2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC)
12-14 February, Shiraz University, Iran

Stator Flux Oriented Control of Brushless Doubly Fed Induction Motor Drives Based on Maximum Torque per Total Ampere Strategy

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Abstract **- This paper introduces the maximum torque per total ampere (MTPTA) strategy for brushless doubly-fed induction motor (BDFIM) drives, for the first time. In the proposed strategy, the reference of control winding (CW) d-axis current is determined through the well-known search-based approach. Accordingly, by tracking this reference, the magnitude of total stator current is minimized for a given load. In addition, using the reduced order model of BDFIM in the power winding (PW) flux reference frame, the torque expression is derived and it is shown that if the CW d-axis current is forced to zero, the maximum torque per inverter ampere (MTPIA) strategy is achieved to allow the minimum inverter loading. Simulation results are finally proposed to verify the effectiveness of the proposed control strategy.**

Index Terms – Brushless doubly-fed induction motor (BDFIM), field-oriented control, maximum torque per total ampere (MTPTA), reduced order model.

NOMENCLATURE

$\vec{V}, \vec{I}, \vec{\psi}$	Voltage, current, flux vectors
T_e, T_l	Electromagnetic torque and load torque
R_1, R_2, R_r	Resistances of PW, CW and, rotor
L_{l1}, L_{l2}, L_{lr}	Leakage inductances of stator windings and rotor
L_{1r}, L_{2r}	Coupling inductances between stator windings and rotor
p_1, p_2	Pole pair numbers of PW and CW
ω_r	Synchronous rotor speed
ω_1, ω_2	Angular speed of PW and CW
ω_n	Natural synchronous speed
s_1, s_2	Slip with respect to PW and CW fields
θ_2	CW current angle
Subscripts	
$1,2,r$	PW, CW and, rotor
d,q	Rotating frame axis

I. INTRODUCTION

The brushless doubly-fed machines (BDFMs) have been shown promising prospect as a substitute for conventional doubly-fed induction machine (DFIM) in the variable speed applications [1]. Hitherto, a number of interesting brushless topologies of the BDFM have been reported. Among the brushless structures, the brushless doubly-fed induction machine (BDFIM) and the brushless doubly-fed reluctance machine (BDFRM) have the same stator structure but in the BDFIM, the reluctance rotor is replaced with a special cage structure that the number of nests are equal to the sum of the stator windings pole pairs. The BDFIM–based drive technology has been found applications in such areas as wind turbines [2-3], industrial drives [4-5] and small hydro plants [6] as well as supplying power to ships [7]. To date, the tendency of the BDFIM literature has been focused on the design and control aspects, however, a few researches have been published with the aim of efficiency improvement of BDFIM drives in general and implementation of MTPA strategy in particular. One of them given in [8], deals with steady-state efficiency optimization of BDFIM based on an off-line search algorithm (look-up table approach). In [9], an analytical method for increasing the torque per ampere capability of BDFIM is presented based on core model. The core model is over simplified version of equivalent circuit of BDFIM obtained by omitting the magnetizing reactances and the stator and rotor resistances [10].

This paper will attempt to present the MTPTA control strategy for the FOC-based BDFIM drive using the reduced order model of BDFIM. This control approach is achieved using a well-known online search method. Based on this method, for a given load torque and rotor speed, the reference of CW d-axis current is adjusted step by step until the magnitude of total stator current is reached to its minimum value, finally. The proposed MTPTA strategy is independent of the all motor parameters which is the inherent feature of search-based methods. The detailed description of the proposed strategies and the control system will be done in the following sections; in section II, the fundamental and modeling

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of BDFIM are discussed. Section III presents the MTPIA and MTPTA strategies. In section IV the simulation results are evaluated. Section V contains the concluding remarks.

II. THE BDFIM MODEL

The equivalent circuit of machine is depicted in Fig. 1. The iron loss is ignored and the BDFIM parameters are referred to PW side. The two-axis dynamic complete model of BDFIM in PW flux frame is expressed as follows:

$$\vec{V}_1 = R_1\vec{I}_1 + \frac{d\vec{\psi}_1}{dt} + j\omega_1\vec{\psi}_1 \tag{1}$$

$$\vec{V}_2 = \vec{R}_2\vec{I}_2 + \frac{d\vec{\psi}_2}{dt} + j(\omega_1 - (p_1 + p_2)\omega_r)\vec{\psi}_2 \tag{2}$$

$$\vec{V}_r = 0 = R_r\vec{I}_r + \frac{d\vec{\psi}_r}{dt} + j(\omega_1 - p_1\omega_r)\vec{\psi}_r \tag{3}$$

$$\vec{\psi}_1 = L_1\vec{I}_1 + L_{1r}\vec{I}_r \tag{4}$$

$$\vec{\psi}_2 = L_2\vec{I}_2 + L_{2r}\vec{I}_r \tag{5}$$

$$\vec{\psi}_r = L_r\vec{I}_r + L_{1r}\vec{I}_1 + L_{2r}\vec{I}_2 \tag{6}$$

The electromagnetic torque is also equal to:

$$T_e = \frac{3}{2}p_1\, Im\left[\vec{\psi}_1^*\vec{I}_1\right] + \frac{3}{2}p_2\, Im\left[\vec{\psi}_2\vec{I}_2^*\right] \tag{7}$$

By expanding (7), it can be seen that the torque expression have three terms. The first term is the synchronous torque which exists due to the indirect coupling of the two stator windings magnetic fields. The other two terms are asynchronous torques composed by direct cross-coupling of the PW and the rotor (first induction machine) as well as the CW and the rotor (second induction machine) [11]. It should be noted that the couplings between stator and rotor fields are poorer than indirect cross-coupling between stator fields and hence, the internal induction machines are negligible [13]. The asynchronous torque components are caused by R_r/s similar to the conventional induction machine. By varying the rotor speed in the range of ±30% about the natural speed, the rotor slips due to the magnetic fields of PW (s_1) and CW (s_2) are high. For instance, for the BDFIM described in Table, s_1 is in the range of 0.57 to 0.77. So, the asynchronous torques corresponding to the resistance R_r^p/s_1 are relatively small and

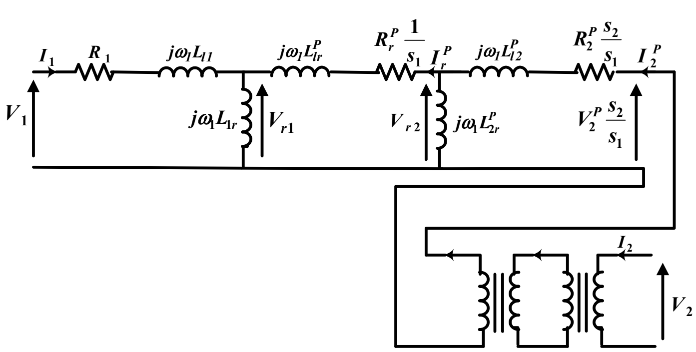

Fig. 1. Steady-state equivalent circuit of BDFIM

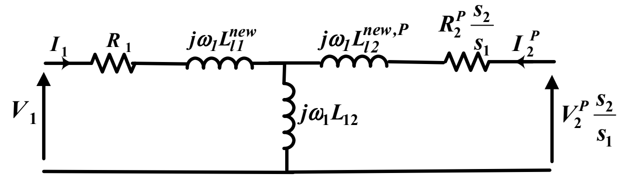

Fig. 2. Steady-state equivalent circuit of BDFIM for reduced order model

therefore can be neglected [12-13]. Due to the high spatial harmonic content of the rotor field, the rotor leakage reactance is relatively large and cannot be neglected. Whereas the conventional induction machine without presence of rotor resistance cannot produce torque, in BDFIM even by neglecting the rotor resistance, power conversion and torque production will be performed. In [10] has been shown by ignoring the rotor resistance, the torque expression can be written similar to a conventional synchronous machine.

In light of foregoing, regardless of the resistance R_r^p/s_1 and by applying $\Delta \rightarrow Y$ transform to the rotor loop reactances in Fig. 1, the steady-state equivalent circuit of BDFIM turns into a reduced order model shown in Fig. 2. For this new model, the following expressions are gained based on inductances of BDFIM complete model:

$$L_{l1}^{new} = L_{l1} + \frac{L_{1r}.L_{lr}}{L_{1r} + L_{2r} + L_{lr}}$$

$$L_{12} = \frac{L_{1r}.L_{2r}}{L_{1r} + L_{2r} + L_{lr}} \tag{8}$$

$$L_{l2}^{new} = L_{l2} + \frac{L_{2r}.L_{lr}}{L_{1r} + L_{2r} + L_{lr}}$$

The BDFIM reduced order model in the PW flux reference frame is stated as [15]:

$$\vec{V}_1 = R_1\vec{I}_1 + \frac{d\vec{\psi}_1}{dt} + j\omega_1\vec{\psi}_1 \tag{9}$$

$$\vec{V}_2 = \vec{R}_2\vec{I}_2 + \frac{d\vec{\psi}_2}{dt} + j(\omega_1 - (p_1 + p_2)\omega_r)\vec{\psi}_2 \tag{10}$$

$$\vec{\psi}_1 = \underbrace{(L_{l1}^{new} + L_{12})}_{L_p}\vec{I}_1 + L_{12}\vec{I}_2 \tag{11}$$

$$\vec{\psi}_2 = \underbrace{(L_{l2}^{new} + L_{12})}_{L_s}\vec{I}_2 + L_{12}\vec{I}_1 \tag{12}$$

Considering (7), (11) and (12), the electromagnetic torque for the reduced order model can be written as:

$$T_e = \frac{3}{2}.\frac{L_{12}}{L_p}.\left(p_2.\mathrm{Im}\left[\vec{\psi}_1\vec{I}_2^*\right] - p_1.\mathrm{Im}\left[\vec{\psi}_1^*\vec{I}_2\right]\right) \tag{13}$$

III. THE PROPOSED CONTROL STRATEGY

The maximum torque per ampere (MTPA) strategy has shown to be very effective method for energy saving in electrical motor-drive systems. Indeed, the purpose of MTPA algorithm is to produce a desired electrical torque with minimum stator current. Generally, there are two main approaches for MTPA realization. One is based on the electrical model of motor which are easy for implementation, but they require the exact motor parameter values. Variation of some parameters during the operation of motor, leads to the non-optimized performance. In this case, the parameter adaptation algorithm is necessary. The other approach is the search-based algorithms to find the minimum stator current for a given torque. Since, in the latter method the exact motor parameters and load condition information are not needed, they could be implemented for various kinds of motors with different control schemes. In this approach, by adjusting the control variable step by step, the magnitude of stator current minimizes.

A. MTPIA Control

In the proposed control approach, firstly, the MTPIA control strategy is considered by applying a reduced order model for BDFIM. By realizing the MTPIA, the minimum inverter loading under the constraint of constant torque is achieved. Under the constant torque, the MTPIA strategy is achieved with minimization of CW current magnitude. So, the torque equation must be rewritten according to the CW current. For this purpose, (13) can be modified as:

$$T_e = \alpha(\psi_{1d} i_{2q} - \psi_{1q} i_{2d}) \tag{14}$$

where $\alpha = -\frac{3}{2}(p_1 + p_2)(\frac{L_{12}}{L_p})$.

The PW flux orientation is achieved by aligning the d-axis of the synchronous reference frame with the PW flux vector $\vec{\psi}_1$.

The resultant d and q-axis PW flux components are:

$$\psi_{1d} = |\vec{\psi}_1| \quad and \quad \psi_{1q} = 0 \tag{15}$$

Therefore, (14) is written as:

$$\frac{T_e}{I_2} = \alpha |\vec{\psi}_1| \sin\theta_2 \tag{16}$$

It is obvious that the (T_e/I_2) will be maximized when $\theta_2 = \pi/2$. In other words, for MTPIA realization, the CW d-axis current must be equal to zero.

B. MTPTA Control

In this paper, to realize the search-based MTPTA strategy, the CW d-axis current is selected as control variable. In this algorithm, the speed error $(\Delta\omega_r)$ is monitored for all time. When, $\Delta\omega_r$ becomes less than a defined value, the steady-state condition is detected. Afterward, the CW d-axis current command is increased step by step and, the total stator current is checked, simultaneously. When the minimum current point is achieved, increasing the CW d-axis current is stopped. In this case, the BDFIM drive continues to operate at a new CW d-axis current.

IV. Simulation Results

To confirm the operation of the presented control approach method the simulation results are proposed, in this section. The overall block diagram of the BDFIM drive system is shown in Fig. 3. Table 1 shows the specifications and parameters of BDFIM.

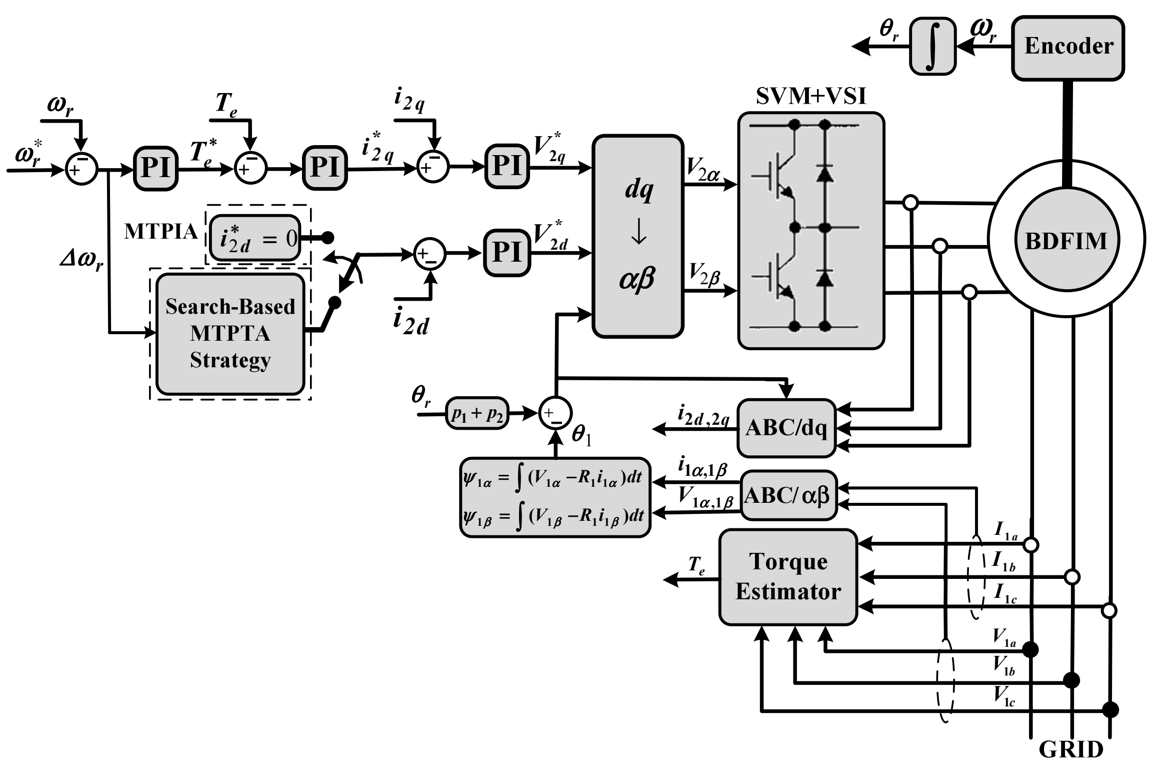

Fig. 3. Block diagram of BDFIM drive system control

TABLE 1: BDFIM PARAMETERS [14]

Parameter	Value	Parameter	Value
PW Pole-Pair	2	L_{l1} (H)	0.017
CW Pole-Pair	4	L_{l2}^{P} (H)	0.021
PW rated voltage (V)	400	L_{lr}^{P} (H)	0.067
CW rated voltage (V)	400	R_1 (Ω)	7.28
L_{1r} (H)	1.125	R_2^{P} (Ω)	6.65
L_{2r}^{P} (H)	0.461	R_r^{P} (Ω)	1.1237

As mentioned in previous section, by realizing the MTPIA strategy, the magnitude of CW current is only minimized. In order to ensure that the said strategy is achieved, the direct component of the CW current is forced to zero (Fig. 4.a). For MTPTA strategy, as shown in Fig. 5.a, when the error of rotor speed reaches to defined value, the MTPTA strategy is started and the CW d-axis current is increased, step by step (Fig. 5.b). This process continues until the total stator current is minimized. After the strategy realization, the CW d-axis current is kept at a new CW d-axis current value. It should be noted that, before the steady state condition, the drive is operated under MTPIA strategy ($i_{2d} = 0$) . Although, by realizing the MTPTA control scheme, the magnitude of CW current is increased (Fig. 5.f), however, the magnitude of total stator current is reduced, as illustrated in Fig. 5.g.

It can be found that by realizing the MTPIA strategy, the CW current magnitude is lower than the MTPTA one. As shown in Figs. 4.c and 5.f, for $T_l = 5\,N.m$ and $\omega_r = 41.88\,rad/\sec(400\,rpm)$, the CW current magnitude for MTPIA and MTPTA strategies is approximately 1 A and 1.8 A, respectively. Since the MTPIA is merely applied to CW, the PW current magnitude increases with decreasing the CW current magnitude. Hence, for a given load torque, the magnitude of total stator current is higher in comparison with MTPTA strategy in which the total stator current is decreased (Fig. 4.d and Fig. 5.g).

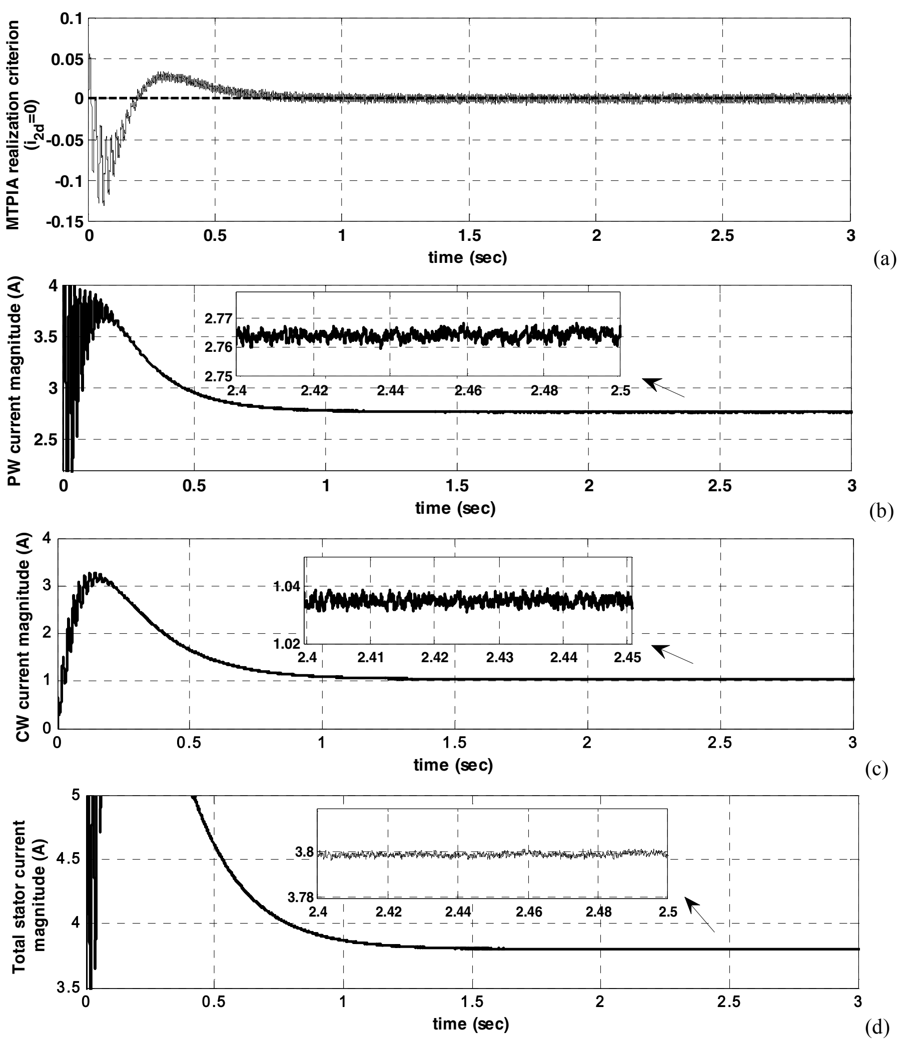

Fig. 4. Simulation results of MTPIA control strategy

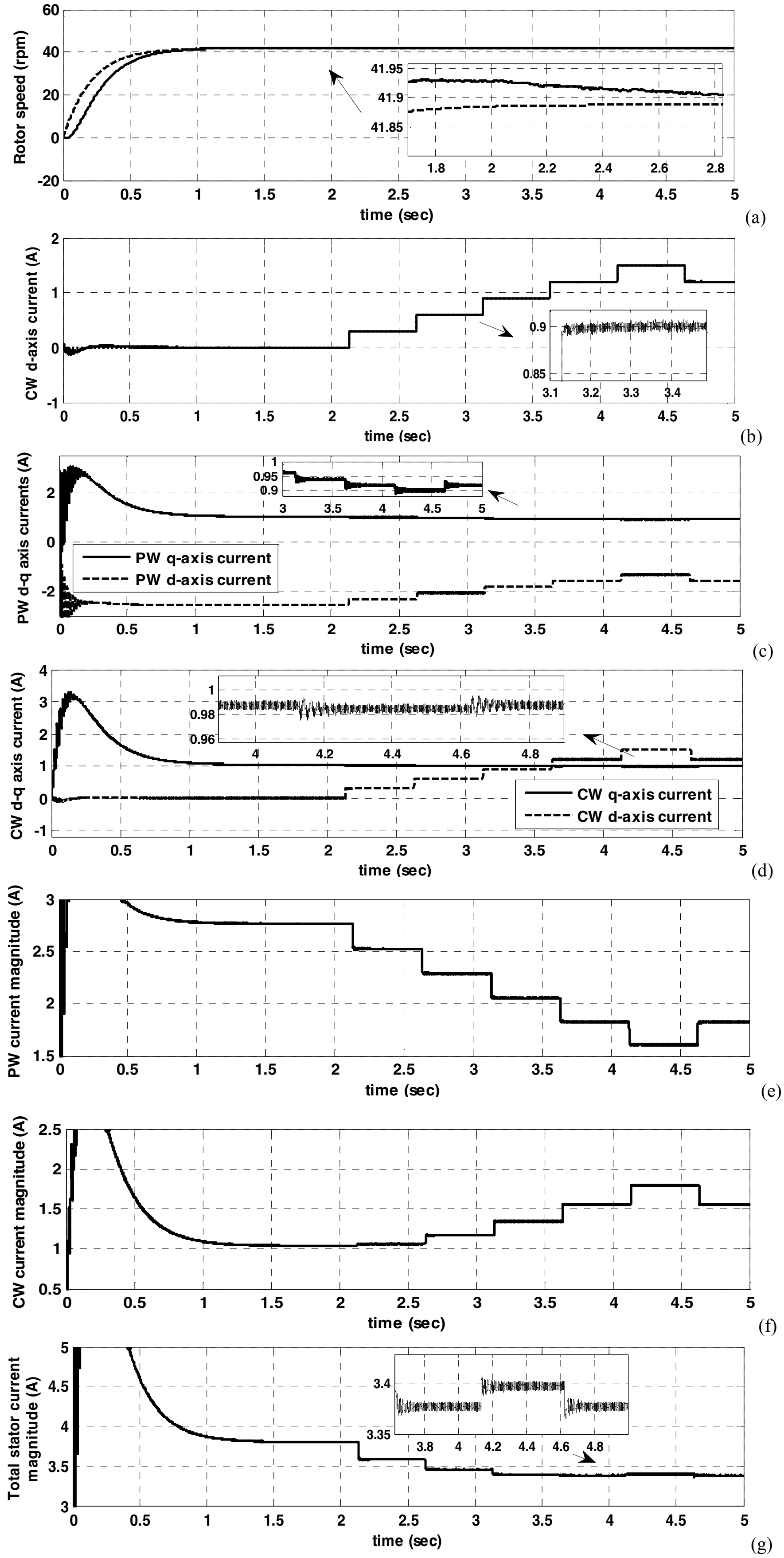

Fig. 5. Simulation results of MTPTA control strategy

V. Conclusion

In this paper, a simple but effective MTPA control strategy was suggested for FOC-based BDFIM drive using an online search-based method. Accordingly, the MTPIA strategy was introduced, first, and it was shown that to minimize the CW current magnitude for a given load torque, the CW d-axis current must be zero. The realization criterion of MTPIA approach is obviously independent of the torque level and CW frequency. Then, sum of the CW and the PW current magnitudes was minimized for a given load torque and rotor speed by adjusting the CW d-axis current. By applying this alternative strategy which was known as MTPTA, the current is appropriately shared between the stator windings. The simulation results verified the capability of the proposed approach.

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