2. System Modeling

2.1. Dynamic Model of Induction Machine

Mathematically, the induction motor can be compactly described by using complex-valued space vectors. From the definition of a space vector in synchronous coordinates and the expression for the derivatives, it follows that the two motor vector equations (1) and (2), are:

$$L_\sigma \frac{d}{dt} i_s(t) = u_s(t) - (R_s + R_r + jL_\sigma \omega_1(t))\, i_s(t) - (jn_p \omega_m - \frac{R_r}{L_m})\, \psi_r(t) \quad (1)$$

$$\frac{d}{dt}\psi_r(t) = R_r i_s(t) - (\frac{R_r}{L_m} + j(\omega_1(t) - n_p \omega_m(t)))\, \psi_r(t) \quad (2)$$

The torque Eq. (3), may now be represented as

$$T(t) = \frac{3}{2} n_p \operatorname{Im}\{\psi_r^*(t)\, i_s(t)\} \quad (3)$$

The synchronous coordinates are often chosen as rotor flux coordinates, i.e., θ1 is chosen as the angle of the rotor flux space vector. In rotor flux coordinates, the q-component of the flux therefore is zero by definition. By splitting equations (1), (2) and (3) in to real and imaginary part we get,

$$\begin{aligned}
\frac{d}{dt}\psi_{sd}(t) &= -\frac{R_s}{\sigma L_s}\left(\psi_{sd} - \frac{L_m}{L_r}\psi_{rd}\right) + \omega_s \psi_{sq}(t) + u_{sd}(t)\\
\frac{d}{dt}\psi_{sq}(t) &= -\frac{R_s}{\sigma L_s}\left(\psi_{sq} - \frac{L_m}{L_r}\psi_{rq}\right) + \omega_s \psi_{sd}(t) + u_{sq}(t)\\
\frac{d}{dt}\psi_{rd}(t) &= -\frac{R_r}{\sigma L_r}\left(\psi_{rd} - \frac{L_m}{L_s}\psi_{sd}\right) + \omega_r \psi_{rq}(t) + u_{rd}(t)\\
\frac{d}{dt}\psi_{rq}(t) &= -\frac{R_r}{\sigma L_r}\left(\psi_{rq} - \frac{L_m}{L_s}\psi_{sq}\right) + \omega_r \psi_{rd}(t) + u_{rq}(t)
\end{aligned} \quad (4)$$

And

$$T(t) = \frac{3}{2} n_p \frac{L_m}{\sigma L_s L_r} \{\psi_{rd}(t)\, \psi_{sq}(t) - \psi_{rq}(t)\, \psi_{sd}(t)\} \quad (5)$$

Simulink induction machine models are available in the literature [9-11], but they appear to be block-boxes with no internal details. Some of them [9-11] recommend using S-functions, which are software source codes for Simulink blocks. This technique does not fully utilize the power and ease of Simulink because S-function programming knowledge is required to access the model variables. S-function run faster than discrete Simulink blocks, but Simulink models can be made to run faster using 'accelerator' functions or producing stand- alone Simulink models.

2.2. Sensor Model

Current, flux and speed sensors are modeled with a pole and a gain.

$$\frac{K}{1+Ts}$$

2.3. Power Electronics Converter Model

The control input to the induction motor is the three-phase stator voltage which is generated through the voltage source inverter. A three phase voltage source inverter is depicted in Fig. 2 consisting of three legs, one for each phase. The legs contain IGBTs (Insulated Gate Bipolar Transistor) in parallel with diodes.

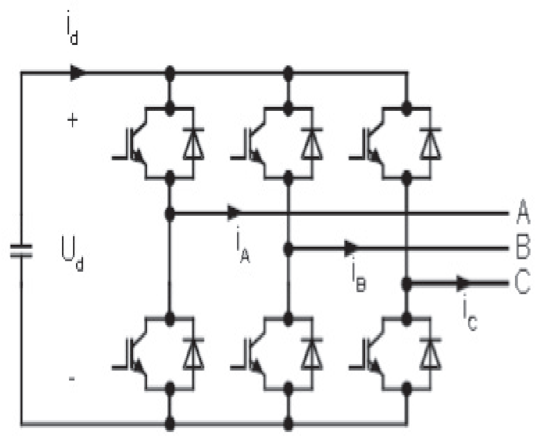


Figure.2 Three-phase voltage source inverter

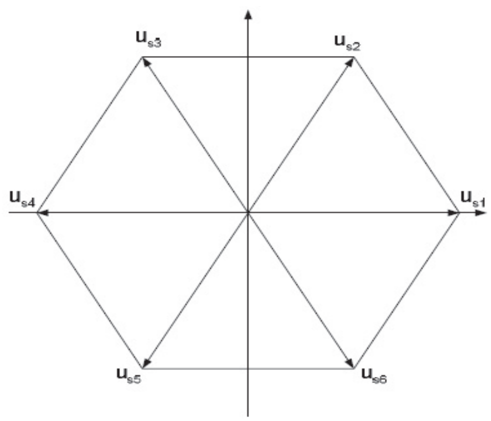


Figure. 3 The vectors *us1 – us6* represent the six non-zero stator voltage space vectors that can be generated by the three-phase voltage source inverter

With two possible positions of each of the six switches, the inverter in Fig.2 may be put in eight different states. Two of these inverter states result in zero stator voltage. These are the combinations with all switches in the upper position or all switches in the lower position. The corresponding (zero) space vectors are sometimes referred to as the zero voltages. The remaining six non-zero stator voltage space vectors are shown in Fig. 3, where the length of each vector is 2/3Ud.

The three (physical) stator voltages uA(t), uB(t) and uC(t) can be obtained from a space vector by projecting it into unit vectors in the directions of us1, us3 and us5 in Fig.3. For example this means that the real part of a space vector corresponds to the A-component of the three-phase quantity.

2.4. Control System Model

2.4.1. Current Controller

According to the equivalent circuit diagram in induction machine model the designed current control loop on axis-A is shown in Fig. 4. Designed of current control loop on axis –B is equivalent.

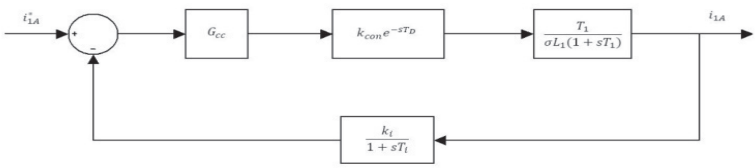


Figure.4 Current control loop on axis –A

In Fig.4, converter is modeled with a delay (Td=0.1ms). Since of dead time between pulses are seldom, it is negligible.

Warning: we cannot compensate pole of converter. With using of optimum margin method we have,

$$G_{cc}(s) = \frac{\sigma L_1(1+sT_1)}{sT_1T_{oi}K_{conv}K_i} \tag{6}$$

By replacing G_{cc} , transfer function i_{1A} to $i_{1A}{}^*$ be is of order two. For sake of simplicity, the approximate transfer function is:

$$\frac{i_{1A}}{i_{1A}{}^*} = \frac{i_{1B}}{i_{1B}{}^*} = \frac{\frac{1}{K_i}}{1+sT_{oi}} \tag{7}$$

2.4.2. Flux Controller

According to the equivalent circuit diagram in induction machine model, with swap current controller transfer function in flux control loop, flux control loop on axis –A are designed in Fig. 5 in the following figure**.**

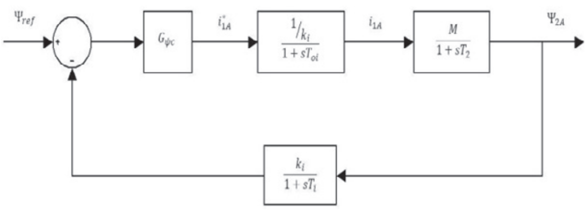


Figure. 5 Current control loop on axis –A

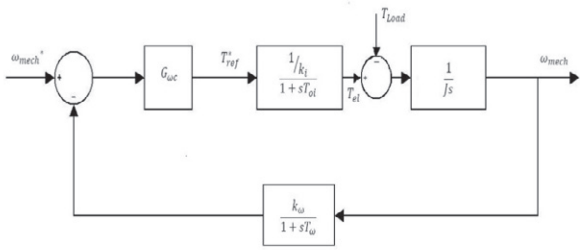


Figure. 6 Speed Control loop on axis -A

By using optimum margin method, we have:

$$G_{\psi c}(s)=\frac{(1+sT_{oi})(1+sT_2)}{sT_{o\phi}M} \tag{8}$$

2.4.3. Speed Controller

Designed speed control loop is shown in Fig.6. Assume maximum speed is equal to synchronous speed .In this method current on axis-A control the flux and current on axis-B control the torque , and in base speed region flux must be maximum and current on axis-A is constant .Therefore control loop on axis-B is active. Since band width of current control loop is greater than speed control loop, transfer function of current control loop with an approximate assumption is $1/k_i/(1+sT_{oi})$ .By using optimum polar method, we have:

$$G_{\omega c}(s)=\frac{K_c(1+sT_c)}{sT_c} \tag{9}$$

3. Simulink Implementation

3.1. Simulation of Dynamic Model of Induction machine

In this paper, simulink models are not used, the model of elements earned from equations. Complete model of induction machine is shown in Fig.7, induction machine model have three main parts: electrical model, mechanical model and transfers block .transfers block convert phase parameter to AB component of K- coordinate.

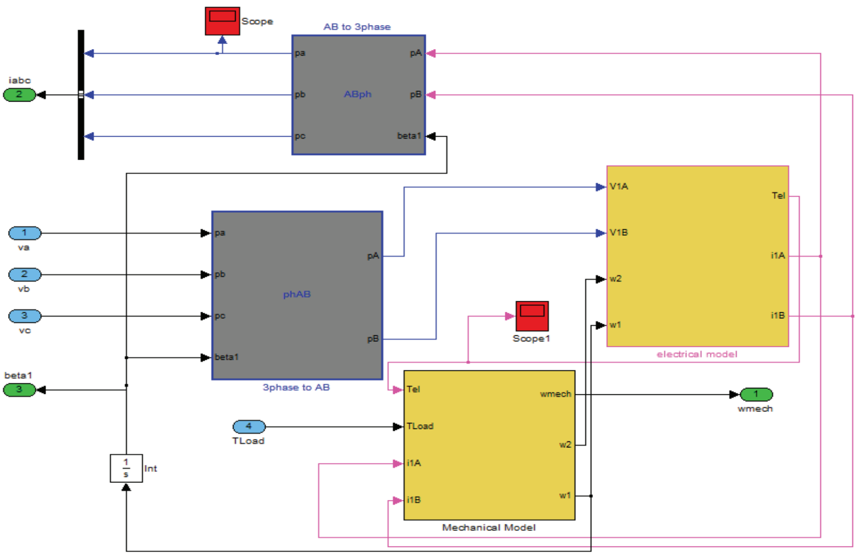


Figure. 7 Complete block diagram of induction machine dynamic model

Electrical part of induction machine model is shown in Fig. 8. This model obtains from implementation of Eqs. (4) and (5).

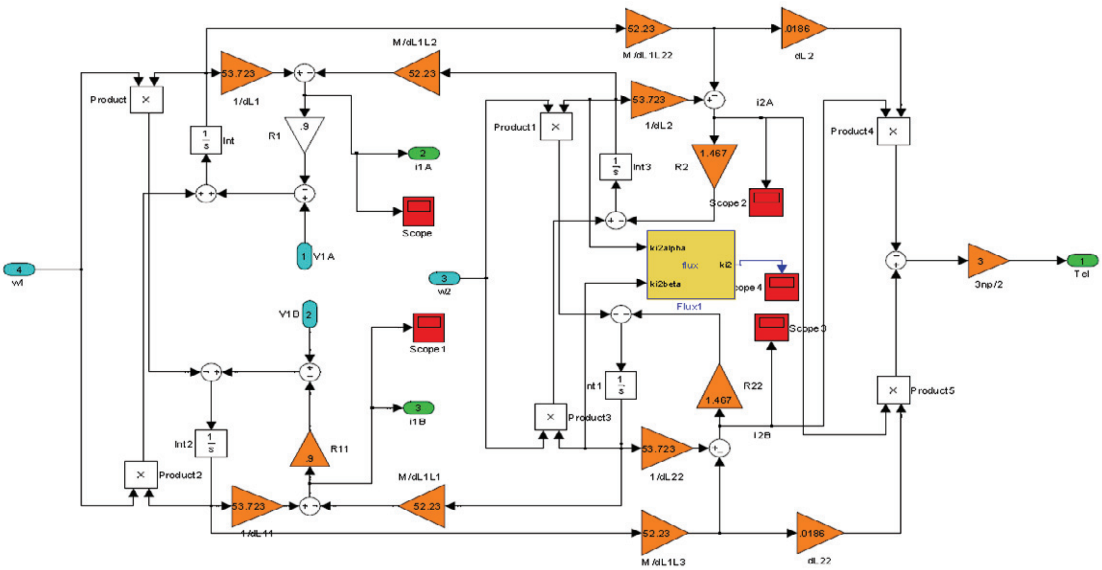


Figure. 8 Block diagram of electrical part of induction machine model

Input parameters are V_{sd} ‘ V_{sq} ‘ ω_s and ω_r (rotor flux speed toward rotor reference). Parameters V_{sd} and V_{sq} be found from transfer block (phase to AB) and ω_s , ω_r comes from mechanical part of induction machine model. From block diagram of electric part of induction machine, electric torque (T_{el}), i_{sd} and i_{sq} are be found then T_{el} straight and i_{sd} and i_{sq} with transmission of transfer block (phase to AB) go to the mechanical part of induction machine. Block diagram of mechanical part is shown in Fig. 9.

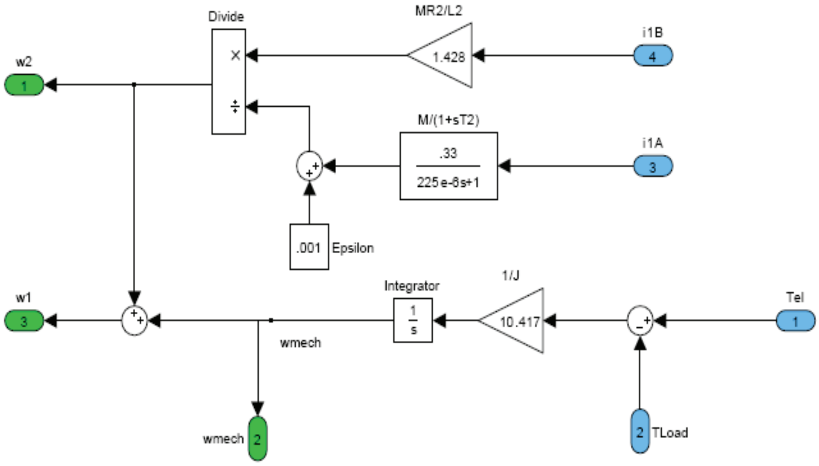


Figure. 9 Block diagram of Mechanical part

By using instantaneous values of i_{sd} and i_{sq} , ω_r could be found, plus with motor mechanical speed (ω_{mech}) produce ω_s. To prevent dividing by zero in simulation, we need to add a negligible constant (Epsilon in Fig.9).Output of mechanical part use for mechanical angle(χ_r), rotor flux angle toward stator and mechanical speed from speed sensor calculation. From Fig. 9, inputs of machine are produce converter voltage and load torque. Outputs of machine are three phase currents, mechanical speed and rotor flux angle. Currents and mechanical speed go to sensor block and rotor flux angle go to composite observer in control system.

3.2. Simulation of Sensor Model

Speed and current sensors block diagram are shown in Fig. 10.

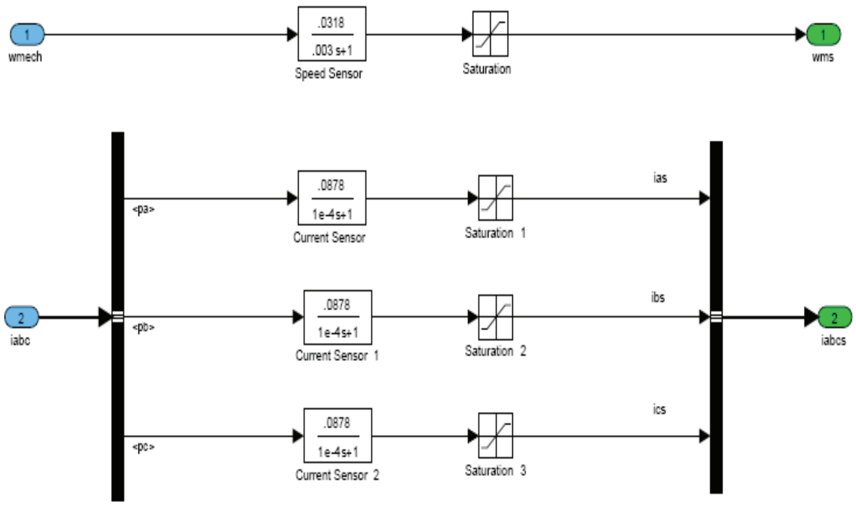


Figure. 10 Speed &current sensors block diagram

Saturation block limit the output of sensors between ±10 V. These operators prevent cross the nominal parameters of the induction machine and protect machine.

3.3. Simulation of Power Electronics Converter Model

Power electronic block diagram is shown in Fig. 11.

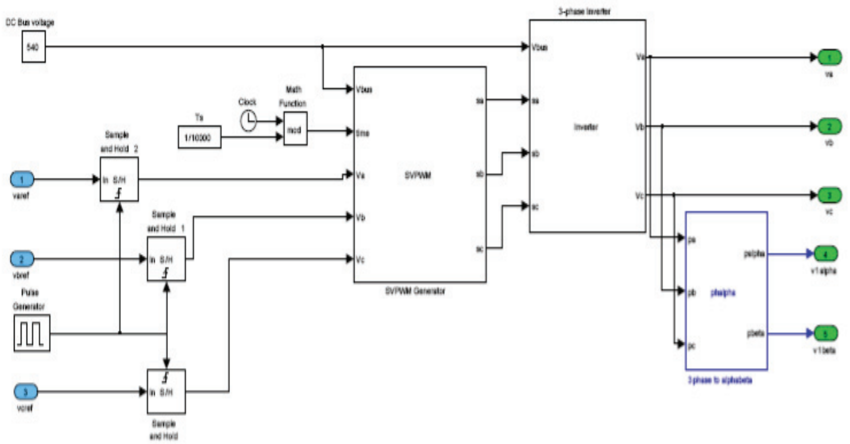


Figure. 11 Speed &current sensors block diagram

Sample and hold blocks sampling the reference voltage values in per 0.1mili second (Ts). Proper switching algorithm implemented in SVPWM Generator and sa, sb and sc are produced switching algorithm. Since connection of machine is delta, voltage values are calculated and given by stator of machine. Reference voltages α-β are used in rotor flux observer block.

3.4. Simulation of Control System Model

In this system rotor flux observer, current, flux and speed controller are designed. Rotor block composite observer is shown in Fig. 12

.

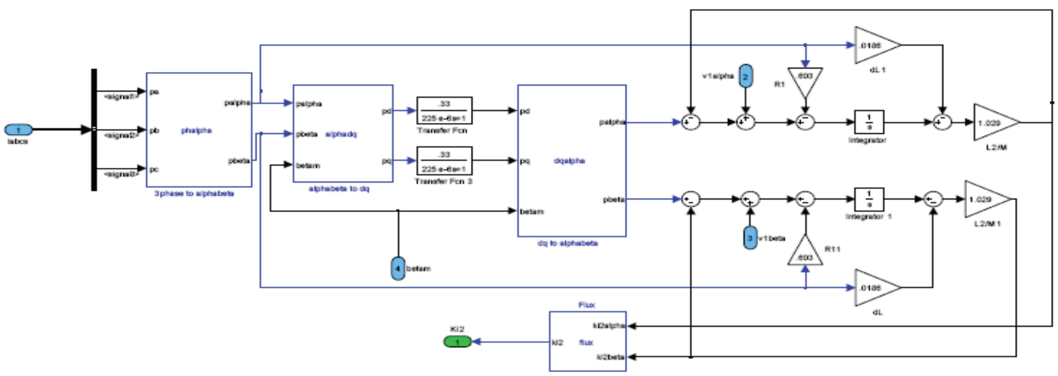


Figure. 12 Rotor flux observer based on composite voltage and current model

Now rotor flux estimate by measuring currents and machine voltages. Control system block diagram is shown in Fig. 13.

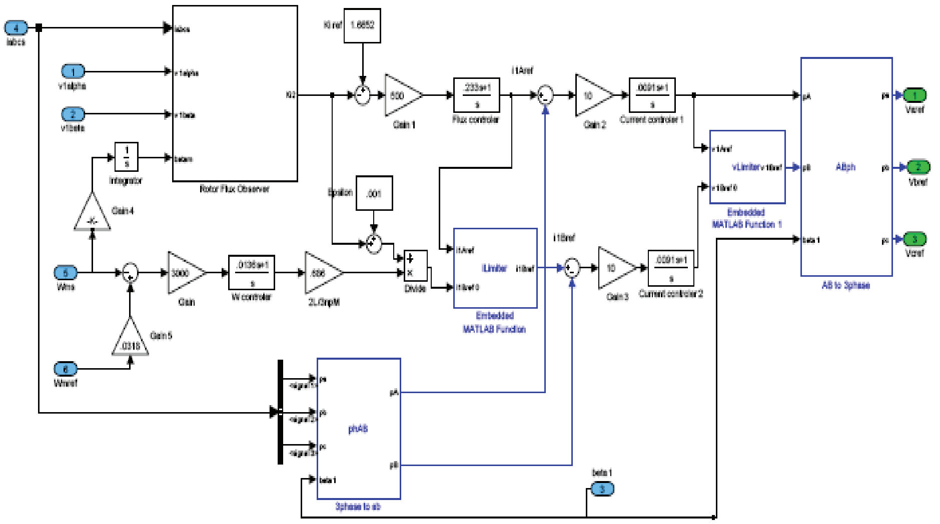


Figure. 13 Control system& block diagram

In this figure, rotor reference flux in base speed region is equal to nominal flux.Speed reference values are free, but we limit voltage and current reference on axis-B by means of 'I limiter' and 'V limiter' that coming follow, $\sqrt{i_{max}^2 - i_{1Ar}}$ and $\sqrt{v_{max}^2 - v_{1Ar}}$.

4. Simulation Results

For testing simulation, by giving nominal torque to system can be saw input current value. Nominal torque is:

$$T_n = 49.48 \quad N.m \tag{10}$$

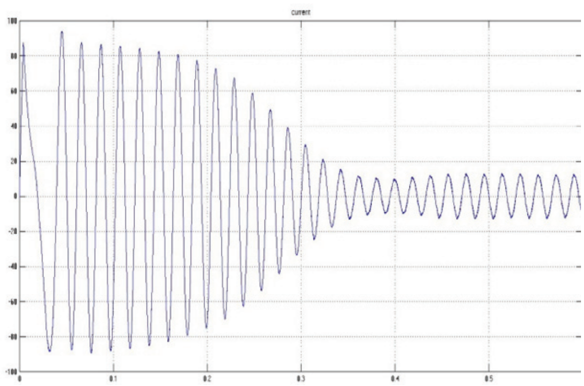


Figure. 14 Input current of machine

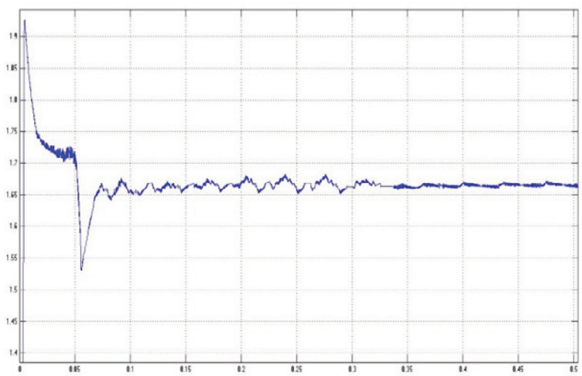


Figure.15 Output of voltage model observer on 5%nominal speed

Output of voltage model observer and current model observer on 5% nominal speed (15.16 rad/s) are shown in Fig.14 and Fig.15 .output on 90% nominal speed (272.85 rad/s) are in Fig.16 and Fig.17.

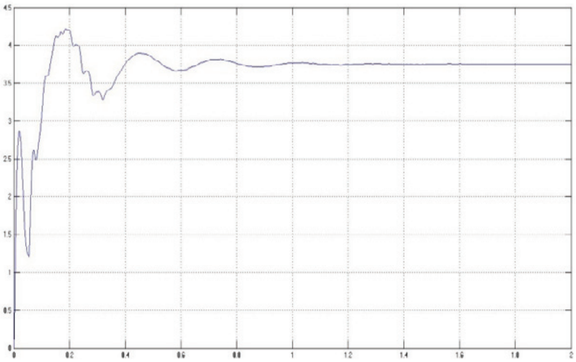


Figure.16 Output of current model observer on 5%nominal speed

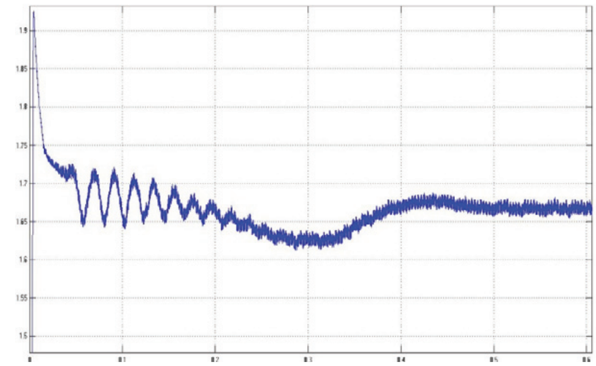


Figure.17 Output of voltage model observer on 90%nominal speed

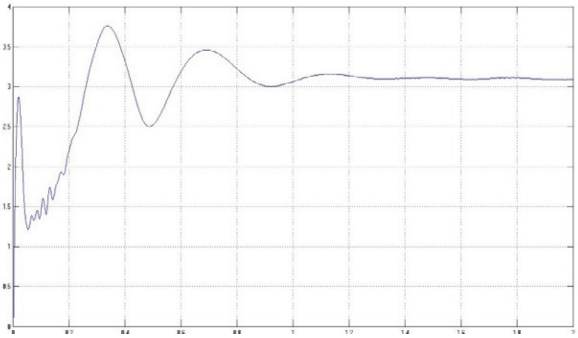


Figure.18 Output of current model observer on 90%nominal speed

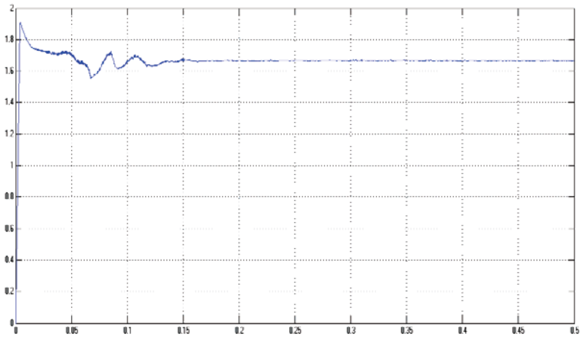
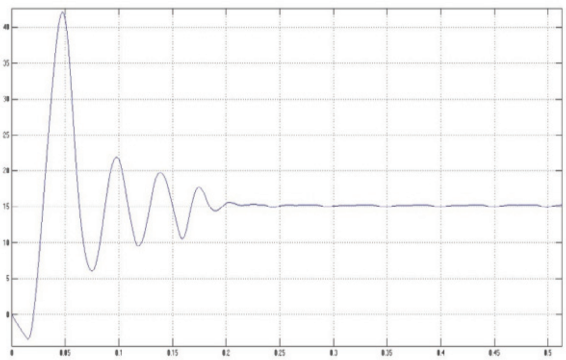


Figure. 19 output of composite model observer on 5%nominal speed

4.1. Operation in 5% nominal speed (15.16 rad/s) with half nominal load



. Figure. 20 Mechanical speed

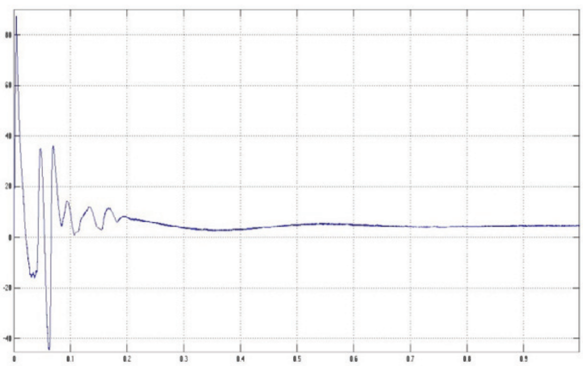


Figure. 21 Stator current on axis-A

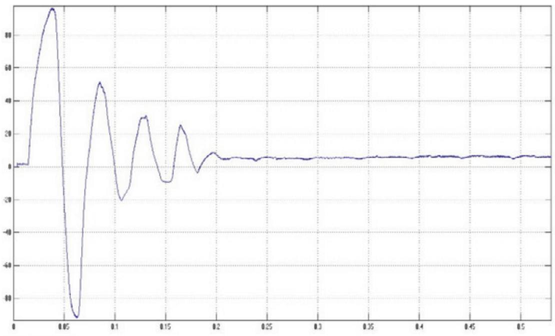


Figure. 22 Stator current on axis-B

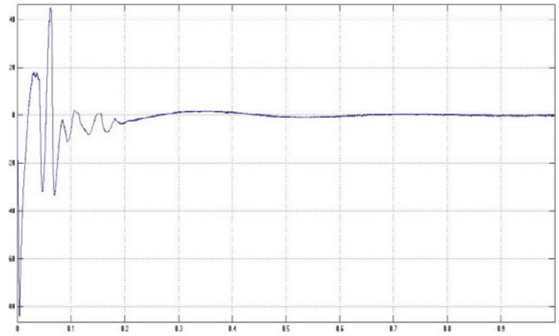


Figure. 23 Rotor current on axis-A

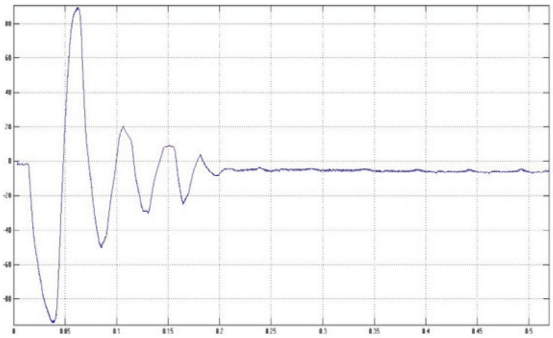


Figure. 24 Rotor current on axis-B

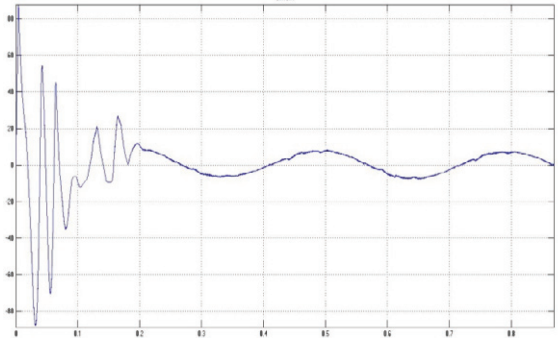


Figure. 25 phase current A

4.2. On previous operation point, reference speed grows up 10% with a step

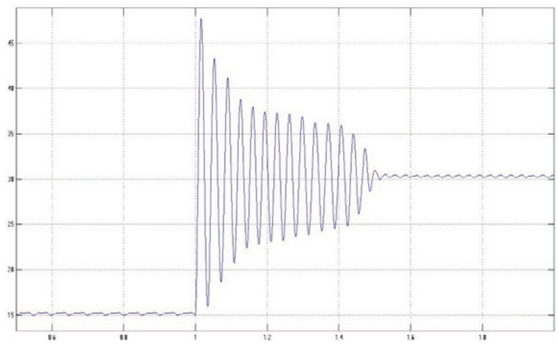


Figure. 26 mechanical speed toward time

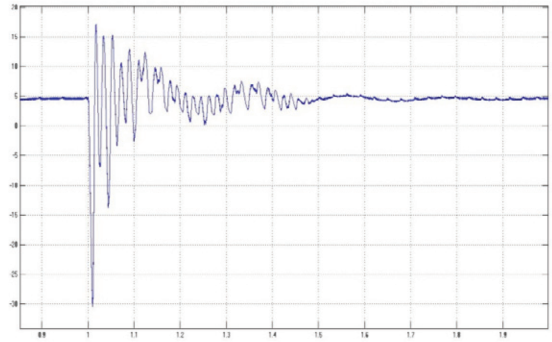


Figure. 27 Stator current on axis-A

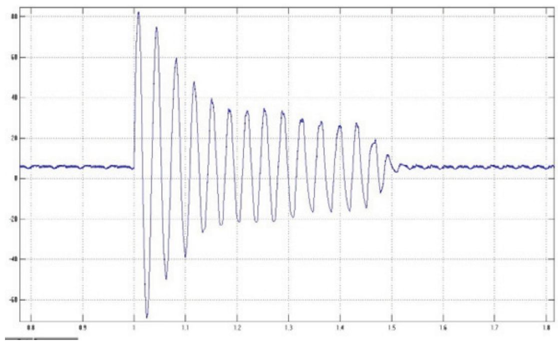


Figure. 28 Stator current on axis-B

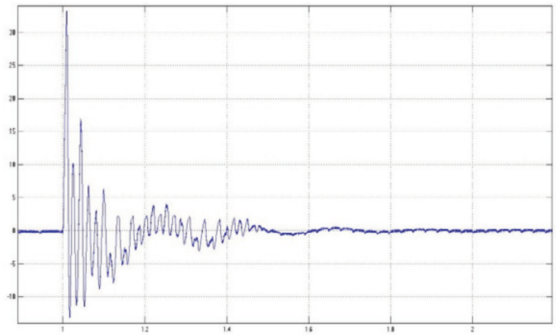


Figure. 29 Rotor current on axis-A

5. Conclusion

Goal of this paper is improvement of learning's in universities with a simulation study of the vector controlled induction motor drive. By implementing of this simulation on devises in advanced electrical machine laboratory students can compare the result of simulation and experimentation. Also, a high performance vector controlled drive employing the rotor flux observer has been presented. Estimation of electric machine parameters is very important for variable speed control using field orientation techniques which are very popular in building services systems such as elevator drives, fan drives and pumps etc. Instead of CM and VM observer models in the vector controlled drive system, the use of the composite model observer has made the drive system capable of operating in entire speed range with more acceptable performance. Comparison between CM and VM shows: 1- In Fig. 14, system is stable around 0.5. 2- In Figs. 15-18, the voltage observer model (VM) has good performance vs. current observer model (CM) in low speed and vice versa in high speed. 3- Voltage observer model has high frequency noise when speed increase. Moreover, composite flux observer shown in Figs.19-20 has good performance in the wide range speed and is stable very quickly. Therefore, students by doing this simulation could guess the behavior of actual induction machine drive.

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