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Coordinated Control Strategy Based on DPC-SVM-DTC Three-Level Dual PWM Converter

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Abstract

In order to reduce power harmonic and reactive power from load devices, in this paper, a novel integrated control scheme for three-level dual PWM converter is presented. To reduce the DC-bus voltage fluctuation of three-level dual PWM converter, DPC-SVM-DTC dual PWM converter coordinated control strategy is proposed. The rectifier and the inverter are both based on the simplified SVM modulation algorithm. The coordinated control strategy is based on load power feed-forward according to the instantaneous active power balance. Some simulation experiments have been done to evaluate the performance of the coordinate control strategy. The results show that the response speed of system was great accelerated, and the DC-bus voltage fluctuation was inhibited effectively.

Keywords*: three-level dual PWM converter; DPC-SVM-DTC; load power feed-forward; DC-bus voltage fluctuation*

1. Introduction

Dual PWM converter has a wide range of applications in HVDC Light, UPFC, flexible power conditioner and other Flexible AC Transmission System due to the advantages of flexible control function, adjustable AC side of the power factor and DC voltage controlled, and bidirectional power flow. Compared to the two-level inverters, multilevel converters have much more advantages such as lower harmonics, higher efficiency, and lower voltage stress for power conversion in high-power applications [1]. Therefore, how to control three-level dual PWM converter is becoming the hot point in recent years. The configuration of three-level dual PWM converter is shown as Figure 1.

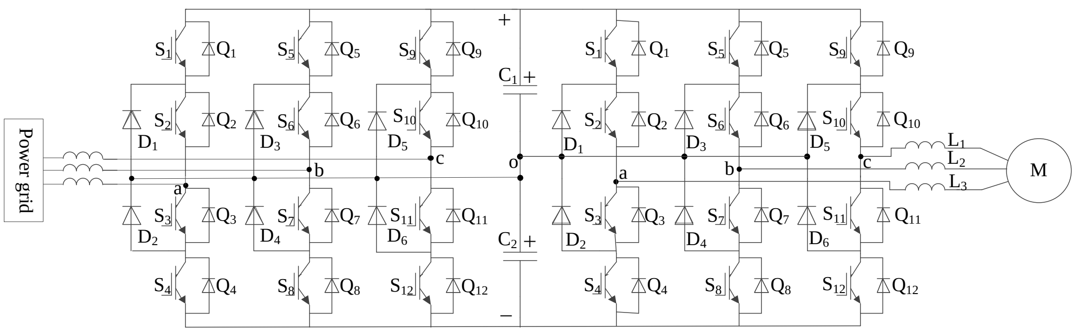

Figure 1. Configuration of Three-Level Dual PWM Converter

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Conventionally, the control method of for ac-dc-ac PWM converter is separately. This control method caused two main problems. One is the DC-bus voltage fluctuation when the inverter side has a sudden load injection. Hence, many electrolytic capacitors in the dc-link are used to provide decoupling between the converter and the inverter. The larger dc-link capacitance is, the less dependence is achieved between the converter and the inverter. This will cause large, heavy, expensive, and unreliable. Also, it requires regular maintenance due to the gradual degradation associated with outgassing along with time [2]. Another one is the lower controllability of the system. Taking the inverter and motor as the load part for the rectifier, the current variation of the load part is a very disturbed. There will be some errors for the only voltage feedback loop control used. The rectifier has no information about the inverter, and the adjusting speed of the rectifier cannot keep up with the speed of current variation in dc-link capacitors.

Various control schemes have been reported for the dual PWM converter. In [3], to speed up the compensation action, the feed-forward compensation term is added to the converter voltage node. In obtaining the feed-forward compensation term, numerical differentiation is utilized based on system dynamics. In this process, U_{dc} is treated as a variable, while input voltages are expressed as switching duties, which are calculated in each PWM period. By small-signal analysis, the proposed controller is better than the existing PI control scheme. Hence, this control method is suit to small-signal control. In [4], load current feed-forward control has been used according to voltage and current double closed loop. The motor status can only change the current reference of current inner loop on the rectifier, and there is no effect on the DC-bus voltage. But due to the load current set by switch table, the sample is difficult and the response feed is lower. Some new control schemes, such as direct power control (DPC) for PWM rectifier and direct torque control (DTC) for PWM inverter-fed motor, are proposed to obtain better dynamic performance [5]. In [6], the direct power control with space vector modulation (DPC-SVM)for front-end rectifier and indirect rotor field oriented control (IFOC) for back-end inverter-fed induction motor are adopted respectively. A power feed-forward control loop from inverter to rectifier side is introduced to obtain better dynamic performance for DC link. For the structure of PWM, constant switch table has been used. In [7], they proposed an optimum feed-forward control strategy using the small-signal model technology, a current sensor replace the state observer to measure load current. In [8], the DPC is adopted for the front-end three-level PWM rectifier, and rotor field oriented control (FOC) is applied for back-end three-level PWM inverter-fed induction motor. Moreover, an additional power feed-forward control loop from inverter to rectifier side is introduced. In [9], their rectifier side adopts a dual close-loop control strategy of the inner current-loop and the outer voltage-loop control based on SVPWM; the inverter side introduces the three-level vector control system based on indirect flux oriented control, proposes the current-loop and the speed-loop control strategy based on SVPWM. However, almost all of them were carried out based on the two-level topology, or using fixed switch table to control the voltage and current.

We focus on keeping the stability of three-level dual PWM converter in high-power applications by integrated control strategy, and present an integrated DPC-SVM-DTC control strategy for the dual PWM converter. The main idea is that motor-side instantaneous active power is directly fed-forward to the grid-side given instantaneous active power node through a constructed load state feed-forward channel, which avoides the slower process of indirect power adjustment through outer voltage loop. The simplified PWM modulation method is used both in the rectifier and the inverter. The direct power control with simplified space vector modulation (DPC-SVM) for front-end rectifier and direct torque control with simplified space vector modulation (SVM-DTC) for back-end inverter. In MATLAB/SIMULINK, we built a simulation model to evaluate the performance of the proposed strategy.

2. Integrated Control Strategy for Three-Level Dual PWM Converter

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The three-level dual PWM converter system can be divided into five parts: AC grid side, PWM rectifier, DC side, PWM inverter, and AC motor side [10]. For our research system, the simplified PWM modulation algorithm [11] is used both in the rectifier and the inverter. The block of the whole control system is shown in Figure 2. For this control system, there are three powers existing that the rectifier side active power p_{rec}, the inverter side active power p_{inv} and the power of capacitors in the dc link p_{cap}. By omitting the power losses of switches, the relationship of them is expressed as

$$p_{cap} = p_{rec} - p_{inv} \tag{1}$$

The power of capacitors in the dc link p_{cap} can be defined as

$$p_{cap} = 2V_{dc} i_{cap} = 2\frac{U_{dc}}{2} \times C \frac{d\frac{U_{dc}}{2}}{dt} = \frac{1}{2} C U_{dc} \frac{dU_{dc}}{dt} \tag{2}$$

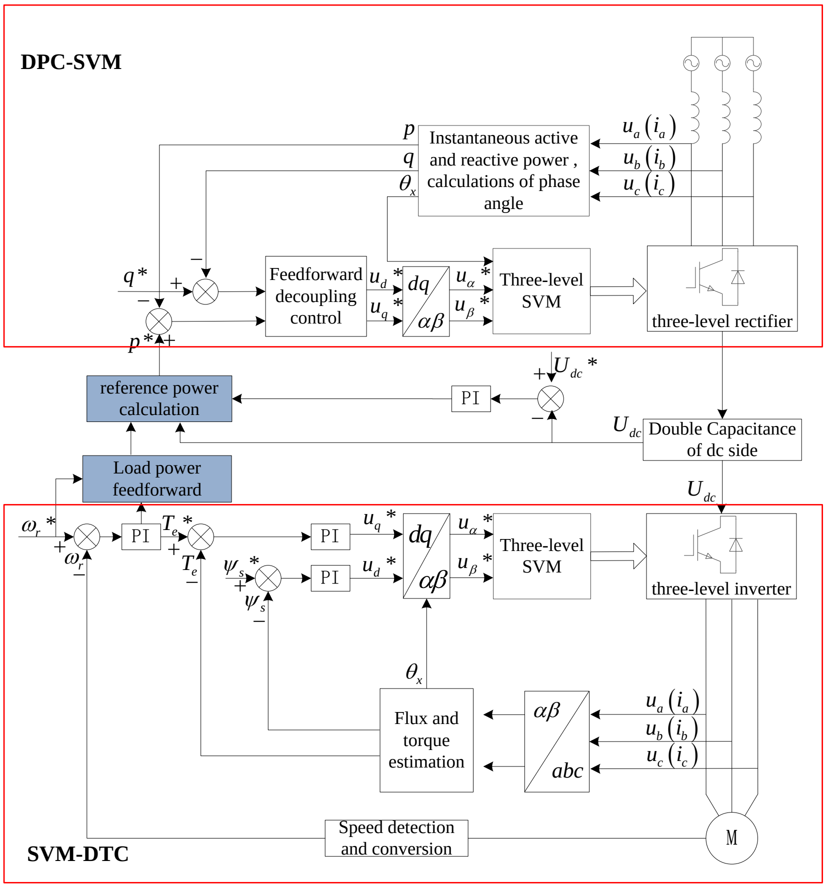


Figure 2. The Block of Coordinated Strategy for the Three-Level Dual PWM Converter

In order to reduce the fluctuation of the DC voltage, the dynamic balance between the active power of rectifier p_{rec} and the inverter side active power p_{inv} need to be kept. The main idea of the integrated strategy, the motor-side instantaneous active power was directly fed-forward to the grid-side given instantaneous active power node through a constructed load state feed-forward channel, which avoided the slower process of indirect power adjustment through outer voltage loop. Considering the system time delay, the block of the load power feed-forward control is shown in Figure 3. T_r , T_i and T_s represent the delay time constant of the rectifier side, the inverter side and electromagnetic torque system.

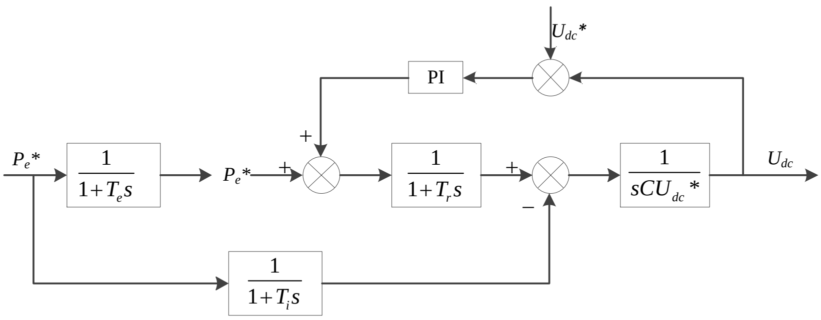


Figure 3. Model of the Load Power Feed-Forward Control

2.1. DPC-SVM three-level PWM Rectifier

Direct Power Control (DPC) is based on the instantaneous active and reactive power control loops [12]. In this technique, switching states are selected from a switching table based on instantaneous errors between commanded and estimated values of active and reactive power. For constant switching frequency, Direct Power Control Space Vector Modulation (DPC-SVM) is used in our PWM rectifier. Instead of the switching table, three-level PWM voltage modulator is applied in the structure of DPC-SVM PWM rectifier. The controlled reactive power q* (set to zero for unity power factor operation) and active power p* (delivered from the outer PI-DC voltage controller) are compared with the estimated q and p values, respectively. The errors are DC quantities that are delivered to PI controllers that eliminate steady state error. The output signals from PI controllers, after decoupling operation and transformation to $\alpha\beta$ coordinates system, are used for switching signals generation by SVM.

Instantaneous active and reactive power in d-q coordinates can be expressed as

$$\begin{cases} p = U_d i_d + U_q i_q \\ q = U_q i_d - U_d i_q \end{cases} \tag{3}$$

Where U_d and U_q are the d- and q-axis components of the AC source voltage, and i_d and i_q are the d- and q-axis currents of the AC source voltage.

The mathematical voltage and current model of the rectifier in static a/b/c coordinates is as follows:

$$\begin{cases} L\dfrac{di_a}{dt} = -Ri_a - (S_{a1} - \dfrac{S_{a1}+S_{b1}+S_{c1}}{3})U_{dc1} + (S_{a2} - \dfrac{S_{a2}+S_{b2}+S_{c2}}{3})U_{dc2} + U_a \\ L\dfrac{di_b}{dt} = -Ri_b - (S_{b1} - \dfrac{S_{a1}+S_{b1}+S_{c1}}{3})U_{dc1} + (S_{b2} - \dfrac{S_{a2}+S_{b2}+S_{c2}}{3})U_{dc2} + U_b \\ L\dfrac{di_c}{dt} = -Ri_c - (S_{c1} - \dfrac{S_{a1}+S_{b1}+S_{c1}}{3})U_{dc1} + (S_{c2} - \dfrac{S_{a2}+S_{b2}+S_{c2}}{3})U_{dc2} + U_c \end{cases} \quad (4)$$

$$\begin{cases} C\dfrac{dU_{dc1}}{dt} = S_{a1}i_a + S_{b1}i_b + S_{c1}i_c - i_{RL} \\ C\dfrac{dU_{dc2}}{dt} = (S_{a2}-1)i_a + (S_{b2}-1)i_b + (S_{c2}ic-1)i_c - i_{RL} \end{cases} \quad (5)$$

The physical meaning of the mathematical model in a/b/c coordinates is pellucid, but variable parameters of ac reactors are unstable which is not suitable for the design of control system. So the mathematical model is rotated in d-q coordinates is

$$\begin{cases} L\dfrac{di_d}{dt} = -Ri_d - V_d + U_d + \omega L i_q \\ L\dfrac{di_q}{dt} = -Ri_q - V_q + U_q - \omega L i_d \end{cases} \quad (6)$$

$$\begin{cases} C\dfrac{dU_{dc1}}{dt} = \dfrac{3}{2}\left(S_{d1}i_d + S_{q1}i_q\right) - i_{RL} \\ C\dfrac{dU_{dc2}}{dt} = \dfrac{3}{2}\left(S_{d2}i_d + S_{q2}i_q\right) - i_{RL} \end{cases} \quad (7)$$

V_d and V_q are the converter voltages in d-q coordinates. R and L represent the equivalent resistance and inductance, respectively, and ω is the source angular frequency.

According to the Equation (6), active and reactive power feed decoupling can be used for the converters. The output voltage is determined by the following PI controller:

$$\begin{cases} V_d = -\left(K_p + \dfrac{K_i}{T}\right)\left(p^* - p\right) - \dfrac{\omega L q}{U_d} + U_d \\ V_q = \left(K_p + \dfrac{K_i}{T}\right)\left(q^* - q\right) - \dfrac{\omega L p}{U_d} \end{cases} \quad (8)$$

Where K_p and K_i are proportional and integral gains. Figure 4 shows the structure of PI and feed forward controller for the rectifier.

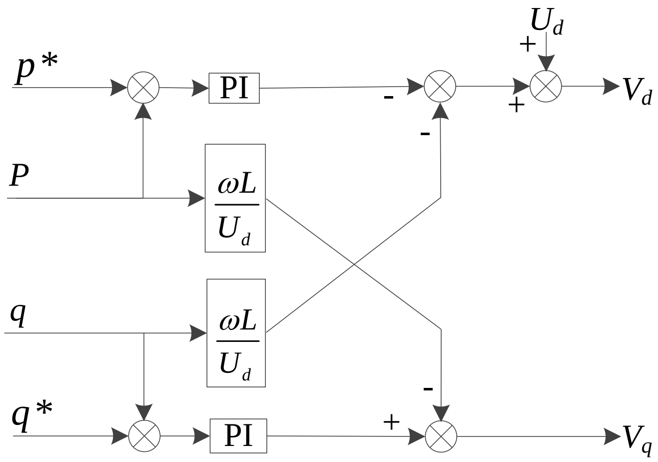


Figure 4. Block Diagram of Decoupled Control for Power

2.2. SVM-DTC Three-level PWM Inverter

The classic DTC employs a specific switching pattern by using a standard switching table. The objective of the DTC-SVM scheme, and the main difference between the classic DTC, is to estimate a reference stator voltage vector U_s* and modulate it by SVM technique, in order to drive the power gates of the inerter with a constant switching frequency. The math principles are described as:

First, the PI controller produces a desirable change in angle $\Delta\theta$ between stator and rotor flux vectors. Then the change in angle $\Delta\theta$ is added in the actual angle of stator flux vector, so we can estimate the reference stator flux vector by using the following formula, in stationary reference frame.

$$\psi_s* = \left|\psi_s*\right| e^{j(\omega_r t+\Delta\theta)} \tag{9}$$

Applying a phase abstraction between the reference and the actual stator flux vector we can estimate the desirable change in stator flux $\Delta\psi_s$.

$$\Delta\psi_s = \psi_s - \psi_s^* \tag{10}$$

Having the desirable change in stator flux, it is easy to estimate the reference stator voltage vector:

$$\begin{cases} u_\alpha^* = (\left|\psi_s*\right|\cos(\theta+\Delta\theta) - \left|\psi_s\right|\cos(\theta)) / T_s + R_s i_\alpha \\ u_\beta^* = (\left|\psi_s*\right|\sin(\theta+\Delta\theta) - \left|\psi_s\right|\sin(\theta)) / T_s + R_s i_\alpha \end{cases} \tag{11}$$

3. Simulation Results

An experimental prototype has been developed to verify the validity of the integrated control strategy in MATLAB/SIMULINK, shown as Figure 5. The simulation parameters are listed as the following: grid line voltage is 380V. DC-bus voltage is 600V. AC side inductance is 2mH. The DC capacitance is 680uF, and the switch frequency is 10kHz. The load resistance is 50Ω.

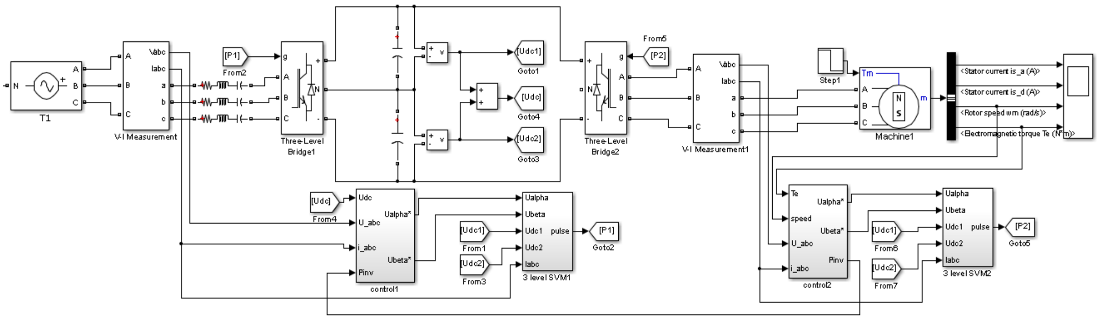
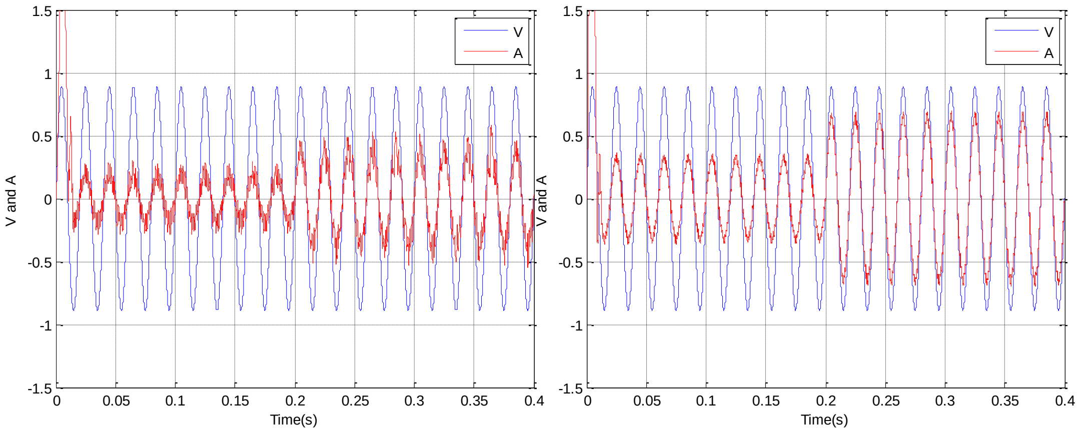


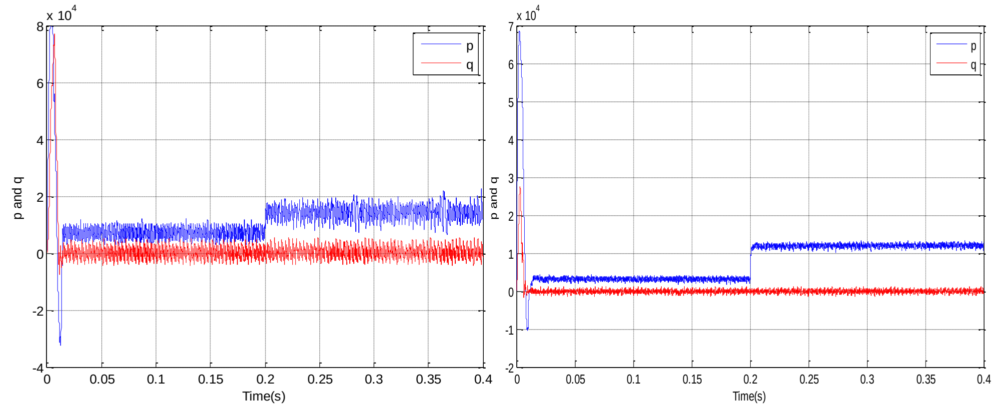
Figure 5. Simulink Model of Three-Level Dual PWM Converter by the DPC-SVM-DTC Coordinated Strategy



(a) Grid waveform of traditional DPC control (b) Grid waveform of DPC-SVM control

Figure 6. Shows The Waveform of Grid Voltage and Current by DPC vs DPC-SVM

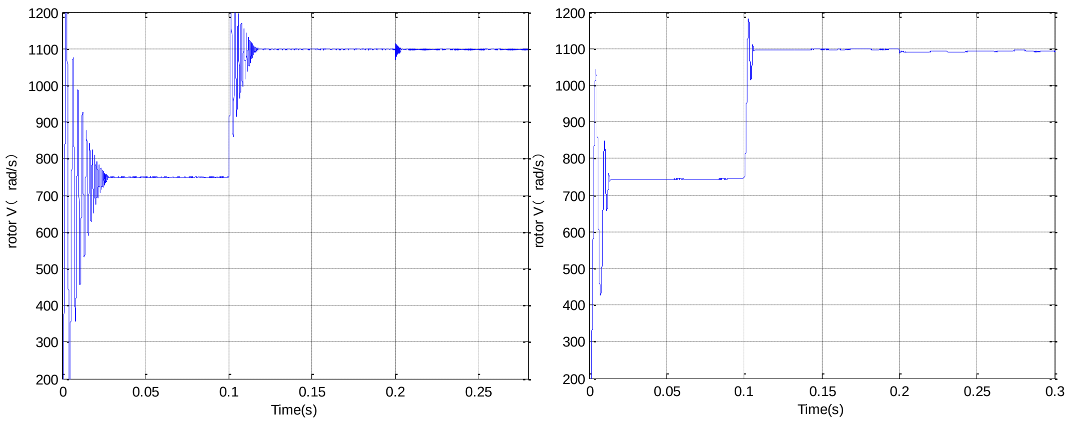
Figure 6 shows the waveform comparison results under the DPC and DPC-SVM control strategy at the rectifier. Compared to traditional DPC control strategy, the waveform of grid voltage and current by DPC-SVM control has a smaller variation and distortion, and if the change of the output current waveform will achieve the stable output when the load changed at t=0.2.



(a) Power waveform of traditional DPC control (b) Power waveform of DPC-SVM control

Figure 7. Comparison Waveform of Instantaneous Active and Reactive Power

Figure 7 shows the simulation results about active power p and reactive power q with traditional DCP control and DCP-SVM control. There are abundant harmonic ripples in the results waveform with traditional DCP. However, with DCP-SVM controller, the waveforms of active power p and reactive power q have much less harmonic ripples. The value of instant reactive power q fluctuated round the zero. The instantaneous active power p changes with the load abruptly at t=0.2 and keep stable.



(a) Rotor speed waveform of traditional DTC system (b) Rotor speed waveform of DTC-SVM system

Figure 8. Comparison Simulation Waveform of Rotate Speed

Figure 8 is the waveform of rotor speed with conventional DTC and DTC-SVM. There is difference between the conventional DTC and DTC-SVM. Obviously the response speed is faster with DTC-SVM. At t=0.1s, the fluctuation of the waveform is due to speed change from 750r/min to 1100r/min. and the other fluctuation is caused by the torque change.

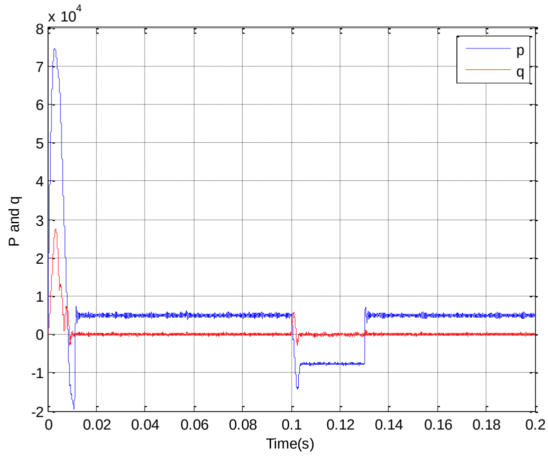


Figure 9. Instant Active Power p and Reactive Power q

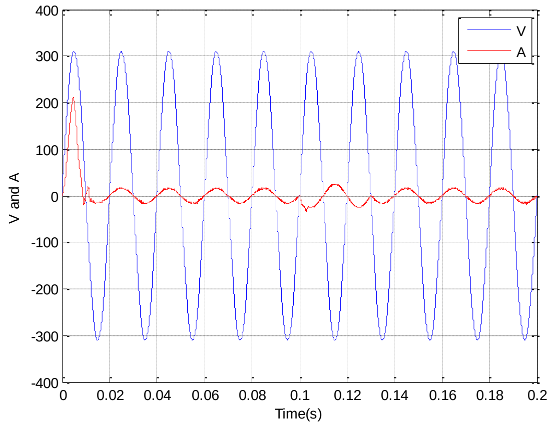


Figure 10. The Waveforms of Grid Side Voltage& Current

Figure 9 shows the simulation results with the integrated control strategy. The instant active power p will recover the original value even if the motor torque change abruptly at t=0.2, and the reactive power will always keep the value about zero and have very small fluctuation due to the torque change. Figure 10 shows the simulation results of grid side voltage and current with the integrated control strategy. The results show that the voltage and current of the dual PWM converter have the same frequency and phase. At t=0.1 some fluctuations happens in the waveforms, for the system load changes. The system will recover its original status with the speed.

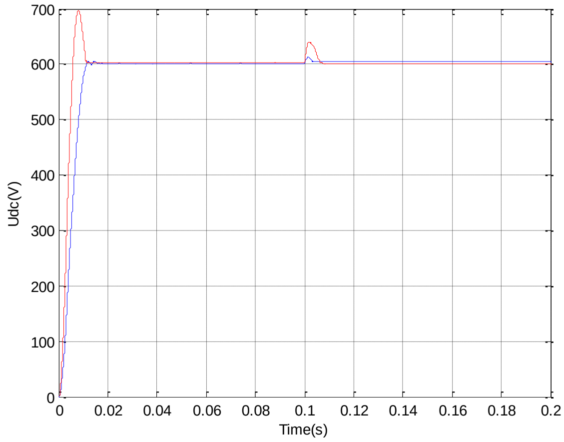


Figure 11. Comparison about Waveforms of Udc Voltage With the Separated Control Strategy & the Integrated Strategy

Figure 11 shows the simulation results of Udc voltage and current with the integrated control strategy. The results show that the voltage and current of the dual PWM converter have the same frequency and phase. At t=0.1 some fluctuations happens in the waveforms, for the load of system changes. The DC-bus voltage of the system will recover its original status speedily.

4. Conclusion

In this paper, for the existing problems about this system with the separated control method, such as the DC voltage fluctuation, larger dc-link capacitance, an integrated control method based on load power feed-forward strategy is adopted. The three-level PWM modulation method is used both in the rectifier and the inverter. DPC-SVM control method has been used for the three-level PWM rectifier. DTC-SVM control has been used for the three-level PWM inverter. An integrated control strategy of load power feed-forward was researched. During operation, the reactive component of PWM rectifier is always zero, which ensures the realization of unity power factor. Meanwhile, the simplified PWM modulation made the system have good speed performance, stable DC-bus voltage and capacity of two-direction flow of energy. The coordinated control strategy is verified by the simulation experiments. Simulating experimental results show that….(include some data of the experiment)

Acknowledgments

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References

[1] L. M. Tolbert, F. Z. Peng and T. G. Habetler, "Multilevel converters for large electric drives", IEEE Transactions on Industry Applications, vol.35, no.1, **(1999)**, pp.36-44.
[2] S.-D. Huang, L. Xiao and K.-Y. Huang, "Operation and control on the grid-side converter of the directly-driven wind turbine with PM synchronous generator during asymmetrical faults", Transactions of China Electro-technical Society, vol.26, no.2, **(2011)**, pp.174-180.
[3] B.-G. Gu and K. Nam, "A DC-Link Capacitor Minimization Method Through Direct Capacitor Current Control", IEEE Transactions on Industry Applications, vol.42, no.2, **(2006)**, pp.573- 581.
[4] L. M. Malesani, L. Rossetto and P. Tomasin, "AC/DC/AC PWM converter with reduced energy storage in the DC link", IEEE Transactions on Industry Applications, vol.31, no.2, **(1995)**, pp.287-292.
[5] M.-Y. Wang, T.-Z. Dai and X.-H. Wu, "Simulation research of dual PWM converter based on power feed forward control strategy", Journal of System Simulation, vol.24, no.4, **(2012)**, pp.892-896.
[6] Y. Zhang, Z. Zhao and B. Feng, "Integrated Control Scheme for Three-level NPC Based Dual-PWM Converter", Transactions of China Electrotechnical Society, vol.26, no.11, **(2011)**, pp.25-31.
[7] S.-J. Li, Y.-H. Li and R. Chen, "Study of the optimum feed-forward control strategy in back to back converter system", Proceedings of the CSEE, vol.26, no.22, **(2006)**, pp.74-79.
[8] Y. Zhang, Z. Zhao and T. Lu, "An Integrated Control Method for Three-level NPC Based PWM Rectifier-Inverter", 2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems, **(2010)**, pp.616-620.
[9] C. Bian, X. Duan and X. Chen, "Dual-PWM Three-Level Voltage Source Converter Based on SVPWM", Lecture Notes in Electrical Engineering, **(2014)** ,pp.583-592.
[10] J. Tu and X. Zhan, "A Study on Dual-PWM VVVF Control System Based on SVPWM", 2010 International Conference on Computer Application and System Modeling, vol.12, **(2010)**, pp.227-230.
[11] J. Hyeong, C. H. Choi and D. S. Hyun, "A New Simplified Space-Vector PWM Method for Three-level Inverters", IEEE Transactions on Power Electronics, vol.16, no.4, **(2001)**, pp.545-550.
[12] M. Malinowski and M. Jasinski, "simple direct power control of three-phase PWM rectifier using space-vector modulation(dpc-svm)", IEEE Tractions on Industrial Electronics, vol.51,no.2, **(2004)**, pp. 447-154.

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