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Power and Current limiting Control of wind turbines based on PMSG under Unbalanced Grid Voltage

[1] .Matre Sadhana Ganpat , [2]Prof. K. Chandra Obula Reddy , [3] Prof. Uddhav G.Takle,
[1]Mtech Electrical Power System, [2]Assistant Professor,HOD [3] Prof, Department of Electrical Engineering
[1]M.S.S College of Engineering, Jalna, India

ABSTRACT:

Unbalanced grid voltage sags are the severe challenge for wind power generation system which connected to the grid successfully. The dc bus voltage and output power will fluctuate under unbalanced grid voltage. Moreover, the voltage sags will lead to the increase of peak current, which will bring potential safety hazards to the operation of wind power system. This paper proposes a simple current limiting control scheme without auxiliary equipment, which based on the detailed analysis of the excessive peak current. In this scheme, the machine side converter (MSC) controller adjusts the electromagnetic power according to the power transmitted to the grid by the grid side converter (GSC). Meanwhile, it converts the unbalanced power on the dc-link into the rotor kinetic energy, avoiding the dc-link overvoltage. The GSC controller can not only ensure that the three-phase inverter currents are in the maximum safe range that the converters can bear, but also provide reactive power support for the grid. Furthermore, the fluctuations on dc bus voltage and output power can be eliminated effectively by using the GSC controller. The feasibility of the proposed scheme and the superiority over the traditional control schemes have been verified by simulations under different types of unbalanced voltage.

INDEX TERMS: Unbalanced grid voltage, peak current, current limiting control, rotor kinetic energy,reactive power support.

magnet synchronous generator.

I. INTRODUCTION:

II. With the increasingly serious environmental problems and energy crisis, many countries around the world have launched strategic deployment in the field of new energy. As a kind of renewable energy which is rich and clean, wind energy has attractedworldwide attention [1][3].Wind power generation system develops rapidly, the power generation occupies the first place in the new energy generation, and the proportion in the power grid is rising. In the different types of wind turbine systems, permanent magnet synchronous generator (PMSG) has gradually become more attractive because of the effectiveness, reliability and wider speed range [4], [5]. According to the structure of wind power system based on PMSG, PMSG is directly connected to power grid through back-to-back (BTB) converters, and the stable operation of converters is vulnerable to unbalanced grid voltage sags.

III. There are many reasons for unbalanced grid voltage, such as complete grounding, incomplete grounding, intermittent grounding, arc grounding, circurt breakage, etc. [6], [7]. Unbalanced grid voltage will lead to negative sequence components in the system. In general, the actual factors such asweak grids may cause output power fluctuations [8]. However, due to the existence of negative sequence components under unbalanced grid voltage, the interaction between positive and negative sequence voltage and current is the main reason for the second-order harmonic fluctuations on dc bus voltage and output power [9], [10]. In addition, the power flowing into the grid will be reduced due to the grid voltage sags. However, MSC is not sensitive to grid voltage sags and generates electric power continuously, resulting in the output power of MSC is not equal to the grid-connected power. This leads to some practical problems, such as dc-link overvoltage or overcurrent of three-phase inverter currents [11].

IV. Traditional control methods can not show good control performance under unbalanced grid faults [12], [13]. Vector control in double rotating coordinate frame is proposed in [14][16] during unbalanced conditions. In these control schemes, positive and negative sequence components of current are controlled independently, which is inevitable to separate the positive and negative sequence components. Meanwhile, these control scheme can suppress the fluctuations on output active power, but the reactive power fluctuations and excessive peak current are not suppressed effectively. A flexible active power control scheme based on a fast current controller and a reconfigurable reference currentselector has been proposed in [17]. The scheme includes ve different current control strategies which are instantaneous active-reactive power control, average active and reactive power control, instantaneously controlled positive-sequence, balanced positive sequence control, positive and negative sequence compensation control. These strategies can realize the elimination of power fluctuations or the balance of three-phase inverter currents, providing a theoretical basis for the follow-up researches. However, the proposed control scheme is not combined with PMSG to solve the practical problems such as overvoltage and overcurrent. Aiming at the problem of excessive peak current, a current limiting scheme is proposed in [18] where the peak current is guaranteed within a safe range by controlling the active power. Nevertheless, the positive and negative sequence separation of voltage and current are inevitable and the degree of voltage imbalance needs to be fully considered in the realization of the control method. Another control strategy is shown in [19], which determines the current reference value by looking up the table, so as to limit the excessive peak current. But this method needs to calculate the data table offiine, which is not easy to realize. A new method for calculating the reference expressions of active and reactive power is presented in [20], which limits the peak current under unbalanced voltage. However, this method will increase the dc bus voltage. In order to reduce the risk of dc-link overvoltage during the grid voltage sags, some schemes which need to use additional devices have been proposed [21][23]. These additional devices mainly contain the braking chopper (BC), crowbar circuit and energy storage equipments, which increase the control costs. An interesting control strategy is presented in [24][26], which can keep the dc-link voltage constant without need for any external equipment. However, MSC and GSC controllers need to exchange their control functions. The dc bus voltage is controlled by MSC controller and the maximum power point tracking (MPPT) is implemented by GSC controller. The control performance of this scheme is good under the symmetrical faults, but it is poor under the asymmetrical faults. Furthermore, it is noteworthy that the controller parameters need to be re-tuned, which makes it more difficult to implement the control scheme.

V. This paper proposes a modied power and current limiting control scheme for enhanced operation of wind power system during unbalanced grid voltage conditions. The proposed control ensures that the three-phase peak currents are in the safe range and the dc bus voltage is stable without any external devices. Meanwhile, reactive power support is provided for power grid according to the sag degree of grid voltage. In this structure, the MSC controller adjusts the electromagnetic power according to the power transmitted to the grid by the GSC, and converts the unbalanced power on the dc-link into the rotor kinetic energy. The fluctuation suppression of dc bus voltage and output power can be realized by the GSC controller. Furthermore, quasi-proportional complex integral (QPCI) controller is used to control the inverter current, the positive and negative sequence separation of currentand tedious double rotating coordinate transformation can be avoided, which simplifies the control structure. This paper is organized as follows: Section II introduces the model of wind power system. Section III describes the proposed control strategy. Section IV shows the control results of the traditional and proposed control under different voltage faults, which validate the effectiveness and superiority of the proposed control. Section V makes a conclusion about this paper.

WECS MODEL

The model of wind power system based on PMSG mainly consists of Five parts: wind turbine, PMSG, MSC, GSC and grid. It can be shown in FIGURE 1.

A. MODELING OF WIND TURBINE

The mechanical power of wind turbine can be obtained by capturing wind, which can be expressed as follows [18]:

$$P_{\mathrm{m}} = \frac{1}{2}\pi\rho R^2 C_{\mathrm{P}}(\beta, \lambda) v^3 \quad (1)$$

where ρ and R denote the air density and radius of blades,respectively, β denotes the pitch angle and λ representstip-speed ratio, v is the wind speed. CP is the wind energyutilization coefficient, which is determined by β and λ canbe expressed as follows:

where Wm represents the mechanical angular velocity.

$$\begin{cases} C_P = 0.58(116\lambda_{\mathrm{m}} - 0.4\beta - 5)\mathrm{e}^{-21\lambda_{\mathrm{m}}} \\ \lambda_{\mathrm{m}} = \dfrac{1}{\lambda + 0.008\beta} - \dfrac{0.0035}{\beta^3 + 1} \\ \lambda = R\omega_m / v \end{cases} \quad (2)$$

The mechanical torque acting on a wind turbine is asfollows:

$$T_{\mathrm{m}} = P_{\mathrm{m}}/\omega_m = \frac{1}{2}\pi\rho R^3 C_{\mathrm{P}}(\beta, \lambda) v^2/\lambda \quad (3)$$

B. MODELING OF PMSG

The voltage equation of PMSG in two-phase rotating d-qcoordinate system can be expressed as [10]:

$$\begin{cases} L_{sd}\dfrac{\mathrm{d}I_{sd}}{\mathrm{d}t} = -R_s I_{sd} + \omega_e L_{sq} I_{sq} + U_{sd} \\ L_{sq}\dfrac{\mathrm{d}I_{sq}}{\mathrm{d}t} = -R_s I_{sq} - \omega_e L_{sd} I_{sd} - \omega_e \psi + U_{sq} \end{cases} \quad (4)$$

where Usd , Usq, Isd and Isq are the d-q components of thestator voltage and current in the rotor flux orientated d-qframe respectively. Rs represents the stator resistance. Lsdand Lsq represent the stator d and q-axis inductances that areequal in the surface-mounted PMSG. and !e represent thepermanent magnet chain and electrical angular speed.The electromagnetic torque of PMSG is written as [10]:

$$T_e = 1.5 n_p \left[(L_{sd} - L_{sq}) I_{sd} I_{sq} + \psi I_{sq}\right]$$

The mechanical characteristics of the system which usingdynamic one-mass model can be expressed as [11]:

$$T_m = J\frac{d\omega_m}{dt} + B\omega_m + T_e \quad (6)$$

where J and B represent the moment of inertia of the transmission system and coefficient of self-damping, respectively.

C. MODELING OF GRID

Since there is no circulation path of zero sequence component in three-phase three-wire system, zero sequence component is not be considered. The three-phase unbalanced voltages can be decomposed into positive sequence and negative sequence voltage components by the delayed signal cancellation (DSC) method [27]. The unbalanced voltages can be written as

$$\begin{bmatrix} u_{ga} & u_{gb} & u_{gc} \end{bmatrix}^T = \begin{bmatrix} U^+ \sin(\omega t + \theta^+) + U^- \sin(\omega t \cdot \\ U^+ \sin(\omega t - 120^\circ + \theta^+) + U^- \sin(\omega t \cdot \\ U^+ \sin(\omega t + 120^\circ + \theta^+) + U^- \sin(\omega t - 120^\circ + \theta^-) \end{bmatrix}$$

where U^+ and θ^+ represent the voltage amplitude and initialphase of the positive sequence component, respectively. U^- and θ^- represent the voltage amplitude and initial phase of

the negative sequence component, respectively. ! representsthe angle frequency of grid voltage.

The three-phase voltages can be converted to stationarycoordinate system by Clark transformation, which can beexpressed as

$$\begin{bmatrix} u_{g\alpha} \\ u_{g\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_{ga} \\ u_{gb} \\ u_{gc} \end{bmatrix} = \begin{bmatrix} u_{g\alpha}^+ + u_{g\alpha}^- \\ u_{g\beta}^+ + u_{g\beta}^- \end{bmatrix}$$

$$\begin{bmatrix} u_{g\alpha}^+ \\ u_{g\beta}^+ \\ u_{g\alpha}^- \\ u_{g\beta}^- \end{bmatrix} = \begin{bmatrix} U^+ \sin(\omega t + \theta^+) \\ -U^+ \cos(\omega t + \theta^+) \\ U^- \sin(\omega t + \theta^-) \\ U^- \cos(\omega t + \theta^-) \end{bmatrix}$$

Where $u_{g\alpha}^+, u_{g\beta}^+$ and $u_{g\alpha}^-, u_{g\beta}^-$ represent the positive and negativesequence voltage components, respectively.Based on instantaneous power theory, the output active andreactive power are as follows

$$\begin{bmatrix} P_g \\ Q_g \end{bmatrix} = \frac{3}{2} \begin{bmatrix} u_{g\alpha} & u_{g\beta} \\ u_{g\beta} & -u_{g\alpha} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

From FIGURE 1, it can be seen that the power is transmitted

from generator side to grid side through dc-link. The

power on dc-link can be expressed as

$$CU_{dc} \frac{dU_{dc}}{dt} = P_e - P_g \tag{11}$$

III. PROPOSED CONTROL SCHEME

A. SUPPRESSION OF POWER FLUCTUATION

In (10), the voltage and current can be expressed in the form ofsuperposition of positive and negative sequence components,and (10) can be rewritten as

$$\begin{bmatrix} P_g \\ Q_g \end{bmatrix} = \frac{3}{2}\begin{bmatrix} u_{g\alpha}^{+} + u_{g\alpha}^{-} & u_{g\beta}^{+} + u_{g\beta}^{-} \\ u_{g\beta}^{+} + u_{g\beta}^{-} & -u_{g\alpha}^{+} - u_{g\alpha}^{-} \end{bmatrix}\begin{bmatrix} i_\alpha^{+} + i_\alpha^{-} \\ i_\beta + i_\beta^{-} \end{bmatrix} \quad (12)$$

By processing (12), it can be rewritten as the sum ofaverage components and fluctuating components

$$\begin{bmatrix} P_{g0} \\ \tilde{P}_g \\ Q_{g0} \\ \tilde{Q}_g \end{bmatrix} = \frac{3}{2}\begin{bmatrix} u_{g\alpha}^{+} i_\alpha^{+} + u_{g\beta}^{+} i_\beta^{+} + u_{g\alpha}^{-} i_\alpha^{-} + u_{g\beta}^{-} i_\beta^{-} \\ u_{g\alpha}^{+} i_\alpha^{-} + u_{g\alpha}^{-} i_\alpha^{+} + u_{g\beta}^{+} i_\beta^{-} + u_{g\beta}^{-} i_\beta^{+} \\ u_{g\beta}^{+} i_\alpha^{+} - u_{g\alpha}^{+} i_\beta^{+} + u_{g\beta}^{-} i_\alpha^{-} - u_{g\alpha}^{-} i_\beta^{-} \\ u_{g\beta}^{+} i_\alpha^{-} + u_{g\beta}^{-} i_\alpha^{+} - u_{g\alpha}^{+} i_\beta^{-} - u_{g\alpha}^{-} i_\beta^{+} \end{bmatrix} \quad (13)$$

where Pg0 and Qg0 represent the average components ofthe active power and reactive power, respectively; QPg andQQ g represent the fluctuating components of the active andreactive powers, respectively.

In order to eliminate the fluctuations on active and reactivepower, PQ g and QQ g are set to zero. Therefore, the active andreactive powers can be expressed as

$$\begin{cases} P_g = P_{g0}^{*} \\ Q_g = Q_{g0}^{*} \\ \tilde{P}_g = 0 \\ \tilde{Q}_g = 0 \end{cases} \quad (14)$$

Substituting (10) into (14), the reference current can becalculated as

$$\begin{cases} K = \frac{2}{3}\frac{\sqrt{P_{g0}^{*2} + Q_{g0}^{*2}}}{(U^{+})^2 + (U^{-})^2 - 2U^{+}U^{-}\cos(2\omega t + \theta^{+} + \theta^{-})} \\ \varphi = \arctan\frac{Q_{g0}^{*}}{P_{g0}^{*}} \\ \delta_a = \arctan\frac{U^{+}\sin(\omega t + \theta^{+} - \varphi) + U^{-}\sin(\omega t + \theta^{-} + \varphi)}{U^{+}\cos(\omega t + \theta^{+} - \varphi) + U^{-}\cos(\omega t + \theta^{-} + \varphi)} \\ \delta_b = \arctan\frac{U^{+}\sin(\omega t + \theta^{+} - \varphi - 120^\circ) + U^{-}\sin(\omega t + \theta^{-} + \varphi + 120^\circ)}{U^{+}\cos(\omega t + \theta^{+} - \varphi - 120^\circ) + U^{-}\cos(\omega t + \theta^{-} + \varphi + 120^\circ)} \\ \delta_c = \arctan\frac{U^{+}\sin(\omega t + \theta^{+} - \varphi + 120^\circ) + U^{-}\sin(\omega t + \theta^{-} + \varphi - 120^\circ)}{U^{+}\cos(\omega t + \theta^{+} - \varphi + 120^\circ) + U^{-}\cos(\omega t + \theta^{-} + \varphi - 120^\circ)} \end{cases}$$

According to (9), the denominator in (15) can be expres

$$\begin{aligned} u_{g\alpha}^2 + u_{g\beta}^2 &= \left(u_{g\alpha}^{+} + u_{g\alpha}^{-}\right)^2 + \left(u_{g\beta}^{+} + u_{g\beta}^{-}\right)^2 \\ &= U^{+2} + U^{-2} - 2U^{+}U^{-}\cos(2\omega t + \theta^{+} + \theta^{-}) \end{aligned} \quad (16)$$

Under unbalanced grid voltage, it is known that

$$\begin{bmatrix} i_\alpha^{*} \\ i_\beta^{*} \end{bmatrix} = \frac{2}{3}\frac{P_{g0}^{*}}{u_{g\alpha}^2 + u_{g\beta}^2}\begin{bmatrix} u_{g\alpha} \\ u_{g\beta} \end{bmatrix} + \frac{2}{3}\frac{Q_{g0}^{*}}{u_{g\alpha}^2 + u_{g\beta}^2}\begin{bmatrix} u_{g\beta} \\ -u_{g\alpha} \end{bmatrix} \quad (15)$$

$U^{-} \neq 0.$: The denominator term contains double frequency uctuation components, which will generate partial harmonic currents [30]. However, the uctuations on output power can be eliminated.

B. ANALYSIS AND LIMITATION OF PEAK CURRENT

The references of three-phase output currents can be obtainedby inverse Clarke transformation (17), as shown at the bottomof the page, where $K, \varphi, \delta_a, \delta_b, \delta_c,$, Therefore, the peak values of three-phase currents can becalculated as

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} \leq \frac{2}{3} \begin{bmatrix} \frac{\sqrt{P_{g0}^{*2} + Q_{g0}^{*2}}(U^+ + U^-)}{(U^+ - U^-)^2} \\ \frac{\sqrt{P_{g0}^{*2} + Q_{g0}^{*2}}(U^+ + U^-)}{(U^+ - U^-)^2} \\ \frac{\sqrt{P_{g0}^{*2} + Q_{g0}^{*2}}(U^+ + U^-)}{(U^+ - U^-)^2} \end{bmatrix} \quad (18)$$

The maximum peak current is written as

$$I_f^{max} = \frac{2}{3} \frac{\sqrt{P_{g0}^{*2} + Q_{g0}^{*2}}(U^+ + U^-)}{(U^+ - U^-)^2} \quad (19)$$

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = K \begin{bmatrix} \sqrt{(U^+)^2 + (U^-)^2 + 2U^+U^- \cos(\theta^+ - \theta^- - 2\varphi)} \sin(\omega t + \delta_a) \\ \sqrt{(U^+)^2 + (U^-)^2 + 2U^+U^- \cos(\theta^+ - \theta^- - 2\varphi + 120^\circ)} \sin(\omega t + \delta_b) \\ \sqrt{(U^+)^2 + (U^-)^2 + 2U^+U^- \cos(\theta^+ - \theta^- - 2\varphi - 120^\circ)} \sin(\omega t + \delta_c) \end{bmatrix} \quad (17)$$

If the grid is in normal condition, $U^- = 0$ can be obtained.The maximum peak current can be obtained as

$$I_n^{max} = \frac{2}{3} \frac{\sqrt{P_{g0}^{*2} + Q_{g0}^{*2}}}{U_n^+} \quad (20)$$

where, UCn represents the positive sequence voltage undernormal grid condition.The peak current under unbalanced grid voltage is obviouslyhigher than the normal grid by comparing (19) and (20),the relationship can be written as

$$I_f^{max} > I_n^{max} \quad (21)$$

Excessive peak current may exceed the maximum allowablerange of converters and even burn up switchgear in severecases. Therefore, the peak current control is of great significance. According to (19), the maximum peak current isdetermined by the positive and negative sequence voltage components, the output active and reactive power. From the moment when the unbalanced voltage occurs, the positive and negative sequence voltage components have been determined. Hence, the peak current can be guaranteed within the safe operation range of the converter by controlling the output active and reactive power.

Setting I max as the maximum current that the converter can withstand. In order to ensure that the output currents are within the safe range, the power control expression can be derived as

When the unbalanced voltage occurs, wind power system should not only ensure the operation without disconnection from the grid, but also provide reactive power support for the grid to facilitate the grid recovery. According to Chinese grid code, the reactive current that wind farms should inject into the grid can be defined as

$$I_q \geq 1.5 \times (0.9 - U_g) I_N (0.2 \leq U_g \leq 0.9)$$

where, Ug represents the per unit value of positive sequencecomponent of grid-connected voltage, IN is the rated current.Combining (22) and (23), it can be inferred that under thecondition of unbalanced grid voltage, the active and reactivepower transmitted from wind farms to power grid are asfollows

$$\begin{cases} P_{lim} = \sqrt{\dfrac{9I^{max2}(U^+ - U^-)^4}{4(U^+ + U^-)^2} - Q_{lim}^2} \\ Q_{lim} = I_q\sqrt{(U^+)^2 + (U^-)^2} \end{cases} \quad (24)$$

Therefore, in order to ensure that the output inverter currentsare always within the safe range, the output power canbe controlled flexibly as follows

$$\begin{cases} \left.\begin{matrix} P_{g0}^* = P_{lim} \\ Q_{g0}^* = Q_{lim} \end{matrix}\right\} (S = 0) \\ \left.\begin{matrix} P_{g0}^* = P_n \\ Q_{g0}^* = Q_n \end{matrix}\right\} (S = 1) \end{cases} \quad (25)$$

According to the different state of grid voltage, different control modes should be chosen to control the output power. If the three-phase grid voltages are balanced, the triggering signal S = 1 is set, the reference of the output active power is Pn, and the reactive power is Qn. If the three-phase grid voltages are unbalanced, the triggering signal S = 0 is set at this moment, and the reference values of output power are Plim and Qlim, which considering the maximum peak **current limitation.**

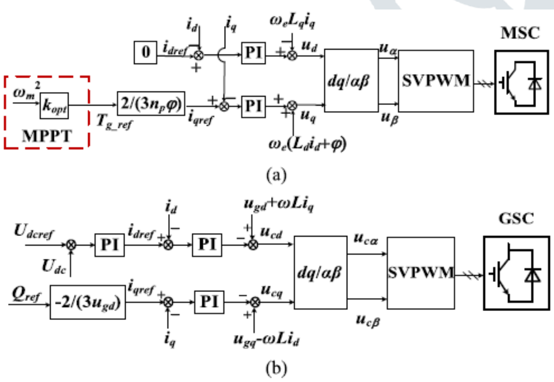
C. ROTOR ENERGY STORAGE PRINCIPLE

As can be seen from FIGURE 1, Pm is the mechanical power obtained by capturing wind energy, Pe is the electromagnetic power of PMSG, Pg is the power transmitted into the power grid through the GSC. When the system is stable without considering losses, it can be known that Pm D Pe D Pg, the generator speed and dc bus voltage are stable.

Compared with the normal grid, it can be seen from equation (10) that the sag and recovery of the grid voltage will cause the change of ugα and ugβ, and the maximum current limiting control of the converter will cause the change of i and i, which will lead to the change of output power Pg. However, due to the isolation effect of the BTB converters, wind turbines still work in MPPT state during unbalanced grid voltage. According to the MPPT curve of PMSG [4], the electromagnetic power Pe only depends on the rotor speed. Considering the large inertia of wind turbines, Pe does not change much in the process of grid disturbance, so the captured wind power basically does not change. It can be concluded that Pe$\neq$ Pg, which will lead to the unbalanced power on the dc- link. From (11), it can be obtained that the unbalanced power will increase the dc bus voltage, which affects the safe operation of wind turbines and the output power quality. If the output power of PMSG can be adjusted in time to ensure Pe=Pg when the power grid is disturbed, the dc-link overvoltage can also be effectively suppressed.

Therefore, a modified control scheme is presented in this section, which can solve the problem of unbalanced power on dc-link without external devices. When the grid voltage is unbalanced, the GSC adopts current limiting control (Pg=Plim) to ensure the three-phase currents are within the safe range. Meanwhile, the MSC adjusts the power Pe to ensure Pe=Pg=Plim, thereby ensuring the power balance on dc-link. As a result, the unbalanced power will be converted to the imbalance between mechanical power Pm and electromagnetic power Pe, which will cause the change of generator speed.Therefore, a modified control scheme is presented in this section, which can solve the problem of unbalanced power on dc-link without external devices. When the grid voltage is unbalanced, the GSC adopts current limiting control (Pg=Plim) to ensure the three-phase currents are within the safe range. Meanwhile, the MSC adjusts the power Pe to ensure Pe=Pg=Plim, thereby ensuring the power balance on dc-link. As a result, the unbalanced power will be converted to the imbalance between mechanical power Pm and electromagnetic power Pe, which will cause the change of generator speed.

FIGURE 2. Conventional control structure



(a) MSC (b) GSC.

From (6), the unbalanced power can be deduced as

$$\Delta P = P_m - P_e = P_m - P_g = J\omega_e \frac{d\omega_e}{n_p^2 dt}$$

(26)

From (26), it can be inferred as follows

$$\int_{t_0}^{t_0+T_k} (P_m - P_{lim})dt = \frac{J}{2n_p^2}(\omega_{e1}^2 - \omega_{e0}^2)$$

where, t0 is the time when the unbalanced voltage occurs, Tk is the duration of the unbalanced faults, !e0 and !e1 are the rotate speed of the pre- and post- fault, respectively. When the rated wind speed is reached, the rated output power of GSC is PN .

It is the most detrimental for the wind power system to achieve fault ride-through (FRT) under unbalanced voltage faults. When the voltage is reduced to 100% of the rated value, the power transmitted to the power grid will become zero, ie. Plim= 0. In this extreme case, (27) can be modified as

$$P_N T_k = \frac{J}{2n_p^2}(\omega_{e1}^2 - \omega_{e0}^2) \quad (28$$

The rotor speed during voltage sags can be deducedfrom (28) as follows

$$\omega_{e1} = \sqrt{\frac{2n_p^2 P_N T_k}{J} + \omega_{e0}^2} \quad (29)$$

Inertial time constant H is defined as

$$H = \frac{J\omega_{eN}^2}{2n_p^2 P_N} \quad (30)$$

where, ω_{eN} represents the rated rotor speed.By substituting (30) into (29), it can be modified as

$$\frac{\omega_{e1}}{\omega_{eN}} = \sqrt{\frac{T_k}{H} + \left(\frac{\omega_{e0}}{\omega_{eN}}\right)^2} \leq \sqrt{\frac{T_k}{H} + 1} \tag{31}$$

The inertia time constant of wind turbine is 3~6s, andthat of generator rotor is 0.4~0.8s [28]. From (31), it canbe drawn that the limit range of generator rotor speed accelerationis 4%~8% during the FRT process by using rotorenergy storage method. Generally, the wind turbines have10% over-speed capability, so this scheme will not causeover-speed protection.

D. THE STRUCTURE OF THE PROPOSED

FIGURE 2 illustrates the traditional control structure of wind power system. MPPT control is implemented by MSC, GSC adopts double-loop structure to control the dc bus voltage and output current. The control scheme has good control performance under balanced grid voltage, but the effect is not satisfactory under unbalanced grid voltage faults. Furthermore, the fluctuations on dc bus voltage/output power and the excessive peak current will occur with the unbalanced sags of voltage.

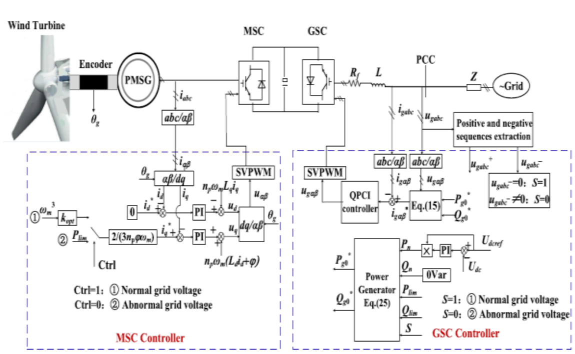


FIGURE 3. Proposed control structure.

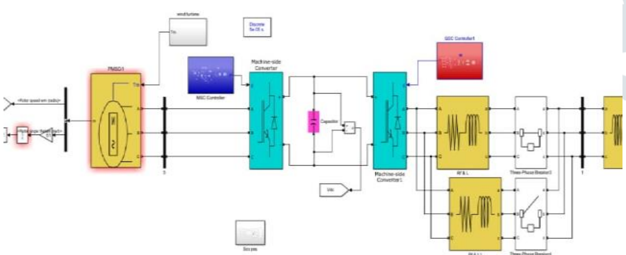
FIGURE 3 illustrates the block diagram of the proposed control strategy. Under normal grid voltage condition, both the MSC and GSC controllers adopt traditional control methods. For the MSC controller, the reference current of d-axis is set to zero in order to avoid demagnetization of permanent magnet and simplify the control structure. The reference current of q-axis can be obtained by optimal torque control (OTC) to achieve MPPT control. For the GSC controller, the outer loop realizes dc bus voltage control and the inner loop realizes current control. Meanwhile, the unit power factor control is realized by setting the reactive power Qn=0. During unbalanced grid voltage conditions, the MSC and GSC controllers need to change their corresponding control modes. For the MSC controller, the power reference of generator side is adjusted according to the power transmitted to the grid, so as to eliminate the unbalanced power on the dc-link, instead of MPPT control. The unbalanced power in the system will be transferred between the mechanical power and electromagnetic power, and stored in the form of rotor kinetic energy. Meanwhile, GSC controller should adopt themaximum current limiting control to solve the over-current problem which is caused by the unbalanced grid voltage. The reference of active power should be switched from Pn to Plim. Moreover, the GSC controller no longer realizes the unit power factor control, the reference of reactive power is converted from Qn to Qlim in order to provide the friendly support for the power grid based on the drop degree of power grid.

In order to avoid the positive and negative sequence separation of current and tedious double rotating coordinate transformation in the control of GSC, the QPCI controller which can effectively control the ac signal is introduced to control the inverter current. The transfer function of QPCI controller can be expressed as

$$G(s) = K_p + \frac{K_i \omega_c}{s - j\omega_0 + \omega_c} \qquad (32)$$

where Kp and Ki represent proportional coefficient and integralcoefficient, respectively. !0 is fundamental angular frequency,!c is frequency bandwidth. The controller has beenproved to be able to eliminate the steady-state error in thestationary frame and effectively avoid the influence of gridfrequency deviation, thereby improving the robustness of thesystem [29].

Many simulation analysis and results using the MATLAB/Simulink to evaluate the control performance of thesystem are presented in this section.



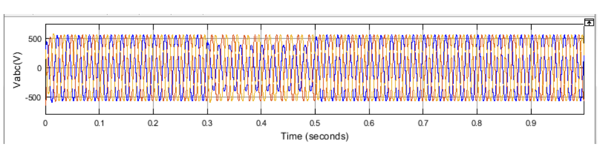
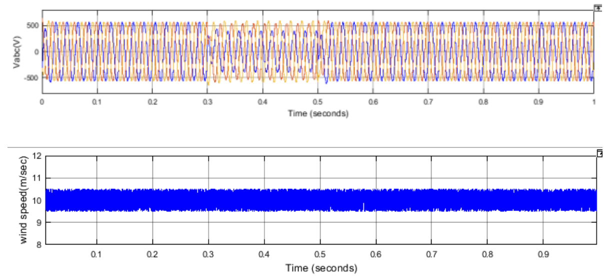
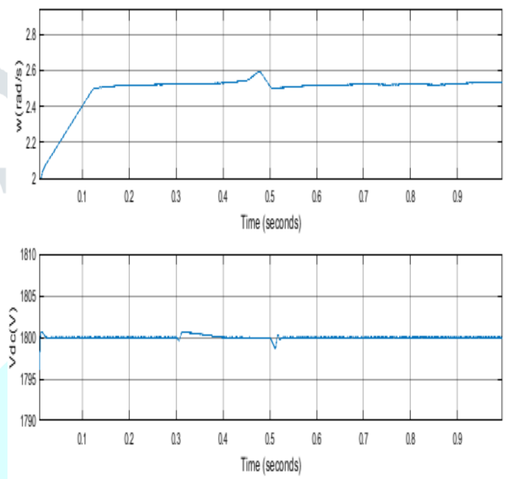


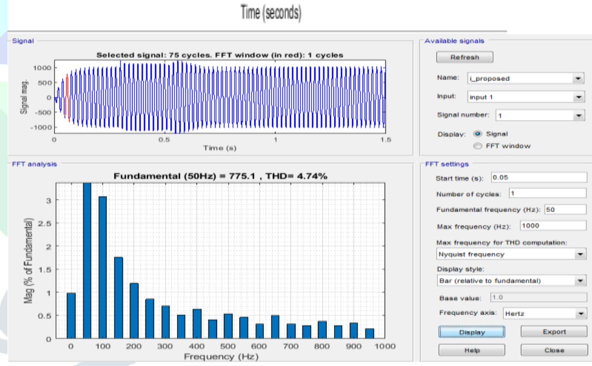
FIGURE. (a)The three-phase unbalanced voltages with case 1,



(b) the three-phase unbalanced voltages with 3956 86_, 5406 □28_, 5886 □148_ under case 2,

(c) wind speed.





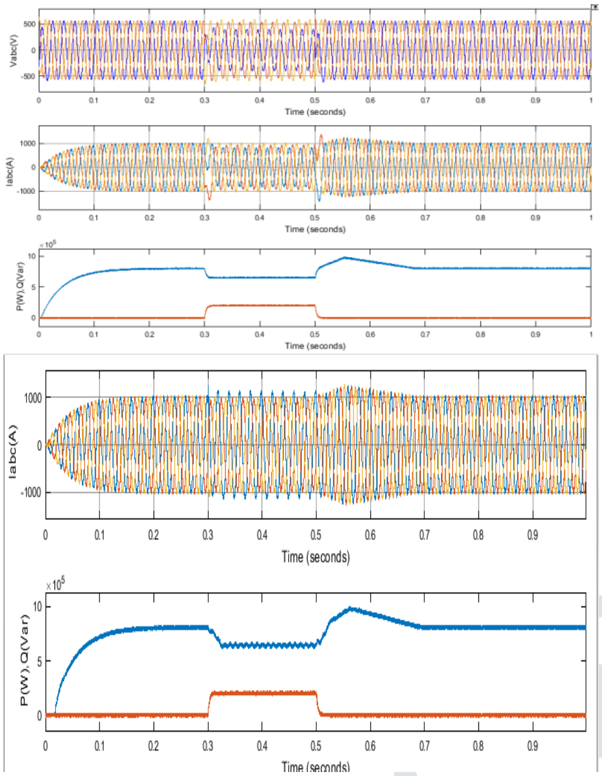


FIGURE :Control performance of different control schemes under case 1 (c) proposed control strategy.

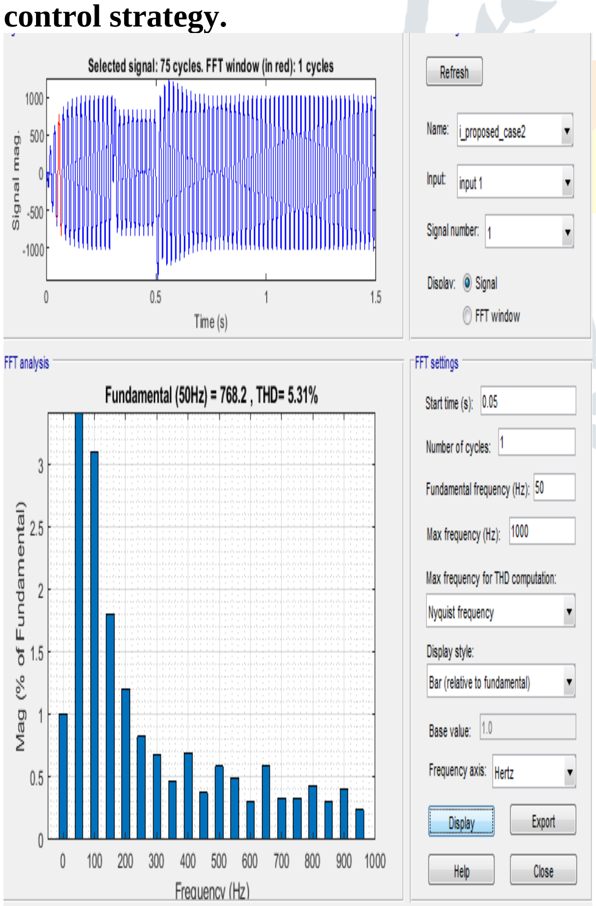


FIGURE 6. Control performance of different control schemes under case 2 (c) proposed control strategy.

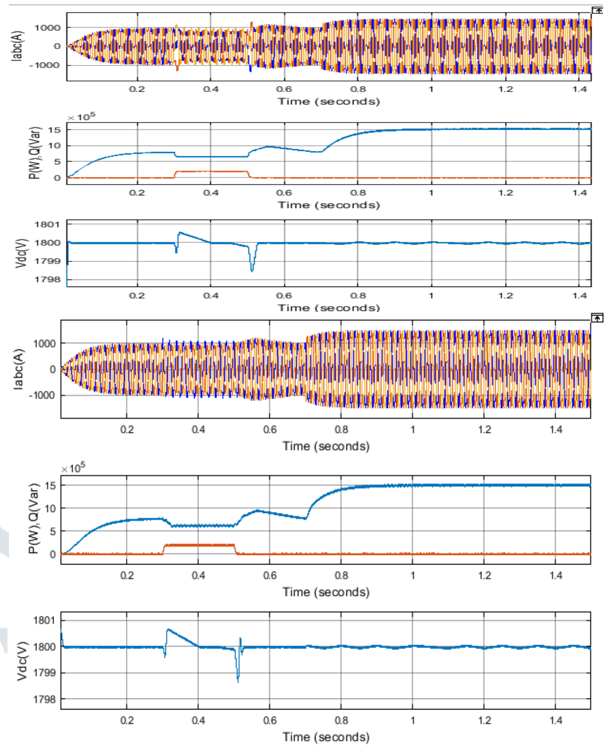
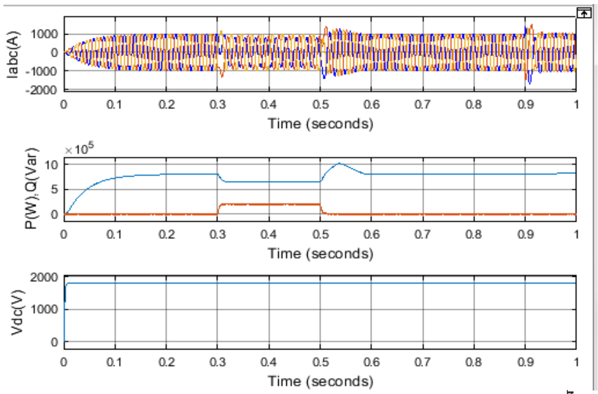
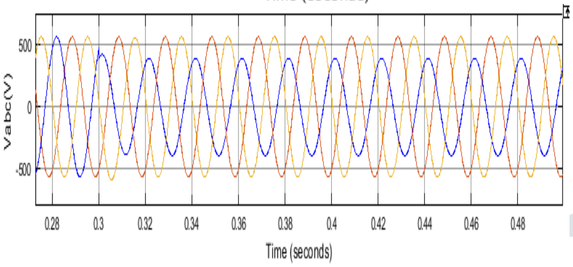


FIGURE 7. Control effect of the proposed control strategy with wind speed step change under two different grid faults (a) Case 1, (b) case 2.





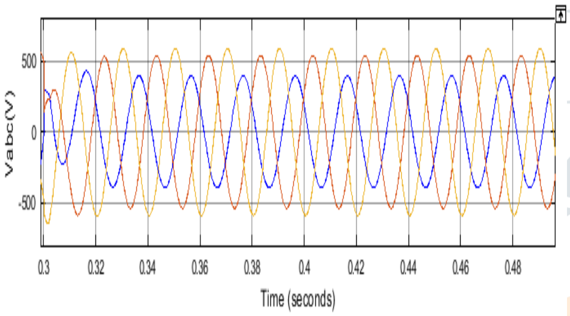
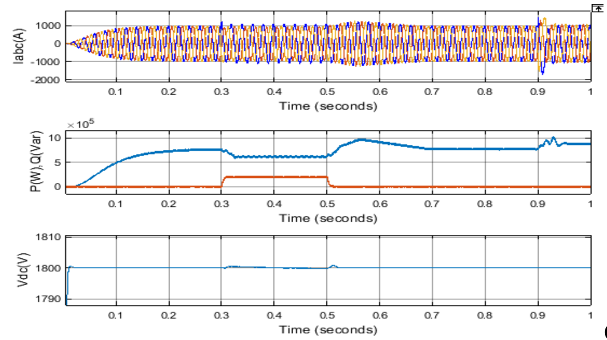


FIGURE 8. Three-phase grid voltages (a) Case 1, (b) case 2.

FIGURE 9. Control results of the proposed scheme when inductance changes (a) Case 1, (b) case 2.

CONCLUSION

This paper presents a new power and current limiting control of wind turbine based on PMSG for enhanced operation performance under unbalanced grid voltage. The



contributions of this work mainly includes the following parts: 1) Based on the detailed analysis of the output current, a peak current limiting scheme is proposed to ensure the three-phase currents are within the safe range; 2) The unbalanced power in the system is converted into rotor kinetic energy, which solves the problem of dc bus overvoltage; 3) The fluctuations on dc bus voltage and output power are eliminated effectively. The advantages of the proposed scheme for this work are as follows: 1) No additional auxiliary equipment is needed, avoiding high costs; 2) There is no need to exchange the control functions of MSC controller and GSC controller, which avoids the problem of resetting the control parameters; 3) The control of three-phase inverter currents is realized in coordinate system, without the separation of positive and negative sequence of current and complex rotating coordinate transformation, the structure is simple. The effectiveness and superiority of the proposed control strategy have been verified by comparing the simulation results with the other two control strategies under the two different grid faults.

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