Research on direct power and torque with space vector modulation for a Dual-PWM converter

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Abstract. This paper proposes an integration control algorithm with DPTC-SVM for a Dual-PWM Converter to optimize the parameters of the rectifier and inverter. The control algorithm utilizes direct power control for the PWM rectifier and direct torque control for the PWM inverter. Compared with the traditional DPTC control algorithm and DPTC-SVM algorithm, the stability of the system was analyzed by adding power feed forward loop. The rapid dynamic response and anti-interference ability are improved with the proposed algorithm, though the capability of the DC-link capacitor decreases. With TMS320LF2407 DSP platform to carry out physical verification of the induction motor current, torque and flux characteristics. Simulation and experimental demonstrations are presented to show that the input-output power matches well and the algorithm fulfill the unity power factor conditions.

Keywords: direct power and torque control; space vector modulation; dual-PWM converter; power control loop; virtual flux.

1 Introduction

Most rectifiers in traditional AC/DC/AC converters use a diode bridge circuit. There are some disadvantages such as low power factor, high level of input current harmonics, and high waste of regenerative energy [1]. In this regard, we put forward reversible single-phase to single-phase DC-link converters, they are composed of paralleled rectifiers and inverters sharing two legs with two dc-links. This single-phase to single-phase converters with a single DC-link circuit is shown in Figure 1.

Figure 1. The single-phase to single-phase converters with a single DC-link circuit

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With the development of the control methods for rectifiers and the control strategy with Pulse Width Modulation (PWM), a dual-PWM converter is common used to the adjustable speed application occasions of energy regeneration. This converter decrease: (i) the number of switches rectifiers and inverters, (ii) the input side of the harmonic content of the output transducer, (iii) the DC-link capacitors loss.

The PWM rectifier operates by using the voltage-oriented control (VOC) [2] and direct power control (DPC) [3]-[5] algorithms. The line voltage, current, and DC-link voltage of the PWM rectifier need to be detected in the VOC algorithm. Although the DPC is simple and fast dynamic response, disadvantage is that variable switching frequency and reactive power section is not controllable. The PWM inverter operates by using the field-oriented control (FOC) [6] and direct torque control (DTC) [7] algorithms. A complex coordinate transform is required, and FOC leads to slow dynamic response. Furthermore, the FOC algorithm largely depends on the parameters of the induction motor. High flux and torque ripples appear owing to its variable switching frequency.

In order to avoid the disadvantages of the conventional converter control algorithm, an integration control algorithm by using direct power and torque with space vector modulation (DPTC-SVM) is presented. An additional feed-forward power control loop (PF) is proposed to match the input-output instantaneous power well [8-9].

2 Traditional DPTC control algorithm

In the traditional DPTC control algorithm, the Insulated Gate Bipolar Transistor (IGBT) switching signals of the rectifier and inverter are generated by the proper switching table voltage vector. The control theory of the traditional DPTC is shown in Figure 2.

In the traditional DPTC control algorithm, the active p and reactive q powers are compared with their required values p^* and q^* . The errors between p^* and p are controlled by the hysteresis comparator. Similarly, the stator flux and electromagnetic torque of the PWM inverter are calculated by the line voltage U_{dc} and current I_s . The command flux and torque are compared with their reference values [10]. The flux and torque errors are controlled by the hysteresis comparators.

Figure 2. Control theory for the conventional DPTC

The stator flux of the PWM inverter controlled by the hysteresis comparator and switching table is expressed by

U_{s1} derived from DC-link voltage U_{dc} :

$$U_{s1} = \begin{bmatrix} U_{s1\alpha} \\ U_{s1\beta} \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} U_{dc} (S_{a1} - \frac{1}{2} S_{b1} - \frac{1}{2} S_{c1}) \\ \frac{1}{\sqrt{2}} U_{dc} (S_{b1} - S_{c1}) \end{bmatrix} \quad (4)$$

The virtual flux and measured line currents can be obtained from

$$\Psi_L = \begin{bmatrix} \Psi_{L\alpha} \\ \Psi_{L\beta} \end{bmatrix} = \begin{bmatrix} \int \left(\sqrt{\frac{2}{3}} U_{dc} (S_{a1} - \frac{1}{2} (S_{b1} + S_{c1})) \right) dt + L I_{La} \\ \int \left(\frac{1}{\sqrt{2}} U_{dc} (S_{b1} - S_{c1}) \right) dt + L I_{L\beta} \end{bmatrix} \quad (5)$$

Where Ψ_L is the virtual flux, and L is the inductance of the input of the rectifier.

Assuming a sinusoidal signal line voltage, p and q can be obtained

$$\begin{cases} p = \omega (\Psi_{L\alpha} I_{L\beta} - \Psi_{L\beta} I_{L\alpha}) \\ q = \omega (\Psi_{L\alpha} I_{L\alpha} + \Psi_{L\beta} I_{L\beta}) \end{cases} \quad (6)$$

The command active power p^* is supplied from the outer PI DC-link voltage controller. To fulfill the unity power factor conditions, q^* is set to zero. The output voltage signals, U_{sp} and U_{sq} , of the PI controller that makes the errors as the input is transformed into the $\alpha - \beta$ stationary coordinate system. Then, the reference voltage vectors, U_{ac} and $U_{\beta c}$, are obtained

$$\begin{bmatrix} U_{\alpha c} \\ U_{\beta c} \end{bmatrix} = \begin{bmatrix} -\sin \gamma_{\Psi_L} & -\cos \gamma_{\Psi_L} \\ \cos \gamma_{\Psi_L} & -\sin \gamma_{\Psi_L} \end{bmatrix} \begin{bmatrix} U_{sp} \\ U_{sq} \end{bmatrix} \quad (7)$$

Where γ_{Ψ_L} is the angle of the VF vector in $\alpha - \beta$ stationary coordinates.

$$\sin \gamma_{\Psi_L} = \frac{\Psi_{L\beta}}{\sqrt{(\Psi_{L\alpha})^2 + (\Psi_{L\beta})^2}} \quad (8)$$

$$\cos \gamma_{\Psi_L} = \frac{\Psi_{L\alpha}}{\sqrt{(\Psi_{L\alpha})^2 + (\Psi_{L\beta})^2}} \quad (9)$$

3.2 DTC-SVM algorithm

The DTC-SVM algorithm uses linear PI controllers to control the flux and torque directly, and the required switching attributes for the inverter are produced by the SVM [14-16]. In $\alpha - \beta$ stationary coordinates, the electromagnetic torque is

$$T_e = p_b \frac{m_s}{2} \frac{L_m}{L_r} \psi_r I_s \sin \gamma \quad (10)$$

Where p_b is the number of pole pairs, m_s is the number of power phases, L_m is the mutual inductance, L_s is the stator inductance, ψ_r is the rotor flux amplitude, I_s is the stator current, and γ is the angle between the rotor current and the stator flux vectors.

The amplitude of the stator and rotor flux we assume is constant. Then, the torque can be controlled by changing the angle between the rotor and stator flux vectors. From (10), T_e is expressed as

$$T_e = p_b \frac{m_s}{2} \frac{L_m}{L_r L_s - L_m^2} \psi_r \psi_s \sin \delta \quad (11)$$

Where δ is the angle between the rotor and stator flux vector. The stator flux can be expressed by

$$\psi_s = \frac{L_m}{L_r} \psi_r + \sigma L_s I_s \quad (12)$$

Where $\sigma = 1 - L_m^2 / L_s L_r$ is the leakage factor.

3.3 Integration control algorithm of the PWM rectifier and inverter

In order to reduce the DC-link voltage ripples in AC/DC/AC converters, the size of the capacitor should be increased [17]. Hence, an integration control algorithm for the PWM rectifier and inverter is developed and shown in Figure 4.

Figure 4. Control diagram of the power feed-forward loop

Ignoring the converter power loss problem, the overall active power of the PWM rectifier P_{VSR}^* is provided energy storage for the change of the DC-link capacitor and the inverter output power P_{VSI}^*

$$P_{VSR}^* = P^* + P_{VSI}^* \quad (13)$$

Ignoring the resistances loss, the active power of the PWM inverter P_{VSI}^* is supplied to the AC motor for generating electromagnetic torque. The electromagnetic power can be written as

$$P_e = T_e \omega_m \quad (14)$$

Where ω_m is the rotor mechanical angular speed, and T_e is the electromagnetic torque.

The required electromagnetic power P_e^* is calculated by the required values for the electromagnetic torque T_e^* and rotor mechanical angular speed ω_m^*

$$P_e^* = T_e^* \omega_m^* \quad (15)$$

In order to satisfied the system stability condition, the T_ω delay should be considered. From (15), the required electromagnetic power P_{ec}^* is expressed as

$$P_{ec}^* = \frac{1}{1 + T_\omega s} P_e^* \quad (16)$$

Where T_ω is a dynamic time constant electromagnetic torque.

$$P_{VSR}^* = P^* + P_{ec}^* \quad (17)$$

The resistances losses of the converter can be neglected, considering the system delay. From (18) and (19), the input power open loop transfer function is

$$G_{VSR0}(S) = \frac{P_{VSR}}{P_{VSR}^*} = \frac{1}{1 + T_{IT}S} \quad (18)$$

$$G_{VSI0}(S) = \frac{P_{VSI}}{P_e^*} = \frac{1}{1 + T_{IF}S} \quad (19)$$

Where P_{VSR} and P_{VSI} are the fact power of rectifier and inverter, respectively, T_{IT} is the time constant of the rectifier power, T_{IF} is the time constant of the inverter power.

3.4 Analysis of the system stability with the PF

The stability of the system cannot be affected by an appropriate feed-forward loop. From Figure 4, converter open loop transfer function is:

$$G_{AO}(S) = \frac{U_{dc}}{T_e^*} = -\frac{\omega_m T_{IU} (1 + sT_U) s^2 (T_\omega + sT_\omega T_{IT})}{(1 + sT_{IF})(1 + sT_\omega)T(s)} \quad (20)$$

where

$$T(S) = s^4 C U_{dc}^* T_{IU} T_U + s^3 C U_{dc}^* T_{IU} (T_{IT} + T_U) + s^2 C U_{dc}^* T_{IU} - K_{PU} (sT_{IU} + 1) U_{dc} \quad (21)$$

In (21), T_U is the DC-link voltage filter time constant, and T_{IU} and K_{PU} are parameters of the voltage PI controller.

Figure 5. Zero-pole points diagram with the PF

Figure 6. Bode diagram with the PF

The zero-pole points and Bode diagrams can be obtained by using the open transfer function, as shown in Figure 5 and Figure 6, respectively. The zero-pole points in Figure 5 that are near and coincide can be neglected. The main pole points are on the left side of zero. And the phase margin in the Bode diagram of the system doesn't pass through -180° .

4 Results

To verify the correctness and feasibility of the proposed algorithm, simulations are performed by using Matlab/Simulink. The experimental analysis is carried out based on the TMS320LF2407 DSP

platform. The parameters of the induction motor are listed in Table 1. During the simulation, the reference stator flux amplitude is 0.9 Wb. The switching frequency of the inverter is set at 10 kHz.

Table 1. Induction motor parameters.

Parameter	Value
Power	55 kW
Voltage	380 V
Frequency	50 Hz
Rated speed	1430 rpm
Stator winding resistance	0.0363 Ω
Rotor winding resistance	0.073 Ω
Stator inductance	0.0232 H
Rotor inductance	0.0232 H
Mutual inductance	0.026 H
Number of pole pairs	2
Moment of inertia	0.0131 kg·m2

When the induction motor operates in the motoring mode, the reference rotating speed is 500 rpm, and the initial value of the reference load torque is 12 N·m. When $t = 1$ s, the load should be set as 20 N·m. When the induction motor operates in the regenerating mode, the reference rotating speed is -500 rpm. When $t = 1$ s, the load should be set as 20 N·m. The results of the simulation and experiment are shown in Figures.7–10.

Figure 7. Waveforms for the motor torque in: (a) motoring mode and (b) regenerating mode

The electromagnetic torque responses changing from 12 N·m to 20 N·m is shown in Figure7, when $t = 1$ s. The simulation results show that the torque follows the required electromagnetic torque quickly.

Figure 8. Waveforms for the motor torque and current: (a) the waveform using DPTC and (b) the waveform using DPTC-SVM.

Figure 9. A phase input current and voltage of the rectifier in: (a) motoring mode and (b) regenerating mode.

A DC motor is used as virtual load. The experimental results are shown in the following Figures. When the specific rotating speed is 1000 rpm, the load torque is 20N·m and the motor is operating stably.

This reduces the stator flux and torque ripples. Compared DPTC-SVM with the traditional algorithm, the torque ripples is reduced by about 8% which is shown in the experimental Waveforms Figure8.

The A phase input current and voltage of the rectifier experimental results are shown in Figure 9, when motor works in motoring mode, the power factor is about 0.98. And when motor works in regenerating mode, the power factor is about -0.92. It shows that it is up to unity power factor, low total harmonic distortion (THD), and sinusoidal waveform for the line current. The experimental results are nearly the same whether it works in motoring mode or regenerating mode. And the voltage is independent of load or speed changes. So the integration control algorithm confirms the anti-interference ability of the system.

When motor works from motoring mode to regenerating mode, the experimental waveform of the motor torque and current is shown in Figure 10 (a). There is a 61% torque overshoot in transformation statement, and the motor is operating stably within 0.1s. It's shown in Figure 10 (b) that the torque is to the steady operation within no more than 0.16s at the starting period. So the system is rapid response and stabilization.

Figure 10. Waveforms for the motor torque and current: (a) statement from motoring to regenerating mode and (b) statement from shutdown to power on

5 Conclusion

An integration control scheme by using the DPTC-SVM algorithm is presented in this paper, which can realize no static error control of the power and torque. SVM is used to realize a constant switching frequency for a dual-PWM converter. The rapid dynamic response of the system is improved, and the active power can be transformed from the DC-link side to the inverter side efficiently. Some advantages are achieved by The DPTC-SVM algorithm compared with DPTC control algorithm traditional, such as power bidirectional flow, unity power factor, input-output power matching well, constant switching frequency for the PWM rectifier and inverter, lower current harmonics and torque ripples. The simulation and experimental results show the validity of the DPTC-SVM algorithm.

Acknowledgment

The authors thank the support both the Foundation of National Natural Science (51377168) and the Foundation of Shandong Province Science and Technology Development Planning (2011GGH20411), which enabled the achievement of the mentioned research results.

References

1. C. C. Hou and H. P. Su, *IPEC*, 2821-2825 (2014).
2. Q. Zhang, Z. X. Li, and Y. C. Zhang, *ICEMS*, 2207-2212(2013).

3. B. Gong, K. J. Wang, J. N. Zhang, J. You, Y. H. Luo, and W. Y. Zhang, *ITEC Asia-Pacific*, 1-5(2014).
4. A. Bouafia, J. P. Gaubert, and A. Chaoui, *EPE*, 2-6(2013).
5. A. M. Razali, M. A. Rahman, G. George, N. Rahim, *IEEE Trans. Ind. Applications.*, **51**, 1189-1200(2015).
6. S. H. Rutuja and J. G. Chaudhari, *ICETET*, 191-194(2011).
7. J. Beerten, J. Vervecken, and J. Driesen, *IEEE Trans. Ind. Electron.*, **57**, 404-412(2010).
8. S. H. Rutuja and J. G. Chaudhari, *PEDSTC*, 242-248(2014).
9. X.-C. Liu, H.-G. Zhang, E.-H. Chu, and S.-J. Yan, *Electr. Mach. Control*, **13**, 47-56(2009).
10. H. Q. Zhang, X. S. Wang, P. F. Wei, and D. G Xu, *Electr. Mach. Control*, **16**, 13-18(2012).
11. F. Benchabane, A. Titaouine, O. Bennis, K. Yahia, and D. Taibi, *Frontiers in Energy*, **6**, 129-137(2012).
12. W. Chen, X.-D. Zou, J. Tang, Z.-X. Huang, F. Li, Z.-X. Wu, and Y.-P. Zou, *Proc. CSEE*, **30**, 35-41(2010).
13. Tey Chin Soon, Hew Wooi Ping and N. A. Rahim, *STUDENT*, 123-128(2012).
14. J. Marek, S. Stynski, P. Mlodzikowski, and M. Malinowski, *Power Electronics for Renewable Energy Systems Transportation and Industrial Applications*, **562**, 319-364(2014).
15. H. Q. Zhang, F. H. Meng, and Z. P. Liang, *IPEMC*, 2372-2376(2012).
16. J.-H. Jiang and X.-D. Ji, *Small and Special Electrical Machines*, **12**, 37-39(2011).
17. W. Chen, C. Chen, Z.-F. Song, and C.-L. Xia, *Proc. CSEE*, **29**, 1-7(2009).