Analysis of PR Control Strategy for Grid-side Converters under Unbalanced Voltager

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Abstract

This paper proposes the control of the grid side converters (GSC) of doubly-fed induction generator (DFIG) based wind generation systems under unbalanced voltage conditions.Firstly, the mathematical model of DIFG and grid-side converter under unbalanced voltage is established. By analyzing the mathematical model in the rotating coordinate system, the problem of double frequency fluctuation of power and DC side voltage is proposed.In order to solve the double frequency fluctuation problem of wind power double-fed power generation under unbalanced voltage, The grid-side converter no longer uses the traditional vector control strategy, but uses a proportional resonance (PR) control strategy. Based on this, the control strategy has been redesigned, including the analysis and design of the main controller and the auxiliary controller. It should be noted that due to limited space, the separation of positive sequence components and negative sequence components is not described in this paper.Finally, simulation verification was carried out.The results show that the fluctuation of the double frequency can be better suppressed, and the stability and safety of the system are effectively improved.

Keywords

Doubly-fed induction generator (DFIG), unbalanced stator voltage , double frequency.

1. Introduction

The variable-speed constant-frequency wind turbine is the mainstream solution for large-scale grid-connected wind power. It combines multi-domain advanced technologies to achieve high efficiency and superior power output. With the increasing maturity and low level of conventional control techniques such as maximum power tracking (MPPT) and power decouplingEnhanced control techniques such as voltage crossover (LVRT), unbalance control, and voltage reactive control have become hot topics of current research[1]-[3].

Wind farms are generally connected to the system through long distance transmission lines, and wind turbines are susceptible to various electrical grid conditions. The misalignment of the three-phase grid voltage caused by the mismatched or unbalanced load is a common phenomenon in the actual grid. The grid-side converter (GSC) acts as the interface between the wind turbine and the grid and will directly withstand the asymmetric grid voltage. The negative sequence voltage generates harmonic waves on the AC and DC sides of the converter, causing the generator to generate vibration and noise, which causes the performance of the machine to drop significantly and even burn out the equipment. It is of great significance to study the effective control of the GSC when the asymmetric network is faulty, and to improve the reliability and safety of the wind turbine and improve its grid-connected operation and fault-to-failure capability. At present, relevant research has become a hot spot and has achieved certain results. In order to suppress the GSC AC negative sequence current, the paper [4] proposed a feed-forward control strategy for the negative sequence electric potential of the grid, but the current loop did not consider the negative sequence component and the control performance was reduced. The literature [5-6] calculates the GSC current command with the equalization of the AC current and the average reactive power equal to 0, but at the same time loses the suppression of the DC voltage ripple, which affects the normal operation of the machine-side converter. In the paper [7], in order to suppress the second harmonic of DC voltage, four methods for the separation of the voltages of the asymmetric grid voltage were proposed, and several control strategies under the dq coordinate system were summarized, but the specific implementation details were not given. The paper [8] adopted the input-output linearization strategy, and the algorithm is good, but the implementation is more complicated. In order to solve the double frequency fluctuation problem of wind power double-fed power generation under unbalanced voltage, In this paper, the proportional resonance control strategy is used to control the grid-side converter.

2. Mathematical model of grid-side converter under unbalanced voltage

When the grid has an asymmetrical fault or a severe load imbalance, the doubly-fed wind turbine system produces a three-phase unbalanced voltage. According to the symmetrical component method, any set of three-phase asymmetric electromagnetic quantities (such as current, voltage, flux linkage, etc.) can be decomposed into three-phase symmetric positive sequence components, negative sequence components and zero sequence components. In view of the fact that today's doubly-fed wind turbines and power grids generally use a three-phase three-wire electrical connection relationship, zero-sequence components do not occur. Therefore, all analysis in this paper is based on the existence of only positive and negative sequence components in the system.

The relationship between the two-phase stationary coordinate system and the two-phase positive direction rotation and the negative direction rotation coordinate system can be expressed as follows[9]:

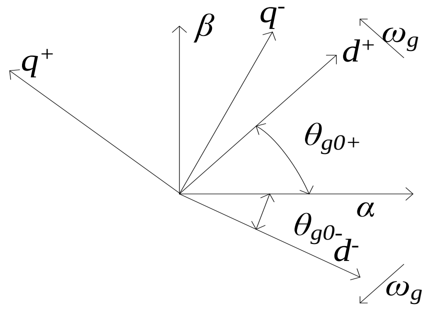

Fig. 1 Two-phase static and forward-reverse synchronous rotation coordinate relationship diagram

The space vector of the electromagnetic quantity is defined F by the analysis of the coordinate system relationship of the above figure. The relationship of vectors in two coordinate systems can be expressed as follows:

$$F_{\alpha\beta} = F_{\alpha\beta+} + F_{\alpha\beta-} \tag{1}$$

$$\begin{cases} F_{dq}^{+} = F_{\alpha\beta} e^{-j\omega_g t} \\ F_{dq}^{-} = F_{\alpha\beta} e^{j\omega_g t} \end{cases} \tag{2}$$

By performing the corresponding coordinate transformation of the two-phase forward direction rotation and the negative direction rotation coordinate system of Equation (1) by Equation (2), the following formula can be obtained:

$$\begin{cases} F_{dq}^{+} = F_{dq+}^{+} + F_{dq-}^{+} = F_{dq+}^{+} + F_{dq-}^{-} e^{-j2\omega_g t} \\ F_{dq}^{-} = F_{dq-}^{-} + F_{dq+}^{-} = F_{dq-}^{-} + F_{dq+}^{+} e^{-j2\omega_g t} \end{cases} \tag{3}$$

The superscripts + and - respectively indicate the two-phase positive direction rotation and the negative direction rotation coordinate system; the subscripts +, - respectively indicate the positive and negative sequence components of the two-phase positive direction rotation and negative direction rotation coordinates. It can be seen that the negative sequence component in the positive direction synchronous rotation coordinate system is a double frequency component; the positive sequence component in the negative direction synchronous rotation coordinate system is a double frequency component. Due to the occurrence of the double frequency component, the result of the vector control strategy is not ideal, so improvement measures must be taken to eliminate the influence of the double frequency component.

According to Equations (1) and (2), we can write the voltage vector equation of the two-phase rotating coordinate system of the grid side converter in the positive direction as

$$U^+_{gdq} = R_g i^+_{gdq} + L_g \frac{di^+_{gdq}}{dt} + j\omega_g L_g i^+_{gdq} + V^+_{gdq} \tag{3}$$

Where $U^+_{gdq} = U^+_{gdq+} + U^-_{gdq-} e^{-j2\omega_g t}$, $i^+_{gdq} = i^+_{gdq+} + i^-_{gdq-} e^{-j2\omega_g t}$, V_g is the grid side converter AC side voltage, and $V^+_{gdq} = V^+_{gdq+} + V^-_{gdq-} e^{-j2\omega_g t}$.

The instantaneous active power and reactive power output to the grid under the condition that the grid voltage is unbalanced by the grid side converter can be expressed by the following formula as

$$\begin{cases} P_g = P_{g0} + P_{\cos 2}\cos(2\omega_g t) + P_{\sin 2}\sin(2\omega_g t) \\ Q_g = Q_{g0} + Q_{\cos 2}\cos(2\omega_g t) + Q_{\sin 2}\sin(2\omega_g t) \end{cases} \tag{4}$$

The two-frequency components of active and reactive power are as follows

$$\begin{bmatrix} P_{g\cos 2} \\ P_{g\sin 2} \\ Q_{g\cos 2} \\ Q_{g\sin 2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} u^-_{gd-} & u^-_{gq-} & u^+_{gd+} & u^+_{gq+} \\ u^-_{gq-} & -u^-_{gd-} & -u^+_{gq+} & u^+_{gd+} \\ u^-_{gq-} & -u^-_{gd-} & u^+_{gq+} & -u^+_{gd+} \\ -u^-_{gd-} & -u^-_{gq-} & u^+_{gd+} & u^+_{gq+} \end{bmatrix} \begin{bmatrix} i^+_{gd+} \\ i^+_{gq+} \\ i^-_{gd-} \\ i^-_{gq-} \end{bmatrix} \tag{5}$$

Where P_{g0}, $P_{g\cos 2}$, $P_{g\sin 2}$ is the average component of the active power, the cosine double-frequency oscillating component, and the sinusoidal double-frequency oscillating component are respectively output from the grid-side converter to the grid; Q_{g0}, $Q_{g\cos 2}$, $Q_{g\sin 2}$ is the grid side converter outputs an average component of active power, a cosine second frequency oscillating component, and a sinusoidal double frequency oscillating component to the grid, respectively.

Combining equations 4 and 5, we can analyze that the positive sequence component in the positive two-phase rotating coordinate system is the DC component, but the negative sequence component appears as the double frequency oscillation component in this coordinate system. To simplify the analysis, we assume that the grid voltage vector is the same as the d-axis direction in the two-phase rotating coordinate system. We can be sure $u^+_{gq+} = 0$.

Combined with the above analysis of the double frequency power can be expressed by the following formula as

$$\begin{cases} P_{g2} = \frac{3}{2}(i_{gd0}^{+}u_{gd2}^{+} + u_{gd0}^{+}i_{gd2}^{+}) \\ Q_{g2} = -\frac{3}{2}(i_{gq0}^{+}u_{gd2}^{+} + u_{gd0}^{+}i_{gq2}^{+}) \end{cases} \tag{6}$$

3. Analysis of power resonance control strategy for grid-side converter under unbalanced voltage.

In the overall control of power resonance compensation, there are generally two parts of the corresponding main controller and auxiliary controller. The main controller is similar to the traditional control strategy, and the role of the auxiliary controller is to compensate the converter for proper resonance compensation for the unbalanced grid to eliminate the double frequency problem**.**

main controller design

The control voltage of the grid-side converter can be designed separately as

$$\begin{cases} u_{cd\_ref} = -L_g v_{gd} + u_{gd} - R_g i_{gd} + \omega_g L_g i_{gq} \\ u_{cq\_ref} = -L_g v_{gq} + u_{gq} - R_g i_{gq} - \omega_g L_g i_{gd} \end{cases} \tag{7}$$

The v_{gd}、 v_{gq} in the above equation can be obtained by the ratio of the current loop and the integral gain.

In order to obtain the control strategy for the double frequency component in the auxiliary controller, deriving (6) (considering the DC component is constant) can be obtained.

Auxiliary controller design

In the design of the auxiliary controller, according to the above PR control, a certain fixed frequency can be filtered according to the actual situation, and the corresponding control purpose is achieved.

The transfer function of the secondary controller is as follows

$$G_{pc(s)} = K_{pc} + \frac{K_{ic}s}{s^2 + (2\omega_g)^2} \tag{8}$$

In order to obtain the control strategy for the double frequency component in the auxiliary controller, deriving (6) (considering the DC component is constant) can be obtained as follows

$$\begin{cases} \frac{dP_{g2}}{dt} = \frac{3}{2}(\frac{di_{gd2}^{+}}{dt}u_{gd0}^{+} + \frac{du_{gd2}^{+}}{dt}i_{gd0}^{+}) \\ \frac{dQ_{g2}}{dt} = -\frac{3}{2}(\frac{di_{gq2}^{+}}{dt}u_{gd0}^{+} + \frac{du_{gd2}^{+}}{dt}i_{gq0}^{+}) \end{cases} \tag{9}$$

By substituting the second-order component of the current in the above equation into the formula (3), the governing equations of the active and reactive second-frequency components are obtained.

$$\begin{cases} u_{cd2\_ref}^{+} = -\frac{2L_g}{3u_{gd0}^{+}}\frac{dP_{g2}}{dt} + \frac{L_g i_{gd0}^{+}}{u_{gd0}^{+}}\frac{du_{gd2}^{+}}{dt} + u_{gd2}^{+} - R_g i_{gd2}^{+} + \omega_g L_g i_{gq2}^{+} \\ u_{cq2\_ref}^{+} = \frac{2L_g}{3u_{gd0}^{+}}\frac{dQ_{g2}}{dt} + \frac{L_g i_{gq0}^{+}}{u_{gd0}^{+}}\frac{du_{gd2}^{+}}{dt} + u_{gq2}^{+} - R_g i_{gq2}^{+} - \omega_g L_g i_{gd2}^{+} \end{cases} \tag{10}$$

The $u_{cd2\_ref}^{+}$、 $u_{cq2\_ref}^{+}$ in the above equations represent the corresponding double-frequency reference voltage of the grid-side converter in the dq0 coordinate system. And compared with the design of the main controller, the last three items in the above formula can be omitted in the design of the auxiliary controller because the main controller has already been included. The corresponding control strategy can be obtained, and its structural block diagram is divided into two parts: active and reactive.

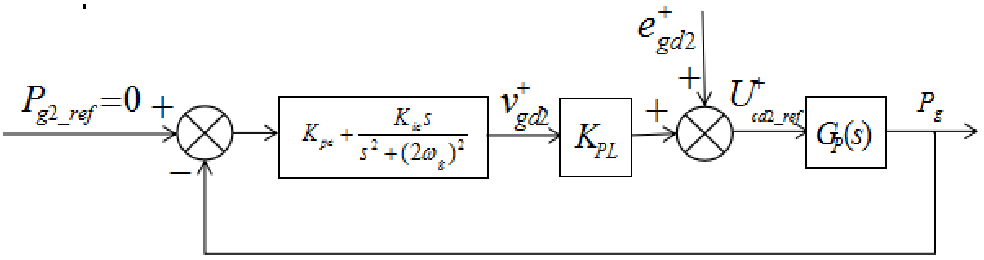

Fig.2 Active power control loop

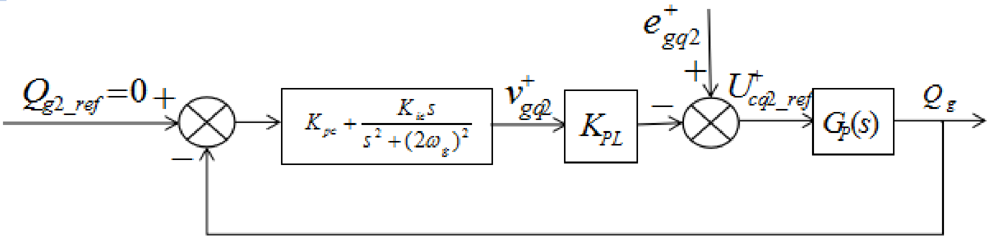

Fig.3 Reactive power control loop

The feedforward interference voltage in the above control design can be expressed as

$$\begin{cases} e^+_{gd2} = -\dfrac{L_g i^+_{gd0}}{u^+_{gd0}} \dfrac{du^+_{gd2}}{dt} + u^+_{gd2} + R_g i^+_{gd2} - \omega_g L_g i^+_{gq2} \\ e^+_{gq2} = -\dfrac{L_g i^+_{gq0}}{u^+_{gd0}} \dfrac{du^+_{gd2}}{dt} + u^+_{gq2} + R_g i^+_{gq2} + \omega_g L_g i^+_{gd2} \end{cases} \quad (11)$$

It can be obtained from the active control block diagram of Fig 2. The closed-loop transfer function e^+_{gd2} and P_g the corresponding transfer function are expressed as follows

$$\begin{cases} F_i(s) = \dfrac{G_{PR}(s) K_{PL} G_P(s)}{1 + G_{PR}(s) K_{PL} G_P(s)} \\ F_u(s) = \dfrac{G_P(s)}{1 + G_{PR}(s) K_{PL} G_P(s)} \end{cases} \quad (12)$$

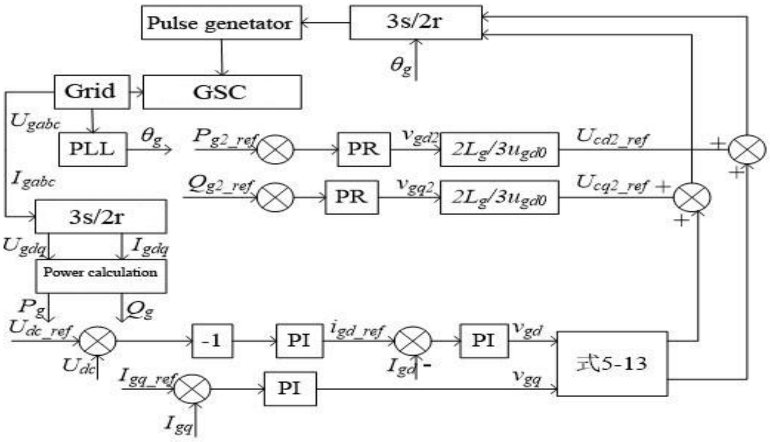

Fig.3 PR control principle block diagram

The fixed frequency $s = j(2\omega_g)$ is substituted into the (11) formula for calculation can be obtained separately $F_i(s)=1, F_u(s)=0$ .It is shown that the control can control the double frequency signal without static difference; and the feedforward interference voltage has no influence on the auxiliary controller, so this factor can be ignored in the overall control strategy. Its control strategy is as follows

4. Simulation.

Based on the above analysis of the PR control strategy of the grid-side converter, and the design of the main controller and the auxiliary controller, the relevant simulation is performed in MATLAB. The parameters of the simulation design are set as follows:

Three-phase power line voltage: $u_{AB} = u_{AC} = u_{BC} = 220\sqrt{3}\text{V}$;DC bus voltage: $u_{dc} = 600\text{V}$;Line impedance: $R = 0.1\Omega$, $L = 5*10^{-3}\text{H}$;DC side capacitor: $C = 4700\mu\text{F}$;DC side load resistor:R=50 Ω .

The waveform of the unbalanced grid voltage (A phase drops 60%) is shown in the figure below.

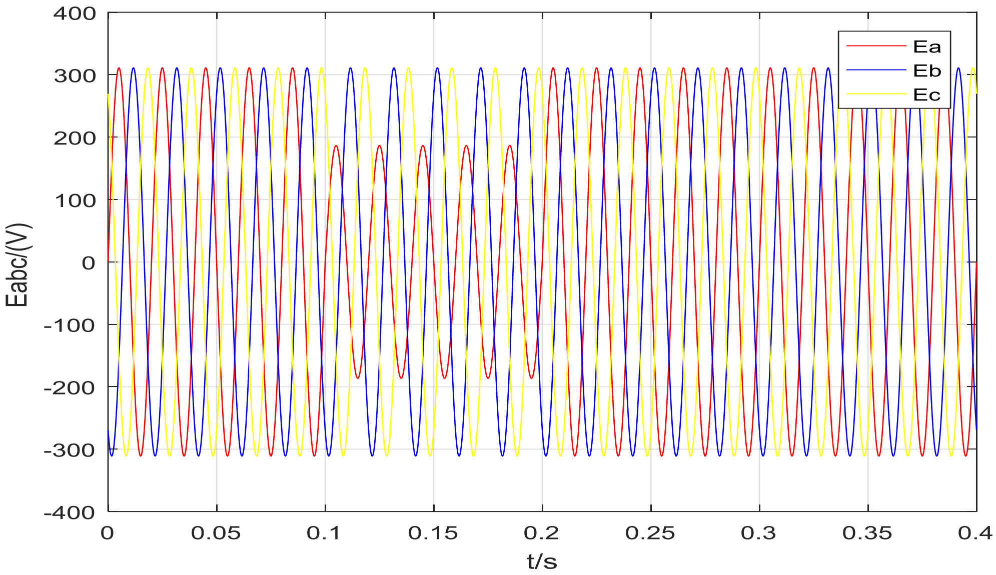

Fig.4 Three-phase unbalanced voltage waveform

The current waveform of the AC side of the converter based on the traditional control strategy under unbalanced voltage is shown in the figure below

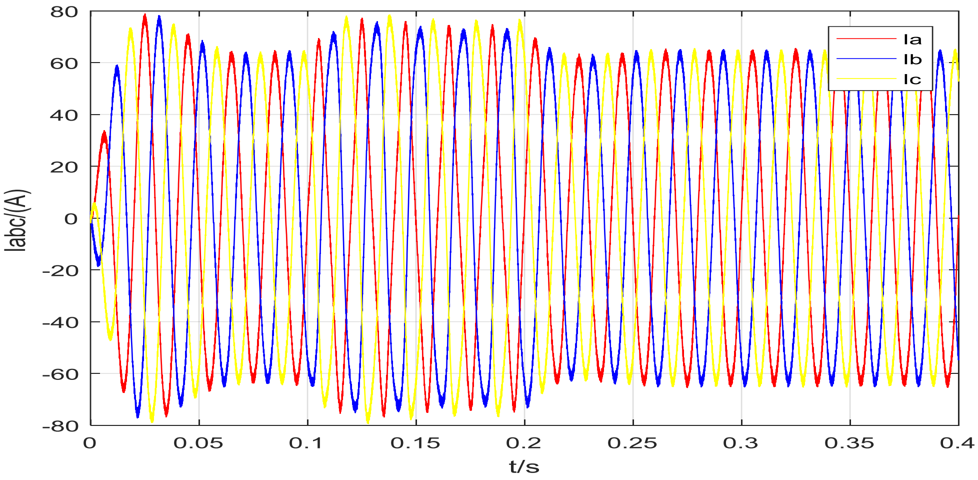

Fig.5 Unbalanced current under grid voltage vector control

The active power and DC voltage under the traditional control strategy are shown in the fig.6 and fig7.

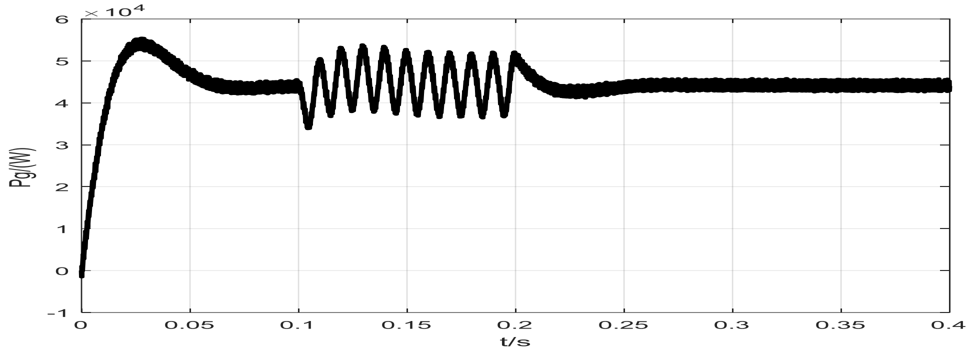

Fig.6 Power waveform under traditional control strategy

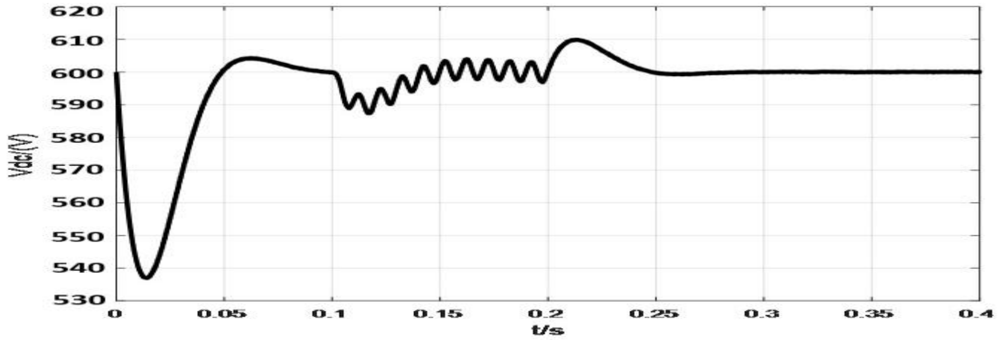

Fig.7 DC bus voltage waveform under vector control

It can be seen from the waveform of the above figure that under the traditional vector control, when the grid voltage is unbalanced, the DC bus voltage will also have a large double frequency fluctuation and thus cause instability of the overall system. And as can be seen from the above figure, the frequency of the fluctuation is 100 Hz.The power waveform and DC side voltage of the PR control strategy are applied as shown

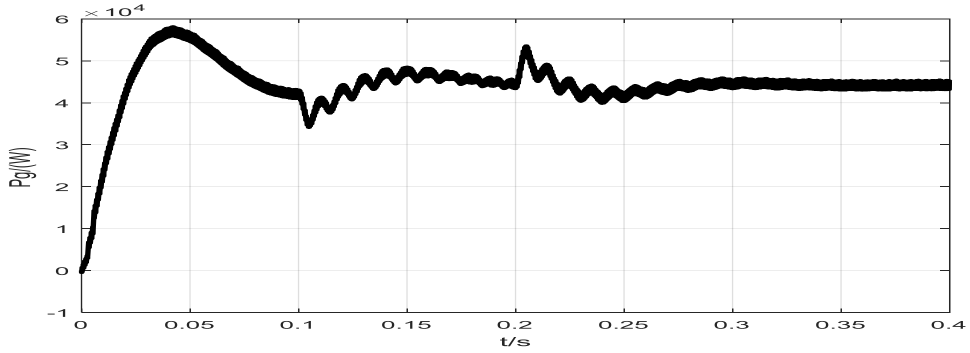

Fig.8 Power waveform under PR control strategy

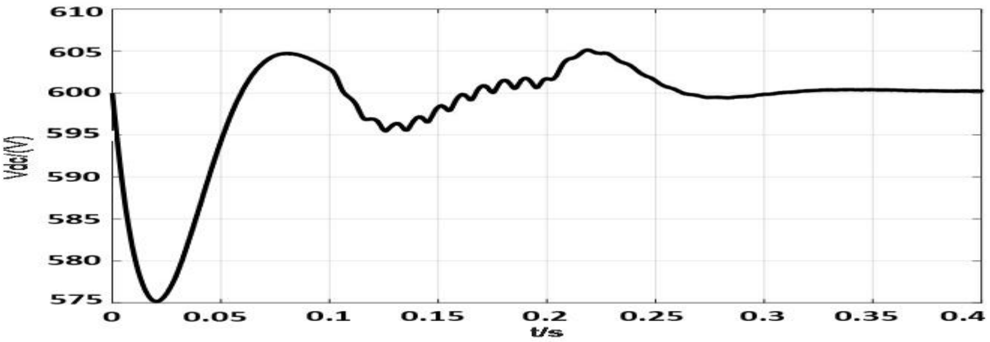

Fig.9 DC bus voltage waveform under PR control

5. Conclusion.

The purpose of power resonance compensation control is to reduce the double frequency fluctuation of power and DC voltage. The double frequency fluctuation of active power and DC bus voltage is more effectively suppressed than the traditional grid-based voltage vector control strategy. The corresponding control effect is good, consistent with the control objectives and achieves the initial corresponding purpose. It is also proved that compared with the traditional grid-side converter based on grid voltage vector control strategy, the new power resonance compensation control strategy is more effective in practical applications, and the problem of reducing its double frequency can be reduced. Damage to system components and negative effects on the grid.

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