SIMULATION AND MODELING OF VECTOR CONTROLLED 3-PHASE MATRIX CONVERTER INDUCTION MOTOR DRIVE

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ABSTRACT

In this paper, a vector controlled matrix converter-fed induction motor drive has been simulated using the MATLAB/SIMULINK package program. The feedforward indirect field orientation technique has been implemented in the drive system. A modulation algorithm giving a unity power factor at the input is used to generate switching signals of the devices in the matrix converter power circuit. Simulation results obtained for various load conditions at 2 kHz switching frequency are presented. The results illustrate the feasibility of the high performance matrix converter drive system.

I. INTRODUCTION

The matrix converter is the most general converter-type in the family of AC-AC direct converters. On the one hand, the matrix converter fulfils the requirements to provide a sinusoidal voltage at the load side, on the other hand it is possible to adjust unity power factor on the mains side under certain conditions [1]. Since there is no dc-link like in common converters, the matrix converter can be built as a full-silicon structure. However, a mains filter is necessary to smooth the pulsed currents on the input side of the matrix converter. Using a sufficiently high pulse frequency, the output voltage and input current both are shaped sinusoidally. The matrix converter is an alternative to an inverter drive for 3-phase frequency control. The converter consists of nine bi-directional switches arranged as three sets of three so that any of the three input phases can be connected to any of the three output lines as shown in Figure 1. The switches are then controlled in such a way that the average output voltages are a three phase set of sinusoids of the required frequency and magnitude [2].

The matrix converter can comply with four quadrants of motor operations, while generating no higher harmonics in the three-phase AC power supply. Compared to conventional drives there is potential for reduced cost of manufacture and maintenance, and increased power/weight and power/volume ratios. The circuit is inherently capable of bi-directional power flow and also offers virtually sinusoidal input current, without the harmonics usually associated with present commercial inverters.

The physical realisation of the matrix converter is not straightforward due to the fact that there are no freewheeling paths. In addition, the number of the devices in the power circuit is high comparing to that of the inverter (for instance 18-switch and 18-diode). Consequently, the timing of the switch actuation signals is particularly critical and protection of the circuit under fault conditions requires very careful consideration [3]. No industrial use has also been made of this converter type up to now.

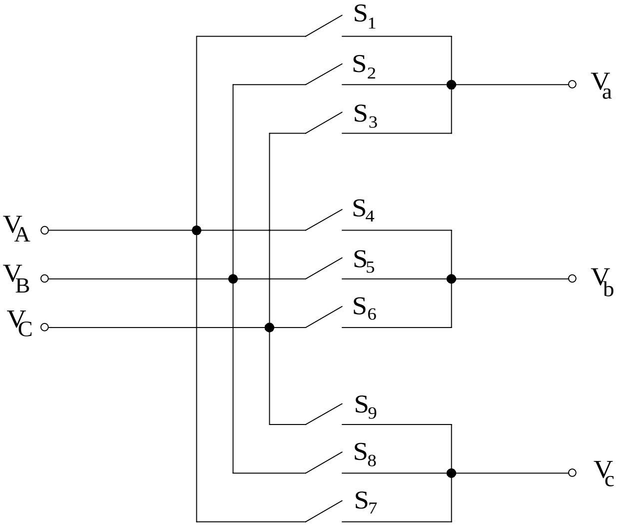

Figure 1. Matrix converter schematic block diagram representation.

Only a few technical papers have dealt with the dynamic behaviour analysis of the vector controlled matrix converter motor drive. The principle of vector control was devised by Blaschke [4] and was developed by Leonhard [5]. This paper concerns dynamic simulation of the vector controlled matrix converter drive that has servo performance and true four quadrant capability.

II. MODULATION ALGORITHM

Many of the published papers on the implementation of modulation algorithms for the matrix converter have employed fixed switching patterns. In this case, for certain output conditions (amplitude, frequency etc.) duty cycles for the switching patterns are pre-calculated and placed into the memory. The fixed switching patterns, for instance using the Venturini algorithm [1], can be only created for certain output frequencies where input and output frequencies are synchronised such as; 25 Hz, 50 Hz, 100 Hz etc. The problem with the modulation algorithms for the matrix converter is more complex than the usual PWM situation since the switch actuation signals must be synchronised to the supply voltage whereas the synthesised output frequency must be totally asynchronous with respect to the supply frequency. For closed loop operation, it is required to calculate the duty cycles every sampling period in order to achieve voltage control in which the output frequency is continuously variable. For unity input displacement factor the duty cycle for the switch connected between the input phase, β and output phase, γ can be defined as;

$$T_{\beta\gamma} = T_s \left[\frac{1}{3} + \frac{2\, V_{o\gamma} V_{i\beta}}{3 V_{im}^2} + \frac{2q}{9\, q_m} \sin(\omega_i\, t + \psi_\beta) \sin(3\, \omega_i\, t) \right] \tag{1}$$

where; ψ_β: 0, $2\pi/3$, $4\pi/3$ corresponds to the input phases A,B and C, respectively, q_m is the maximum voltage ratio (0.866), q is the desired voltage ratio, V_{im} is the input voltage vector magnitude and $V_{o\gamma}$ is given by;

$$\begin{aligned} V_{o\gamma} = q\, V_{im} \cos(\omega_o\, t + \psi_\gamma) - \frac{q}{6} V_{im} \cos(3\, \omega_o\, t) \\ + \frac{1}{4} \frac{q}{q_m} V_{im} \cos(3\, \omega_i\, t) \end{aligned} \tag{2}$$

where; ψ_γ: 0, $2\pi/3$, $4\pi/3$ corresponds to the output phases, a,b and c, respectively. Note that the desired output voltage has third harmonic components at the input and output frequencies added to it to produce $V_{o\gamma}$. This is a requirement to get the maximum possible voltage ratio [2]. Equations (1) and (2) are used to calculate switching times for the matrix converter.

III. VECTOR CONTROL STRATEGY

The vector control strategy has been simulated in the matrix converter induction motor drive. The specifications of the motor are given in the appendix. The induction machine is controlled in synchronously rotating d-q axis frame with the d-axis oriented along the stator flux vector position. In this way a decoupled control between the electrical torque and the rotor excitation current is obtained. The indirect vector control technique using impressed voltages and control of field and torque current components has been implemented in the drive system. The control requires the measurements of the stator currents and the rotor position.

Equations (3-5) are the fundamental equations for vector control [5] and allows the induction motor to act like a separately excited DC machine with decoupled control of torque and flux, making it possible to operate the induction motor as a high-performance four-quadrant servo drive.

$$i_{sd} = \tau_r \frac{di_{mrd}}{dt} + i_{mrd} \tag{3}$$

$$\omega_{sl} = \left(\frac{1}{\tau_r i_{mrd}} \right) i_{sq} \tag{4}$$

$$T_e = 3 \left(\frac{P}{2} \right) \frac{L_o^2}{L_r} i_{sd} i_{sq} \tag{5}$$

Figure 2. shows a schematic block diagram for the vector-controlled matrix converter induction motor drive where three output currents and rotor position are required to be measured. The vector control method shown in Figure 2. imposes a rotor flux vector angle Θ_e which is aligned to the d-axis. The motor speed, ω_r is measured and compared to the demanded speed, ω_r*. The resulting speed error is then processed by a proportional-integral (PI) controller to produce an i_{sq}* demand, which in the constant torque region is proportional to the torque demand providing that the system is field oriented. The flux current demand is maintained constant at just under saturation level when the machine runs below synchronous-speed. However, field weakening must be introduced above synchronous-speed operating conditions so that the flux current reference is reduced as the speed is increased above its synchronous base.

The transformation of the instantaneous stator currents into field oriented d and q axis components is carried out in two stages. First, the three instantaneous currents $i_{sa}(t)$, $i_{sb}(t)$ and $i_{sc}(t)$ are transformed to the stationary two axis currents, $i_{s\alpha}(t)$ and $i_{s\beta}(t)$. These are then transformed into the rotating d-q axis currents, i_{sd} and i_{sq}. The equivalent complex operator $e^{-j\Theta e}$ is used in this transformation. Θ_e denotes the instantaneous flux vector angle which is determined by summing the rotor position signal and the commanded slip position obtained by integrating Equation (4). The inverse transformation of d and q axis values to the instantaneous stator reference frame is represented by the complex operator $e^{j\Theta e}$. The two current controllers which employ PI control process the i_{sd} and i_{sq} errors to give V'_{sd} and V'_{sq}. Voltage compensation terms are added to the output of each current controller to get the resulting voltage reference signals V_{sd}* and V_{sq}*. These voltages are then converted to the three-phase voltages using the complex operator $e^{j\Theta e}$. The three-phase voltages V_{ao}*, V_{bo}*, V_{co}* and instantaneous flux vector angle, Θ_e are

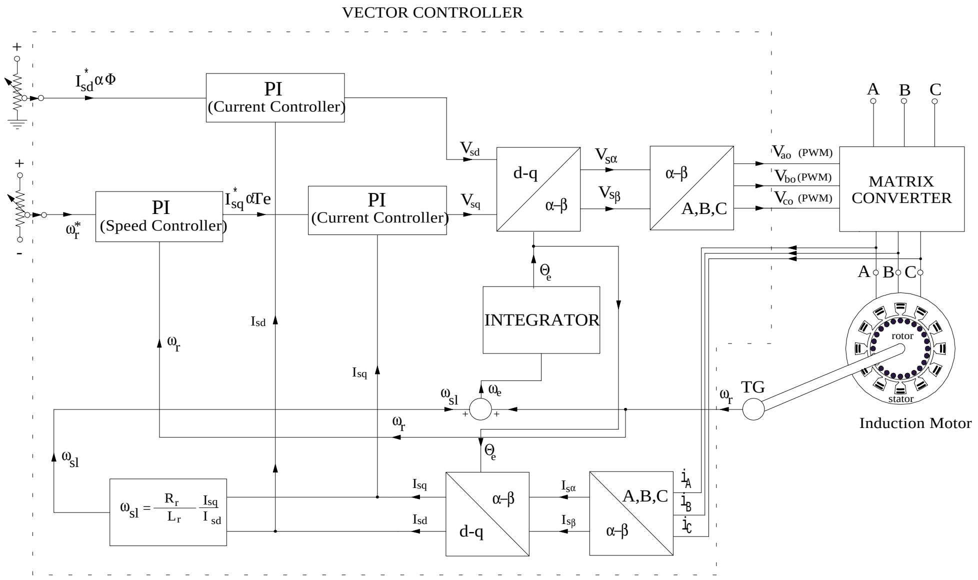

Figure 2. Block diagram for vector controlled matrix converter induction motor drive.

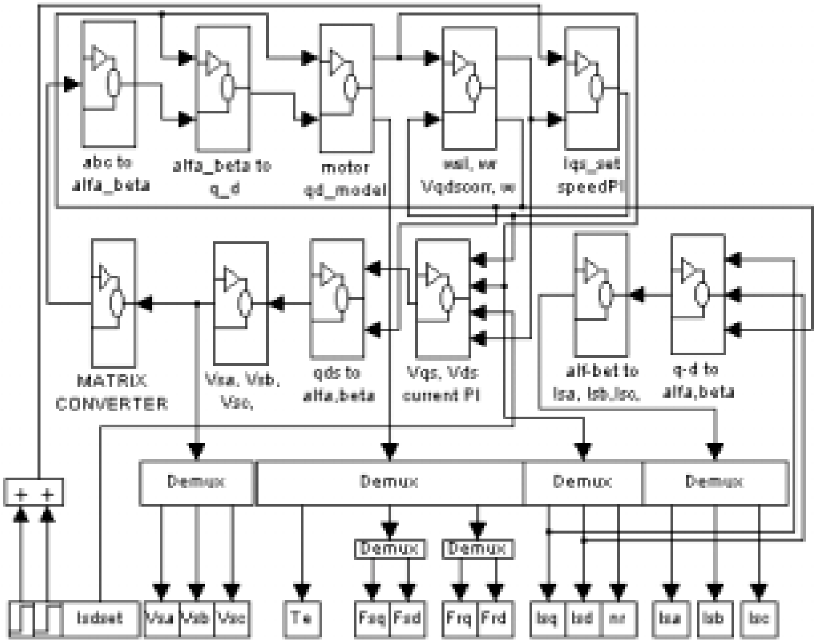

Figure 3. Simulink model of the vector controlled matrix converter induction motor drive.

used as the input signals for the Venturini algorithm (Equations (1-2)) to generate the duty cycles for each switch in the matrix converter.

IV. SYSTEM SIMULATION

The simulation program is constructed in Matlab/Simulink package. The Simulink model for overall system is shown in Figure 3. The model mainly consists of the d-q induction motor model, matrix converter and vector controller. On the top of the figure the d-q Simulink model of the three-phase induction motor is given together with the transformation blocks of a-b-c/α-β and α-β/d-q. The "ω_{sl}-ω_r .."block performs Equation (4) and calculates the voltage compensation terms to be added to the current controller outputs. In addition, this block calculates the rotor flux vector angle Θ_e. The "Iqs set.." block is the speed PI controller in the vector control scheme. Output of this block produces the torque reference current, I_{qs}*. The "V_{qs}-V_{ds} current PI" block implements the current PI's for I_{qs} and I_{ds} in the vector controller in Figure 2. The output of these controllers are the V_{qs} and V_{ds} d-q demand voltages and inputs to the transformation block of "qds to alpha-beta. Then, the block of "V_{sa}, V_{sb}, V_{sc}" performs transformation from alpha-beta to a,b,c which are the target output voltages of the matrix converter. The "matrix converter" block in Figure 3. is given in detail for one output phase in Figure 4.

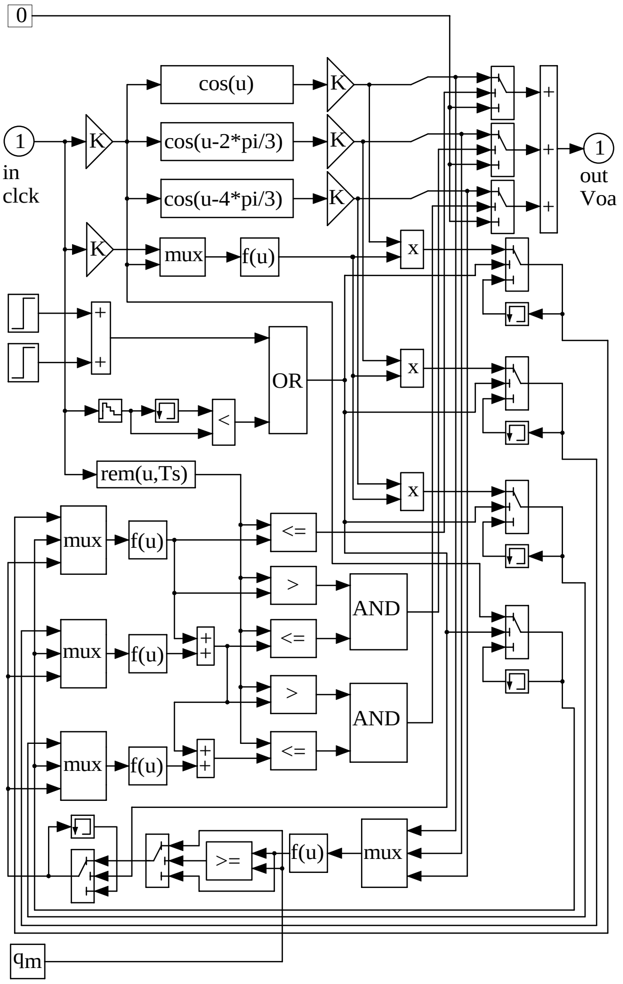

Figure 4. Simulink model of the matrix converter for one output phase.

V. SIMULATION RESULTS

Simulation results for vector controlled matrix converter-fed induction motor for various operating conditions are presented through Figures 5-13. Figure 5. shows the motor speed and d-q currents from standstill to 1000 rpm. The motor in this instance was not loaded and the total load is the inertia and friction of the motor itself. The linear acceleration shows that the torque reference current is held at its limiting value throughout the entire transient. In Figure 6. the motor speed and d-q currents are given for speed reversal from –1000 rpm to 1000 rpm for the same load condition. Figure 7. illustrates the motor speed and torque for various speed reference conditions on no-load. In this case, the motor is accelerated from standstill to 1000 rpm and stays in steady-state for a while. Then, the reference is changed to –1000 rpm. Therefore, the motor speed decelerates following this reference signal. After the motor speed reaches -1000 rpm and remains at that speed for a certain time the reference command signal is again changed to 1000 rpm. As can be seen from this figure the motor operates at four regions. This is main advantage of the matrix converter comparing to dc link inverter drives. Figure 8 shows one of the output phase voltages of the matrix converter which is reconstructed by the chopped three-phase input voltage. Motor steady-state current and the rotor flux compenents on no-load condition are given in Figures 9. and 10., respectively.

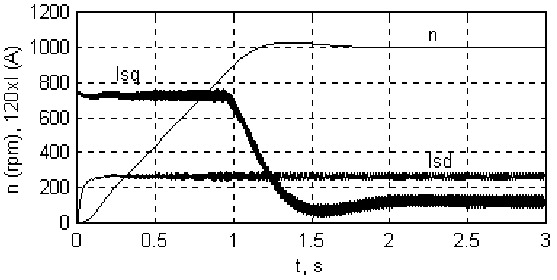

Figure 5. Motor speed and d-q currents from standstill to 1000 rpm on no-load.

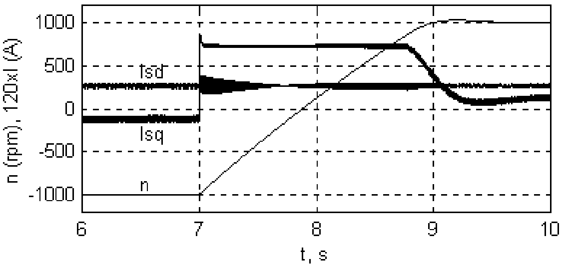

Figure 6. Motor speed and d-q currents for speed reversal from –1000 rpm to 1000 rpm on no-load.

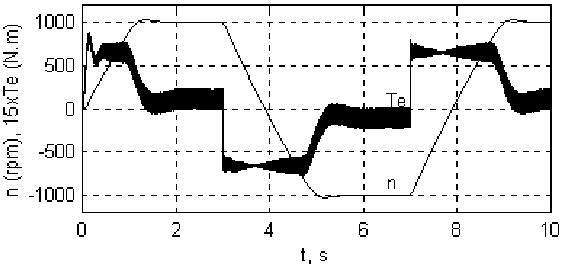

Figure 7. Motor speed and torque for various speed reference conditions on no-load.

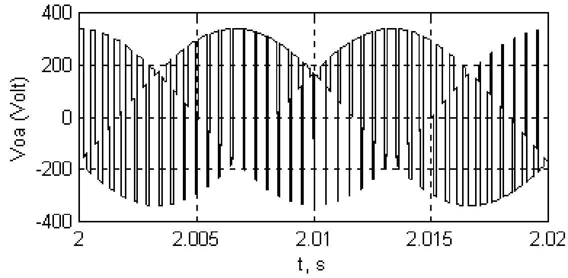

Figure 8. One output phase voltage of the matrix converter.

Figures 11-14 show the simulation results for a constant load of 27 Nm. In Figure 11. motor speed and d-q currents are presented for a speed refrence of 500 rpm to 1000 rpm. As can be seen the motor takes longer time to accelerate because of the load. Figure 12 illustrates the motor speed and d-q currents for speed reversal from 1000 rpm to -1000 rpm where the motor operates as a generator (IV. region) in steady-state when the motor speed reaches to target speed of –1000 rpm. The motor speed and torque for various speed reference conditions are shown in Figure 13. Figure 14. demonstrates the three-phase steady-state motor currents under load.

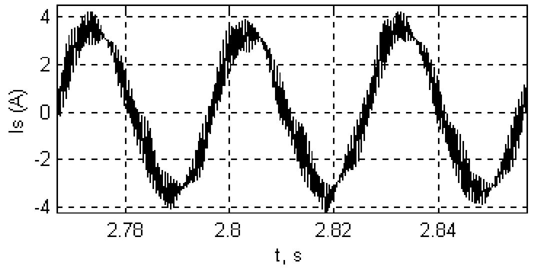

Figure 9. Motor steady-state current on no-load.

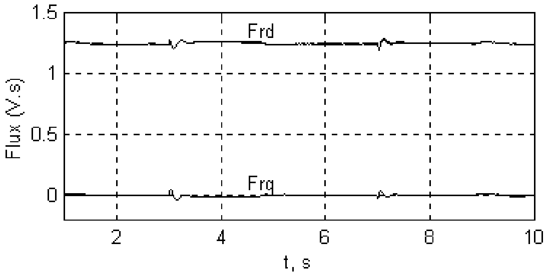

Figure 10. Rotor flux compenents on no-load.

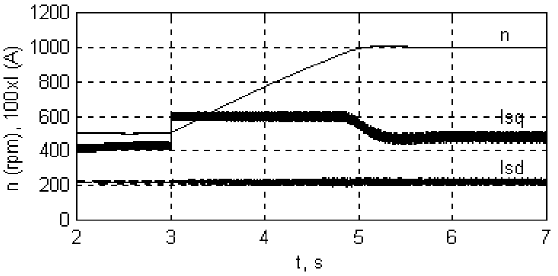

Figure 11. Motor speed and d-q currents from 500 rpm to 1000 rpm on load.

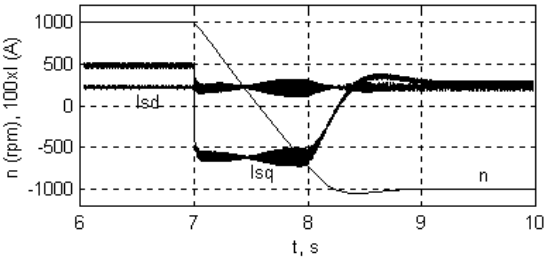

Figure 12. Motor speed and d-q currents for speed reversal from 1000 rpm to -1000 rpm on load.

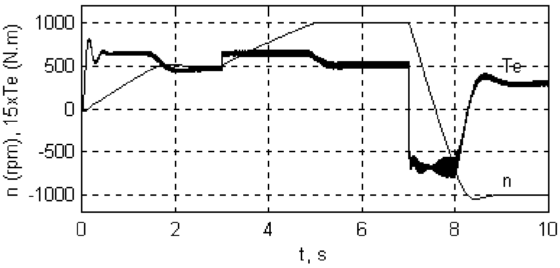

Figure 13. Motor speed and torque for various speed reference conditions on load.

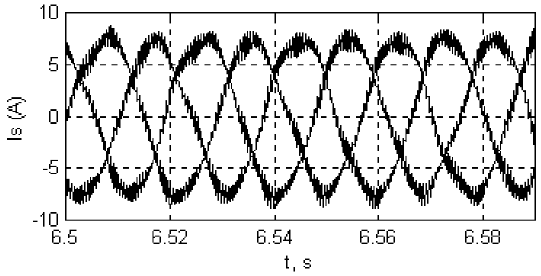

Figure 14. Three-phase steady-state motor currents on load.

VI. CONCLUSION

In this paper, a simulation study of the vector controlled matrix converter-fed induction motor drive has been done. A high performance vector controlled drive employing the matrix converter has been presented. Instead of the inverter with dc link in the vector controlled drive system, the use of the matrix converter has made the drive system capable of operating in all four quadrant regions. The simulation results agree with the nature of high performance motor drive system.

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APPENDIX

The ratings of the three phase 50 Hz, 415 V, 4 kW, delta connected , 1420 rpm squirrel cage induction motor are:

R_s=5.32 Ω, R_r'=4.14 Ω, T=27 Nm., L_s=0.6 H, L_r=0.59 H, J=0.4 kgm^2, L_o=0.565 H, B=0.707 Nm.s/rad, cosφ=0.83, I_s=8.1 A, P=4 poles