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Comparison Between Direct Power Control and Direct Torque Control of Induction Motor Drive

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Abstract

This paper presents a comparative study between direct torque control (DTC) and direct power control (DPC) of Induction motor drive. The comparison is based on various criteria including basic control characteristics, dynamic performance, and implementation complexity. The simulation and evaluation of both control strategies are performed using actual parameters of Induction Motor fed by an PWM inverter. The simulation results show good performance of both methods.

Keywords: direct power control (DPC), direct torque control (DTC), flux control, induction motors (IMs)

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INTRODUCTION

Induction motors are the most regularly utilized electric drives as a part of the commercial enterprises because of its strength, less upkeep, and ease. The electric drives must have great element reaction to react to little changes in the load or in the reference speeds.[1,2]

The control schemes available for the induction motor drives are the scalar control (v/f), vector or field oriented control (FOC), direct torque and flux control (DTC) and direct power control (DPC). The first one is considered as scalar control since it adjusts only magnitude and frequency of voltage or current with no concern about the instantaneous values of motor quantities. It does not require knowledge of the parameters of the motor, and it is an open-loop control. Thus, it is low cost simple solution for low-performance applications such as fans and pumps. The other two methods are in space vector control category because they utilize both magnitude and angular position of space vectors of motor variables, such as voltage and flux. They are employed in the high performance applications, such as positioning drives or electric vehicles.[3,4]

Direct power control is a control technique that straightforwardly chooses output voltage vector states taking into account the power and flux mistakes utilizing hysteresis controllers and without utilizing current loops. In this admiration, it is likely to understand direct torque control (DTC) strategy portrayed in the literary works for different AC motors.[5] What is in common among these applications is that they all are the power output devices needed to provide real power to the load. DPC technique basically is applied to the generators, but it has been tried to the employ it to control of electrical motors instead of DTC technique, due to problems of torque estimation and dependency to the motor's parameters in DTC. In this way, DPC strategy appreciates all favorable circumstances of DTC, for example, quick dynamic and simplicity of execution, without having the DTC's issues. In any case, publications about direct power control are basically gone for either rectifiers,[6] converters,[7,8] dual-fed induction generators (DFIG)[9,10] or permanent magnet synchronous generators (PMSG),[11,12] and there isn't any research about using the DPC technique for Induction motor.

Dynamic Model of Induction Motor

The IM model has been determined in various distinctive reference outlines. This makes it less demanding to settle the reference frame to a specific motor quantity and change the model as needs be. The majority of induction motors are the rotary type with fundamentally a stationary stator and a rotating rotor. The dynamic model of induction motor is derived by transforming the three phase quantities into two phase direct and quadrature axes quantities. The mathematical model in the compact form can be given in the stationary reference frame as follows.[5]

Where the voltage equation is:

$$V_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds} \quad \text{Eq. (1)}$$

$$V_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} + \omega_e \psi_{qs} \quad \text{Eq. (2)}$$

$$V_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr} \quad \text{Eq. (3)}$$

$$V_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} + (\omega_e - \omega_r)\psi_{qr} \quad \text{Eq. (4)}$$

Where, V_{qr}, $V_{dr} = 0$

The electromagnetic torque of the machine can be presented as follow:

$$T_e = \frac{3PL_m}{4L_r}(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \quad \text{Eq. (5)}$$

Where P, denote the number of pole in the motor. If the vector control is contains the q component of the rotor field ψ_{qr} would be zero. Hence the electromagnetic torque will be controlled only by q-axis stator current and becomes:

$$T_e = \frac{3PL_m}{4L_r}(\psi_{dr} i_{qs}) \quad \text{Eq. (6)}$$

Principals of the Direct Torque Control (DTC) of Induction Motor

DTC is direct torque and flux control, with two parameters included in the control system, so it is likewise named as direct torque and flux control (DTFC) in a few literatures. DTC is a control technique that specifically chooses inverter states taking into account the torque and flux errors. Hysteresis (relay) controllers are utilized, and no current controllers are available. The voltage source inverter appeared in Figure 1 in the general block diagram of direct torque and flux control framework will be utilized as a part of all frameworks considered in this paper. Figure 2 represents a detailed DTC system diagram.

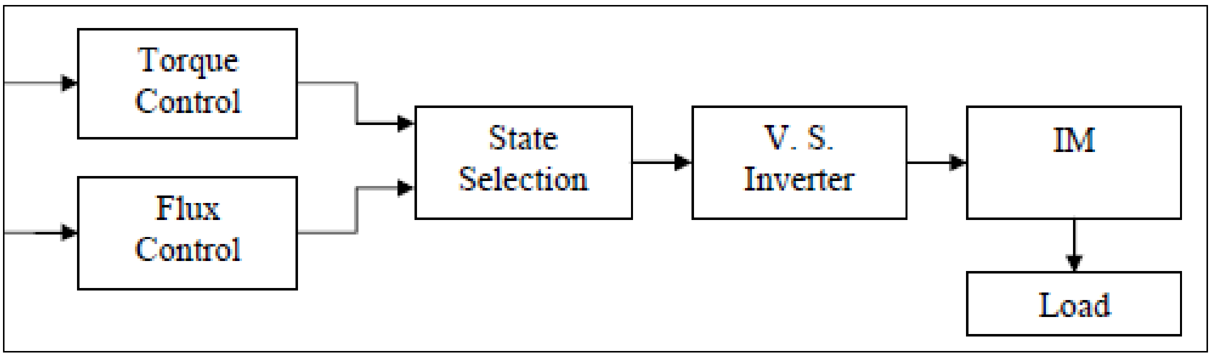

Fig. 1. *Block Diagram of Direct Torque and Flux Control System.*

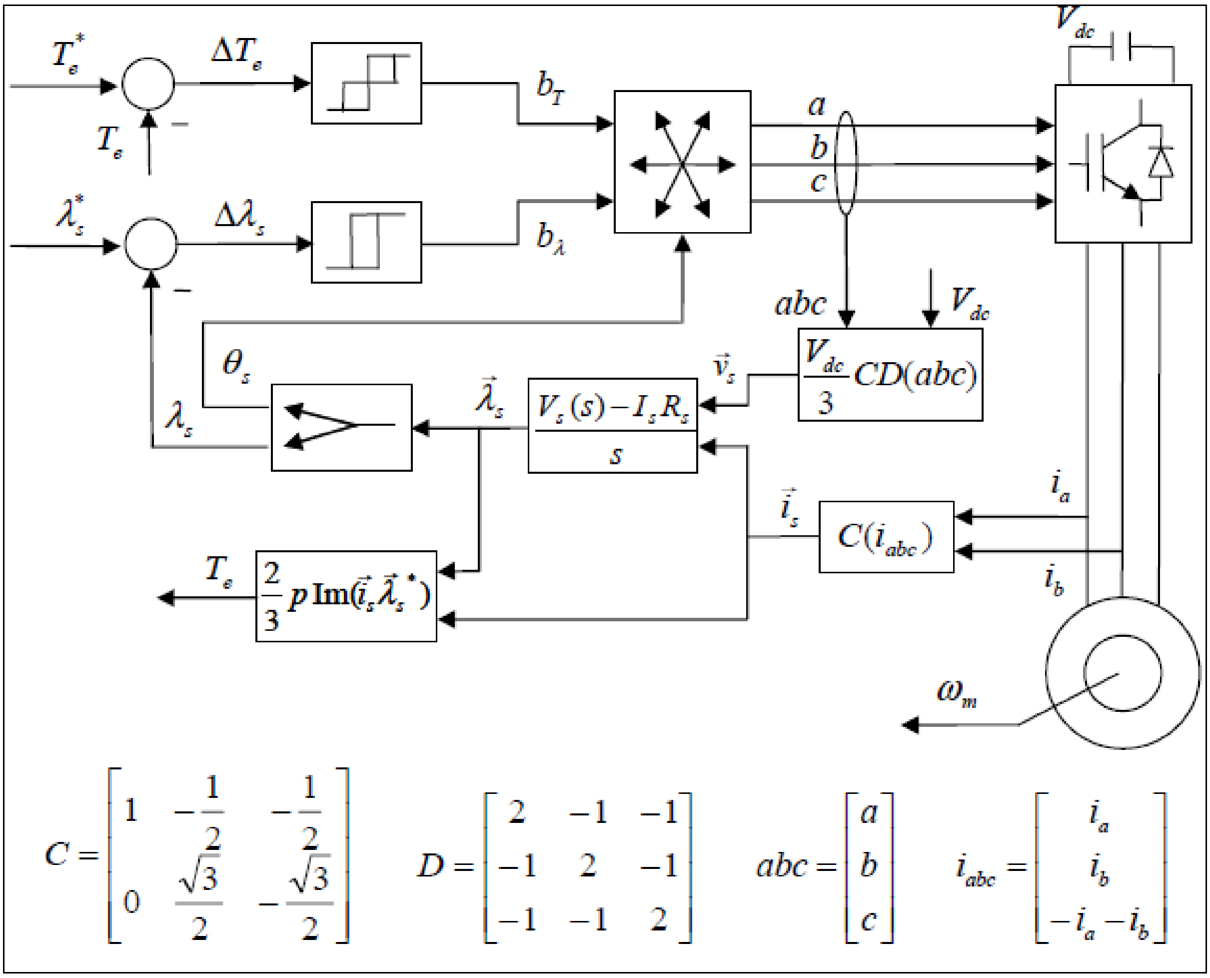

Fig. 2. *Direct Torque and Flux Control System without a Speed Control Loop.*

Flux Control Principles

Flux linkage is very important in IMs. Constant flux can give enough electromagnetic torque and abstain from magnetizing current saturation in the iron core of the IM.

Along these lines in direct torque and flux control proposed the flux is looked after steady. In the stator stationary reference frame, the frame rotation speed is zero and the rotor voltage is zero for squirrel- cage IMs.

$$\vec{V}_s = R_s\vec{i}_s + \frac{d\vec{\lambda}_s}{dt} \quad \text{Eq. (7)}$$

$$\vec{0} = R_r\vec{i}_r + \frac{d\vec{\lambda}_r}{dt} - j\omega_r\vec{\lambda}_r \quad \text{Eq. (8)}$$

If we neglect the small voltage drop across the stator resistance, we have

$$\vec{V}_s \cong \frac{d\vec{\lambda}_s}{dt} \quad \text{Eq. (9)}$$

Integrating Eq. (9) and writing it in a discrete form, we obtain

$$\vec{\lambda}_s(t_{n+1}) = \vec{\lambda}_s(t_n) + \vec{V}_s\Delta t \quad \text{Eq. (10)}$$

that is,

$$\Delta\vec{\lambda}_s \cong \vec{V}_s\Delta t \quad \text{Eq. (11)}$$

Where $\Delta t = t_{n+1} - t_n$ equals the switching interval.

Therefore, within a switching interval Δt, the increase of stator flux is proportional to the stator voltage space vector. This is the principle of direct flux control in DTC.

Electromagnetic Torque Control Principle

The electromagnetic torque generated in motors is a key parameter responsible for dynamic performance of electric drive systems. In traditional motor control methods such as the FOC, it is indirectly controlled through the control of current. In DTC, it is controlled directly by the selection of the inverter states.

The stator and rotor current vectors are given by

$$\vec{i}_s = \frac{\vec{\lambda}_s - L_m \vec{i}_r}{L_s} \qquad \text{Eq. (12)}$$

$$\vec{i}_r = \frac{\vec{\lambda}_r - L_m \vec{i}_s}{L_r} \qquad \text{Eq. (13)}$$

Substituting (13) in (12) yields

$$\vec{i}_s = \frac{L_r \vec{\lambda}_s - L_m \vec{\lambda}_r}{L_s L_r - L_m^2} \qquad \text{Eq. (14)}$$

Electromagnetic torque is

$$T_e = \frac{2}{3} p \mathrm{Im}(\vec{i}_s \vec{\lambda}_s^{\,*}) \qquad \text{Eq. (15)}$$

By substituting Eq. (14) in Eq. (15), the electromagnetic torque generated in the IM can be expressed as

$$T_e = \frac{2}{3} p \mathrm{Im}\left(\vec{i}_s \vec{\lambda}_s^{\,*}\right) = \frac{2}{3} p \mathrm{Im}\left(\frac{L_r \vec{\lambda}_s - L_m \vec{\lambda}_r}{L_s L_r - L_m^2} \vec{\lambda}_s^{\,*}\right)$$
$$= -\frac{2}{3} p \frac{L_m}{L_\sigma^2} \mathrm{Im}\left(\vec{\lambda}_r \vec{\lambda}_s^{\,*}\right) = \frac{2}{3} p \frac{L_m}{L_\sigma^2} \mathrm{Im}\left(\vec{\lambda}_s \vec{\lambda}_r^{\,*}\right)$$
$$= \frac{2}{3} p \frac{L_m}{L_\sigma^2} \lambda_s \lambda_r \sin(\theta_s - \theta_r) \qquad \text{Eq. (16)}$$

Where $L_\sigma^2 = L_s L_r - L_m^2$.

Rotor flux is inertial equating with the stator flux, so inside a small sampling interval Δt, it can be measured constant. Then torque can be controlled by changing the stator flux angle θ_s which is affected by the voltage vectors shown in Figure 3.

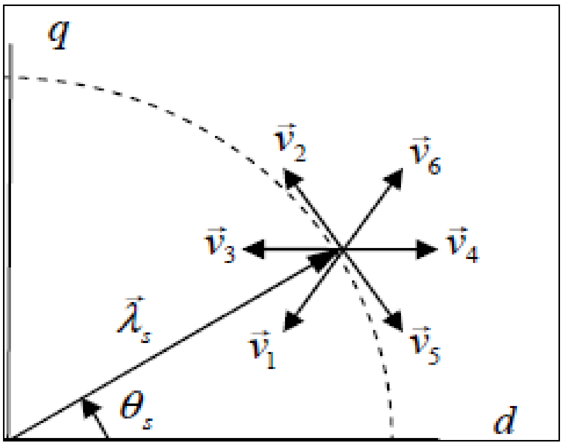

Fig. 3. *Illustration of Torque and Flux Control through Selection of Voltage Vectors in A Stationary D-Q Frame.*

Switching Table

The Figure 4 depicts the thinkable dynamic locus of the stator flux, and its dissimilar variation dependent on the VSI states chosen. In classical DTC, the probable global locus is divided into six diverse sectors.

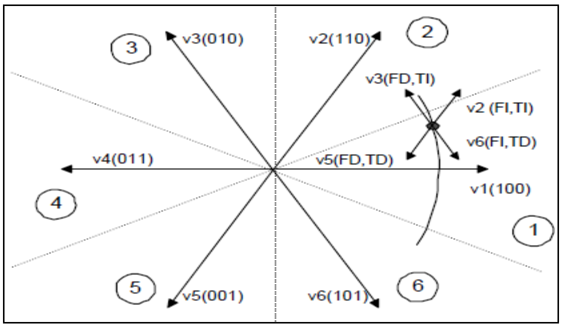

Fig. 4. *Stator Flux Vector Locus and Different Possible Switching Voltage Vectors. Fd: Flux Decrease. Fi: Flux Increase. TD: Torque Decrease. TI: Torque Increase.*

In agreement with Figure 4, the common Table 1 can be formed which shows, that the states V_k and V_{k+3}, are not reflected in the torque as they can both increase (first 30 degrees) or decrease (second 30 degrees) the torque at the same sector reliant on the stator flux position. The use of these states for controlling the torque is thought one of the purposes to improve in the present paper, dividing the total locus into twelve sectors instead of just six.

Table 1. *General Selection Table for Direct Torque Control.*

VOLTAGE VECTOR	INCREASE	DECREASE
Stator Flux	V_k, V_{k+1}, V_{k-1}	$V_{k+2}, V_{k-2}, V_{k+3}$
Torque	V_{k+1}, V_{k+2}	V_{k-1}, V_{k-2}

being "k" the sector number.
Finally, the DTC classical look up table is as follows:

Table 2. *Look up Table for Direct Torque Control.*

φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
FI	TI	V_2	V_3	V_4	V_5	V_6	V_1
	T=	V_0	V_7	V_0	V_7	V_0	V_7
	TD	V_6	V_1	V_2	V_3	V_4	V_5
FD	TI	V_3	V_4	V_5	V_6	V_1	V_2
	T=	V_7	V_0	V_7	V_0	V_7	V_0
	TD	V_5	V_6	V_1	V_2	V_3	V_4

FD/FI: flux decrease/increase. TD/=/I: torque decrease/equal/increase. Sx: stator flux sector. F: stator flux modulus error after the hysteresis block. t: torque error after the hysteresis block.

The segments of the stator flux space vector are indicated from S_1 to S_6. Stator flux modulus mistake after the hysteresis block (Φ) can take only two qualities. Torque error after the hysteresis block (τ) can take three distinct values.

The zero voltage vectors V_0 and V_7 are chosen when the torque error is inside of the given hysteresis restrains, and should stay unaltered.

PRINCIPALS OF THE DIRECT POWER CONTROL (DPC) OF INDUCTION MOTOR

The direct power control strategies talked about in this paper bear certain closeness to the direct power control (DTC). In this way, DPC is very direct power and flux control, with two parameters included in the control methodology, so it is likewise named as direct power and flux control (DPFC) in a few literatures.[13,14] Direct power and flux control (DPFC) of IMs is a control strategy that specifically chooses output voltage vector states taking into account the power and flux errors utilizing hysteresis controllers. Figure 5 demonstrates the block diagram of a general open-circle DPFC framework.

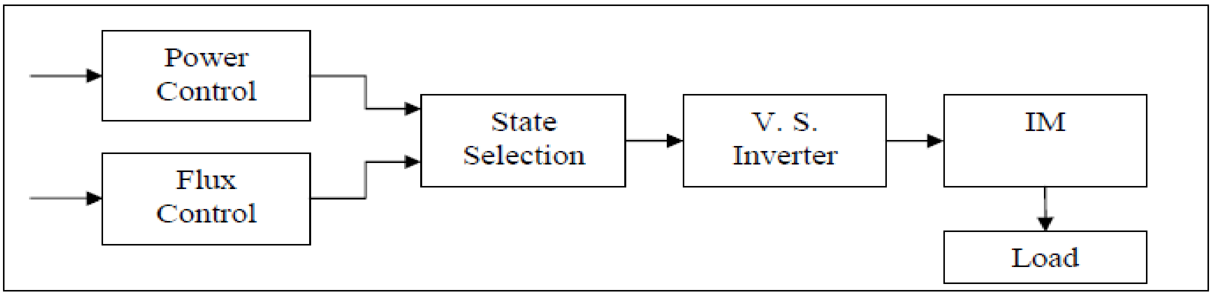

Fig. 5. *Block Diagram of Direct Power and Flux Control System.*

Flux Control Principle

In DPFC, the flux is still maintained constant and the control principles of the flux are the same as that in DTC.

The output real power is given by

$$P_{out} = T_e\omega_m = T_e\frac{\omega_r}{p}$$

And

$$T_e = \frac{2}{3}p\mathrm{Im}\left(\vec{i}_s\vec{\lambda}_s^{\,*}\right) = \frac{2}{3}p\mathrm{Im}\left(\frac{L_r\vec{\lambda}_s - L_m\vec{\lambda}_r}{L_sL_r - L_m^2}\vec{\lambda}_s^{\,*}\right)$$
$$= -\frac{2}{3}p\frac{L_m}{L_\sigma^2}\mathrm{Im}\left(\vec{\lambda}_r\vec{\lambda}_s^{\,*}\right) = \frac{2}{3}p\frac{L_m}{L_\sigma^2}\mathrm{Im}\left(\vec{\lambda}_s\vec{\lambda}_r^{\,*}\right) \qquad \text{Eq. (17)}$$
$$= \frac{2}{3}p\frac{L_m}{L_\sigma^2}\lambda_s\lambda_r\sin(\theta_s - \theta_r) \qquad \text{Eq. (18)}$$

Substituting the torque in Eq. (17) with Eq. (18), the output power becomes

$$P_{out} = \frac{2}{3}\omega_r\frac{L_m}{L_\sigma^2}\mathrm{Im}(\vec{\lambda}_s\vec{\lambda}_r^*)$$
$$= \frac{2}{3}\frac{L_m}{L_\sigma^2}\omega_r\lambda_s\lambda_r\sin(\theta_s - \theta_r) \qquad \text{Eq. (19)}$$

Following the magnitude of the stator flux is kept steady and the rotor flux does not change much because of its inactivity, the rotor speed and point can be viewed as consistent as well. The equation above demonstrates that the change of output power depends just on the change of stator flux angle. The stator voltage vector that can expand the stator angle should be brought up so as to build the output power.

The real output power mathematical statement acquired above is substantial for clarification of the standards of power control. Be that as it may, it is not suitable with the end goal of assessing the actual power in simulations.

Output Power Reference

The output power reference is the command value, or the set point, for the power control. In a closed-loop speed control framework, the reference of the power controller is acquired from the output of the PI-sort speed controller (see

Power Control Principle

From the power flow charts in induction motor, it is obvious that real output power is the part that creates the torque, and is what the user of the system is typically interested in.

Figure 6). The speed error is characterized as the distinction of the reference speed and the assessed actual speed.

$$\Delta\omega_m = \omega_m^* - \omega_m \qquad \text{Eq. (20)}$$

Where ω_m^* is the reference speed (the asterisk denotes a reference value). Then, the reference torque can be obtained through a conventional PI controller as

$$T_e^* = K_p(\Delta\omega_m) + K_i\int(\Delta\omega_m)dt \qquad \text{Eq. (21)}$$

The continuous standard form above can also be expressed in discrete incremental PI control form, which is more suitable for the digital implementation.

$$T_e^*(t_{n+1}) = T_e^*(t_n) + K_p[\Delta\omega_m(t_n) - \Delta\omega_m(t_{n-1})] + K_i\Delta T\Delta\omega_m(t_n)$$
$$(t_{n-1})] + K_i\Delta T\Delta\omega_m(t_n) \qquad \text{Eq. (22)}$$

The subscript (n) signifies the current sampling instant, (n-1) is the last instant, and (n+1) is the next one. The proportional gain is represented by K_p, K_i is the integral gain, which Equals K_p divided by the integral time constant T_i , and ΔT is the sampling time interval between the n and (n+1) sampling instants. The output power reference expressed as the process of obtaining the output power reference from the speed reference is illustrated in Figure 3.

For simulations, the actual motor speed ω_m can be obtained as

$$\omega_m = \frac{1}{J}\int (T_e - T_{ld})dt \quad \text{Eq. (23)}$$

In practice the speed is either measured directly or estimated from the current and voltage signals. The magnitude of stator flux is kept constant in the simulation, thus the flux reference λ_s^* is a constant. The error of the stator flux is

$$\Delta\lambda_s = \lambda_s^* - \lambda_s \quad \text{Eq. (24)}$$

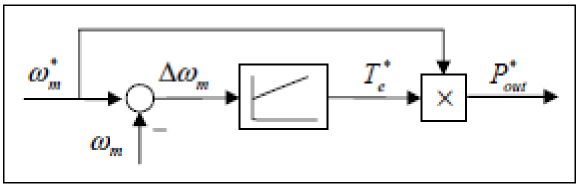

Fig. 6. *Diagram of Output Power Reference Obtained From Speed Loop.*

Power and Flux Hysteresis Controllers

Both the output power and the stator flux controllers are of hysteresis type. Depending on the control error, the output of controller is set to two or three discrete values. The power controller has a three level output.[15-16]

The values are 1, 0 and -1, representing an increase, no change, and decrease of the controlled variable, respectively. The number of flux controller output levels is two, with 1 and 0 meaning an increase and decrease commands, respectively. Figure 7 illustrates characteristics of these two controllers.

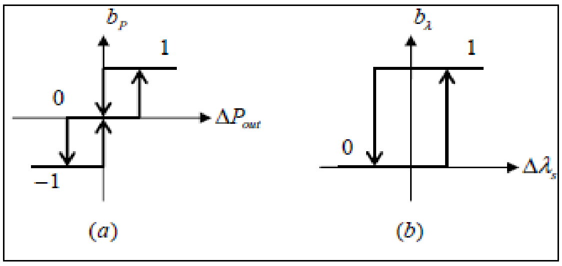

Fig. 7. *Characteristics of the Hysteresis Controllers: (a) Power Controller, (b) Flux Controller.*

Switching Table

The task of the state selector in direct power control is to combine the outputs of the power controller and flux controller to select the values of the switching variables a, b, and c. These variables describe the required voltage vectors of inverter.

To make it easier to implement, the combination of the two controller outputs can be expressed as follows:

$$b = 3b_\lambda + b_p + 2 \quad \text{Eq. (25)}$$

In the above equation, the variable b = 1, 2, 3, 4, 5, 6, while b_λ= (0, 1) and b_p= (-1, 0, 1).

Alternatively, Eq. (25) can also be represented by Table 3.

Table 3. *Combination of the Power and Flux Controller Outputs.*

$b_p = -1$	$b_p = 0$	$b_p = 1$
1	2	3
4	5	6

A whole stator flux cycle of 360° is divided equally into 6 sectors, each one spanning 60°. Combining with the sector numbers from 1 through 6, produces the lookup Table 2 for the state selection.

The concept of state selection is illustrated in Figure 8.

Table 4. *State Selection Loop-Up Table.*

	b=1	b=2	b=3	b=4	b=5	b=6
Sector 1	1	0	2	5	7	6
Sector 2	5	7	6	4	0	2
Sector 3	4	0	1	6	7	3
Sector 4	6	7	5	2	0	1
Sector 5	2	0	4	3	7	5
Sector 6	3	7	6	1	0	4

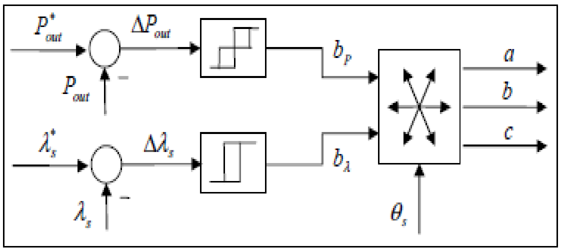

Fig. 8. *Block Diagram of the Inverter State Selection.*

Note that the stator flux angle θ_s must be converted to a sector number of 1 through 6 for the use of Table 4 for state selection.

SIMULATION RESULTS

DTC Results

In Figure 9 a possible schematic of Direct Torque Control is shown. Figure 10 shows the tracking of reference Torque of the motor. Torque controller has the desired response.

Moreover, in Figure 11, the speed reference tracking has been shown using direct Torque control strategy.

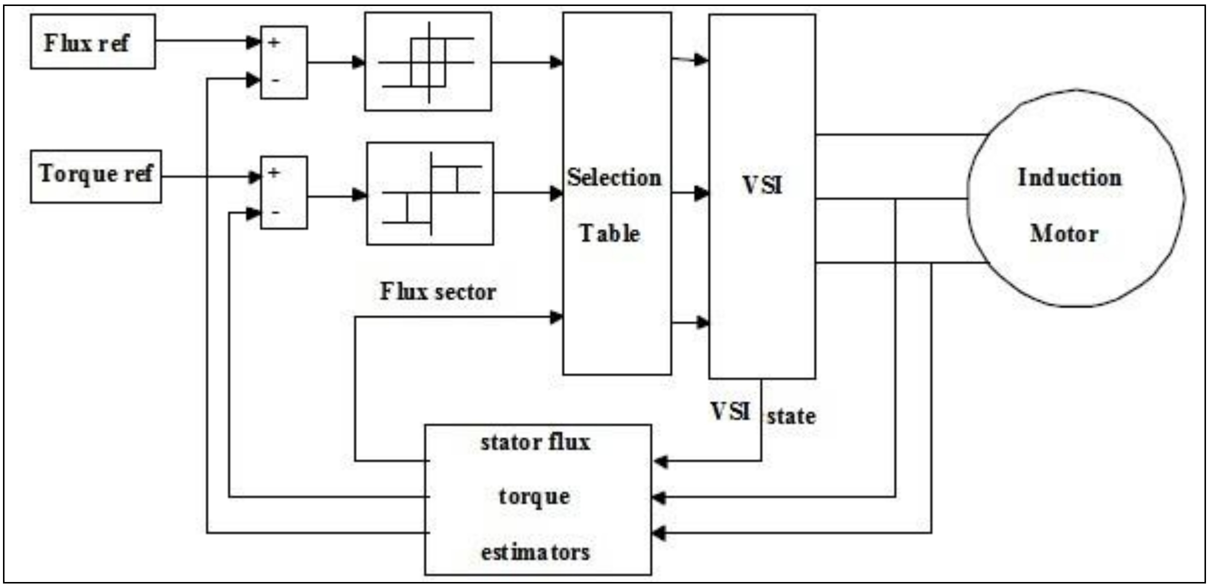

Fig. 9. *Direct Torque Control Schematic.*

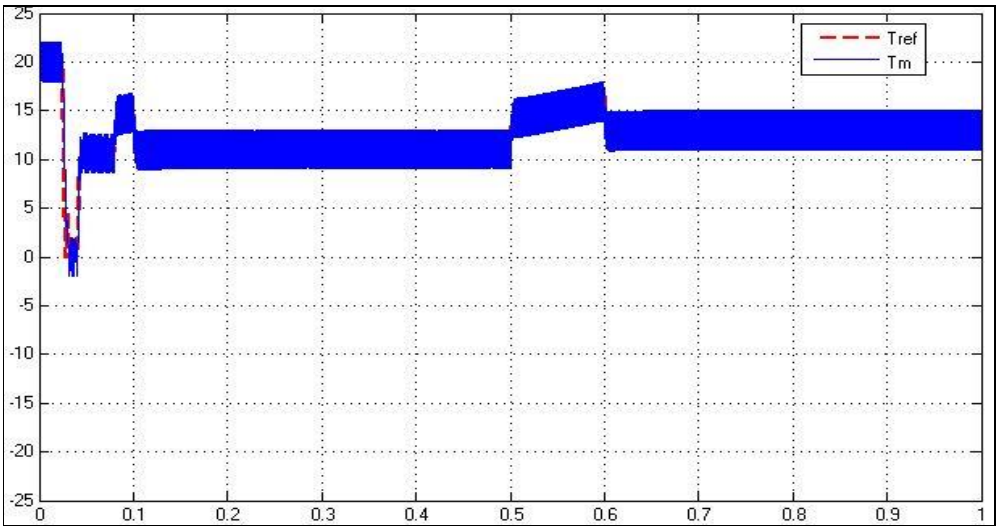

Fig. 10. *Electromagnetic Torque Tracking Using DTC Strategy.*

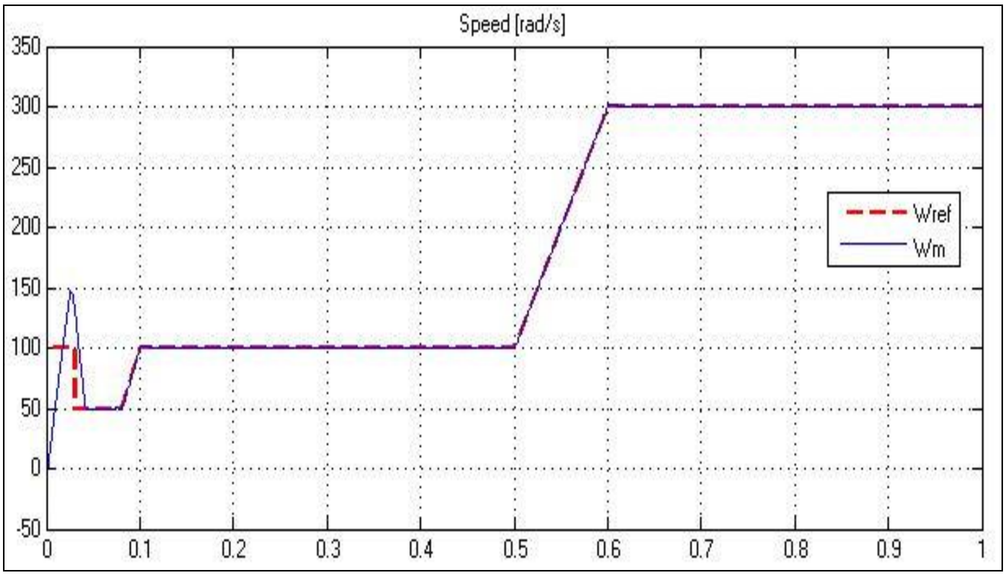

Fig. 11. *Speed Reference Tracking Using DTC Strategy*.

DPC Results

The simulation was carried out using MATLAB. The whole system setup is shown in Figure 12.

It can be seen that this is a power and flux dual-controller system. While the flux control has only one loop, a speed loop is present outside the power control.

Figure 13 shows the tracking of reference power of the motor. Power controller has the desired response. Moreover, in Figure 14, the speed reference tracking has been shown using direct power control strategy.

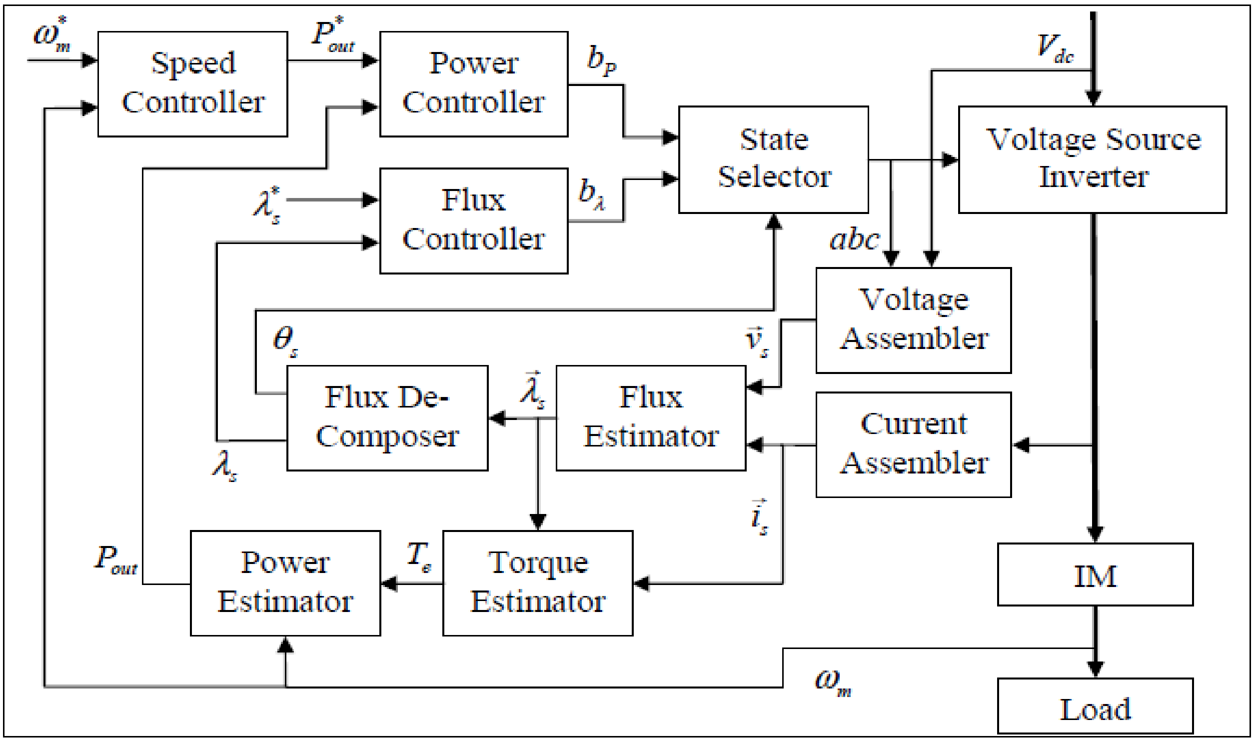

Fig. 12. *Block Diagram of the Direct Out Power and Flux Control System for IM With Closed-loop Speed Control*.

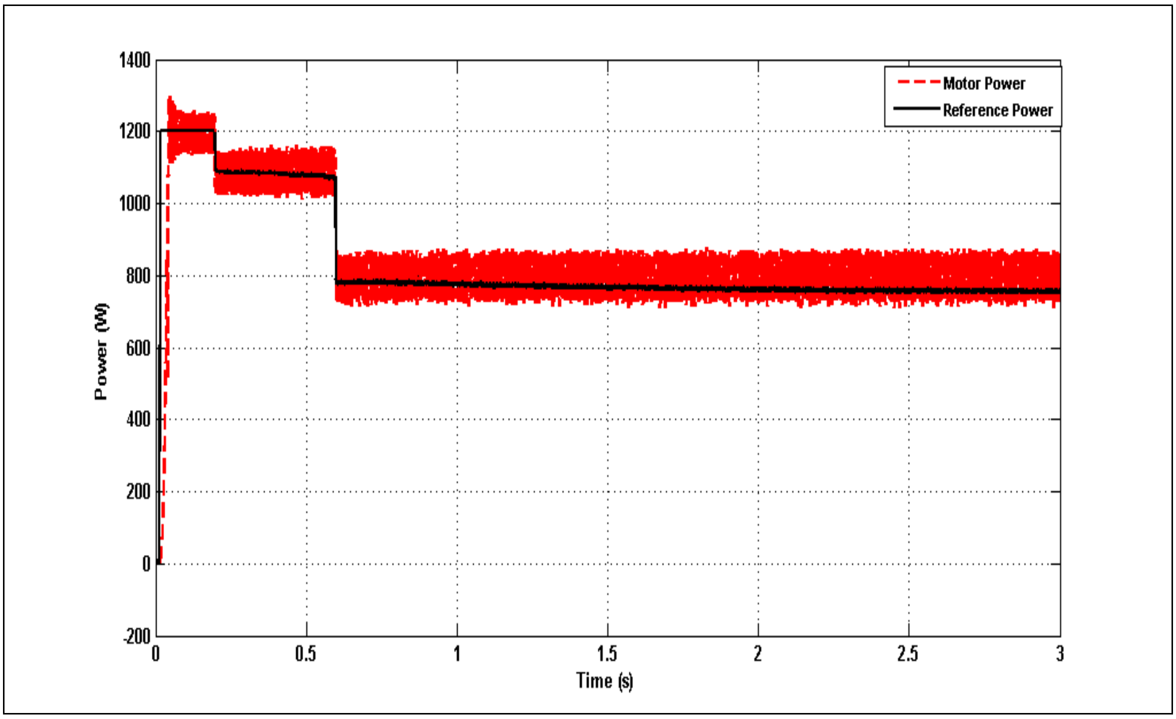

Fig. 13. *Air-Gap Power Tracking using DPC Strategy.*

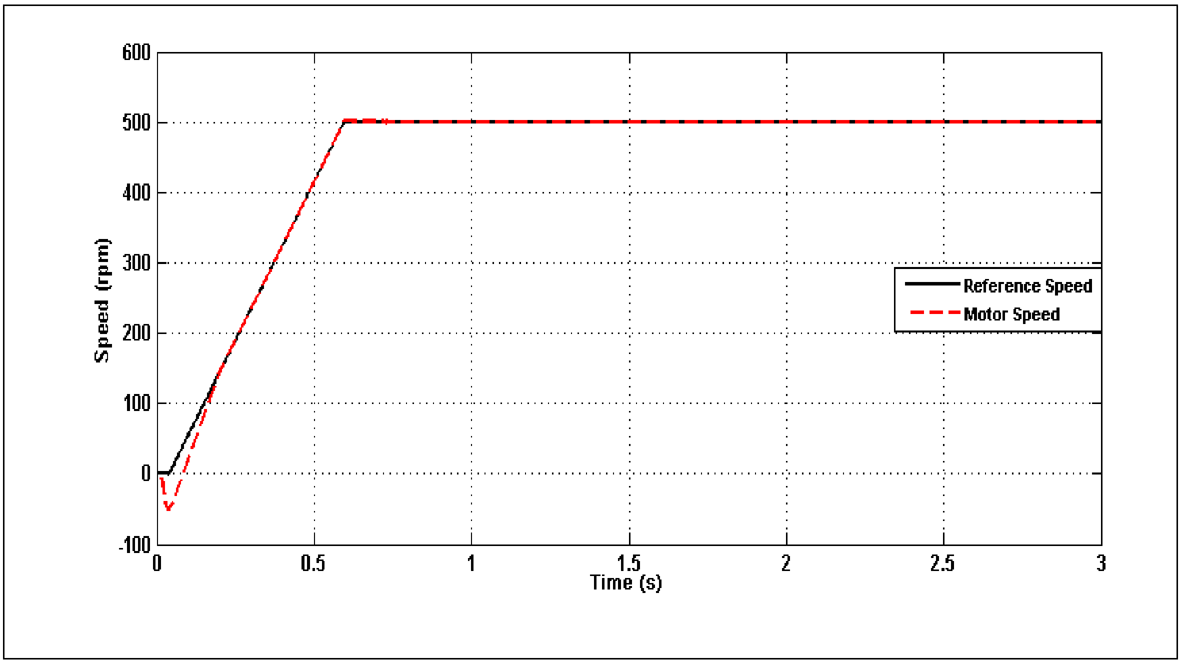

Fig. 14. *Speed Reference Tracking Using DPC Strategy.*

CONCLUSION

In this paper, main characteristics of direct power control and direct torque control schemes for Induction motor drives are studied by simulation with a view to highlighting the advantages and disadvantages of each approach. direct power control (DPC) in addition to simply direct torque control of and high dynamic response, problems with direct torque control (DTC) does.

The implementation of DPC control systems no longer need to know the values of model parameters for induction motors do not have time at least.

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