Direct power control in pulse-width modulation rectifier based on virtual flux estimation

Bo Fan¹,², Xian-Bo Wang³, Zhi-Xin Yang³, Lu Song¹ and Shu-Zhong Song¹

Abstract
Pulse-width modulation rectifier plays an important role in the field of electric energy conversion. It has many advantages such as the grid side current sinusoidal, bidirectional energy flow, and unit power factor. In order to improve the power factor, this article proposes a new control method for the three-phase pulse-width modulation rectifier, that is, direct power control strategy based on virtual flux orientation. The original concept of AC motor stator flux is introduced into the proposed scheme for the three-phase pulse-width modulation rectifier so as to remove the grid voltage sampling circuit. The instantaneous power is estimated by the virtual flux vector orientation to realize the pulse-width modulation rectifier control in unbalanced condition. The two-order filter replaces the pure integrator in this process of implementation to solve the initial value problem of this pure integrator and achieve the better filtering property. With the estimation of virtual flux, the control strategy with space vector modulation realizes the fixed switching frequency to virtual flux orientation direct power control system, where the DC side output voltage is stable, the grid side current distortion rate is low, and anti-disturbance ability is strong. Experimental results show that this method has good performance in real three-phase grid condition. The control performance meets the requirements of power quality.

Keywords
Pulse-width modulation rectifier, direct power control, virtual flux, unit power factor, two-order filter

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Introduction
Parameters of the running AC motor are vulnerable to the influences coming from inner or outer conditions. The variables of the motor temperature and slip frequency affect rotor resistance. It may rise temperature by 50% in a short time if the rotor current is in high frequency. These parameters, such as rotor time constant, caused by these changes may lead to the distortion of feedback signal, which is calculated by fixed parameters. Based on such feedback, the flux orientation will deviate from the real one, and cause large speed and torque pulsation, that leads to the control performance decrease significantly. Therefore, for the running of variable-frequency drive system, it needs to adjust the motor parameters with its change to ensure the rightness of the feedback and the control performance.

In addition, the working condition and vibration noise also affect the setting of operation parameters of the AC motor.¹,²

The recent research of power electronic technology shows two shortcomings, on one hand, it brings the harmonic problem; on the other hand, the power electronic devices provide the solution for the harmonic

¹School Information Engineering, Henan University of Science & Technology, Luoyang, China
²CITIC Heavy Industries Co., Ltd, Luoyang, China
³Department of Electromechanical Engineering, Faculty of Science and Technology, University of Macau, Taipa, Macau, China

Corresponding author:
Zhi-Xin Yang, Department of Electromechanical Engineering, Faculty of Science and Technology, University of Macau, Taipa, Macau 999078, China.
Email: zxyang@umac.mo

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elimination problem.³ Pulse-width modulation (PWM) technology in inverter circuit is applied in full controlled devices to compose the rectifier circuit, which realizes the grid side current sinusoidal, unit power factor, and bidirectional energy flow.⁴–¹¹ This is called PWM rectifier that achieves the green power conversion. With PWM modulation, the rectifier can greatly improve the grid content; and its filter inductor ensures the system runs at any angle with the unit power factor. From 1980s, the academia has never stopped the study of PWM converter. Along with the deepening of research, the development of PWM rectifier topology and control, its related application and researches have been in development, such as an active filter, AC drive, superconducting magnetic energy storage, high-voltage direct current transmission, and unified power flow control, which promotes the development of PWM rectifier and its control methods. A conventional three-phase voltage PWM rectifier involves four types of sensors: AC voltage sensors, AC current sensors, DC voltages sensors, and DC current sensors. They play very important roles in direct power control (DPC) on PWM rectifier,¹²–¹⁷ except that they are used in protective circuit. In the common control system, the AC voltage sensors detect the three-phase grid voltage amplitude, which is also used to calculate the instantaneous power of the converter. At the same time, the AC voltage sensors detect the synthetic vector rotation angle of grid voltage by phase locked loop to constitute the synchronous signal source. While the AC current sensors are used to detect the AC current value and estimate the instantaneous power with grid voltage amplitude, which constitute the inner loop feedback signal. The DC voltage sensor detects the DC voltage value to constitute the outer loop feedback signal, while the DC current sensor acts as the feed forward of load in system to enhance the performance of load anti-disturbance. However, the sensors are not essential. More sensors not only increase the cost of the system but also greatly reduce the reliability of the system. Therefore, it is necessary to study the control methods of decreasing parts of sensors.

T Noguchi et al.¹² proposed PWM rectifier control strategy without grid electric potential sensor, which simplified the signal detection of voltage source. J-H Youm and B-H Kwon¹⁸ proposed two solutions to compose the rectifier circuit, which realizes the green power conversion. With PWM modulation, the rectifier can greatly improve the grid content; and its filter inductor ensures the system runs at any angle with the unit power factor. From 1980s, the academia has never stopped the study of PWM converter. Along with the deepening of research, the development of PWM rectifier topology and control, its related application and researches have been in development, such as an active filter, AC drive, superconducting magnetic energy storage, high-voltage direct current transmission, and unified power flow control, which promotes the development of PWM rectifier and its control methods. A conventional three-phase voltage PWM rectifier involves four types of sensors: AC voltage sensors, AC current sensors, DC voltages sensors, and DC current sensors. They play very important roles in direct power control (DPC) on PWM rectifier,¹²–¹⁷ except that they are used in protective circuit. In the common control system, the AC voltage sensors detect the three-phase grid voltage amplitude, which is also used to calculate the instantaneous power of the converter. At the same time, the AC voltage sensors detect the synthetic vector rotation angle of grid voltage by phase locked loop to constitute the synchronous signal source. While the AC current sensors are used to detect the AC current value and estimate the instantaneous power with grid voltage amplitude, which constitute the inner loop feedback signal. The DC voltage sensor detects the DC voltage value to constitute the outer loop feedback signal, while the DC current sensor acts as the feed forward of load in system to enhance the performance of load anti-disturbance. However, the sensors are not essential. More sensors not only increase the cost of the system but also greatly reduce the reliability of the system. Therefore, it is necessary to study the control methods of decreasing parts of sensors.

The control strategy without grid voltage sensors not only detects the grid voltage values, but also the grid voltage that is not needed to be rebuilt in control system. The control method depends on the grid voltage value for calculation.¹⁹ The virtual flux method is introduced to meet the requirement of the control system. The input voltage of AC side in three-phase rectifier may produce the harmonic and unbalance conditions.²⁰ The phase locked is inaccurate. At the same time, the power estimation should introduce the AC harmonic component that affects the control system and grid current. Usually, the filter can deal with this harmonic component, but in the DPC system with hysteresis comparator, due to the high real time, it is difficult for the time constant of this filter to meet the demands of real-time control and harmonic component filter at same time.²¹,²² Additionally, since there are differences and temperature drift in sampling setting circuits, even if the three-phase grid is in ideal condition, the negative sequence component may be brought by the sampling circuits. The stator flux, defined as virtual flux, is introduced into the three-phase PWM rectifier in this article. With the virtual flux oriented vector control and estimation of instantaneous power, the DPC strategy without grid voltage sensors is obtained. The virtual flux DPC system and the space vector modulation are combined, and the combined control strategy is proposed. With the practice and experiment, the design method is discussed.

**The estimation for the virtual flux of PWM rectifier**

For the three-phase PWM rectifier, voltage of AC side is affected by the grid voltage and the energy of AC side inductance, which is equivalent to be an AC motor.²³ The schematic diagram of the equivalent three-phase PWM rectifier and AC motor is shown in Figure 1, in which R and L are the stator resistance and leakage inductance of the virtual motor. The grid voltage can be seen as obtained by the virtual air gap flux induction. The grid voltage vector is integrated transformation to obtain the virtual air gap flux vector.

The relationship between voltage vectors in three-phase static coordinate system is as follows

$$
\vec{u}_s + \vec{u}_L + \vec{u}_r = 0 \tag{1}
$$

where $u_s$ is the grid voltage, $u_L$ is the AC side inductance voltage, and $u_r$ is the AC side voltage of rectifier.

Similarly, the relationship between the virtual fluxes is obtained by

$$
\vec{\psi}_s + \vec{\psi}_L + \vec{\psi}_r = 0 \tag{2}
$$
where \( \psi_r \) denotes the virtual fluxes on grid side, \( \psi_L \) is the virtual fluxes of inductance on AC side, and \( \psi_r \) is the virtual fluxes of rectifier on AC side.

In the static \( \alpha-\beta \) coordinate system, equations (1) and (2) are modified as

\[
u_a = L \frac{di_a}{dt} + u_{ra}, \quad \nu_\beta = L \frac{di_\beta}{dt} + u_{r\beta}
\]

where \( u_{ra} \) and \( u_{r\beta} \) indicate the grid voltage on \( \alpha\beta \) coordinate, \( i_a \) and \( i_\beta \) are the inductance current on \( \alpha\beta \) coordinate, and \( u_{ra} \) and \( u_{r\beta} \) indicate the voltage of rectifier.

The transform equation of \( ab-c \) coordinate to \( \alpha-\beta \) coordinate is as follows. The power transformation method is used to find the value range of \( S_a \) and \( S_\beta \) in vector space

\[
S_a = \left\{ \pm \frac{\sqrt{3}}{2} \pm \frac{1}{6} \right\}, \quad S_\beta = \left\{ \pm \frac{1}{2} \right\}
\]

Voltage integral is flux, which can be expressed by the following equation

\[
\begin{bmatrix} \psi_{a} \\ \psi_{\beta} \end{bmatrix} = \begin{bmatrix} u_{a}dt \\ u_{\beta}dt \end{bmatrix}
\]

\[
\psi_a = u_{dc} S_a dt + Li_a, \quad \psi_\beta = u_{dc} S_\beta dt + Li_\beta
\]

From equations (5) and (6), the virtual flux is estimated according to the DC side voltage and the chosen space vector information. \( \psi_{a} \) and \( \psi_{\beta} \) are applied to obtain the location of virtual flux in vector space for orientation. It is critical calculation step for the estimation and integral of voltage in equation (6). Figure 2
denotes the amplitude frequency curve and phase frequency curve in frequency domain.

From Figure 2, it is seen that the amplitude frequency curve is a straight line through the origin of coordinates, whose slope is every 10 times \(-20 \text{ dB}\). The pure integral has the attenuation for all AC signals whose angular frequency is bigger than 1, except that the angular frequency of this signal is 1. Assuming that an AC signal’s amplitude is \( A_1 \), its angular frequency is \( \omega \) (\( \omega > 1 \)), and its amplitude after the pure integral is \( A_2 \), equation (8) is derived according to the amplitude frequency

\[
\log \omega \times (-20 \text{ dB}) = 20 \log \frac{A_2}{A_1} \text{(dB)}
\]

After simplified, \( A_2 = A_1/\omega \), let \( \zeta = A_2/A_1 \) be the attenuation coefficient, which is the reciprocal of angular frequency \( \omega \). The phase frequency curve of the pure integral is a straight line on \(-90^\circ\). The pure integrator will make any AC signals’ phase lag of 90 degrees. Let
the rotation vector be $Ae^{j\omega t}$, its original function and reciprocal are $j\omega A\dot{e}^{j\omega t}$ and $(1/j\omega) Ae^{j\omega t}$. Their amplitudes zoom in and out $\omega$ times, respectively, and their phases led and lag 90 degrees, respectively. They are the same to Bode diagram analysis. The virtual flux involves the integral of grid voltage, so the phase of virtual flux vector lags of 90 degrees than the grid voltage. With the flux orientation, the virtual flux vector position is in $d$ axis, whose phase lags of 90 degrees than the grid voltage. The phase relationship of vector space is shown in Figure 3.

**The calculation of instantaneous power based on virtual flux**

According to the definition of complex power, the instantaneous power exchanged between converter and grid is obtained by virtual flux value and AC current sampling value. The three voltage vectors in AC side have the relationships

$$
\ddot{u}_s = L \dddot{i} + d \dddot{\psi}_r = L \dddot{i} + \dddot{u}_r \tag{8}
$$

From the theory of the instantaneous power, the instantaneous active power and reactive power are the real part and the imaginary part of complex power, respectively. Their equation is as

$$
p = \text{Re}(\ddot{u}_s \cdot \dddot{i}), \quad q = \text{Im}(\ddot{u}_s \cdot \dddot{i}) \tag{9}
$$

where $\dddot{i}$ is the complex conjugate of grid current vector.

The estimation of the virtual flux is used to estimate the grid voltage value. That is as follows

$$
\ddot{u}_s = \frac{d}{dt} \psi_s = \frac{d}{dt} (\psi_s e^{j\omega t}) = \frac{d\psi_s}{dt} e^{j\omega t} + j\omega \psi_s \tag{10}
$$

The estimation voltage vector is projected to two-phase static coordinate system, and the formula is as follows

$$
\ddot{u}_s = \frac{d\psi_s}{dt} \alpha + j \frac{d\psi_s}{dt} \beta + j\omega (\psi_{sa} + j\psi_{sb}) \tag{11}
$$

where $\psi_{sa}$ and $\psi_{sb}$ are the virtual vector projection component values in $\alpha-\beta$ coordinate, respectively. The complex conjugate of the grid current is multiplied on both sides of equation (17) and then it is into the power estimation equation. That is as follows

$$
\ddot{u}_s \cdot \dddot{i} = \left\{ \frac{d\psi_s}{dt} \alpha + j \frac{d\psi_s}{dt} \beta + j\omega (\psi_{sa} + j\psi_{sb}) \right\} (i_a - j i_b) \tag{12}
$$

Equations (8), (9), and (11) are combined to calculate the instantaneous active power and reactive power

$$
p = \left\{ \frac{d\psi_s}{dt} |\alpha i_a + \frac{d\psi_s}{dt} |\beta i_b + \omega (\psi_{sa} i_b - \psi_{sa} i_a) \right\} \tag{13}
$$

$$
q = \left\{ -\frac{d\psi_s}{dt} |\alpha i_b + \frac{d\psi_s}{dt} |\beta i_a + \omega (\psi_{sa} i_a + \psi_{sa} i_b) \right\}
$$

In the ideal grid conditions, the amplitude of the virtual flux vector does not change basically and its integral approximate to zero. Therefore, the instantaneous power under ideal grid conditions is as follows

$$
p = \omega (\psi_{sa} i_b - \psi_{sa} i_a), \quad q = \omega (\psi_{sa} i_a + \psi_{sa} i_b) \tag{14}
$$

**The principle of the DPC in three-phase voltage PWM rectifier**

From the view of energy, in certain AC voltage, if the instantaneous power is controlled in the permitted scope, the instantaneous current is controlled indirectly in permitted scope, which is the DPC strategy. There are several remarkable characteristics in PWM rectifier with DPC: (1) by choosing the optimal switch state to control the active and reactive power directly; (2) eliminating the grid side voltage sensors, not for the measurement of AC voltage; (3) the control system does not contain the current and voltage regulator; and (4) by AC current, DC voltage, and the switch devices’ state to estimate active and reactive power.

With the control of the instantaneous power, DPC method controls the instantaneous current, makes the grid side current sinusoidal, and achieves unity power factor. Compared with the conventional current control strategy, it has the advantages of high power factor, low total harmonic distortion (THD), high efficiency, and simple algorithm and program. The circuit construction of the traditional voltage source DPC is
shown in Figure 4. The vector space is divided into 12 sectors in DPC rectifier system, as shown in Figure 5.

The rectifier bridge is composed of six switch tubes, and the two tubes in the same bridge arm can only pass complementary. There are eight kinds of switch states. They are represented by $S_a$, $S_b$, and $S_c$, which may be one of $000$, $100$, $110$, $010$, $011$, $001$, $101$, and $111$. These states are expressed as $(V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7)$, shown in Figure 5. $V_0$ and $V_7$ are the amount of zero. Their states represent AC input voltages and the corresponding values of $U_{ma}$ and $U_{mb}$, as shown in Table 1.

From Figure 5, the voltage source reference voltage vector is as follows

$$\phi = \tan^{-1}\left(\frac{U_a}{U_b}\right), \quad -\frac{\pi}{6} \leq \phi \leq \frac{11\pi}{6} \quad (15)$$

$$\pi(n-2)\frac{\pi}{6} \leq \phi_n \leq (n-1)\frac{\pi}{6}, \quad n = 1, 2, \ldots, 12 \quad (16)$$

DPC also needs to be prepared in a switching table, in which the appropriate switch state can be chosen during the system working. Table 2 is the switching table used in the traditional DPC system. The above is the principle of the traditional DPC and its realization method. Hysteresis loop width and switching table determine the control performance. It can be seen from Table 2 that if the reference voltage vector is in the even number sector, the instantaneous active power error signal $S_p$ is 1 and the system uses $V_1$ or $V_7$ as the switch state. The instantaneous reactive power in the even number sectors tends to certain phenomenon that are out of control. As it affects the system’s control performance, better realization method is required.

**Design and realization of DPC system based on virtual flux**

The construction of DPC system based on virtual flux

According to analysis and inference in front, we can carry out the orientation and power estimation using virtual flux. However, there are some technical problems in the process of implementation of system design,
Table 1. The rectifier voltage space vector table.

| $V_i$ | $U_{ia}$ | $U_{ib}$ | $U_{ic}$ | $U_{ia}$ | $U_{ib}$ |
|-------|---------|---------|---------|---------|---------|
| $V_0$ | 0       | 0       | 0       | 0       | 0       |
| $V_1$ | $\frac{2}{3}U_{dc}$ | $-\frac{1}{3}U_{dc}$ | $-\frac{1}{3}U_{dc}$ | $\sqrt{\frac{2}{3}}U_{dc}$ | 0       |
| $V_2$ | $\frac{1}{3}U_{dc}$ | $\frac{1}{3}U_{dc}$ | $\frac{2}{3}U_{dc}$ | $\frac{1}{\sqrt{6}}U_{dc}$ | $\frac{1}{\sqrt{2}}U_{dc}$ |
| $V_3$ | $-\frac{1}{3}U_{dc}$ | $\frac{2}{3}U_{dc}$ | $-\frac{1}{3}U_{dc}$ | $-\frac{1}{\sqrt{6}}U_{dc}$ | $\frac{1}{\sqrt{2}}U_{dc}$ |
| $V_4$ | $-\frac{2}{3}U_{dc}$ | $\frac{1}{3}U_{dc}$ | $\frac{1}{3}U_{dc}$ | $-\frac{1}{\sqrt{6}}U_{dc}$ | 0       |
| $V_5$ | $-\frac{1}{3}U_{dc}$ | $-\frac{1}{3}U_{dc}$ | $\frac{2}{3}U_{dc}$ | $-\frac{1}{\sqrt{6}}U_{dc}$ | $-\frac{1}{\sqrt{2}}U_{dc}$ |
| $V_6$ | $\frac{1}{3}U_{dc}$ | $-\frac{2}{3}U_{dc}$ | $\frac{1}{3}U_{dc}$ | $\frac{1}{\sqrt{6}}U_{dc}$ | $-\frac{1}{\sqrt{2}}U_{dc}$ |

Table 2. Traditional direct power control system adopts the switch state.

| $S_p$, $S_q$ | $\varphi_1$ | $\varphi_2$ | $\varphi_3$ | $\varphi_4$ | $\varphi_5$ | $\varphi_6$ | $\varphi_7$ | $\varphi_8$ | $\varphi_9$ | $\varphi_{10}$ | $\varphi_{11}$ | $\varphi_{12}$ |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|----------------|----------------|-------------|
| 1, 0         | $V_6$       | $V_7$       | $V_1$       | $V_0$       | $V_2$       | $V_7$       | $V_3$       | $V_0$       | $V_4$       | $V_0$         | $V_0$         | $V_0$       |
| 1, 1         | $V_7$       | $V_7$       | $V_0$       | $V_0$       | $V_7$       | $V_7$       | $V_0$       | $V_0$       | $V_7$       | $V_0$         | $V_0$         | $V_0$       |
| 0, 0         | $V_6$       | $V_1$       | $V_1$       | $V_2$       | $V_2$       | $V_3$       | $V_3$       | $V_4$       | $V_4$       | $V_5$         | $V_5$         | $V_4$       |
| 0, 1         | $V_1$       | $V_2$       | $V_2$       | $V_3$       | $V_3$       | $V_4$       | $V_4$       | $V_5$       | $V_5$       | $V_6$         | $V_6$         | $V_1$       |

Figure 6. The DPC system based on virtual flux.
such as the integral initial value, which will directly affect the control features.

A DPC system based on virtual flux, shown in Figure 6, is different from the traditional DPC system. In this new system, the grid voltage sampling circuit is removed, and virtual flux (VF) vector estimation and phase detector replaces the grid voltage vector discriminator. The functions of power and VF estimation are divided into the following steps, as shown in Figure 7: the first step is estimated based on the DC voltage and a moment three-phase bridge arm switch function \( S \) on the AC side voltage; the second step is to calculate the \( VF \) value by the AC inductance, AC current, and AC side voltage; the third step is to estimate the instantaneous power by the \( VF \) estimation and AC current sampling value; and finally the estimation is put into controller. This system is a double-loop system based on hysteresis comparator.

This system can get good control performance in the condition of non-ideal power grid. This is because the \( VF \) produces the integral role. The non-ideal grid is divided into two types: one is three-phase symmetrical grid, each phase voltage contains the same harmonic amplitude; another is that the sine degrees of the three-phase grid voltages are good but the voltage amplitudes are different. One or all of the types may occur in grid. We will analyze the difference between the orientation of grid voltage vector and \( VF \) vector in these two types of grid conditions. In the traditional DPC system oriented by grid voltage vector angular, when the grid voltage contains harmonic components, the estimation of power has been affected. This leads to the harmonic introduced to calculation of the instantaneous power, the operation of hysteresis comparator has been affected, and this harmonic is involved in AC current. Another serious situation is caused by the out of phase of fundamental harmonics of grid voltage, which results in the error in phase locked loop (PLL). The sector judgment of grid voltage vector has been affected directly, so as to occur the mistake in switch vector choice and not to control the power. When the grid voltage is unbalanced, the negative sequence of fundamental voltage disturbs the estimation of the instantaneous power, and even the negative sequence current is occurred. The safe operation of converter is brought a threat. In DPC system based on \( VF \), the grid voltage angular is changed to the vector angular of \( VF \). Because the flux is the integral of grid voltage, and the integrator has the feature of the low-pass filter, the multiple attenuation of harmonic voltage amplitude will be larger \( K \) times than that of fundamental (\( K \) is the harmonic number). Therefore, the orientation with \( VF \) vector not only cancels the grid voltage sensors but also overcomes the zero-offset problem caused by harmonic voltage, so as to ensure the accuracy of oriental angle. In the unbalance phenomenon of the grid voltage fundamental, there are two times of harmonic voltage in converter DC side. This low order harmonics can be removed by power estimation with \( VF \).

**The two-order replacement of the integral value problem**

From the integral definition, if the function \( F(t) \) is the original function of the function \( f(\tau) \), the time \( \tau \) integral of the function \( F(T) \) is obtained by the following equation:

\[
\int_{t_1}^{t_2} f(\tau) d\tau = F(t_2) - F(t_1)
\]

(17)

It is seen that the time \( t_2 \) integral can be calculated with the original function form and the time \( t_1 \) function initial value. The realization of pure integration in
di diL

(21), in order to obtain the initial value of grid flux is observed by current amount and equation are added before PWM rectifier operation. The virtual VF trajectory will make the space sector judgment not be known. Otherwise, a flux observer is obtained in the premise of system under steady state. The key to solve the problem is to observe accurately. The performance has the effect on the instantaneous power calculation and voltage space vector choice. The PWM rectifier has the too larger impact current during its starting and will not work in normal if the impact is more serious. Therefore, a flux observer need to be built to resolve the initial value problem, to ensure that the accurate observed method of the initial value will be introduced to the VF estimation. This results in that the flux trajectory is a circle in \( \alpha-\beta \) coordinates and the DC bias is the center of this circle.

The orientation of spatial angle obtained from this flux trajectory will make the space sector judgment not be accurate. The performance has the effect on the instantaneous power calculation and voltage space vector. The pure integral cannot eliminate the DC component. If the initial value has error, the output will always contain the DC component with the same error as initial value. Therefore, it is difficult to use the integral to estimate \( VF \) value if its initial value is not known. Otherwise, a DC bias with related integral initial value will be introduced to the \( VF \) estimation. This method omits the effects on AC impedance of fundamental, the inertia link will decay the fundamental frequency in AC voltage side and direct short circuit. Since the instantaneous current is very large, the estimation accuracy has been affected if the obvious AC impedance voltage drop is ignored. The similar problems are in the direct torque control to AC motors. When the stator side flux is estimated, the pure integral is simple. The parameter related to the motor parameter is stator resistance, which is easier to determine. But it is easy of the pure integral to be affected by the input signal DC bias to be saturated, the low pass filter, \( T_c/(T_c s + 1) \) with low cutoff frequency, replaces the pure integral to inhibit the effect on DC bias, in which \( T_c \) is small and can be used as the time constant of the stator. The phase lag of state estimation caused by inertia is compensated according to the signal of stator flux \( \psi^* \) filter. The pure integral is replaced by one order inertial. The DC bias caused by the inaccuracy initial value is removed. This is actually equivalent to a pure integrator and a first-order high pass filter, as shown in Figure 9. However, this high-pass filter would spend more time on removing the DC bias under the condition of uncertain initial value, so that the dynamic response of PWM rectifier starting has the worse performance and the phase compensation amount is uneasy to determine.

The pure integrator replacement to the two-order link is presented in this article, which is better equivalent of pure integrator in fundamental frequency. From observation, the inertia link’s gain at the cutoff frequency is \(-3\) dB and its phase lags 45°. If the cutoff frequency is set to the angular frequency of the fundamental, the inertia link will decay the fundamental signal amplitude into times \((-3\) dB). Its phase lags 45°. The decay is higher than 1, the harmonic is \( \omega^{-1} \).

\[
Y(k) = Y(k - 1) + [X(k) - X(k - 1)]/2f_s \tag{18}
\]

where \( f_s \) is the sampling frequency of system.

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This inertia link’s transfer function is equation (22). The cascaded two inertia links will decay the fundamental frequency signal into two times. It is the two-order filter with 90° phase lag, whose transfer function is as equation (23)

\[
\frac{1}{s^2} + \frac{100\pi}{s} + 1 = \frac{100\pi}{s^2 + 100\pi}
\]

\[
\left(\frac{1}{s^2} + 1\right)^2 = \left(\frac{100\pi}{s + 100\pi}\right)^2 = \frac{314^2}{s^2 + 628 + 314^2}
\]

\[
VF-DPC \text{ can get better control performance in the unideal grid condition. At the same time, there are also the inherent disadvantages with the usage of hysteresis comparator and DPC system:}

1. The switching frequency is not fixed so that the design of input filter has more difficulty;
2. The switch polarity is not coherent and the switching stress is big;
3. The hysteresis controllers need the higher sampling frequency in digital control system;
4. The digital processor and analogue-to-digital (AD) chip are needed the higher speed in this system.

Therefore, the application of VF-DPC has a distance to industrial field. However, the space vector modular instead of switching table can eliminate these disadvantages after the transformation of the modulation. The idea of DPC based on space vector modulation is introduced to VF-DPC, in which space voltage pulse-width modulation (SVPWM) and PI regulator are used to accomplish the fixed switching frequency control. The difference between the two methods is due to orientation. VF vector angle \(\gamma\) lags the grid voltage vector angle \(\theta\) to 90 degrees, which is \(\theta = \gamma + \pi/2\). According to the relationship between the transform matrix of two-phase rotating \(d-q\) coordinate to two-phase stationary \(\alpha-\beta\) coordinate and the two vectors’ angles, the matrix is obtained when VF vector is in orientation, then the relationship between controller output and the set value of converter’s AC voltage is as follows

\[
\begin{bmatrix}
u_{\alpha}\sin \phi_{\alpha} + u_{\beta}\cos \phi_{\beta} \\ u_{\beta}\sin \phi_{\beta} - \cos \phi_{\alpha}
\end{bmatrix}
= \begin{bmatrix}
-\sin \phi_{\alpha} & -\cos \phi_{\alpha} \\
\cos \phi_{\alpha} & -\sin \phi_{\alpha}
\end{bmatrix}
\begin{bmatrix}
u_{\alpha}\sin \phi_{\alpha} + u_{\beta}\cos \phi_{\beta} \\ u_{\beta}\sin \phi_{\beta} - \cos \phi_{\alpha}
\end{bmatrix}
\]

where \(u_{\alpha}\) and \(u_{\beta}\) are the active and reactive outputs of PI regulators, respectively. The \(VF\) vector angles are calculated according to its projection value in \(\alpha-\beta\) coordinate

\[
\sin \phi_{\alpha} = \frac{\psi_{\alpha}}{\psi_{\alpha}^2 + \psi_{\beta}^2}, \cos \phi_{\beta} = \frac{\psi_{\beta}}{\psi_{\alpha}^2 + \psi_{\beta}^2}
\]

\[
\sin \phi_{\beta} = \frac{\psi_{\beta}}{\psi_{\alpha}^2 + \psi_{\beta}^2}, \cos \phi_{\alpha} = \frac{\psi_{\alpha}}{\psi_{\alpha}^2 + \psi_{\beta}^2}
\]

\[
VF-DPC-SVM \text{ is shown in Figure 10, which not only contains the advantage of VF method but also has the stress on space voltage modulation (SVM) modulation with fixed frequency after the improvement. It is a very ideal DPC system.}

Simulation and experimental results analysis

Simulation platform and results

Simulation of the traditional DPC system for PWM rectifier. The traditional DPC strategy for PWM rectifier is simulated using MATLAB/Simulink to build simulation platform. Setting the parameters as follows: line voltage effective value is 380 V, the grid frequency \(f_b\) is 50 Hz, the DC side capacitor \(C_d\) is 5000 \(\mu\)F, load resistance is 100 \(\Omega\), DC voltage is 700 V, grid side inductance \(L\) is 5 mH, and the internal resistance is 0.5 \(\Omega\).

Figure 11 is a simulation platform model built using MATLAB/Simulink, which uses the traditional voltage oriented DPC. Three phase voltage and current are sampled directly from the network side through the sensor, and the switch tube is made of insulated gate bipolar transistor (IGBT) with anti-parallelized diode. The simulation results are shown in Figure 12.

Figure 12(a) shows the output DC voltage waveform of the traditional three-phase voltage PWM rectifier, we can see that the voltage is stable at 700 V after 0.05 s, dynamic performance is better, overshoot within 5%. Figure 12(b) shows the output DC current waveform of the traditional three-phase voltage PWM rectifier. It can be seen that the current follows the voltage very well. After 0.05 s, the current is stable at 7 A, and the dynamic performance is good. Figure 12(c) is the waveform of the phase A current and voltage at the grid side. It can be seen that the stable current waveform basically presents a sine wave, but the current harmonic content is very large. Figure 12(d) is the PWM rectifier AC side of the A-phase current and its harmonic analysis. It can be seen that the AC side current contains more harmonics, especially the low harmonic content is very high, the THD reached 32.64%. This is far beyond the International Electrical Commission of the THD of less than 5% of the standard.

Simulation of DPC system for PWM rectifier with VF. The DPC strategy for PWM rectifier with VF is simulated using MATLAB/Simulink to build simulation platform. Set the parameters as follows: the line voltage effective value is 380 V, the grid frequency is 50 Hz, the DC side capacitor is 5000 \(\mu\)F, load resistance is 100 \(\Omega\), DC voltage is 600 V, and switching frequency is 500Hz. According to the filter design rules to select
Figure 10. The VF-DPC-SVM control system structure diagram.

Figure 11. Simulink of the traditional direct power control for PWM rectifier with L filter.
Figure 12. Simulation results of traditional direct power control for PWM rectifier: (a) output DC waveform of voltage, (b) output DC waveform of current, (c) current and voltage of A-phase on grid side, and (d) current harmonic spectrum of A-phase on grid side.

Figure 13. Simulink of the direct power control for PWM rectifier with VF.
suitable parameters: grid side inductance is 1 mH, internal resistance is 0.1 $\Omega$; AC side branch filter capacitor is 16 $\mu$F; AC side of the inductor is 2 mH, and the resistance is 0.2 $\Omega$.

The traditional DPC scheme has the disadvantages of high switching frequency and poor stability of the system, and this article proposes a DPC based on virtual flux without voltage sensor. The control system adopts the double closed-loop control structure of voltage outer loop and power inner loop. A simulation platform model has been built using MATLAB/Simulink as shown in Figure 13. The DPC for PWM rectifier with VF, PI regulator instead of the traditional hysteresis comparator, and SVPWM other than the traditional switch table, are used. The simulation results are shown in Figure 14.

Figure 14(a) shows the output DC voltage waveform of the PWM rectifier with VF, we can see that the voltage is stable at 700 V after 0.02 s, dynamic performance is very good, overshoot within 5% and achieve desired control results. Figure 14(b) shows the output DC current waveform of the PWM rectifier with VF. It can be seen that the current follows the voltage very well. After 0.02 s, the current is stable at 6 A, and the dynamic performance is good and achieves desired control results. Figure 14(c) is the waveform of the phase A current and voltage at the grid side. It can be seen that the stable current waveform is a sine wave, current and
voltage phase is the same, the current harmonic distortion is small. Figure 14(d) is the PWM rectifier AC side of the A-phase current and its harmonic analysis. It can be seen that the AC side current contains less harmonic, the THD is only 2.01%, near the switching frequency of 5 kHz, the high-order harmonic amplitude is less than 1%. Resonance is better suppressed, and the current harmonics of the grid side are greatly reduced, and the expected control effect is achieved. This is fully in line with the International Electrical Commission of the THD of less than 5% of the standard. Figure 14(e) is the waveform of the reactive power and active power. It can be seen that the reactive power is zero, and the control system achieves the result of unity-power factor operation. Although the presence of the filter capacitor will reduce the power factor of the control system, the power factor is still greater than 0.98.

Based on the simulation and analysis of traditional DPC strategy for PWM rectifier and DPC strategy for PWM rectifier with VF, the results show that DPC strategy for PWM rectifier with VF has better dynamic performance. Network side current harmonic is greatly reduced, and the unity-power factor control can be achieved, and a very superior control effect is achieved.

**The system experiment and its results analysis**

The experimental platform is established as shown in Figure 15. The experimental parameters values are shown in Table 3. The experimental parameters are AC autotransformer is 30 kVA; the output of AC side is adjustable from 0 to 470 V; the air switches select D10/4P; the resistance of limiting current is 60Ω; filter capacitors are 4 × 2200 μF; and intelligent power model (IPM) is select as the power semiconductor with 100 A current capacity. TMS320LF2812DSP is select to control the system. Oscilloscope of Agilent-600 is

| Experimental parameters | Values       |
|-------------------------|--------------|
| AC autotransformer      | 30 kVA       |
| Output of AC side       | 0–470 V      |
| Switches                | D10/4P       |
| The resistance of limiting current | 60Ω         |
| Filter capacitors       | 4 × 2200 μF  |
| Current capacity of IPM | 100 A        |
| IPM dead time           | 2.6 μs       |
| Load power              | 4 kW         |

**Figure 15.** Experiment platform of PWM rectifier.

**Figure 16.** The voltage and current waveforms: (a) DC side voltage, (b) grid side voltage and phase current, and (c) the grid side current waveform.
used to observe the output waveforms. The experiments of hardware platform are operated, in which the rated load power is 4 kW, input voltage is 120 V, the given frequency is 50 Hz, and IPM dead time is 2.6 μs. The results are shown in Figure 16.

The output waveform of DC link voltage is shown in Figure 16(a). In Figure 16(b), grid side line voltage \( u_{AB} \) and phase current \( i_{A} \) are shown and compared, in which their phase angle is about 30°. The waveforms of grid side phase currents \( i_{A} \) and \( i_{B} \) are shown in Figure 16(c). It can be seen that the experimental waveforms are similar to the simulation waveforms. Because of the electromagnetic interference in the experimental measurement, there are several burrs in experimental waveforms.

**Conclusion**

In this article, the DPC method of three-phase PWM rectifier based on virtual flux orientation is proposed and realized, which improves the reliability of the system without the grid voltage sensors. Moreover, the proposed method runs well under the condition of non-ideal power grid. The space vector modulation method combined with DPC strategy based on virtual flux is discussed and its advantages and disadvantages are analyzed, thus it is proved a very valuable control method. Furthermore, the experiment platform of three-phase voltage source PWM rectifier is established for theoretical analysis and simulation verification. The experimental results show that the DC output voltage is stable, the AC side current distortion rate is low, the power factor is high, and it has a strong ability to resist load disturbance and can satisfy the control requirements and then verify the validity of the control scheme.

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