Analysis on using a fuzzy logic controller to improve the power and current limiting abilities of wind turbines powered by PMSG in a microgrid

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ABSTRACT
In this study, we suggest a microgrid-fed wind power generating system using fuzzy logic controllers. The main problem for wind power production systems that successfully connects to the grid is imbalanced grid voltage sags. Under an uneven grid voltage, the output power and dc bus voltage will vary. Additionally, voltage sags will cause a rise in peak current, which might pose a threat to the functioning of the wind power system. Based on a thorough investigation of the high peak current, this research suggests a straightforward FLC current limiting control system without the need of any additional hardware. In this system, the grid side converter (GSC) transmits power to the machine side converter (MSC) controller, which modifies the electromagnetic power (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.

KEYWORDS: MSC, GSC, FLC, DC-LINK VOLTAGE.

INTRODUCTION
Many nations throughout the world have started strategic deployment in the new energy sector in response to the world's worsening environmental issues and energy dilemma. Wind energy has garnered interest on a global scale as a type of clean, renewable energy [1][3]. The wind power generating system is evolving quickly, taking the lead in terms of new energy production, and its share of the power grid is growing. Because of their efficiency, dependability, and larger speed range, permanent magnet synchronous generators (PMSGs) have rapidly gained in popularity among the many types of wind turbine systems [4], [5]. The back-to-back (BTB) converters that link PMSG directly to the power grid in accordance with the design of the wind power system based on PMSG ensure reliable operation of converters is vulnerable to unbalanced grid voltage sags. There are many reasons for unbalanced grid voltage, such as complete grounding, incomplete grounding, intermittent grounding, arc grounding, circuit breakage, etc. [6], [7]. Unbalanced grid voltage will lead to negative sequence components in the system. In general, the actual factors such as weak 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 owing 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 over current of three-phase inverter currents [11].

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, this 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 recognizable reference current selector has been proposed [17]. The scheme includes five 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 peakcurrent, 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 sequenceseparation 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 offline, 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.

PROPOSED SYSTEM
This paper proposes a modified power and current limiting control scheme for enhanced operation of wind powersystem during unbalanced grid voltage conditions. The proposed control scheme 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 therotor kinetic energy. The fluctuation suppression of dc bus voltage and output power can be realized by the GSC controller. Furthermore, quasi-proportionalcomplex integral (QPCI) controller is used to control the inverter current, the positive and negative sequence separation of current and tedious double rotating coordinate transformation can be avoided, which simplifies the control structure.

Fig.1. Simplified system structure

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]:

\[ P_m = \frac{1}{2} \pi \rho R^2 C_p(\beta, \lambda) v^3 \]  (1)

where and R denote the air density and radius of blades, respectively, denotes the pitch angle and \( \lambda \) represents tip-speed ratio, \( v \) is the wind speed. \( CP \) is the wind energy utilization coefficient, which is determined by and , can be expressed as follows
where \( \omega_m \) represents the mechanical angular velocity. The mechanical torque acting on a wind turbine is as follows:

\[
T_m = \frac{P_m}{\omega_m} = \frac{1}{2} \pi \rho R^3 C_p(\beta, \lambda) \omega^2 / \lambda
\]

### B. MODELING OF PMSG

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

\[
\begin{align*}
L_{sd} \frac{dI_{sd}}{dt} &= -R_s I_{sd} + \omega_L I_{sq} + U_{sd} \\
L_{sq} \frac{dI_{sq}}{dt} &= -R_s I_{sq} - \omega_L I_{sd} + U_{sq}
\end{align*}
\]

where \( U_{sd} \), \( U_{sq} \), \( I_{sd} \) and \( I_{sq} \) are the d-q components of the stator voltage and current in the rotor flux orientated d-q frame respectively. \( R_s \) represent the stator resistance. \( L_{sd} \) and \( L_{sq} \) represent the stator d and q-axis inductances that are equal in the surface-mounted PMSG. And represent the permanent magnet chain and electrical angular speed. The electromagnetic torque of PMSG is written as [10]:

### 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

\[
\begin{bmatrix}
U_a \\
U_b \\
U_c
\end{bmatrix} = \left[ \begin{array}{ccc}
U^+ \sin(\omega t + \theta^+) + U^- \sin(\omega t + \theta^-) \\
U^+ \sin(\omega t - 120^\circ + \theta^+) + U^- \sin(\omega t + 120^\circ + \theta^-) \\
U^+ \sin(\omega t + 120^\circ + \theta^+) + U^- \sin(\omega t - 120^\circ + \theta^-)
\end{array} \right]
\]

where \( U_a \) and \( U_c \) represent the voltage amplitude and initial phase of the positive sequence component, respectively. \( U_r \) and \( U_e \) represent the voltage amplitude and initial phase of the negative sequence component, respectively. \( \omega \) represents the angle frequency of grid voltage. The three-phase voltages can be converted to stationary coordinate system by Clark transformation, which can be expressed as

\[
\begin{bmatrix}
u_{ga} \\
u_{gb} \\
u_{gc}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -1/2 & -1/2 \\
-\sqrt{3}/2 & 0 & -\sqrt{3}/2 \\
\sqrt{3}/2 & -\sqrt{3}/2 & 0
\end{bmatrix} \begin{bmatrix}
u_{sa} \\
u_{sb} \\
u_{sc}
\end{bmatrix}
\]

where

\[
\begin{bmatrix}
u_{ga} \\
u_{gb} \\
u_{gc}
\end{bmatrix} = \begin{bmatrix}
u_{g+} + \nu_{g-} \\
u_{s+} + \nu_{s-} \\
u_{c+} + \nu_{c-}
\end{bmatrix}
\]

\[
\begin{bmatrix}
u_{g+} \\
u_{s+} \\
u_{c+}
\end{bmatrix} = \begin{bmatrix}
U^+ \sin(\omega t + \theta^+) \\
-U^+ \cos(\omega t + \theta^+) \\
U^- \sin(\omega t + \theta^-) \\
-U^- \cos(\omega t + \theta^-)
\end{bmatrix}
\]
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 $Q_{D0}$. 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 the maximum 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 $P_n$ to $P_{lim}$. Moreover, the GSC controller no longer realizes the unit power factor control, the reference of reactive power is converted from $Q_n$ to $Q_{lim}$ 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

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

where $K_p$ and $K_i$ represent proportional coefficient and integral coefficient, respectively, $\omega_c$ is fundamental angular frequency and $\omega_0$ is frequency bandwidth. The controller has been proved to be able to eliminate the steady-state error in the stationary frame and effectively avoid the incense of grid frequency deviation, thereby improving the robustness of the system.

**SIMULATION RESULTS**

![Simulation Results Image](image-url)
3.1 PROPOSED SIMULINK DIAGRAM

FIGURE 5 illustrates the control results using control schemes I, II and proposed scheme under case 1. The influence of voltage sag is not fully taken into account in the design of control scheme I. Therefore, the output power and dc bus voltage fluctuate significantly. In addition, the peak current is significantly higher than the normal value.
Fig 6 Conventional Control Case 2
Fig 6 proposed Control C
The control results of different control strategies under case 2 are presented in FIGURE 6. FIGURE 6(a) illustrates the control results using control scheme I, the fluctuations on output power are quite large and the peak value of output current obviously exceeds the normal value during the grid voltage sag.

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

CONCLUSION
This research provides a novel fuzzy logic controller-based power and current limiting control of a PMSG-based wind turbine for improved operating performance under imbalanced grid voltage. The following are the primary contributions of this work:
1) A peak current limiting scheme is proposed based on a detailed analysis of the output current 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; and 3) The fluctuations in dc bus voltage and output power are effectively eliminated. The following are the benefits of the suggested system for this work: 1) 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.

REFERENCES

