PSPICE SIMULATION OF SPLIT PHASE INDUCTION MOTOR FED BY A DIRECT AC-AC CONVERTER

Mehmet ÖZDEMİR* Sedat SÜNTER* Barış YURTSEVEN* Güven ÖNBİLGİN**

*Fırat University, Dept. Of Electrical and Electronics Engineering, Elazığ- TURKEY
**Ondokuz Mayıs University, Dept. of Electrical and Electronics Engineering, Samsun - TURKEY

Abstract: Direct ac-ac converters have a number of advantages compared to dc link converters used in motor control applications. A split phase ac-ac converter can be easily realised using power IGBTs. This paper has provided a model for the steady-state and transient behaviour of a split phase induction motor fed by a direct ac-ac converter via use of PSPICE software as a novel approach to the performance evaluation of such systems.

The advantage of this method over the others is that it does not involve the utilisation of specialised programs and mathematical difficulties such as the solution of stiff differential equation.

1. Introduction

Single phase induction motors are widely used in industry and home applicants. These are inherently single and comparatively constant speed machines. In case of applications requiring variable speed operation, a supply with variable frequency and voltage is needed. Variable frequency-voltage supplies are available in the form of inverters but these involve disadvantages such as the size of capacitors and the fact that for bi-directional power flow the input of the inverter has to be controlled. On the other hand single-phase direct AC-AC converters do not suffer from these problems, have the advantages of fast dynamic response, low weight/power ratio and single phase input and output[1]. Single phase bipolar converter allows for higher voltage inputs through the employment of an appropriate modulation, as well as limited switching frequency ranges. IGBTs have better chopping characteristics and simpler driving circuits. The bilateral switches needed for this purpose are usually realised using power transistors. The use of bilateral switches enables the process of regeneration, which is a desirable feature in motor control applications, to take place. IGBTs have been used as controlled switch to reach higher switching frequencies as well as higher powers.

This study involves split phase motors. In the previous studies, performance analysis of single phase induction motor fed from a variable frequency variable voltage supply involved steady-state equivalent circuit of the machine[2]. This study provides an analysis of the machine with the auxiliary winding fed by a variable frequency-voltage supply(i.e. direct AC-AC converter) to provide both the time-varying(transient) and steady-state behaviour at various frequencies. The mathematical model required has been obtained through the use of voltage equations in direct phase model[3].

In recent years, many numerical methods have been proposed and implemented to simulate data the time-varying behaviour of such systems which apparently include several different topologies depending on switching patterns, and differential equations which may be stiff and/or non-linear in some cases. These may require highly sophisticated numerical and device modelling approaches with varying decrease of complexity and approximations that may render the mentioned methods as ones of less practical value. In this study, PSPICE software has been utilised to model and simulate the machine-converter system with the advantage of near realistic modelling of IGBT switches and providing some sort of an analogue-computer like simple approach to the simulation [4].

2. Single Phase Direct AC-AC Converter

A direct ac-ac converter chops the input ac voltage at a relatively high frequency and reconstructs the output waveform at desired frequency. The power circuit of a converter feeding an induction motor is shown in Fig.1.

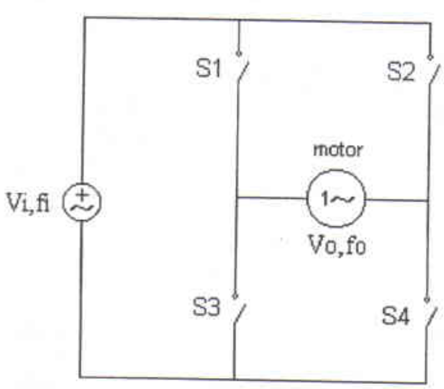


Fig.1 Power circuits of single-phase ac-ac converter

The bilateral switches S1 and S4 are driven by a PWM switching signal Fs derived from a chosen modulation scheme. Each of the switches is realised using power IGBTs as shown in Fig 2. The PWM control signal will be phase-split and applied as the gate inputs to the two bi-directional switches S and S'. The body diode of one IGBT in the switching module serves as the return path when the other switch is conducting.

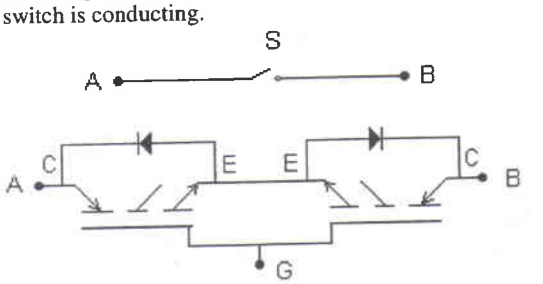


Fig 2 . Power IGBT bilateral switch

When the switching signal Fs is positive, S1 and S4 are closed making $V_0 = V_i$. When it is zero, S1 and S2 are closed resulting in the output voltage zero. When the switching signal is negative, S2 and S3 are closed making $V_0 = -V_i$. If V_i is given by;

$$V_i = V_m \operatorname{Cos} w_i t \tag{1}$$

then,

$$V_0 = Fs.V_m \operatorname{Cos} w_i t \tag{2}$$

If the switching signal Fs has a frequency, f_s then the output voltage V_0 will have a fundamental frequency $f_0 = (f_s - f_i)$. In addition, there will be a number of harmonics. A suitable modulation of F_s will help reducing the harmonics. A uniform modulation scheme using a reference square wave and a high frequency triangular wave is shown in fig. 3.

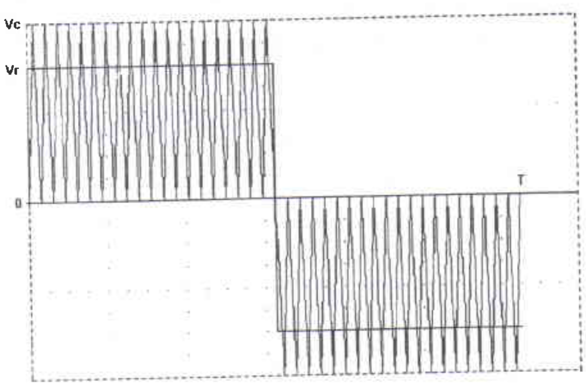


Fig. 3 Waveforms of uniform triangular modulation

3. Mathematical Model of the Split-Phase Motor

3.1 Electrical Relations

For the stator and auxiliary windings, rotor sets up voltage equations(two for each) can be given in closed form as follows;

$$[V_{s,r}] = [R_{s,r}][i_{s,r}] + [L_{s,r}]\left[\frac{di_{s,r}}{dt}\right] + \left[\frac{dL_{s,r}}{d\theta}\right][i_{s,r}]\frac{d\theta}{dt} \tag{3}$$

where the matrix, $[L_{s,r}]$ is the inductance matrix and is to be defined by flux-linkage equations, the resistance matrix, $(R_{s,r})$ is a diagonal matrix consisting of phase winding resistance.

$$\begin{bmatrix}\Psi_{sa}\\ \Psi_{sb}\\ \Psi_{ra}\\ \Psi_{rb}\end{bmatrix} = \begin{bmatrix} L_{sa} & 0 & M_{sa,ra} & M_{sa,rb}\\ 0 & L_{sb} & M_{sb,ra} & M_{sb,rb}\\ M_{ra,sa} & M_{ra,sb} & L_{ra} & 0\\ M_{rb,sa} & M_{rb,sb} & 0 & L_{rb}\end{bmatrix}\begin{bmatrix} i_{sa}\\ i_{sb}\\ i_{ra}\\ i_{rb}\end{bmatrix} \tag{4}$$

The circuit model parameters are then determined by neglecting the variation of the degree of saturation, the space harmonics in the flux wave, and iron losses with the assumptions of balanced/identical windings and uniform air-gap following simplifications arise:
The elements of the resistance and inductance matrixes in Eq.(3) are defined as;
Rsa: Resistance of the main stator winding.
Rsb: Resistance of the auxiliary stator winding
Rra=Rrb=Rr: Resistance of the rotor winding.
Lsa: Inductance of the main winding
Lsb: Inductance of the auxiliary winding.
Lra=Lrb=Lr: Inductance of the rotor winding.

Mutual inductances in the flux-linkage equation (4) are given as follow;

$$M_{sa,ra} = M_a Cos\theta \qquad M_{sa,rb} = M_a Cos(\theta + \frac{\pi}{2})$$

$$M_{sb,ra} = M_b Cos(\theta - \frac{\pi}{2}) \qquad M_{sb,rb} = M_b Cos\theta$$

Where; Ma is maximum value of the mutual inductance between main stator and rotor windings. Mb is maximum value of the mutual inductance between auxiliary stator and rotor windings.

The voltage equation (3) includes mutual inductances dependent on angular position θ whereas,
dθ/dt gives the rotor angular speed as;

$$\frac{d\theta}{dt} = \omega \tag{5}$$

The derivative of the inductance matrix is;

$$\left[\frac{dL_{s,r}}{d\theta}\right] = \begin{bmatrix} 0 & 0 & -M_a Sin\theta & -M_a Cos\theta\\ 0 & 0 & M_b Cos\theta & -M_b Sin\theta\\ -M_a Sin\theta & M_b Cos\theta & 0 & 0\\ -M_a Cos\theta & -M_b Sin\theta & 0 & 0\end{bmatrix} \tag{6}$$

3.2 Electromechanical Relations

The instantaneous torque developed can be expressed in terms of the phase variable as;

$$T_e = -\frac{p}{2}\left[i_{s,r}\right]\left[\frac{\partial L_{s,r}}{\partial\theta}\right]\left[i_{s,r}\right] \tag{7}$$

Elaboration of the operation given in the above relation results in;

$$T_e = p[(i_{ra}i_{sa}M_a + i_{rb}i_{sb}M_b)Sin\theta] + [(i_{sa}i_{rb}M_a - i_{sb}i_{ra}M_b)Cos\theta] \tag{8}$$

3.3 Mechanical Relations

Equation of motion for the machine is known to have the form of;

$$(T_e - T_L) = J\frac{d\omega}{dt} \tag{9}$$

and can be rewritten for the angular speed, ω as;

$$\frac{d\omega}{dt} = \frac{1}{J}(T_e - T_L) \tag{10}$$

This relation shows the requirements for an integration process.

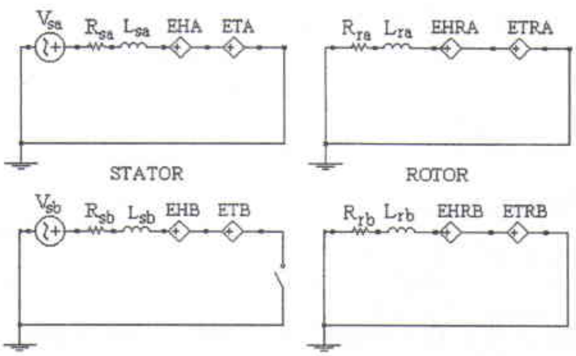
4. PSICE Simulation Method

PSPICE package, just as some other circuit simulation packages, aid the design of circuits by provision of analysis in time domain. PSPICE 5.4 package has been used to set up the stator and rotor circuits, ac-ac converter circuits and circuits simulating the system equations for the motor electrical and electromechanical behaviour.

The operation of the ac-ac converter can be simulated on a digital computer and all the required waveforms can be obtained. The performance of the converter with IGBT switches and its effectiveness at the chosen frequency has to be first analysed using the simulation package PSPICE 5.4 . It is extremely useful in analysing converter circuits containing a variety of semiconductor devices. Each bilateral switch consists of two IGBTs and the associated drive circuitry is located in the form of a 'subcircuit' which is recalled whenever a switch is encountered.

The modulated switching function Fs is created using PSPICE and applied as input to each bilateral switch shown in Fig.2. The transient response for different duty cycles is obtained in the form of data set.

Fig.4 gives the circuit representation for PSPICE simulation of the split-phase asynchronous motor system. This circuit is valid in the time domain and the software package program accepts non-linear functional parameters as well. In the circuit model, 's' is the centrifugal switch, denoting starting period with 's' closed and running condition with 's' open. Consequently, both stator windings are used during starting, and then, in the case of the split-phase machines, one of the windings is disconnected from the source when the machine reaches 60 to 80 percent of synchronous speed. Thus, the normal mode of the operation as many single-phase induction machines involves with only one stator winding. In every phase of the stator two induced e.m.f.'s are present and represented by controlled voltage sources. Induced e.m.f.'s due to current derivatives are the 'transformer e.m.f.'s and those due to rotor speed are 'motional e.m.f.'s.



$$EHA = -M_a\omega\left[i_{ra}Sin\,\theta + i_{rb}Cos\,\theta\right]$$

$$EHB = M_b\omega\left[i_{ra}Cos\,\theta - i_{rb}Sin\,\theta\right]$$

$$EHRA = -\omega\left[M_a i_{sa}Sin\,\theta - M_b i_{sb}Cos\,\theta\right]$$

$$EHRB = -\omega\left[M_a i_{sa}Cos\,\theta + M_b i_{sb}Sin\,\theta\right]$$

$$ETA = M_a\left[\frac{di_{ra}}{dt}Cos\,\theta - \frac{di_{rb}}{dt}Sin\,\theta\right]$$

$$ETB = M_b\left[\frac{di_{ra}}{dt}Sin\,\theta + \frac{di_{rb}}{dt}Cos\,\theta\right]$$

$$ETRA = M_a\frac{di_{sa}}{dt}Cos\,\theta + M_b\frac{di_{sb}}{dt}Sin\,\theta$$

$$ETRB = -M_a\frac{di_{sa}}{dt}Sin\,\theta + M_b\frac{di_{sb}}{dt}Cos\,\theta$$

Fig 4. PSPICE simulation circuit model for the split-phase induction motor in the time domain

The derivatives of the inductances are obtained by the matrix in Eq.(6). The circuit in Fig.4. is used to obtain the current derivatives. This with $R_T.C_T=1$ has as its input a controlled voltage source with the value phase current and its output becomes negative derivative of the phase current.

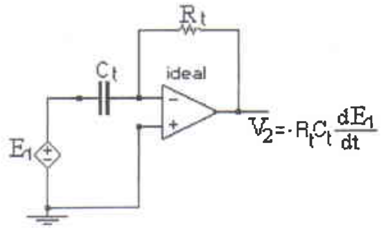


Fig 5. Circuit for the derivative of currents

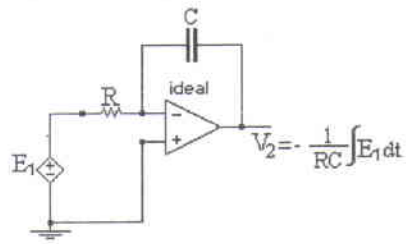


Fig 6. Integration circuit

The induced torque equation utilises the another controlled voltage source and the integration circuit in Fig.6. is used for the mechanical equations.

This circuit's input voltage consists of the induced torque and total load torque divided by j(moment of inertia) respectively, in the form of controlled voltage sources with R.C taken as unity, the circuit generates rotor speed 'ω' as required by Eq.10. Similarly integration of the voltage representing 'ω' produce rotor angle θ. This completes the simulation of the mathematical model.

5. Results

The converter and split-phase motor is first simulated on a digital computer. The parameters of the split-phase induction motor used in simulation are given in appendix. First, split-phase induction motor was fed by 30 and 50 Hz frequencies with constant v/f in constant torque region. Second, the machine has been operated in constant power region at 70 Hz output frequency. The motor speed in transient for various frequencies are shown in Fig.7. As can be seen from Fig.7, at 30 and 50 Hz operation frequencies the acceleration times of the motor are almost equal due to the constant v/f operation. However, at 70 Hz, the acceleration takes longer time due to the fact that the machine operates in constant power region and hence with lower v/f ratio. The main stator winding currents obtained for 30, 50 and 70 Hz are given in Fig.8,9,10, respectively. The auxiliary stator winding currents obtained for 30, 50 and 70 Hz are given in Fig.11,12,13, respectively.

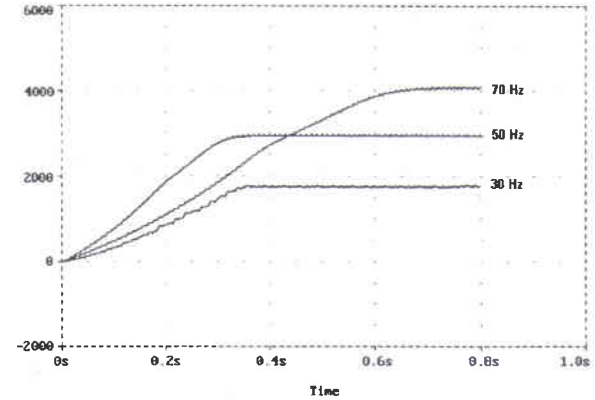


Fig 7 . Speed versus time graphics at various frequencies

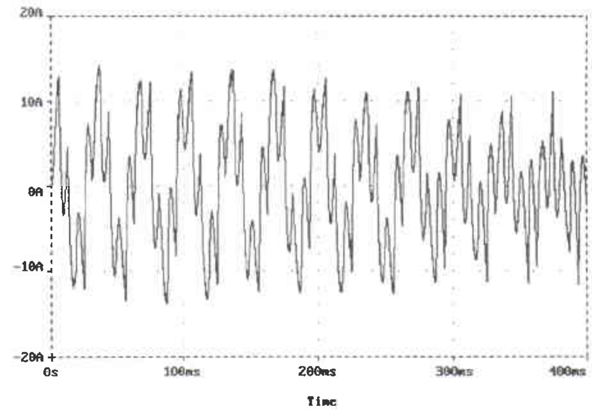


Fig 8 . The main stator winding current obtained for 30 Hz in transient

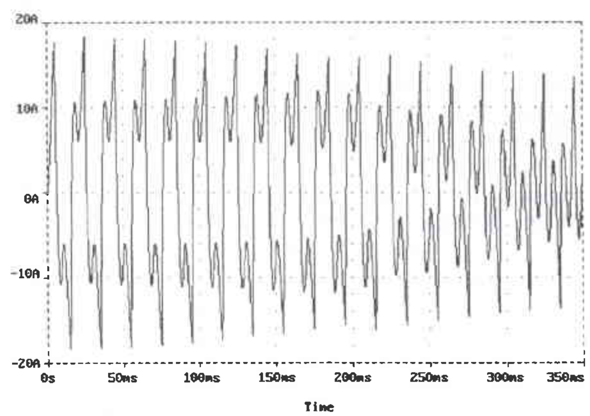


Fig 9 . The main stator winding current obtained for 50 Hz in transient

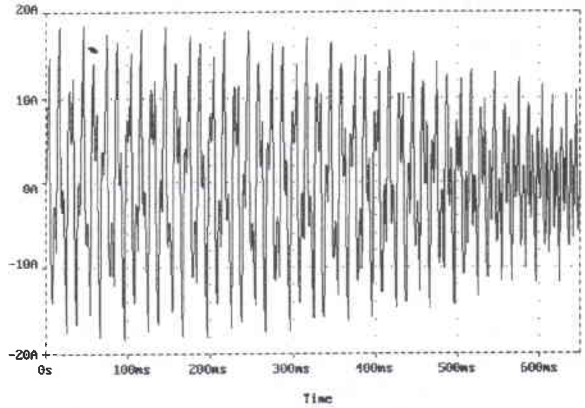


Fig 10 . The main stator winding current obtained for 70 Hz in transient

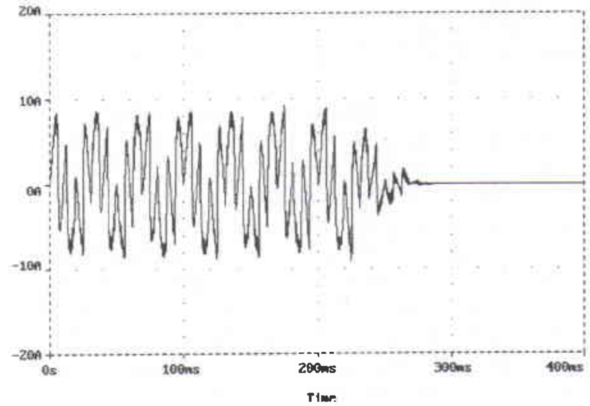


Fig 11 . The auxiliary stator winding current obtained for 30 Hz in transient

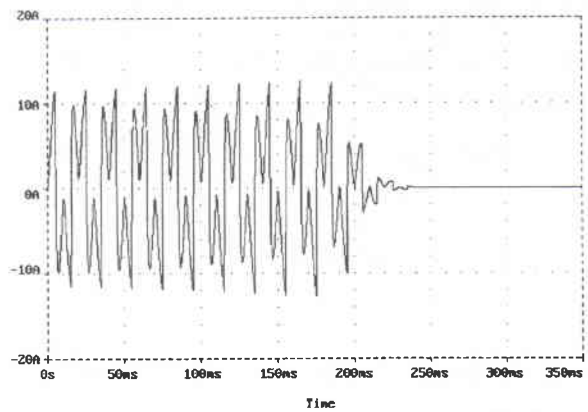


Fig 12 . The auxiliary stator winding current obtained for 50 Hz in transient

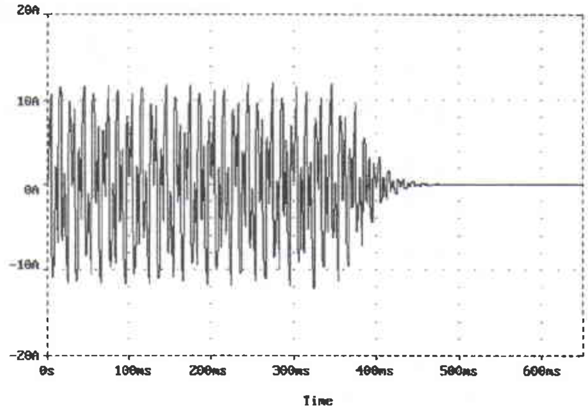


Fig 13 . The auxiliary stator winding current obtained for 70 Hz in transient

6. Conclusions

This paper has presented a PSPICE based simulation model of split-phase induction motor fed by a direct ac-ac converter. The distinguished feature is that it does not require any programming language or special programming effort as well as being very effective to predict and analyse the dynamic (time-varying) behaviour of the system. Simulation have been carried out to reveal that, in open loop speed control applications of split-phase induction motors, variable frequency supplies can be provided by direct ac-ac converters employing IGBT switches at low and medium power range. It has been demonstrated that with this system it is possible to work above synchronous speed at constant power region as well.

References

[1] Khoui, A and Yuvarajan, S.: Single phase ac-ac converters using power MOSFETs. IEEE Trans. Ind. Electronic., Vol. 35, No. 3, pp.442-443, Aug. 1988.

[2] Khoui, A. and Yuvarajan, S.: Steady state performance of a single phase induction motor fed by a direct ac-ac converter. Conf. Rec., IEEE IAS Annual Meeting, pp. 128-132 (Pittsburg), 1989.

[3] Krause, P.C.: Analysis of Electric Machinery. Mcgraw-Hill, Inc., 1986.

[4] Özdemir, M., Bayındır, M.İ. and Önbilgin, G.: A pspıce simulation of a series excited synchronous motor. Symposium on power electronics industrial drives power quality traction systems(SPEEDAM 96), June 1996.

Appendix

Parameters of split phase induction motor

220V, 300 W, 2 pole, J=0.001 kg.m^2

R_{sa}=7 Ohms R_{sb}=20 Ohms L_{sa}=0.531 H L_{sb}=0.5278 H

R_{ra}=R_{rb}=R_r = 6.11 Ohms L_{ra}=L_{rb}=L_r= 0.53 H M_a= 0.517 H

M_b = 0.522 H B = 0.00005569 Nm.s/rad