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Application of a matrix converter in a slip energy recovery drive system

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SUMMARY

This paper describes speed control of wound-rotor induction motor using the slip energy recovery principle. The proposed drive system uses a matrix converter to extract the slip energy from the rotor into the mains instead of using converter cascade. The system enables the motor to be operated at both subsynchronous and supersynchronous regions. Comprehensive simulation results are given to demonstrate transient and steady state operation of the drive system.

Key words: *Matrix converter, wound-rotor induction motor, slip energy recovery principle, drive system.*

1. INTRODUCTION

The operation of an induction motor in slip energy recovery drive system at subsynchronous and supersynchronous speeds is well known. One known as Scherbius drive employs doubly-fed wound-rotor induction motor using AC-DC-AC converter in the rotor circuit [1]. Such a scheme requires a low rating converter for handling rotor slip power. However, the converter requires two-stage power conversion, namely rectification and inversion which demands a complicated control strategy and large DC link capacitors, making the system bulky and expensive. In addition, the system allows the motor to operate only at subsynchronous speed region if an uncontrolled rectifier is used in the converter cascade. This restriction can be eliminated by using two phase-controlled thyristor bridges, one operating at slip frequency as a rectifier or inverter, while the other operates at mains frequency as an inverter or rectifier [2]. But, a difficulty is experienced near synchronism when the slip-frequency emfs are insufficient for natural commutation. In this case, devices with a self-turn-off capability are necessary for the passage through synchronism. Attractive solution is to use back-to-back PWM converter connected between rotor side and mains [3]. In such a configuration sinusoidal currents can be obtained from both the stator and rotor windings. However, complex control strategy for converter cascade and large DC link capacitors make the system bulky and costly.

Another approach in achieving bidirectional power flow in the cascade circuit is to use a line-commutated cycloconverter in which the AC power conversion is performed in a single-stage. The cycloconverter must be controlled so that the frequency of the injected slip-ring voltages follows the rotor slip frequency. With the cycloconverter cascade for slip energy recovery it is possible to operate at both subsynchronous and supersynchronous speed regions [1]. However, the cycloconverter, of which the output voltage is composed a great deal of harmonics and the power factor at the input side is very low due to natural commutation bringing a series harmonic pollution to both the supply and the motor [4]. In addition, in the line-commutated cycloconverter the maximum rotor frequency is approximately three to one of the supply frequency with near-sinusoidal frequency voltage and current. This corresponds to operation at *67 %* of synchronous speed.

In this paper, a matrix converter is used to control the rotor-side currents of wound-rotor induction motor. Such a configuration can offer the advantages given by its back-to-back counterpart while converting AC power in a single stage and eliminating the large DC link capacitor. In addition, the control scheme required by a direct AC-AC conversion scheme is simpler than that used by a two-stage power conversion [5]. The maximum rotor frequency limitation in the cycloconverter cascade is also eliminated by using the matrix converter.

This paper presents a simulation study of a matrix converter controlled wound-rotor induction motor for variable speed applications.

Low speed operation of a wound-rotor induction motor can be simply obtained by the introduction of external rotor resistance to dissipate the slip power. Variation of the external resistance can be provided either mechanically in discrete steps or statically and steplessly by a high-frequency chopper. However, it is not essential that the slip power is dissipated in the external rotor resistance. It can be removed from the rotor circuit and utilized externally, with the result of improving the overall efficiency of the drive system. Such a drive system is shown in Figure 1 where the slip power is taken from the rotor circuit and given to the grid via the matrix converter. The proposed drive system combines a matrix converter and a wound-rotor induction motor in a slip energy recovery drive system as shown in Figure 1.

This drive system finds an important place in wind-power generation applications where variable-speed constant frequency scheme produces electricity for a wide range of wind speeds.

2. MATRIX CONVERTER AND ITS SIMULINK MODELLING

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 [6]. 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 are both 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 [7]. The matrix converter can comply with four quadrants of motor operations, while generating no higher harmonics in the three-phase AC power supply. The circuit is inherently capable of bi-directional power flow and it also offers virtually sinusoidal input current, without the harmonics usually associated with present commercial inverters.

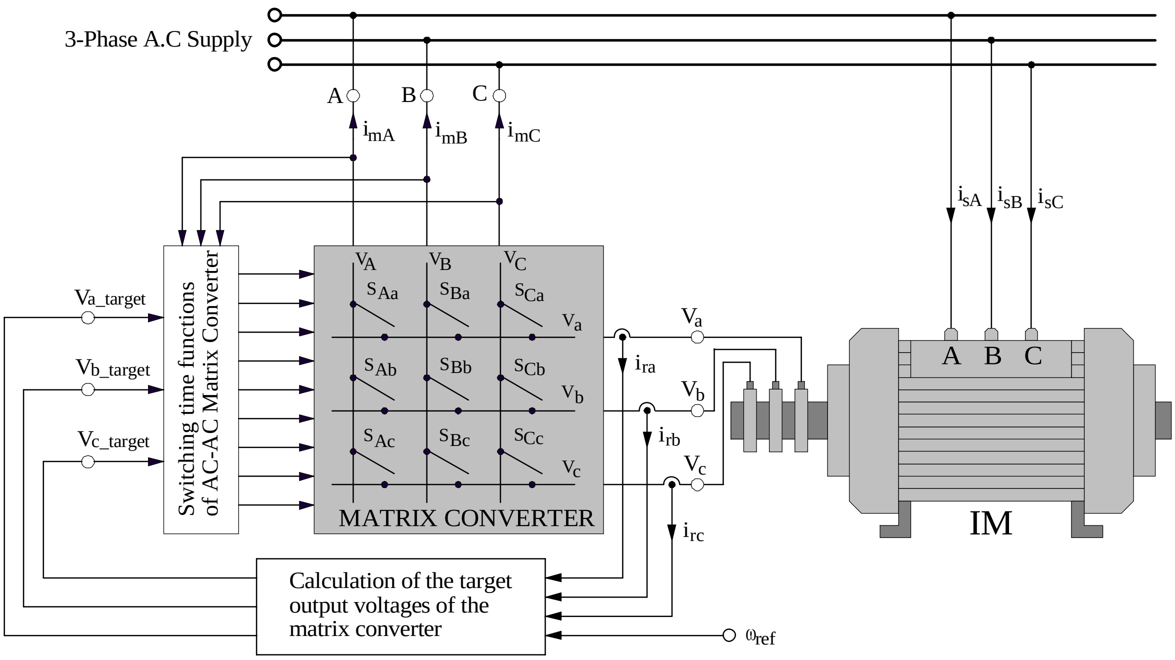

Fig. 1 Slip energy recovery drive system with a matrix converter

The Venturini algorithm [6] has been used to control the matrix converter. The modulation algorithm provides the method for controlling the input displacement factor of the converter as well as for achieving the possible maximum output voltage. A simplified form of the Venturini algorithm proposed in [8] provides a control algorithm with unity input displacement factor and it is suitable for real time implementation.

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:

$$t_{\beta\gamma} = \frac{T_s}{3}\left[1 + \frac{2V_{r\gamma}V_{i\beta}}{V_{im}^2} + \frac{2q}{3q_m}\sin\left(\omega_i t + \psi_\beta\right)\sin\left(3\omega_i t\right)\right] \quad (1)$$

where ψ_β is: *0, 2π/3* and *4π/3* correspond to the input phases *A*, *B* and *C*, respectively, q_m is maximum voltage ratio, *0.866*, *q* is the desired voltage ratio, V_{im} is the input voltage vector magnitude, T_s is the sampling period which is taken *500 μs*, $V_{i\beta}$ is the input phase voltage and $V_{r\gamma}$ is given by:

$$V_{r\gamma} = qV_{im}\cos\left(\omega_o t + \psi_\gamma\right) - \\ -\frac{q}{6}V_{im}\cos\left(3\omega_o t\right) + \frac{1}{4}\frac{q}{q_m}V_{im}\cos\left(3\omega_i t\right) \quad (2)$$

where ψ_γ is: *0, 2π/3, 4π/3* corresponding to the output phases *a*, *b*, *c*, respectively. Note that the desired output voltage has third harmonic components at the input and output frequencies added to it to produce $V_{r\gamma}$. This is a requirement to get the maximum possible voltage ratio [7]. Equations (1) and (2) are used for the duty cycle calculation of the switches in the matrix converter.

The simulink model of the matrix converter is given in Figure 2. The model consists of six main blocks. The blocks in the first column implement the equations of the Venturini algorithm to generate PWM signals for the power devices in the converter. The blocks “SPA”, “SPB” and “SPC” represent the signal generations for the switches of output phases *a*, *b* and *c*, respectively. The measured line voltage signals V_{AB} and V_{BC} are input to the blocks, SPA, SPB and SPC in which the phase voltages V_A, V_B and V_C are calculated and then used in Eq. (1). The clock signal is used for generating the carrier signal to be used in PWM implementation. On the other hand, the target output voltage vector, V_{rabc} is used in Eq. (2). The blocks “MCA”, “MCB” and “MCC” in the second column of Figure 2 represent the power circuit of the matrix converter each having three bidirectional switches. Three-phase input voltage and PWM signals are input to those blocks. Output of the blocks feeds a three-phase load, in our case it is the rotor windings of a slip-ring induction motor.

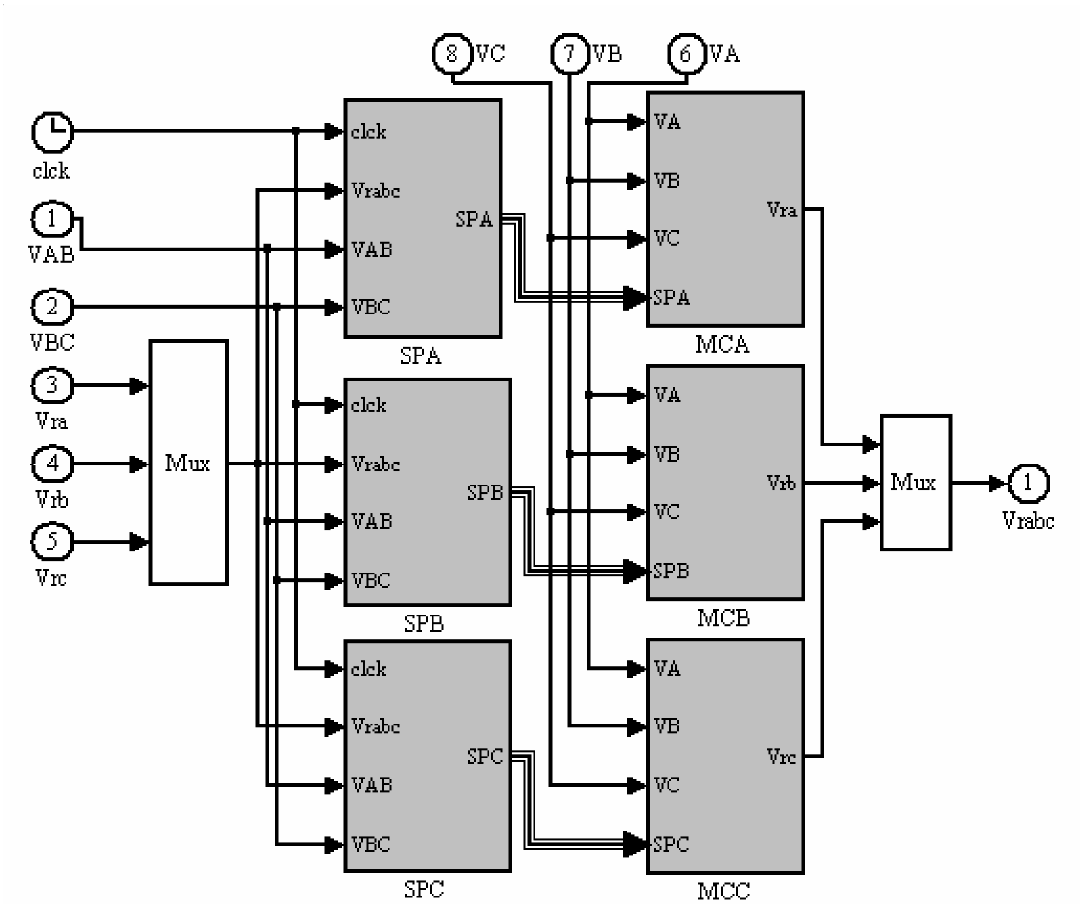

Fig. 2 Simulink scheme of a three-phase matrix converter

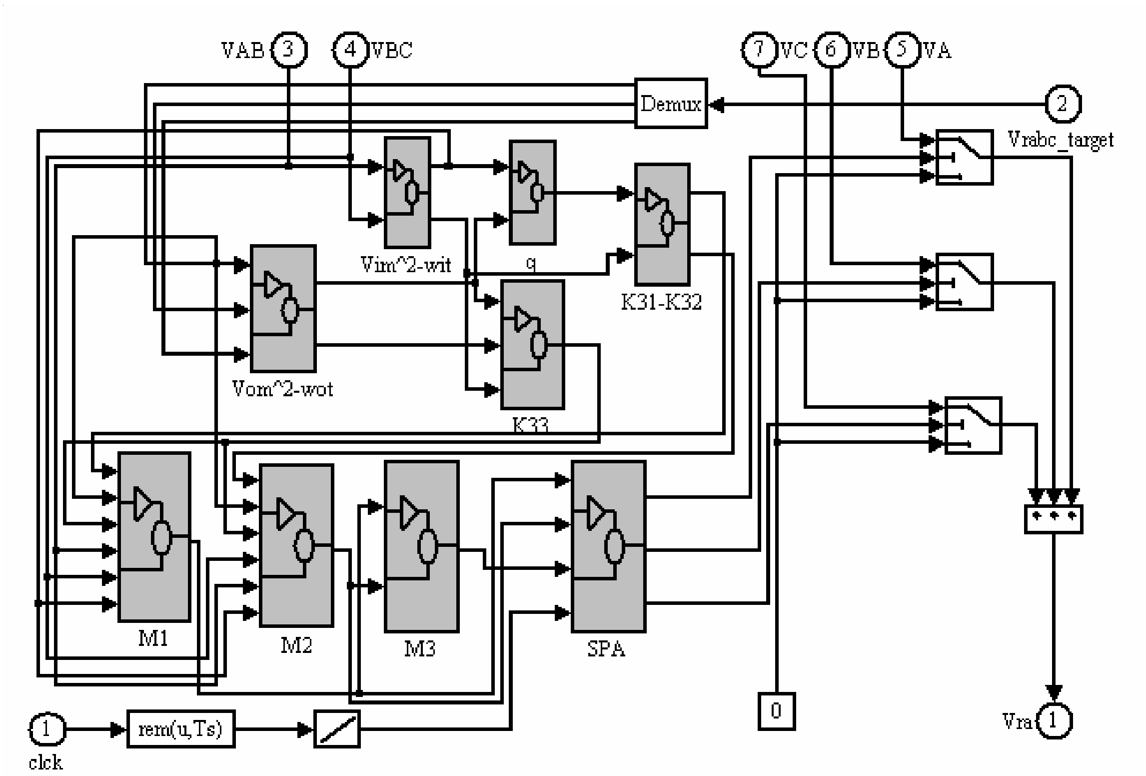

Fig. 3 Detail Simulink representation of one output phase

Figure 3 illustrates a detail Simulink representation of one output phase of the matrix converter. A detailed explanation of each block in Figure 3 can be found in [9]. Implementation of the other two output phases is the same as in Figure 3 except for 120° displacement.

3. MODELING OF WOUND-ROTOR INDUCTION MOTOR

A mathematical equation set of a wound-rotor induction motor for the Simulink model is required. The motor's voltage equations in α–β reference frame can be given as [10]:

$$
\begin{aligned}
V_{s\alpha\beta} &= R_s I_{s\alpha\beta} + \frac{d\Psi_{s\alpha\beta}}{dt} \\
V_{r\alpha\beta} &= R_r I_{r\alpha\beta} + \frac{d\Psi_{r\alpha\beta}}{dt}
\end{aligned} \tag{3}
$$

where $V_{s\alpha\beta}$, $V_{r\alpha\beta}$, $I_{s\alpha\beta}$, $I_{r\alpha\beta}$, $\Psi_{s\alpha\beta}$ and $\Psi_{r\alpha\beta}$ are the stator and rotor voltage, current and flux vectors, respectively. Diagonal matrices R_s and R_r are the resistances of the stator and rotor phase windings. The stator and rotor fluxes are:

$$
\begin{aligned}
\Psi_{s\alpha\beta} &= L_s I_{s\alpha\beta} + L_m I_{r\alpha\beta} e^{j\theta_r} \\
\Psi_{r\alpha\beta} &= L_r I_{r\alpha\beta} + L_m I_{s\alpha\beta} e^{-j\theta_r}
\end{aligned} \tag{4}
$$

where L_s and L_r are the stator and rotor self inductances and L_m is the mutual inductance. θ_r is the electrical position of the rotor. From Eq. (4) stator and rotor currents can be found as:

$$
\begin{aligned}
I_{s\alpha\beta} &= \frac{1}{\sigma L_s L_r}\left(L_r \Psi_{s\alpha\beta} - L_m \Psi_{r\alpha\beta} e^{j\theta_r} \right) \\
I_{r\alpha\beta} &= \frac{1}{\sigma L_s L_r}\left(L_s \Psi_{r\alpha\beta} - L_m \Psi_{s\alpha\beta} e^{-j\theta_r} \right)
\end{aligned} \tag{5}
$$

where the leakage coefficient, σ is:

$$
\sigma = \frac{L_s L_r - L_m^2}{L_s L_r} \tag{6}
$$

Equation (3) can be split into α–β components as:

$$
\begin{aligned}
V_{s\alpha} &= R_s I_{s\alpha} + \frac{d\Psi_{s\alpha}}{dt} \\
V_{s\beta} &= R_s I_{s\beta} + \frac{d\Psi_{s\beta}}{dt}
\end{aligned} \tag{7}
$$

$$
\begin{aligned}
V_{r\alpha} &= R_r I_{r\alpha} + \frac{d\Psi_{r\alpha}}{dt} \\
V_{r\beta} &= R_r I_{r\beta} + \frac{d\Psi_{r\beta}}{dt}
\end{aligned} \tag{8}
$$

The flux components are derived from Eqs. (7) and 8):

$$
\begin{aligned}
\Psi_{s\alpha} &= \int \left(V_{s\alpha} - R_s I_{s\alpha} \right) dt \\
\Psi_{s\beta} &= \int \left(V_{s\beta} - R_s I_{s\beta} \right) dt
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
\Psi_{r\alpha} &= \int \left(V_{r\alpha} - R_r I_{r\alpha} \right) dt \\
\Psi_{r\beta} &= \int \left(V_{r\beta} - R_r I_{r\beta} \right) dt
\end{aligned} \tag{10}
$$

Equation (5) can be split into α–β components as:

$$I_{s\alpha} = \frac{1}{\sigma L_s L_r}\left(L_r \Psi_{s\alpha} - L_m \cos\theta_r \Psi_{r\alpha} + L_m \sin\theta_r \Psi_{r\beta}\right)$$
$$I_{s\beta} = \frac{1}{\sigma L_s L_r}\left(L_r \Psi_{s\beta} - L_m \sin\theta_r \Psi_{r\alpha} - L_m \cos\theta_r \Psi_{r\beta}\right) \qquad (11)$$

$$I_{r\alpha} = \frac{1}{\sigma L_s L_r}\left(-L_m \cos\theta_r \Psi_{s\alpha} - L_m \sin\theta_r \Psi_{s\beta} + L_s \Psi_{r\alpha}\right)$$
$$I_{r\beta} = \frac{1}{\sigma L_s L_r}\left(L_m \sin\theta_r \Psi_{s\alpha} - L_m \cos\theta_r \Psi_{s\beta} + L_s \Psi_{r\beta}\right) \qquad (12)$$

The produced torque of the motor in α–β terms is given [10]:

$$T_e = 3\frac{P}{2} L_m\, Im\left\{ I_{s\alpha\beta}\left(I_{r\alpha\beta} e^{j\theta_r}\right)^*\right\} \qquad (13)$$

where $Im\{\ \}$ shows the imaginary part and * is the complex conjugate. Therefore:

$$T_e = 3\frac{P}{2} L_m\left[\left(I_{s\beta} I_{r\alpha} - I_{s\alpha} I_{r\beta}\right)\cos\theta_r - \left(I_{s\alpha} I_{r\alpha} + I_{s\beta} I_{r\beta}\right)\sin\theta_r\right] \qquad (14)$$

Mechanical dynamic equation of the motor is:

$$J\frac{2}{P}\frac{d\omega_r}{dt} = T_e - T_L - f_v \omega_m \qquad (15)$$

where J is inertia; P is pole number; ω_r is electrical angular speed; T_L is load torque; f_v is friction and ventilating coefficient which was ignored and ω_m is mechanical angular speed. From Eq. (15) electrical angular speed can be expressed as:

$$\omega_r = \frac{P}{2J}\int\left(T_e - T_L - f_v \omega_m\right) dt \qquad (16)$$

The rotor position is then calculated from above equation as:

$$\theta_r = \theta_{ro} + \int \omega_r dt \qquad (17)$$

where θ_{ro} is the initial position of the rotor.

Hence, the Simulink model of the wound-rotor induction motor shown in Figure 4 is obtained using Eqs. (9), (10), (11), (12), (14,) (16) and (17), which are the machine's equation set.

4. SPEED OPEN-LOOP CONTROL OF A SLIP-RECOVERY DRIVE SYSTEM

Voltage, flux and the electromagnetic torque equations of the motor given in Eqs. (3), (4) and (13) represent the motor dynamic in both transient and steady-state. Steady-state equations of the motor can be derived by some algebraic manipulations using these equations as:

$$V_s = \left(R_s + jX_{ls}\right) I_s + jX_m\left(I_s + I_r\right)$$
$$V_r = \left(R_r + R_r\frac{1-s}{s} + jX_{lr}\right) I_r + jX_m\left(I_s + I_r\right) - V_r\frac{1-s}{s} \qquad (18)$$

and:

$$T_e = 3\frac{P}{2} L_m\, Im\left\{I_s I_r^*\right\} \qquad (19)$$

where V_s, V_r, I_s and I_r are the stator and rotor voltage and current vectors, X_{ls} and X_{lr} are the stator and rotor leakage reactances, respectively, X_m is the mutual reactance, and s is the slip.

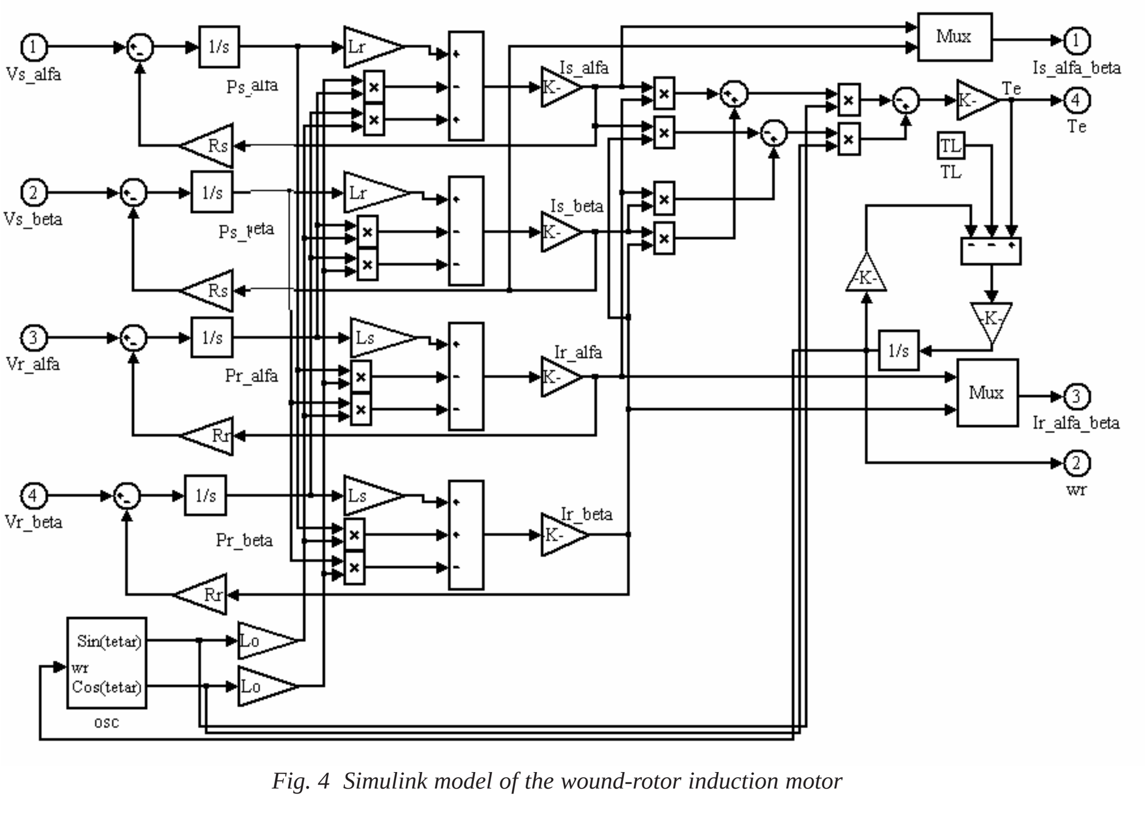

Fig. 4 Simulink model of the wound-rotor induction motor

Note that the following relations have been used for the sake of simplicity in deriving Eq. (18):

$$X_s = \omega L_s \quad ; \quad X_r = \omega L_r \quad ; \quad X_m = \omega L_m$$
$$X_{ls} = X_s - X_m \quad ; \quad X_{lr} = X_r - X_m \tag{20}$$
$$\frac{R_r}{s} = R_r + R_r \frac{1-s}{s} \quad ; \quad \frac{V_r}{s} = V_r + V_r \frac{1-s}{s}$$

where ω is angular frequency of the source and X_s, X_r are the stator and rotor self reactances respectively. From the steady-state equations the well known conventional per-phase equivalent circuit can be illustrated as in Figure 5.

In the speed control of a wound-rotor motor connected to the AC utility, if the rotor resistance control is performed by introducing external resistance there is a requirement for the calculation which external rotor resistance will be used. This is done by considering the equivalent circuit in Figure 5 and taking into account the load torque. The fundamental power delivered to the rotor across the air gap, P_{ag} is divided between the mechanical power output, P_{mech} and the rotor copper loss, P_2 [2]. The following equations can be derived from Figure 5:

$$P_2 = sP_{ag}$$
$$P_{mech} = (1-s)P_{ag} \tag{21}$$
$$P_{ag} = T_e \frac{2}{P}\omega$$

From above equations it is obvious that, for instance, at half synchronous speed, the air gap power is divided equally between mechanical power output and rotor I^2R loss giving an overall efficiency less than *50 %* when considering stator losses. Therefore, the introduction of external rotor resistance for speed control is inherently inefficient especially at low speed operations. However, the slip power (P_2) can be recovered and it is not essential that this power is dissipated in resistance losses, because it can be removed from the rotor circuit and utilized externally, thereby improving the overall efficiency of the motor. The slip-frequency voltage drop in the external rotor resistance corresponds to the injected voltage which is required to extract the slip power into the AC utility. The main problem is to provide a suitable emf source that the frequency of the injected voltage must match the slip frequency at all motor speeds. In this study the emf source is provided by a matrix converter.

In Figure 6 speed-torque characteristics of a wound-rotor induction motor for various external rotor resistances and constant load torque have been drawn by using the equivalent circuit. In addition, the rotor voltages, V_r which correspond to the voltage drops in the external rotor resistances have been calculated and used to obtain the speed-torque characteristics as given in the same figure.

In Figure 6, for instance, if *22.74 Ω* of an external resistance is introduced in the rotor circuit, the rotor speed will operate at *1000 rpm* for *10 Nm* of a load torque. This causes sP_{ag} of heat dissipation in the rotor circuit. Instead of using this external resistance, *59.73 V* of V_r is applied to the rotor circuit in which the same operating point is obtained as labeled "A" in the figure. Similar results can be obtained for the operating points, "B" and "C".

For the control of the slip recovery drive system, Matlab/simulink [11] block diagram is given in Figure 7. The mains which are represented by the block "Source" are applied to the input of matrix converter represented by the block "Matrix Converter" and to the stator windings of the motor represented by the block "Ind_Motor". To calculate the target output rotor voltages, the reference speed and three-phase rotor currents are required and they are an input to the block "Vr_Target_Out" where three-phase rotor voltages are outputs. While rotor currents are used to determine the rotor frequency, reference rotor speed is used to determine rotor voltage amplitude from steady-state equivalent circuit. Taking into account the load torque, the rotor voltage to be applied for a reference rotor speed can be calculated from the steady-state equivalent circuit according to the equations given below:

$$A_o = \left(R_s X_r\right)^2 + \left(X_s X_r - X_m\right)^2$$
$$A_1 = 2R_s X_m^2 - \frac{3X_m^2 |V_s|^2}{T_L(2/p)\omega} \tag{22}$$
$$A_2 = R_s^2 + X_s^2$$

$$\Delta = \sqrt{A_1^2 - 4A_2A_o} \tag{23}$$

$$R_e = s\frac{-A_1 + \Delta}{2A_2} - R_r \tag{24}$$

$$|V_r| = R_e \frac{X_m |V_s|}{\sqrt{a^2 + b^2}} \tag{25}$$

$$a = R_s\left(R_e + R_r\right)/s - X_s X_r + X_m^2$$

$$b = R_s X_r + X_s\left(R_e + R_r\right)/s$$

where A_o, A_1, A_2 and Δ in Eqs. (22) and (23) are the coefficients used for the calculation of the rotor external resistance, R_e in Eq. (24). Then, the corresponding voltage drop V_r is calculated by Eq. (25). From Eqs. (24) and (25) it can be concluded that if the load torque is considered constant the required external resistance R_e and therefore voltage drop *Vr* are proportional to the motor speed.

Once the rotor voltage target outputs of the matrix converter for a reference speed are determined, these signals with the measured line voltages are an input to the block represented by "Signal Process" in Figure 7 where the PWM signals are generated for the power switches of block, "Matrix Converter".

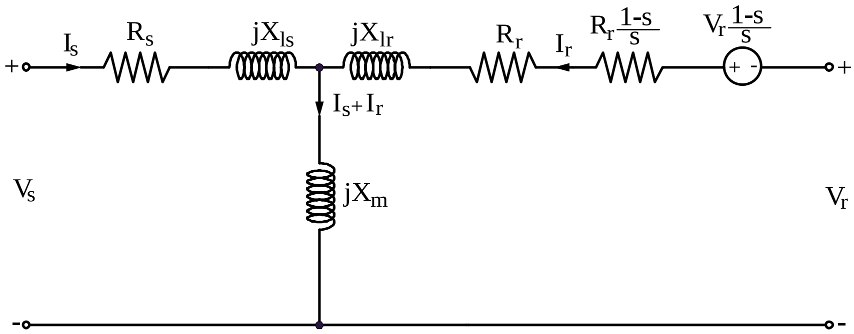

Fig. 5 Steady-state equivalent circuit of the wound-rotor induction motor

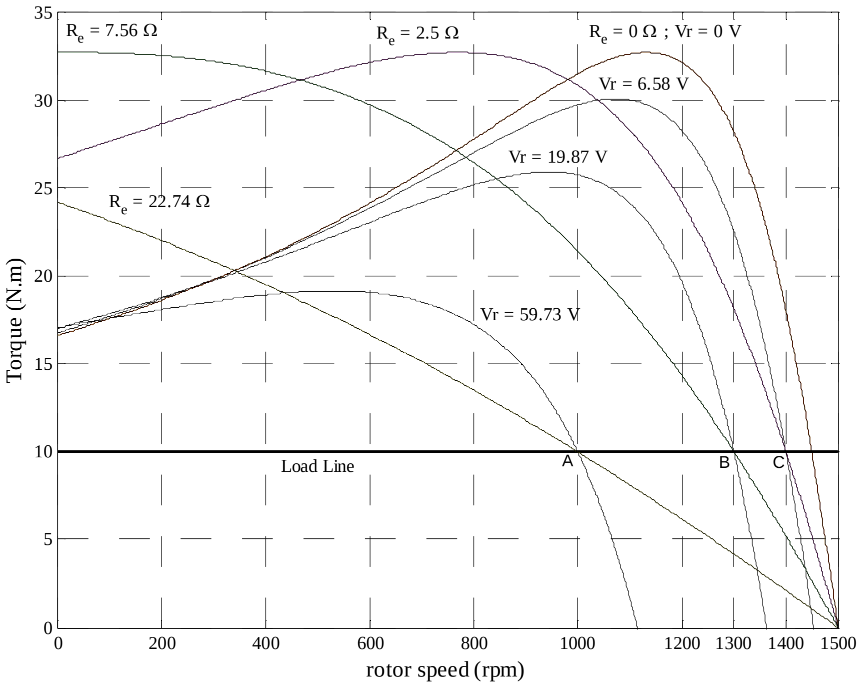

Fig. 6 Speed-torque characteristics for various rotor resistances and rotor voltages

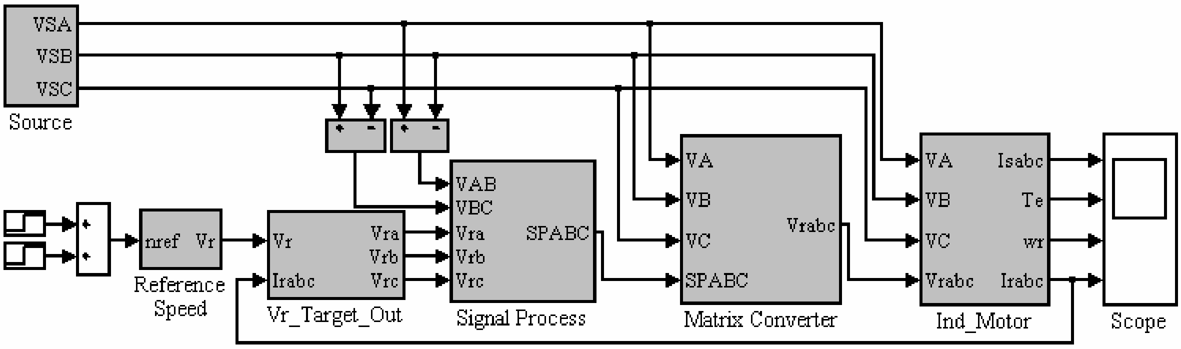

Fig. 7 Block diagram of the slip recovery drive system

5. SIMULATION RESULTS

Simulation results have been taken for various operating conditions. First, the motor has been operated with a speed reference of *500 rpm* following steady-state operation and finally the speed reference was increased from *500 rpm* to *1000 rpm*. The corresponding simulation results are given in Figures 8 and 9. As it can be seen from Figure 8 the motor speed follows the reference speed command. In Figure 9(a), the rotor current and the applied rotor voltage are in opposite phase which is the requirement for slip energy recovery drives. Figure 9 (a and b) shows the input current and voltage waveforms of the matrix converter. Here, it is obviously seen that the converter performs two functions; by taking the slip energy from the rotor into the mains and applying the required rotor voltage corresponding to the reference speed. In Figure 9(c), the recovered power, input and mechanical powers of the motor are shown where the recovered power varies with the rotor speed. As it can be seen the recovered power at *500 rpm* is higher than that of *1000 rpm* since the recovered power is inversely proportional to the speed.

Similar results have been taken at *5 Nm* and *10 Nm* load torques to demonstrate the machine's behaviour in acceleration, steady-state and deceleration modes. In Figure 10, the motor accelerates to *1200 rpm* with *5 Nm* load torque and in steady-state operation the load torque is increased to *10 Nm* at instant, *0.4 second*. The corresponding rotor speed slightly decreases and then recovers quickly since the applied reference voltage remains constant. The reference speed is changed to *550 rpm* at the instant of *0.5 second* as shown in Figure 10(a). The corresponding rotor current and voltage, input voltage and current of the matrix converter and motor powers are illustrated in Figure 11. Again, increasing the load torque and decreasing the motor speed will increase the recovered power as shown in Figure 11(c).

Note that the simulation results illustrated so far were taken at subsynchronous region. The results shown in Figures 12 and 13 have been taken at supersynchronous region. In Figure 12, the reference speed is given as *1500 rpm* under *10 Nm* load torque. The motor accelerates and reaches the reference speed command. Under supersynchronous operation the motor requires energy both from the stator and rotor as shown in Figure 13. The voltages and currents both of the rotor and matrix converter are in phase which proves that the motor operates at supersynchronous region.

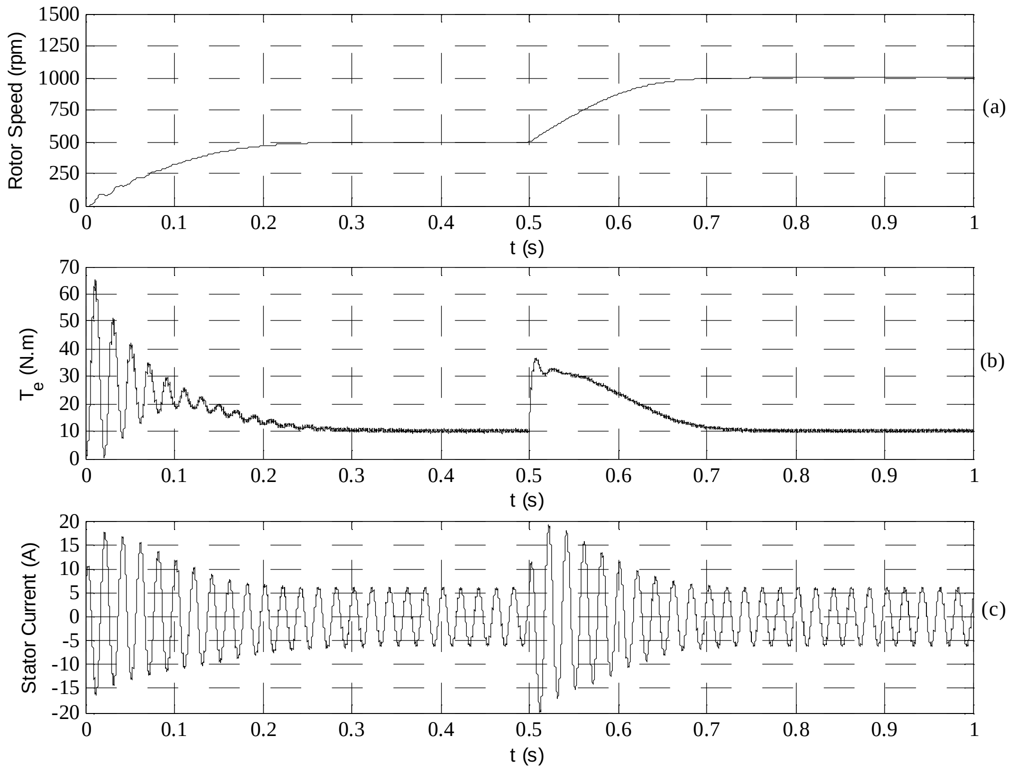

Fig. 8 Simulation results for acceleration and steady-state modes at 10 Nm constant load torque: (a) Rotor speed; (b) Motor torque; (c) Stator current

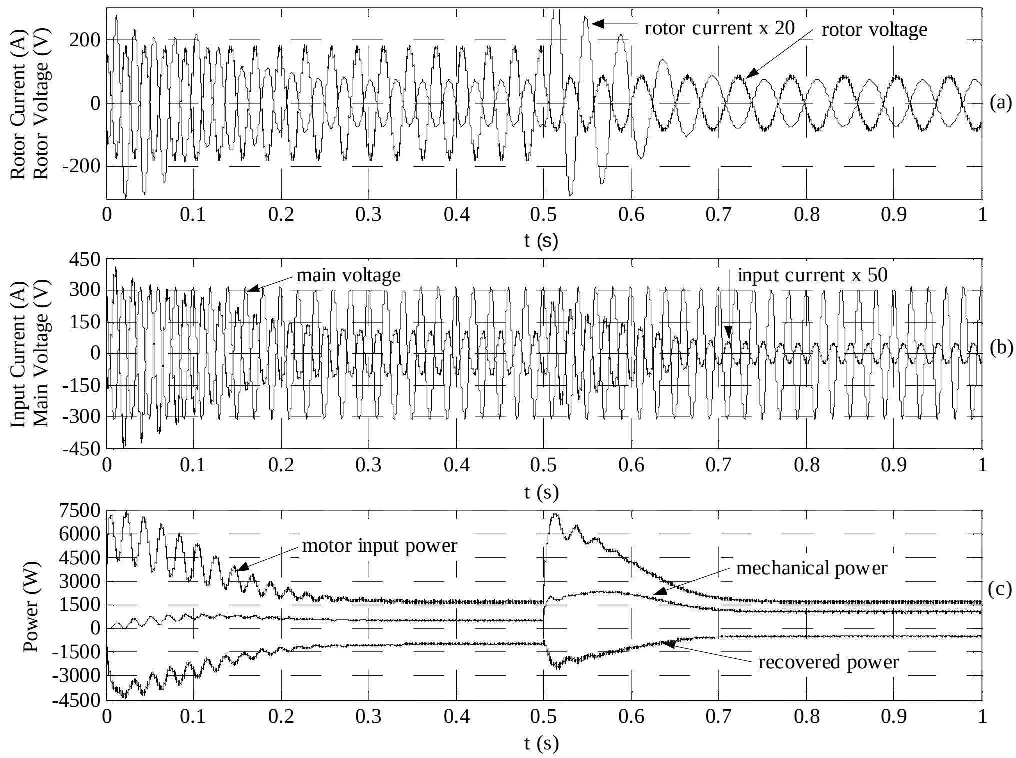

Fig. 9 Simulation results for acceleration and steady-state modes at 10 Nm constant load torque: (a) Rotor current and voltage; (b) Converter input voltage and current; (c) Motor input and output powers, recovered power

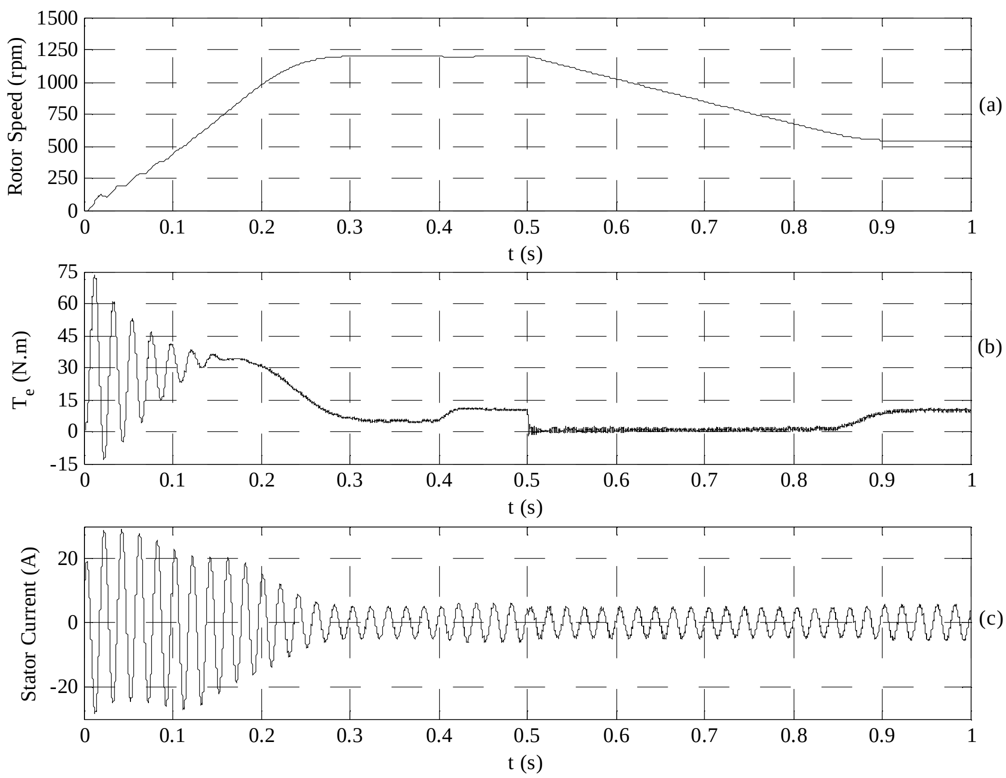

Fig. 10 Simulation results for acceleration and deceleration modes at various load torques: (a) Rotor speed; (b) Motor torque; (c) Stator current

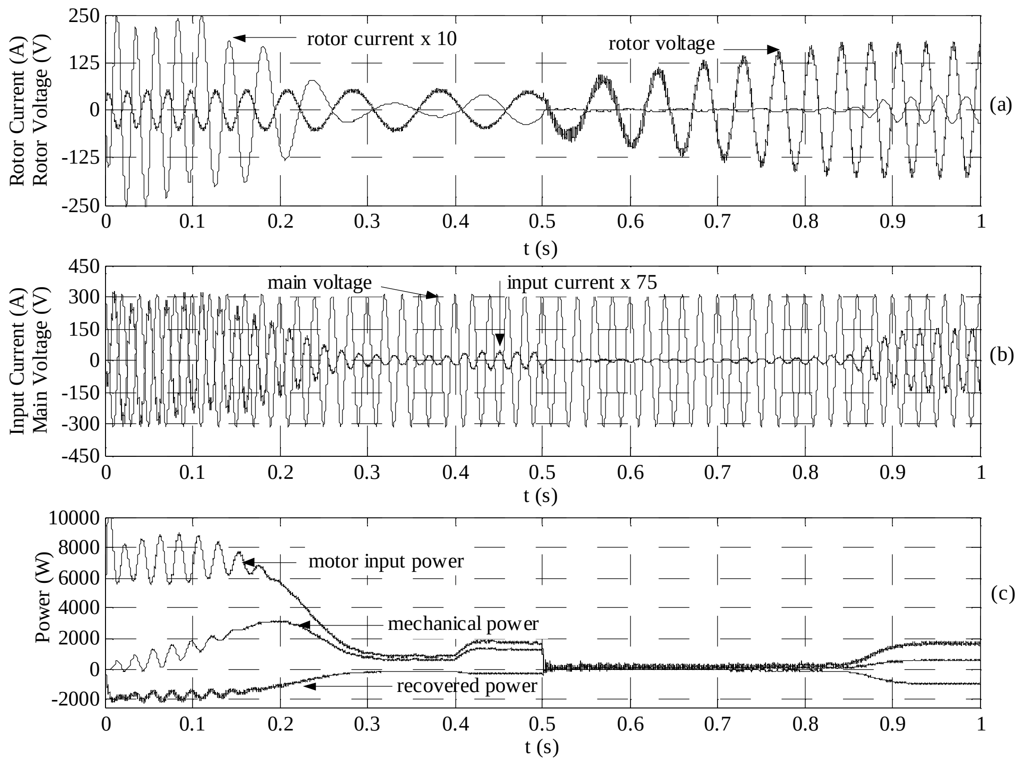

Fig. 11 Simulation results for acceleration and deceleration modes at various load torques: (a) Rotor current and voltage; (b) Converter input voltage and current; (c) Motor input and output powers, recovered power

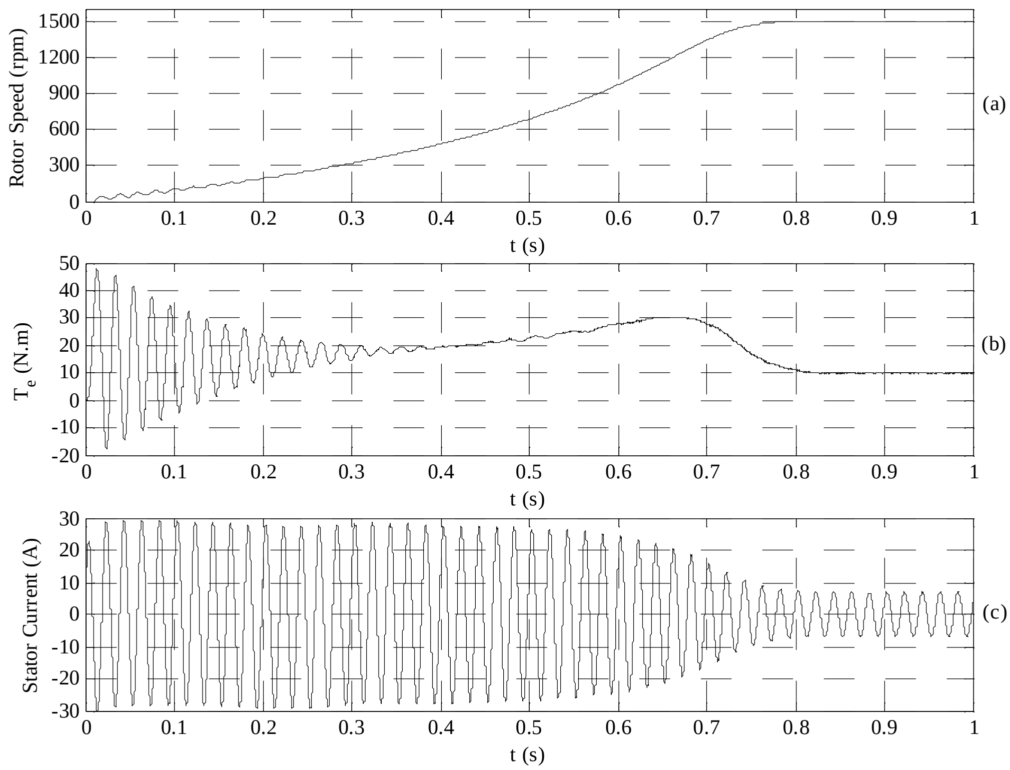

Fig. 12 Simulation results for acceleration and steady-state modes at 10 Nm constant load torque in supersynchronous region: (a) Rotor speed; (b) Motor torque; (c) Stator current

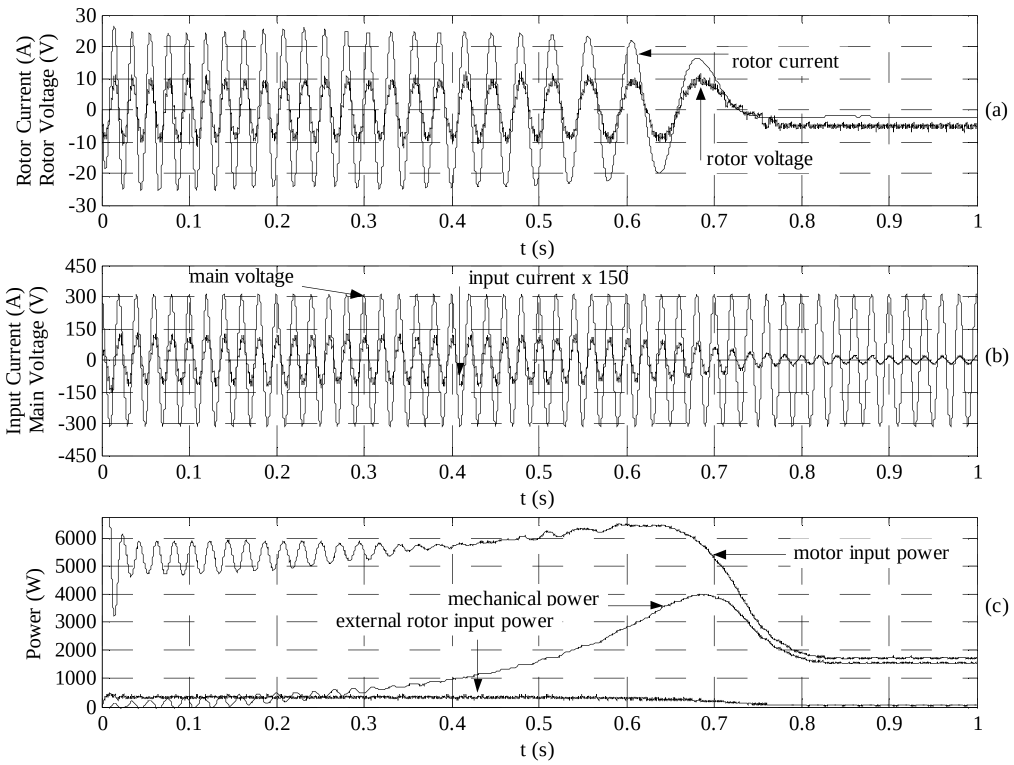

Fig. 13 Simulation results for acceleration and steady-state modes at 10 Nm constant load torque in supersynchronous region: (a) Rotor current and voltage; (b) Converter input voltage and current; (c) Motor input and output powers, external rotor input power

6. CONCLUSIONS

The speed open-loop control of wound-rotor induction motor using the slip energy recovery principle has been modelled and simulated in Matlab/Simulink. In the drive system a matrix converter has been used to extract the slip energy from the rotor into the mains in subsynchronous region, and to supply the rotor in supersynchronous region. It has been shown that the use of the matrix converter in the drive system has the advantages of single stage power conversion, operation in both subsynchronous and supersynchronous speed regions, sinusoidal voltage and current waveforms and simpler control scheme than other converters used instead.

It has been demonstrated with simulation results that the matrix converter drive system operates efficiently at subsynchronous speeds where the slip power is transferred from rotor windings to the mains through the matrix converter with sinusoidal currents and voltages. Simulation results have also shown that the system allows the machine to operate at supersynchronous speeds, as well.

APPENDIX

- The parameters of the wye connected wound-rotor induction motor are:
  1.5 kW, *380 V*, *4 A*, *1500 rpm*, with *10 Nm* torque.
- Rotor inertia: *0.05 kg.m*^{2}, pole numbers: *4*.
- Stator and rotor resistances: *2.33* Ω and *2.55* Ω, respectively.
- Stator and rotor self inductances: *0.213* and *0.22 H*, respectively.
- Mutual inductance: *0.2 H.*

REFERENCES

[1] J.M.D. Murphy and F.G. Turnbull, *Power Electronic Control of AC Motors*, Pergamon Press, 1988.

[2] I. Cadirci and M. Ermis, Double-output induction generator operating at subsynchronous and supersynchronous speeds: Steady-state performance optimisation and wind-energy recovery, *IEE Proc.*, Vol. 139, No. 5, pp. 429-442, 1992.

[3] R. Pena, J.C. Clare and G.M. Asher, A doubly fed induction generator using back-to-back PWM converter supplying an isolated load from variable speed wind turbine, *IEE Proc.,Electric Power Applications*, Vol. 143, No. 5, pp. 380-387, 1996.

[4] H. Keyuan and H. Yikang, Investigation of a mtrix converter-excited brushless doubly-fed machine wind-power generation system, Proc. of the 5th International Conference on Power Electronic and Drive Systems, PEDS'03, Vol. 1, pp. 743-748, 2003.

[5] L. Zhang, C. Watthanasarn and W. Shepherd, Application of a matrix converter for the power control of a variable-speed wind-turbine driving a doubly-fed induction generator, 23rd International Conference on Industrial Electronics, Control and Instrumentation, IECON'97, Vol. 2, pp. 906-911, 1997.

[6] M. Venturini, A new sine wave in sine wave out conversion technique which eliminates reactive elements, Proc. Powercon 7, San Diego, E3-1, E3-15, 1980.

[7] A. Alesina and M. Venturini, Solid-state power conversion: A Fourier analysis approach to generalized transformer synthesis, *Proc. IEEE Transactions on Circuit and Systems*, Vol. CAS-28, No. 4, pp. 319-330, 1981.

[8] S. Sunter, A vector controlled matrix converter induction motor drive, Ph.D. Thesis, Department of Electrical and Electronic Engineering, University of Nottingham, 1995.

[9] H. Altun and S. Sunter, Matrix converter induction motor drive: Modeling, simulation and control, *Electrical Engineering*, Vol. 86, pp. 25-33, 2003.

[10] P.C. Krause, *Analysis of Electrical Machinery*, McGraw-Hill, New York, 1986.

[11] MATLAB® for Microsoft Windows, The Math Works Inc., 1999.

PRIMJENA MATRIČNOG PRETVARAČA U OBNOVI ENERGIJE KLIZANJA VOZNOG SUSTAVA

SAŽETAK

Ovaj rad opisuje kohitni asinkroni motor koji koristi načelo povratka energije klizanja. Predloženi vozni sustav koristi matrični pretvarač za izvlačenje energije klizanja iz rotora u glavni vod, umjesto korištenja kaskade pretvarača. Sistem omogućava rad motora u subsinkronim i supersinkronim područjima. Rezultati opsežne simulacije pokazuju tranzijentna i stacionarna stanja rada elektromotornog pogona.

Ključne riječi: *matrični pretvarač, wound-rotor indukcijski motor, načelo obnavljanja energije, vozni sustav.*