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A Novel Three-phase Matrix Converter Based Induction Motor Drive Using Power Factor Control

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ABSTRACT

Direct Torque Control (DTC) for Induction Motors using Matrix Converters is a high performance motor control scheme with fast torque and flux responses. This paper presents a new power factor control along with the existing DTC matrix converter induction motor drive. The main advantages of the DTC matrix converter are improved with those of the power factor technique, generating the required voltage vectors under 0.86 input power factor operations. The implementation of this kind of controller is done by using the TMS320F28335. The results demonstrate the good quality and robustness in the proposed system dynamic response and reduction in the transient motor ripple torque.

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INTRODUCTION

Direct torque control (DTC) method becomes one of the high-performance control strategies for induction motor due to its very fast torque and flux control (Lee, H.H., *et al*., 2009). It is the direct control of torque and flux of an electrical motor by the selection through a look-up table, of the power converter voltage space vectors. The main advantage of DTC is its structural simplicity, since no coordinate transformations, current controllers and PWM are needed. Moreover, the controller does not depend on motor parameters. DTC is considered to be a simple and robust control scheme which achieves a quick and precise torque control response. For such advanced reasons, the combination of the advantages of the matrix converter with those of the DTC method is effectively possible (Chen, D.F., Liao, C.W. and Yao, K.C., 2008). However, some research is still being done to reduce the electromagnetic torque ripple, which is its main drawback that leads to the rising stator current distortion noise (Alesina, A. and Venturini, M.G.B., 2003).

The following methods are applied to improve the effects of the ripple on the torque output: fuzzy logic controller, multilevel inverter, the modulation methods of the SVM (Casadei, D., Serra, G.and Tani, A., 2000; Lascu, C., Boldea I., and Blaabjerg, F. , 2002; Buja, G.S. and Kazmierkowski, M.P., 2004; Ghoni, R., Abdalla, A.N. and Sujod, Z., 2010) and so on. Using the above functions algorithm is involved. It is crucial to keep the short sampling period methods always increases the complication of the system structure and burdens the workload of the DSP because of calculations such as square root and trigonometric time in order to maintain the electromagnetic torque ripple within an acceptable hysteresis band (Buja, G.S. and Kazmierkowski, M.P., 2004). It is difficult to implement DTC using common IC hardware. The DTC algorithm is usually implemented by serial calculations on a DSP board. However, as a predictive control scheme, the DTC has a steady-state error produced by the time delay of the lengthy computations, which depends largely on the control algorithm and hardware performance. A typical DSP (TMS32010) execution time of the DTC algorithm for a VSI-fed induction motor is more than 250μs (Habetler, T.G., *et al*., 2002). ANN as faster parallel calculation and a simpler structure, so it is superior to a DSP board in execution time and hardware structure. The execution time of neural devices is less than 0.5μs for analogue or 0.8μs for digital per neuron (Zaghloul, M.E., Meador, J.L. and Newcomb, R.W., 1994). Thus, DTC of VSI-fed induction motor based on ANN had been pointed out (Shi, K.L., Chan, T.F. and Wong, Y.K., 2002; Dung, P.Q. and Thuong, H.T.N., 2004). Moreover, the designers must possess plentiful experiences on related theories.

In this paper, the new power factor control is introduced along with the existing DTC control for matrix converter and leading to the reduction of the electromagnetic torque. The experimental results demonstrate the effectiveness of the proposed control scheme was presented.

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2. Modelling of Induction Motor:

Induction motor is a high-end, non linear, strong coupling multivariable system. In order to facilitate analysis of the mathematical model of the induction motor, some assumptions must be made, which are; ignore the space harmonics, assuming symmetrical three phase winding, and the air gap magnetic field is generated by the sine distribution, ignore the phenomenon of magnetic saturation, excluding the core loss and disregard the frequency and the impact of temperature change on the winding. Voltage equation of induction motor in stationary dq frame is given in Eq. (1):

$$\begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_s + L_s\delta & 0 & L_m p & 0 \\ 0 & R_s + L_s\delta & 0 & L_m\delta \\ L_m\delta & \omega L_m & R_r + L_r\delta & \omega L_r \\ -\omega L_m & L_m\delta & -\omega L_r & R_r + L_r\delta \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (1)$$

Where, L_s, L_r and L_m are the stator, rotor and the stator magnetizing inductance, ω is the angular velocity, δ is the different symbols for $\delta = \frac{d}{dt}$, subscript s and r respectively for the stator and rotor; and d and q are for dq frame. The flux equation is given in Eq. (2).

$$\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (2)$$

Where, ψ_{sd} and ψ_{sq} is the dq stator flux, and ψ_{rd} and ψ_{rq} are the rotor flux. The electromagnetic torque equation is as Eq. (3);

$$T_e = \frac{3}{2} p_n L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq} \right) \quad (3)$$

According to the flux Eq. (2), Eq. (3) can be rewritten as Eq. (4):

$$T_e = \frac{3}{2} p_n L_m \left(\psi_{sd} i_{sq} - i_{sd\,\psi_{sq}} \right) \quad (4)$$

The mathematical model of the electric drive system equations of motion is done by disregard the electric drive transmission mechanism in the viscous friction and torsional flexibility as shown in Eq. (5):

$$T_e = T_L + \frac{J}{p_n} d\omega / dt \quad (5)$$

Where, T_L is the load torque, T_e is the electromagnetic torque for the motor, J is the moment of inertia and p_n is the number of motor pole pairs.

3. Induction Motor Efficiency and Power Factor Control:

From Eq. (1), the IM efficiency and power factor were calculated. The calculation of the motor active power, P and reactive power Q is as Eq. (6) and (7);

$$P = \left(V_{ds} i_{ds} + V_{qs} i_{qs} \right) \quad (6)$$

$$Q = \left(V_{qs} i_{ds} - V_{ds} i_{qs} \right) \quad (7)$$

Using the Eq. (1) and Eq. (6) -(7), the IM efficiency, η and power factor, $\cos\varphi$ are derived, without taking account the mechanical losses. The efficiency is given as Eq. (8):

$$\eta = \frac{T_e \Omega_r}{P} = \frac{T_e \omega_r}{p_n P} = \frac{L_m^2 R_r \omega_r \Delta\omega}{(R_s L_r^2 + R_r L_m^2)\Delta\omega^2 + L_m^2 R \omega_r \Delta\omega + R_s R_r^2} = f_1(\Delta\omega, \omega_r) \quad (8)$$

where, f_1 is the stator frequency. The active power and power factor is equal to the ratio of the apparent power as in Eq. (9)

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$$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{(a_2\Delta\omega^2 + a_1\omega_r\Delta\omega + a_0)}{\sqrt{(a_2\Delta\omega^2 + a_1\omega_r\Delta\omega + a_0)^2 + (b_3\Delta\omega^3 + b_2\omega_r\Delta\omega^2 + b_1\Delta\omega + b_0\omega_r)^2}} = f_2(\Delta\omega, \omega_r) \quad (9)$$

where, $L_\sigma = \frac{L_sL_r - L_m^2}{L_r}$ $a_2 = \Gamma_r(R_s\Gamma_r + L_s - L_\sigma)$, $a_1 = \Gamma_r(L_s - L_\sigma)$, $a_0 = R_s$, $b_3 = b_2 = L_\sigma\Gamma_r^2$, $b_1 = b_0 = L_s$, f_2 is the rotor frequency and $\Gamma_r = \frac{L_r}{R_r}$, is the rotor time constant.

Equation (8) and (9) show that the IM efficiency and power factor is the relationship of the rotor and a slip function angular frequency. In other words, when the rotor and slip angular frequency is constant, the value of the efficiency and power factor is also constant. Thus, the maximum efficiency of the IM power factor values can be calculated.

Fig. 1 is the graph of efficiency versus the rotor and slip frequency. When $\Delta\omega$ is fixed, the motor efficiency increases with the increasing of the rotor angular frequency. However, when ω_r is fixed, the motor efficiency is increases at first, and starting to show the decreasing trend with the maximum changing process. The value is the maximum efficiency with the increasing of the rotor angular frequency.

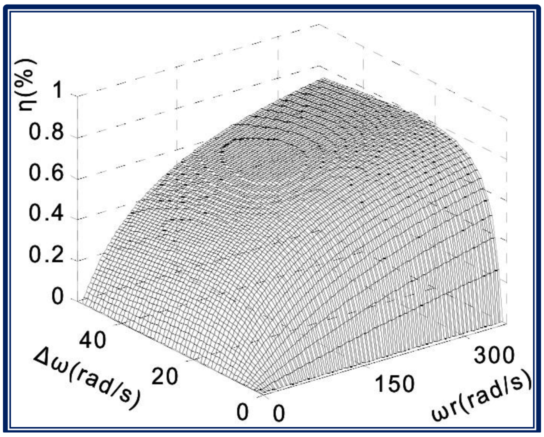


Fig. 1: Efficiency versus rotor and slip frequency

Fig. 2 shows that the power factor has small changes when the speed is large, but when the speed is lowered to its maximum of about 10%, the power factor increases rapidly. The curve bends of Figure 2 shows the clear trend. The power factor increases with the increases of the slip frequency when ω_r is fixed.

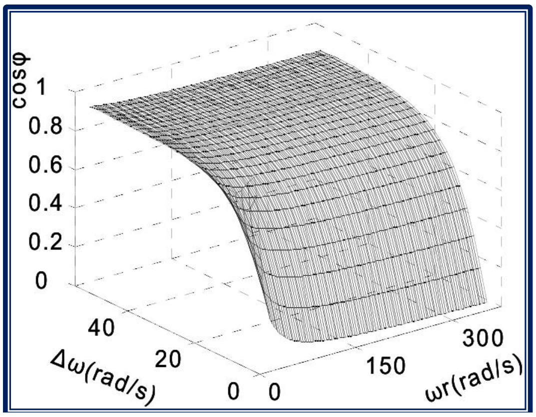


Fig. 2: Power factor versus rotor and slip frequency

From the previous analysis, it was concluded that the power factor is not at its highest when the efficiency is maximized, but the relationship is one to one. Thus, the power factor can be used as the control volume. The implementation of closed-loop power factor control by comparison of the given power factor with the actual can be used to adjust the motor terminal voltage in real time and allowing the system to achieve the optimum efficiency. From Eq. (8), the value of the efficiency derivation can be drawn as Eq. (10):

$$\frac{\delta\eta}{\delta\Delta\omega} = \frac{\delta f(\Delta\omega)}{\delta\Delta\omega} = 0 \quad (10)$$

and

$$\Delta\omega^B = \sqrt{\frac{R_s R_r^2}{R_r L_m^2 + R_s L_r^2}} \quad (11)$$

$\Delta\omega^B$ is the efficiency of a rotor angular frequency corresponding to the maximum point of the slip frequency. From Eq. (9), the efficiency of a rotor angular frequency corresponding to the maximum point of the power factor is given in Eq. (12):

$$\cos\varphi^B = f_2(\Delta\omega^B, \omega_r) \quad (12)$$

From Eq. (12), the $\Delta\omega^B$ and $\cos\varphi^B$ are the motor parameters to achieve the maximum efficiency. From Eq. (12), the best power factor angle of the rotor frequency curve can be calculated and shown in Fig. 3.

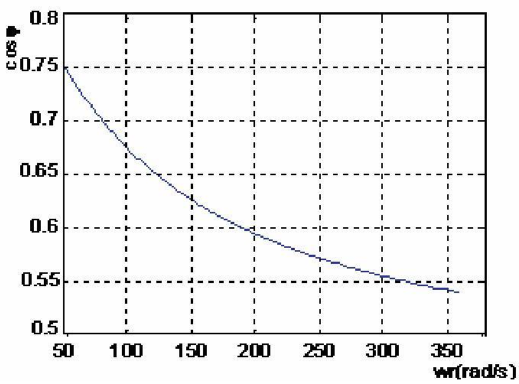


Fig. 3: Relation between the rotor frequency and best power factor

It can be seen in the normal operating speed range, the best power factor changes between 0.55 to 0.75. From the control perspective, the power factor should be controlled along with the changes of a given speed so that it is always running at a maximum efficiency state. As can be seen from the above analysis, the power factor control, is the motor slip frequency control for different operating conditions by adjusting the input voltage to keep the slip frequency $\Delta\omega^B$ around $\Delta\omega$.

The use of the power factor closed-loop control system will optimize the efficiency of the establishment in constant pressure based on the frequency ratio control to control the amount of the power factor, compromising in the stability of the actual power factor. The system block diagram is shown in Fig. 4.

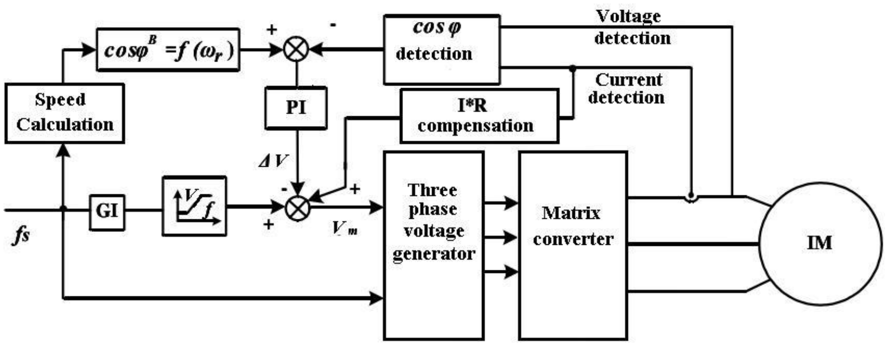


Fig. 4: Efficiency optimization control system

Efficiency optimization control system includes the following main modules: the best power factor calculation, function generator, power factor measurement, the reference wave generation, SVPWM, the drive circuit, MC, efficiency calculations, IM and other parts. The system model is shown in Fig. 5.

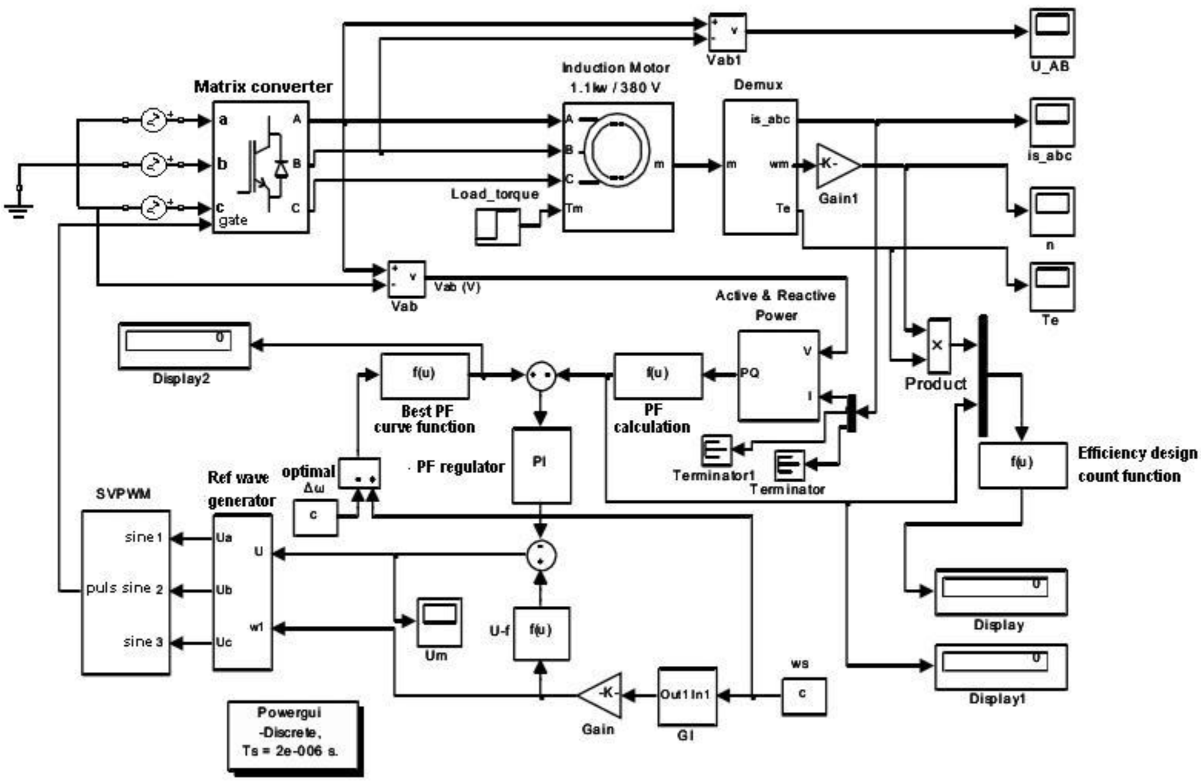


Fig. 5: Modelling of efficiency optimisation system

The best angle for a given power factor according to the method described previously calculates the optimum power factor for a given value as the changes of the rotor speed.

RESULT AND DISCUSSION

The proposed algorithms were implemented in a TMS320F28335 DSP and the system setup is shown in Fig. 6.

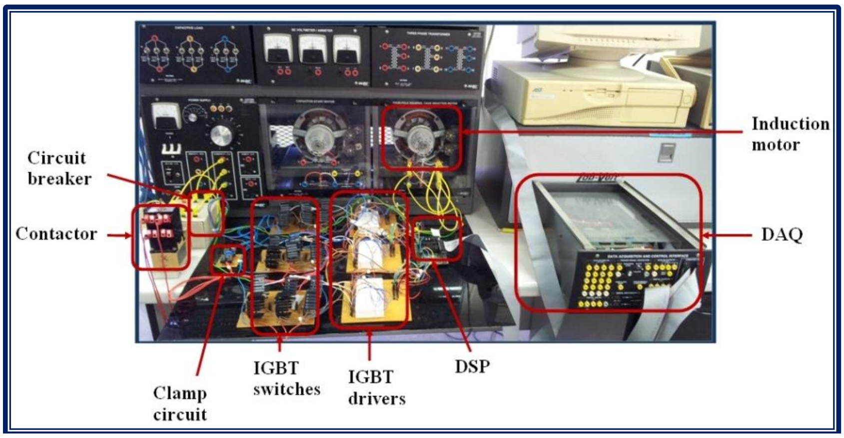
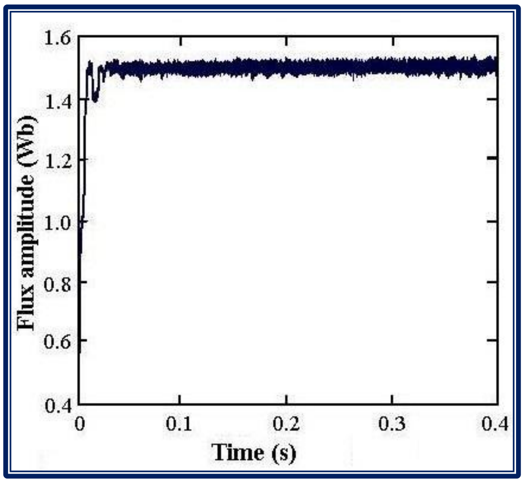
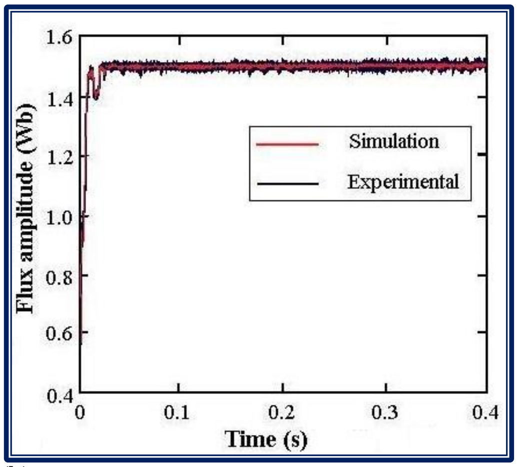


Fig. 6: Complete MC hardware

Fig. 7 shows the simulation and experimental results for the flux transient response at given amplitude of 1.5Wb. The time taken to the flux motor to reach the steady-state is less than 0.05s.



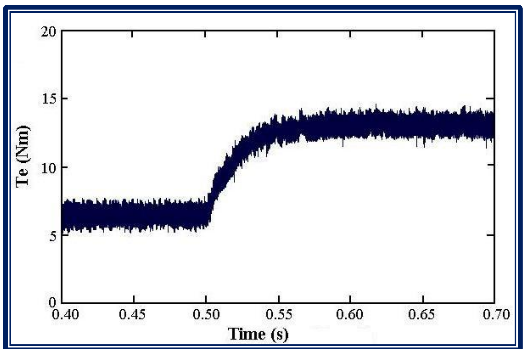
(a)



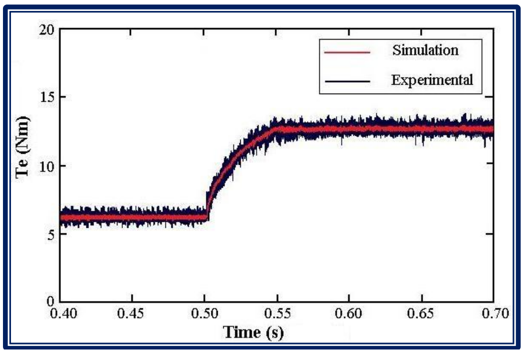
(b)

Fig. 7: Flux amplitude at transient response; (a) Conventional method; (b) proposed method

Fig. 8 shows shows the response of torque and phase *a* stator current when the torque is changed from 6Nm to 12Nm. It can be seen that the stator current response to the changes of torque command as shown in Fig. 9(b).

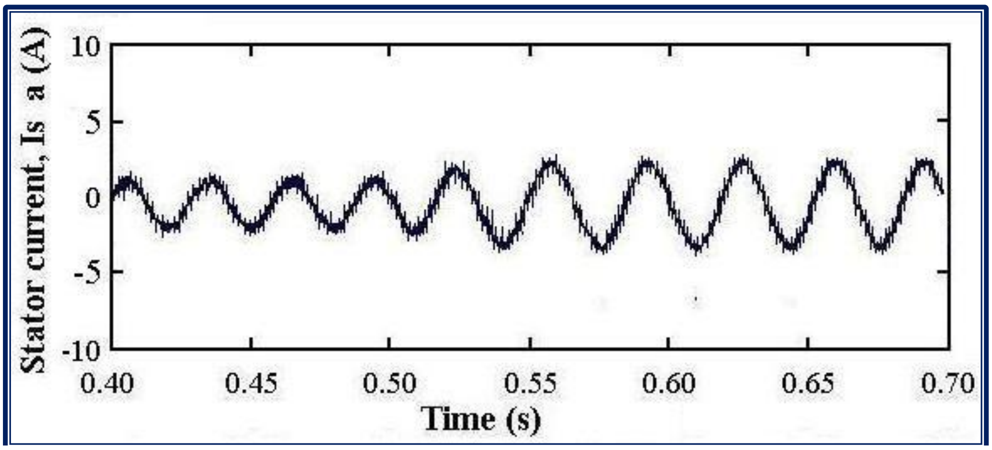


(a)

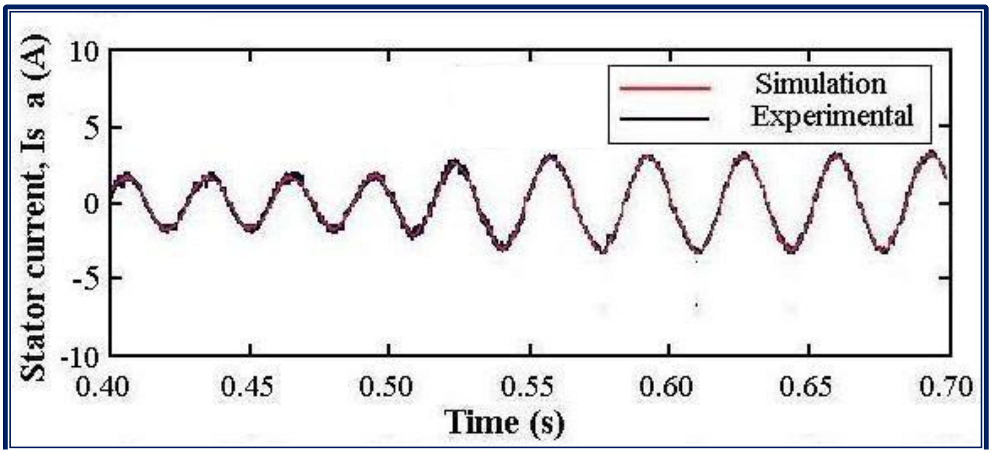


(b)

Fig. 8: Torque changes from 6Nm to 12Nm; (a) conventional method; (b) proposed method



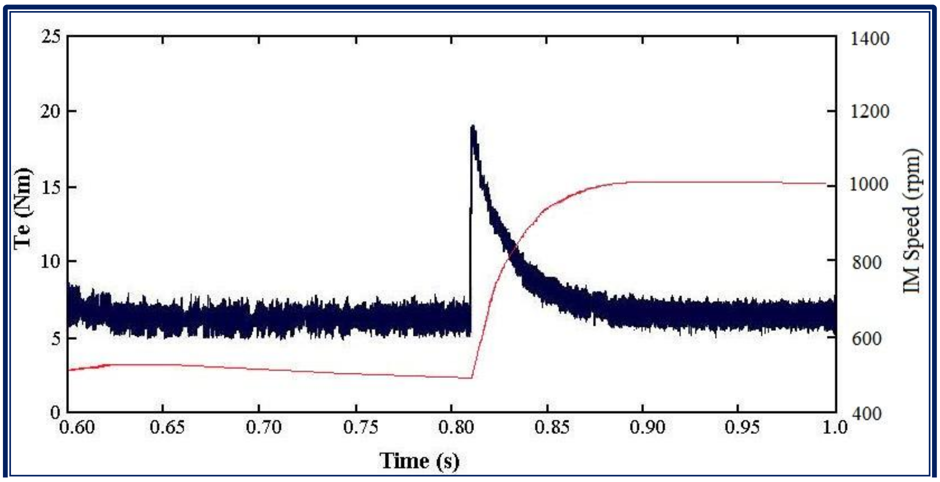
(a)



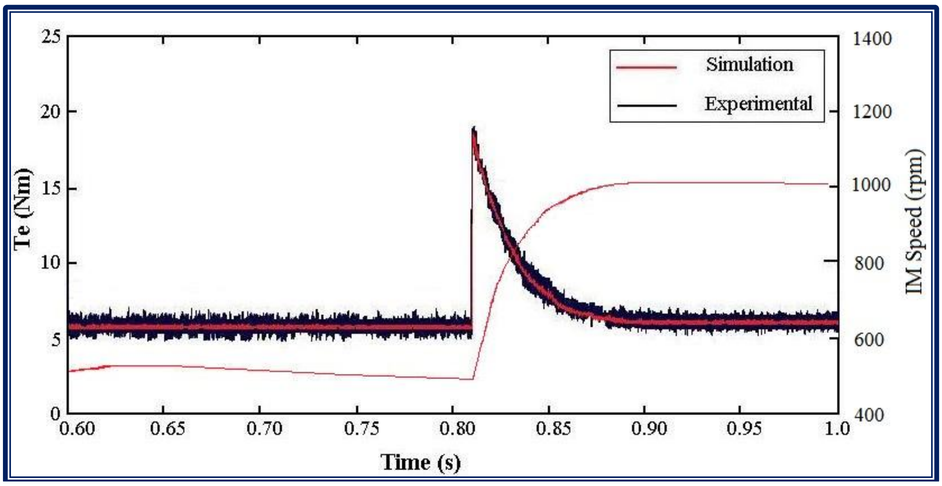
(b)

Fig. 9: Stator current with torque changes; (a) conventional method; (b) proposed method

Fig. 10 shows the torque response when the speed increased from 500rpm to 1000rpm, without using the proposed method. The greater torque impact is achieved with the speed increases at less than 0.05s.



(a)



(b)

Fig. 10: Effect of changes the motor speed of the torque response; (a) conventional method; (b) proposed method

When the curve of the speed changes in Figure 4.11(a), the torque response changes with the speed changes. The electromagnetic torque is reversed following the speed command as in Figure 4.11(b).

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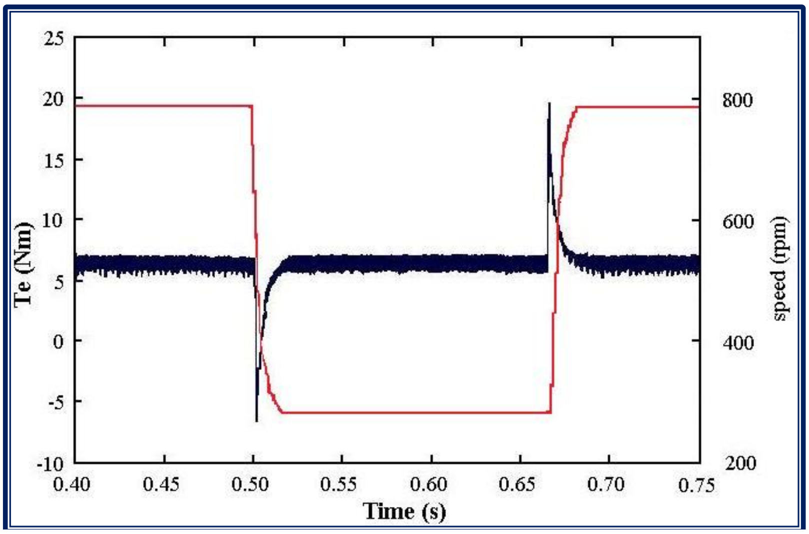
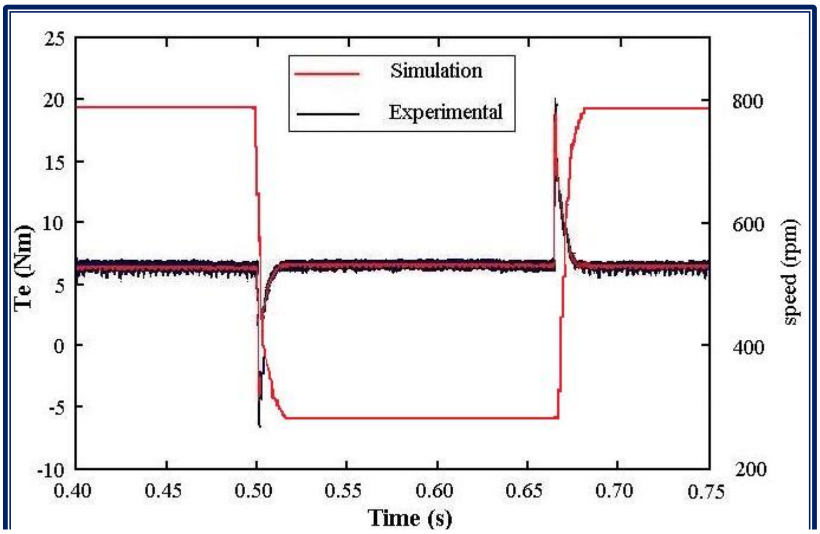


(a)



(b)

Fig. 11: Torque response with dynamic changes of motor speed (a) conventional method (b) proposed method

Conclusion:

The proposed power factor control in this paper will optimize the efficiency of the establishment in constant pressure based on the frequency ratio control to control the amount of the power factor, compromising in the stability of the actual power factor. The power factor control reduced the torque ripple hence improving the matrix converter performance.

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