The control strategy of wind energy conversion system based on H-MMC under asymmetrical grid faults

Rong, Fei; Yan, Jiajun; Sun, Wenlong; Huang, Sheng; Wu, Qiuwei

Published in:
I E T Power Electronics

Link to article, DOI:
10.1049/iet-pel.2019.0108

Publication date:
2019

Document Version
Peer reviewed version

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
The control strategy of wind energy conversion system based on H-MMC under asymmetrical grid faults

Fei Rong 1,*, Jiajun Yan 1, Wenlong Sun 1, Sheng Huang 2, Qiuwei Wu 2

1 Department of Electrical and Information Engineering, Hunan University, Changsha 410082, China
2 Center for Electric Power and Energy, Department of Electrical Engineering, Technical University of Denmark, Elektrovej 325, Kgs. Lyngby, DK 2800, Denmark

*rf_hunu@126.com

Abstract: This paper proposes a topology of wind energy conversion system (WECS) based on hexagonal modular multilevel converter (H-MMC), which can connect the wind turbine and the AC grid with one stage conversion. It has the advantages of low power losses, low ripple of capacitor voltage and transformer-less grid connection. The operation principle of the proposed topology is analyzed in detail. Then, the positive and negative sequence control method is proposed to eliminate the 2nd harmonics in the output power of H-MMC under asymmetrical grid faults. The double proportional resonant (PR) controller is proposed to track arm current references without steady error. The effectiveness of the proposed topology and its control method are verified by simulations and HIL tests. Keywords: WECS, AC/AC, hexagonal modular multilevel converter, double PR controller, asymmetrical grid faults.

1 Introduction

As a clean and renewable energy source, wind energy has developed rapidly in recent years [1]. With the power rating of wind turbine growing year by year, its rated voltage gradually increases from 690V to a medium-voltage (MV) level, such as 3.3kV or 6.6kV [2, 3]. At present, the major problem in interfacing such wind turbine to the grid is the voltage level limitation of available power devices in the power converter.

The two level voltage source converter (VSC) with series-connected devices in each bridge arm is applied for MV WECS in reference [4], which is a simple solution for MV operation. However, it exposes some technical challenges, such as equal voltage sharing of each power device and strictly simultaneous gating requirement. A feasible option to avoid the above problems is the use of multilevel VSCs.

The three level neutral point clamped (3L-NPC) converter is applied for WECS in reference [5]. However, the output power of 3L-NPC is limited, due to unequal loss distribution among the semiconductor devices [6]. To overcome this problem, the three level active NPC (3L-ANPC) converter for WECS is proposed in reference [7]. While, both of them need a step-up transformer to connect the WECS to medium voltage grid. To achieve higher output voltage, the five-level ANPC converter is proposed for PMSG-based WECS in reference [8]. However, its voltage balance control of capacitors is very complex [9].

The multilevel converter with flying capacitor is applied for WECS in reference [10], which need a large number of capacitors and each of them requires a pre-charging circuit. Compared with the above multilevel converters, modular multilevel converter (MMC) has the advantages of modular design, good scalability, redundancy, low switching frequency and high efficiency [11, 12]. A back-to-back MMC (BTB-MMC) is proposed for WECS in reference [13]. However, due to the low frequency characteristic of stator currents of wind power generator, the fluctuation of submodule (SM) capacitor voltage is very serious, which restrict its widely application in wind power generation system. A modular multilevel cascade converter formed by three identical sub-converters is applied in a 10MW WECS based on a three-phase open winding PMSG [14], which carries out direct AC/AC power conversion. However, the generator suffers from additional power losses and current distortion, which is caused by the zero-sequence current owing to the open windings. The multilevel matrix converter (M3C) is proposed for MV PMSG-based WECS in reference [15], which is high efficiency for being only one stage conversion. While, it has numerous internal channels for loop current. As a result, its loop current analysis and control method are very complex [16].

However, these conventional MMCs use many SMs, switching devices and dc capacitors. Researchers have been trying to propose new modular multilevel topologies that require fewer components. Reference [17] proposes a cost-effective three-phase MMC with reduced number of arms. However, its output voltage is only 57.7% of the conventional three-phase MMC. A novel MMC-Based converter utilizing a middle arm to connect the conventional MMC’s upper and lower arms is introduced in reference [18], which can cut down the number of SM capacitors and high frequency switches significantly. However, this topology requires parallel low-frequency switching IGBTs on the dc side, and these IGBTs require multiple series when the converter is used in high voltage applications. Reference [19] proposes a novel reduced switch count multilevel AC/AC converter, which reduces the number of switches and related drive circuits by 25% compared with conventional cascaded H-bridge multilevel converter. However, bulky multi-winding transformer is required for each phase to split input voltage between the SMs, thereby incrementing the size and cost of converter.

In reference [20], the hexagonal modular multilevel AC/AC converter (H-MMC) is proposed, which enables the
connection between two three-phase AC systems with different frequency and amplitude by using only six bridge arms. Reference [21, 22] shows that H-MMC has smaller capacitor voltage fluctuation than BTB-MMC when they are used for low frequency drive. In reference [23], the bridge arm energy variances of H-MMC and BTB-MMC are studied, then the on-state losses and switching losses of their semiconductors devices are analysed in detail. The results show that H-MMC requires only half the number of SMs with smaller capacitors and has a higher expected efficiency compared with BTB-MMC. Reference [24] studies a battery energy storage system based on H-MMC and proposes a state-of-charge (SOC) balancing control method of the battery units by controlling currents in SMs. Reference [25] presents a method to control the arm energies of H-MMC at low to zero frequency operation, and H-MMC is considered to be an alternative to high-power and high-voltage adjustable speed drive converter systems operating at low electrical speed.

This paper applies H-MMC to MV PMSG-based WECS, which can connect the wind turbine and the AC grid with one stage conversion, and has the advantages of low power losses, low ripple of capacitor voltage and transformer-less grid connection. The operation principle of the proposed topology is analyzed. And the average power of each arm under asymmetrical grid faults is deduced. Then, the Maximum power point tracking (MPPT) control, the grid side current control under asymmetrical grid faults, the voltage stability control and the current tracking control based on PR are designed in detail, which improves the fault tolerant capability against asymmetrical grid faults in wind power transmission of this system. The work of this paper lays a foundation for the practical engineering application of the WECS based on H-MMC.

Fault tolerant capability against asymmetrical grid faults in wind power transmission is becoming more and more important. Reference [26] proposes a dual proportional integral (PI) current control strategy in the synchronous frame, which can achieve the desired control objectives of WECS under asymmetrical grid faults. However, a separation algorithm for the positive and negative sequence components of the grid voltages and currents is needed and dual PI current control strategy has four inner control loops, which is complex and difficult to adjust their parameters. The proportional integral resonance (PIR) controller in the positive synchronous frame is applied for WECS in reference [27], which can directly regulate the currents without decomposing sequential components. Reference [28] proposes a model predictive current control method to meet low-voltage ride through requirement under unbalanced grid voltage conditions. In this paper, the positive and negative sequence control method is proposed to eliminate the 2nd harmonics in the output power of H-MMC under asymmetrical grid faults and the double proportional resonant (PR) controller is used to track arm current references without steady error, which can reduce the pulsations of active power under asymmetrical grid faults without extracting positive and negative sequence components from the grid currents.

This paper is organized as follows. Section 2 introduces the topology of the WECS based on H-MMC. The power transmission characteristics of the system under asymmetrical grid faults is analyzed in section 3. Control method of the system under asymmetrical grid faults is presented in section 4. Simulations and HIL tests are presented in section 5 and section 6, respectively. Finally, section 7 gives the conclusions.

2 Proposed topology

The proposed topology of the wind power generation system based on H-MMC is shown in Fig. 1. The H-MMC consists of six bridge arms forming a hexagonal ring. Each arm consists of \( N \) cascaded full bridge submodules and one inductor. The phases of PMSG (marked as A, B, C) and power grid (marked as U, V, W) are connected alternately to the six vertices of the hexagon converter. With this connection mode, each phase of one AC system is connected to two phases of the other AC system by two bridge arms. Therefore, the voltage and the current of any bridge arms must contain two frequency components of both the PMSG and the AC grid. The power of this wind power generation system flows from the PMSG to the grid, and the topology structure H-MMC is symmetrical, thus the active power flows evenly from A to W and V, B to U and W, C to V and U.

In order to facilitate the circuit analysis of the system, the wind turbine can be equivalent to a three-phase ac voltage source, and the cascaded SMs in each bridge arm can be equivalent to a voltage source. The filter capacitor \( C_f \) and inductor \( L_f \) are neglected. Thus, the simplified circuit of the proposed system can be obtained, as shown in Fig. 2.

The three phase voltages and currents of the PMSG are define as \( v_{a1}, v_{a2}, v_{a3}, i_{a1}, i_{a2}, i_{a3} \), respectively. The three
phase voltages and currents of the grid are defined as $v_{g1}$, $v_{g2}$, $v_{g3}$, $i_{k1}$, $i_{k2}$, $i_{k3}$, respectively. The total voltage of the cascaded SMs in bridge arm $x$, the output voltage and current of the bridge arm $x$ are represented by $v_x$, $i_x$, respectively, where $x = 1, 2, 3, 4, 5, 6$, indicates the $x^{th}$ bridge arm. The neutral points of the three phase system of the PMSG and grid are $S$ and $T$, respectively. Defining the neutral point $T$ as zero potential reference point, the neutral point $S$ has a voltage of $V_{s0}$. The loop current of H-MMC is defined as $i_{loop}$. According to Kirchhoff’s voltage law, the voltage state equations of the wind power generation system can be described as,

$$
\begin{align*}
    \frac{dv_1}{dt} &= -L_{d1}i_{d1} + v_{st} \\
    \frac{dv_2}{dt} &= -L_{d2}i_{d2} + v_{st} \\
    \frac{dv_3}{dt} &= -L_{d3}i_{d3} + v_{st} \tag{1}
\end{align*}
$$

As shown in Fig. 2, the simplified circuit of the proposed topology can be divided into seven meshes and the mesh currents are $i_{mv}$, $i_{mv}$, $i_{mv}$, $i_{mC}$, $i_{mB}$, $i_{mb}$ and $i_{io}$ respectively. Then, according to the relationships between the mesh currents, the grid phase currents and the PMSG phase currents, the current phasor diagrams of Fig. 3 can be obtained.

![Fig. 3 The current phasor diagrams of the circuit](image)

(a) The current phasor diagram of the grid. (b) The current phasor diagram of the PMSG

Taking the bridge arm $1$ as an example, as seen in Fig. 2. there are three mesh currents flowing through it, namely $i_{mv}$, $i_{mb}$, and $i_{io}$. From the current phasor diagrams of Fig. 3. it can be concluded that $i_{mv}$ is equal to $1/3 (i_{m2} - i_{m3})$ and $i_{mb}$ is equal to $1/3 (i_{m1} - i_{m2})$. Then $i_1$ can be obtained by the superposition principle. Similarly, the currents of other bridge arms can be deduced, so the current state equations of the wind power generation system can be described as,

$$
\begin{align*}
    i_1 &= \frac{1}{3} (i_{m1} - i_{m2} + i_{m3}) + i_{i1} \\
    i_2 &= \frac{1}{3} (i_{m2} - i_{m3} + i_{m1}) + i_{i2} \\
    i_3 &= \frac{1}{3} (i_{m3} - i_{m1} + i_{m2}) + i_{i3} \\
    i_4 &= \frac{1}{3} (i_{m2} - i_{m3} + i_{m1}) + i_{i4} \\
    i_5 &= \frac{1}{3} (i_{m3} - i_{m1} + i_{m2}) + i_{i5} \\
    i_6 &= \frac{1}{3} (i_{m1} - i_{m2} + i_{m3}) + i_{i6} \tag{2}
\end{align*}
$$

### 3 Working principle under asymmetrical grid faults

Asymmetrical grid faults can cause grid voltage drop and three-phase voltage imbalance, including single-phase ground shorts, two-phase ground shorts, etc. The calculations in this section divide the unbalanced network into three-phase balanced positive and negative sequence networks, and the working principle applies to all types of asymmetric faults, which can ensure the grid-connected operation of the wind turbine of this system under asymmetrical faults.

The absorbed active power $P_g$ and reactive power $Q_g$ of the power grid can be expressed by (3) with dq-coordinate frame under asymmetrical grid faults [29].

$$
\begin{align*}
    P_g &= P_0 + P_{es} \cos(2\omega_2t) + P_{es} \sin(2\omega_2t) \\
    Q_g &= Q_0 + Q_{es} \cos(2\omega_2t) + Q_{es} \sin(2\omega_2t) \tag{3}
\end{align*}
$$

where,

$$
\begin{align*}
    P_0 &= \begin{pmatrix}
        u_{p0}^p & u_{q0}^p & u_{p0}^u & u_{q0}^u & u_{p0}^N & u_{q0}^N \\
        u_{p0}^u & u_{q0}^u & u_{p0}^p & u_{q0}^p & u_{p0}^N & u_{q0}^N \\
        u_{p0}^N & u_{q0}^N & u_{p0}^u & u_{q0}^u & u_{p0}^p & u_{q0}^p \\
        u_{q0}^p & u_{p0}^p & u_{q0}^N & u_{p0}^N & u_{q0}^u & u_{p0}^u \\
        u_{q0}^u & u_{p0}^u & u_{q0}^N & u_{p0}^N & u_{q0}^p & u_{p0}^p \\
        u_{q0}^N & u_{p0}^N & u_{q0}^u & u_{p0}^u & u_{q0}^p & u_{p0}^p 
\end{pmatrix} \begin{pmatrix}
        i_{p0}^p \\
        i_{q0}^p \\
        i_{p0}^u \\
        i_{q0}^u \\
        i_{p0}^N \\
        i_{q0}^N
\end{pmatrix} \tag{4}
\end{align*}
$$

where, $\omega_2$ is the frequency of the grid, $u_{p0}^p$, $u_{q0}^p$, $u_{p0}^u$, $u_{q0}^u$, $u_{p0}^N$, $u_{q0}^N$, $i_{p0}^p$, $i_{q0}^p$, $i_{p0}^u$, $i_{q0}^u$, $i_{p0}^N$, $i_{q0}^N$ are the grid voltages and currents in dq-coordinate frame, respectively. Note that, the superscript P, N are used to distinguish positive and negative sequence components, respectively.

It can be seen from Eq. (3) and Eq. (4) that the output power contains $2^{rd}$ harmonic component, which will deteriorate the fluctuation of the SM capacitor voltage.

Define the voltages and currents of the PMSG as,

$$
\begin{align*}
    V_{mk} &= \sqrt{2}V_1 \sin \left( \omega_1t - \frac{2(k-1)\pi}{3} \right) \\
    I_{mk} &= \sqrt{2}I_1 \sin \left( \omega_1t - \frac{2(k-1)\pi}{3} - \phi_1 \right) \tag{5}
\end{align*}
$$

where, $k=1, 2, 3, \omega_1, \phi_1$ are the frequency and power factor angle of the PMSG respectively. $V_1, I_1$ are the RMS values of the voltages and currents of the PMSG, respectively.

Define the voltages and currents of the grid under asymmetrical grid faults as follows,
\[
\begin{align*}
    v_{ek}^d &= v_{ek}^d + v_{ek}^N = \sqrt{2}V_s^d \sin\left(\omega_s t - \frac{2(k-1)\pi}{3} + \theta^d\right) \\
    v_{ek}^q &= v_{ek}^q = \sqrt{2}V_s^q \cos\left(\omega_s t + \frac{2(k-1)\pi}{3} + \theta^q\right) \\
    i_{ek}^d &= i_{ek}^d + i_{ek}^N = \sqrt{2}I_s^d \sin\left(\omega_s t - \frac{2(k-1)\pi}{3} + \varphi^d\right) \\
    i_{ek}^q &= i_{ek}^q = \sqrt{2}I_s^q \cos\left(\omega_s t + \frac{2(k-1)\pi}{3} + \varphi^q\right)
\end{align*}
\]

where, \(\omega_s\) is the frequency of the grid; \(V_s^d, V_s^q, I_s^d, I_s^q\) are the RMS values of the positive or negative sequence voltages and currents of the grid, respectively; \(\theta^d, \theta^q, \varphi^d, \varphi^q\) are the initial angles.

Defining the average power of each arm under asymmetrical grid faults is \(P_i\) (i=1-6). According to the positive direction of the voltage and current defined in Fig. 2, the average power of bridge arms can be calculated by (7).

\[
P_i = \frac{1}{T} \int_{t} v_i x dt
\]

Supposing \(v_{in}, i_{ew}\) are constant which are denoted as \(V_{in}\) and \(I_{ew}\) respectively. \(P_i\) can be obtained by substituting (1), (2), (5), and (6) into (7), as shown in (8), where \(\delta=\theta^d-\varphi^d, \delta_2=\theta^q-\varphi^q, \delta_3=\theta^q-\varphi^d\).

\[
P_i = -\frac{1}{2} \left[ V_l I_s \cos \delta + V_l^2 I_s^2 \cos \delta_1 + V_l^2 I_s^2 \cos \delta_2 \right] + \frac{\sqrt{3}}{6} V_l^3 I_s^3 \cos \left( \delta_3 + \frac{\pi}{6} \right) + \frac{\sqrt{3}}{3} V_l^2 I_s^2 \cos \delta_3
\]

According to the definition of (5), the active power \(P_m\) and reactive power \(Q_m\) of the PMSG can be expressed as,

\[
P_m = 3V_l I_s \cos \theta\]
\[
Q_m = 3V_l I_s \sin \theta
\]

According to (4) and (6), the constant portion of \(P_i\) and \(Q_i\) can be expressed by,

\[
P_0 = 3V_l^2 I_s^2 \cos \delta + 3V_l^2 I_s^2 \cos \delta_2
\]
\[
Q_0 = 3V_l^2 I_s^2 \sin \delta - 3V_l^2 I_s^2 \sin \delta_2
\]

The following relationship can be obtained by combining (8), (9), and (10).

\[
\begin{align*}
    \sum_{i=1}^{3} P_{2i-1} &= -\frac{1}{2} (P_m + P_0) - \frac{\sqrt{3}}{6} (Q_m - Q_0) - 3V_l I_s \cos \delta \cos \varphi^d - 3V_l I_s \cos \delta \cos \varphi^q + \frac{\sqrt{3}}{6} (Q_m - Q_0) - 3V_l I_s \cos \delta \cos \varphi^d - 3V_l I_s \cos \delta \cos \varphi^q
    \\
    \sum_{i=2}^{3} P_{2i} &= -\frac{1}{2} (P_m + P_0) + \frac{\sqrt{3}}{6} (Q_m - Q_0) + 3V_l I_s \cos \delta \cos \varphi^d - 3V_l I_s \cos \delta \cos \varphi^q
\end{align*}
\]

In order to ensure that H-MMC operates normally, the average power of each arm \(P_i\) (i=1-6) must equal to zero, otherwise the arm capacitors will be charged or discharged circularly. Then, both \(P_1+P_3+P_5\) and \(P_2+P_4+P_6\) need to be equal to 0, that is, Eq. (11) needs to be equal to 0. Thus, to achieve bridge arm capacitor voltage balance, the following stable operation constraints must be satisfied.

\[
P_m = -P_0
\]

\[
V_s I_i = -\frac{\sqrt{3}}{18} (Q_m - Q_0)
\]

4 Control method of the proposed topology under asymmetrical grid faults

4.1 MPPT control

Maximum power point tracking (MPPT) control is the basis for efficient utilization of wind energy. The reference value of wind turbine’s angular speed \(\omega_{ref}\) can be calculated by,

\[
\omega_{ref} = \frac{\lambda_{mpv} v}{R}
\]

where \(\lambda_{mpv}\) is the optimum tip speed ratio; \(v\) is the wind speed; \(R\) is the radius of the turbine blade.

The MPPT control can be expressed by,

\[
\begin{align*}
    i_{md, ref} &= 0 \\
    i_{mq, ref} &= K_{pt} \frac{K_{iq}}{s} (\omega_{ref} - \omega)
\end{align*}
\]

The PMSG adopts \(i_{md}\) control mode, so the d-axis reference current is set to 0. The difference between \(\omega_{ref}\) and the actual wind turbine’s angular speed \(\omega\) is passed through a PI controller to obtain the reference value of q-axis current. Then, with current tracking control, the MPPT can be achieved.

4.2 Positive and negative sequence control of the grid current

The following control strategy is adopted to obtain the reference of \(P_0\), which is introduced in Eq. (10)

\[
R_{0, ref} = \left[ K_{q2} + K_{iq} \right] (U_{C, ref} - \hat{U})
\]

where \(U_{C, ref}\) is the rated voltage of capacitors; \(\hat{U}\) is the average value of capacitor voltages of six bridge arms; \(K_{q2}\) is the proportional coefficient, \(K_{iq}\) is the integral coefficient.

Through the control of (16), \(P_0\) can be adjusted to track \(P_m\). As a result, Eq. (12) is satisfied.

According to the power transmission characteristics described in section 3.1, in order to reduce the fluctuation of the SM capacitor voltage, it is necessary to eliminate the 2nd harmonic component of the output power of H-MMC under asymmetrical grid faults.

In the positive sequence frame, the \(d^p\)-axis of the positive sequence synchronous rotating coordinate frame is oriented in the direction of positive sequence voltage vector, and the \(d^q\)-axis is oriented in the direction of negative sequence voltage vector, that is,

\[
\begin{bmatrix}
    u^p_g \\
    u^q_g \\
    u^p_N \\
    u^q_N
\end{bmatrix} =
\begin{bmatrix}
\sqrt{2}V_s^p \\
0 \\
\sqrt{2}V_s^q \\
0
\end{bmatrix}
\]

From Eq. (4), it can be seen that to ensure the output active power to be constant, \(P_{c2}\) and \(P_{c2}\) must equal to zero. Thus, one yields,
where $Q_0_{ref}$ is the reference of the output reactive power, which is set to 0 in order to ensure the grid power factor to be 1; $i_{g_{d_{ref}}}$, $i_{g_{q_{ref}}}$, $i_{g_{d_{ref}}}$, $i_{g_{q_{ref}}}$ are the positive and negative sequence current references in dq-coordinate frame, respectively.

By controlling the grid currents according to Eq. (18), the 2nd harmonic component of the output active power can be eliminated.

4.3 Voltage balance control of arm capacitors

The difference of $P_1$+$P_2$+$P_3$ and $P_2$+$P_4$+$P_6$ is related to the input and output active power of the H-MMC, which can be seen in Eq. (11) clearly, and the imbalance reactive power will cause unbalance energy between odd and even bridge arms.

As seen in Eq. (13), to compensate the imbalance reactive power between the input side and output side of the H-MMC, the dc component reference of $i_{x_{n}}$ and neutral point voltage reference are given by,

$$i_{x_{n_{1_{ref}}}} = \left( K_{p3} + \frac{K_{i3}}{s} \right) U_{C_{1.3.5} - U_{C_{2.4.6}}}$$  \hspace{1cm} (19)

$$v_{x_{st_{-ref}}} = \left( K_{p4} + \frac{K_{i4}}{s} \right) U_{C_{1.3.5} - U_{C_{2.4.6}}}$$  \hspace{1cm} (20)

where $U_{C_{1.3.5}}$, $U_{C_{2.4.6}}$ are the average capacitor voltages of arms 1, 3, 5 and 2, 4, 6, respectively; $K_{p3}$ and $K_{p4}$ are the proportional coefficients, $K_{i3}$ and $K_{i4}$ are the integral coefficients. $i_{x_{n_{1_{ref}}}}$, $v_{x_{st_{-ref}}}$ are the dc component references of loop current and neutral point voltage references, respectively.

The capacitor voltage balance of all bridge arms is realized by controlling the ac component of loop current with a proportional controller, as can be expressed by,

$$i_{x_{n_{2_{ref}}}} = \sum_{x=1}^{6} K_{p5} v_{x_{0_{x_{ref}}}} \left( U_{C_{x_{-ref}} - U_{C_{x}}} \right)$$  \hspace{1cm} (21)

where $U_{C_{x}}$ is the average value of the capacitor voltages of arm $x$; $K_{p5}$ is proportional coefficient; $i_{x_{n_{2_{ref}}}}$ is the ac component reference of $i_{x_{n_{1_{ref}}}}$.

Therefore, the loop current reference $i_{x_{n_{st_{-ref}}}}$ can be obtained,

$$i_{x_{n_{st_{-ref}}}} = i_{x_{n_{1_{ref}}}} + i_{x_{n_{2_{ref}}}}$$  \hspace{1cm} (22)

To balance the capacitor voltages of all SMs in the same bridge arm, a compensation is obtained by,

$$v_{x_{un_{-ref}}} = K_{p6} \left( U_{C_{x_{-ref}} - U_{C_{x}}} \right)$$  \hspace{1cm} (23)

where $U_{C_{x}}$ is the capacitor voltage of the $x$th SM in bridge arm $x$; $K_{p6}$ is proportional coefficient; $v_{x_{un_{-ref}}}$ is the compensation, which will be added to the total modulation voltage, as will be discussed in next section.

4.4 Current tracking control of bridge arms

After obtaining $i_{x_{d_{ref}}}$, $i_{x_{q_{ref}}}$, $i_{g_{d_{ref}}}$, $i_{g_{q_{ref}}}$, the references of stator currents and grid currents can be gotten through the reverse dq-coordinate transformation, as labelled with $i_{x_{d_{ref}}}$ (k=1,2,3) and $i_{g_{d_{ref}}}$ (k=1,2,3), respectively. By substituting $i_{x_{d_{ref}}}$ and $i_{g_{d_{ref}}}$ to Eq. (2), the bridge arm current references $i_{x_{ref}}$ ($x$=1-6) can be calculated.

The bridge arm currents contain two components with different frequencies, those are the voltage frequencies of PMSG and grid. Therefore, the double quasi-PR controller is applied, which can achieve current tracking control without steady error, as expressed by,

$$v_{x_{-ref}} = \left( K_{p7} + \frac{K_{i7} \omega_{x_{1_{st}}}}{s} \right) + \frac{K_{p8} \omega_{x_{2_{st}}}}{s^2 + 2 \omega_{x_{1_{st}}} s + \omega_{x_{1_{st}}}} (i_{x_{-ref}} - i_x)$$  \hspace{1cm} (24)

where $v_{x_{-ref}}$ ($x$=1-6) are the voltage references of bridge arms; $K_{p7}$ is the proportional coefficient; $k_{1_{st}}$ and $k_{2_{st}}$ are resonance coefficients; $\omega_{x_{1_{st}}}$ and $\omega_{x_{2_{st}}}$ are cut-off angular frequencies; $\omega_{x_{1}}$ and $\omega_{x_{2}}$ are the frequencies of the PMSG and grid, respectively.

Fig. 4 Bode diagram of the double quasi-PR controller under different $\omega_{x_{1}}$ and $\omega_{x_{2}}$ ($K_{p7}=100$, $K_{i7}=1.0$, $K_{p8}=1.0$, $\omega_{x_{1}}=59\text{rad/s}$, $\omega_{x_{2}}=314\text{rad/s}$)

Fig. 4 is the bode diagram of the double quasi-PR controller under different cut-off angular frequencies when $K_{p7}=100$, $K_{i7}=1.0$, $K_{p8}=1.0$, $\omega_{x_{1}}=59\text{rad/s}$, $\omega_{x_{2}}=314\text{rad/s}$.

As seen in Fig. 4, the smaller the cut-off frequency is, the better the frequency selection performance of the controller will be, while the greater the fluctuation of the regulator gain will be, which will deteriorate the stability of the system. The cut-off frequency determines the bandwidth of the controller, which generally takes $5-15\text{rad/s}$ to provide a good compromise in practical applications [30]. In this paper, $\omega_{x_{1}}$ and $\omega_{x_{2}}$ are taken as $5\text{rad/s}$.

Finally, combining (20), (23) and (24), the modulation waveform of the $n$th SM in arm $x$ can be expressed by (25),

$$v_{x_{un_{-ref}}} = v_{x_{st_{-ref}}} + v_{x_{un_{-ref}}} + (-1)^n v_{x_{st_{-ref}}}$$  \hspace{1cm} (25)

Note that, $(-1)^n$ means that $v_{x_{un_{-ref}}}$ must plus to the modulation waveforms of the odd bridge arms, while minus to the modulation waveforms of the even bridge arms, according to Eq. (1).
In summary, the block diagram of the control method is shown in Fig. 5.

Fig. 5 Block diagram of control method

5 Simulation

In order to verify the proposed topology and control method, the simulation model is setup with MATLAB/Simulink. The parameters of wind turbine and grid, the parameters of the topology and the parameters of control strategy are given in Table 1, Table 2 and Table 3, respectively. Note that, the cut-off frequencies $\omega_{c1}$ and $\omega_{c2}$ of PR controller are taken as $5 \text{ rad/s}$, which is analyzed in section 5.1. The remaining PI and PR control parameters in Table 3 are obtained through simulation tuning.

H-MMC can apply the same modulation methods as conventional cascaded H-bridge inverter. This paper adopts unipolar carrier phase-shifted sinusoidal pulse width modulation (CPS-SPWM) and its phase shift angle is $2\pi/N$ ($N$ is the number of SMs per arm). And the triangular carrier frequency is $200 \text{ Hz}$.

Table 1 Parameters of wind turbine and the grid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>5MW</td>
</tr>
<tr>
<td>Wind speed $v$</td>
<td>10m/s</td>
</tr>
<tr>
<td>Radius of the turbine blade $R$</td>
<td>74.4m</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>9.4Hz</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>3.3kV</td>
</tr>
<tr>
<td>Synchronous inductance $L_d = L_q$</td>
<td>4mH</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>0.05Ω</td>
</tr>
<tr>
<td>Rated voltage of the grid</td>
<td>10kV</td>
</tr>
<tr>
<td>Rated frequency of the grid</td>
<td>50Hz</td>
</tr>
</tbody>
</table>

Table 2 Parameters of the topology

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of SMs per arm $N$</td>
<td>6</td>
</tr>
<tr>
<td>SM capacitor $C_{sm}$</td>
<td>20mF</td>
</tr>
<tr>
<td>Rated SM voltage</td>
<td>2500V</td>
</tr>
<tr>
<td>Arm inductor $L$</td>
<td>10mH</td>
</tr>
<tr>
<td>Filter inductor $L_f$</td>
<td>2mH</td>
</tr>
<tr>
<td>Filter capacitor $C_f$</td>
<td>250uF</td>
</tr>
</tbody>
</table>

Table 3 Parameters of control system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{P1}$, $K_{I1}$</td>
<td>150, $1.5 \times 10^5$</td>
</tr>
<tr>
<td>$K_{P2}$, $K_{I2}$</td>
<td>$3.0 \times 10^3$, $3.0 \times 10^5$</td>
</tr>
<tr>
<td>$K_{P3}$, $K_{I3}$</td>
<td>1.0, 6.0</td>
</tr>
<tr>
<td>$K_{P4}$, $K_{I4}$</td>
<td>10, 50</td>
</tr>
<tr>
<td>$K_{P5}$</td>
<td>$4.6 \times 10^6$</td>
</tr>
<tr>
<td>$K_{P6}$</td>
<td>0.02</td>
</tr>
<tr>
<td>$K_{P7}$, $K_{Ic1}$, $K_{Ic2}$</td>
<td>100, 1.0, 1.0</td>
</tr>
<tr>
<td>$\omega_{c1}$, $\omega_{c2}$</td>
<td>5.0rad/s, 5.0rad/s</td>
</tr>
<tr>
<td>Carrier frequency $f_{sw}$</td>
<td>200Hz</td>
</tr>
</tbody>
</table>

5.1 Taking the conventional control method

In this simulation, the wind speed is set to 10m/s all the time, $v_{c1}$ is set to its rated voltage, then drops by 50% at 1s, and comes back at 1.3s. The simulation results are shown in Fig. 6. Note that, one goal of the conventional control method is to maintain the balance of the three phase output currents of H-MMC. As a result, it eliminates the negative sequence current of the grid.

As seen in Fig. 6(a), the grid currents are always balance, and the amplitude increases from 408A to 511A within 0.12s when $v_{c1}$ drops by 50%.

The active power of PMSG is 4.99MW, as can be seen in Fig. 6(b). When $v_{c1}$ drops at 1s, the active power of the grid contains 2nd harmonic component with the peak-to-peak value of 2.1MW, which is 42.1% of the total active power. When $v_{c1}$ returns back to rated voltage, the active power of the grid gradually comes back to 4.96MW within 0.36s, and the power converter efficiency is 99.4%. Note that, the efficiency obtained here is the ideal value of the simulation, and the internal resistances of the IGBTs in simulation are 1mΩ.

The average voltage of each arm capacitors fluctuates around 2500V with a ripple of ±240V under asymmetrical grid faults. After $v_{c1}$ returns to rated voltage, the voltage ripple decreases to ±134V at 2.7s.

Fig. 6(d) shows the loop current of H-MMC. When $v_{c1}$ drops at 1s, the loop current fluctuates between -79A and 133A. After $v_{c1}$ returns to rated voltage at 1.3s, the fluctuation of loop current gradually stabilizes between 38A and 91A.
to 27A with a ripple of 10A.

Fig. 8(a) is the current of arm 1. It can be seen that the $i_1$ can track its reference $i_{1_{\text{ref}}}$ without steady error, which verifies the effectiveness of the current tracking control based on double quasi-PR controller.

Fig. 8(b) gives the voltage waveforms of bridge arm $x$ ($x \in {1, 6}$). Note that, the voltage of bridge arm inductor is not considered. Their partially enlarged waveforms are given in Fig. 8(c). As seen in Fig. 8(b) and Fig. 8(c), the waveform of $v_c$ is a multilevel staircase wave, and its amplitude is about ±15kV, which is consistent with Eq. (1).

Through the simulation results above, it can be concluded that the proposed control method can suppresses the 2nd harmonic component of the output active power of H-MMC and reduces capacitor voltage fluctuation effectively. As a result, it requires smaller loop current to maintain the voltage balance of the arm capacitors compared to the conventional control method, which is favorable to reduce system losses. Furthermore, the proposed method can reach a steady state more quick than that of taking the conventional control method.

---

**Fig. 6 Simulation results under the conventional control method**

(a) Phase currents of the grid, (b) Active power of the PMSG and grid, (c) Average voltage of each arm capacitors, (d) Loop current

**Fig. 7 Simulation results under the proposed control method**

(a) Phase currents of the grid, (b) Active power of the PMSG and grid, (c) Average voltage of each arm capacitors, (d) Loop current
Fig. 8. Simulation results under the proposed control method (a) Current of bridge arm 1, (b) Voltage of bridge arm x, (c) Voltage of bridge arm x (partially enlarged)

6 RT-Lab HIL Test

The RT-Lab hardware in loop (HIL) test is set up to verify the proposed topology and control method. The DSP+FPGA is selected as the controller, and RT-Lab OP5600 is used to simulate the WECS based on H-MMC. The test parameters are all the same of those in simulations.

Fig. 9. RT-Lab HIL test setup

Fig. 10 and Fig. 11 are the simulation results when taking the conventional control method and proposed control method, respectively.

With both the control method, the line to line voltage \( u_{m12} \) and phase current \( i_{m1} \) of the PMSG are both 4578V and 1272A, respectively, as shown in Fig. 10(a) and Fig. 11(a).

Fig. 10(b) shows that the phase currents of the grid are balance all the time when taking the conventional control method. While, the three phase currents are 608A, 406A and 464A respectively under asymmetrical grid faults when taking the proposed control method, as can be seen in Fig. 11(b).

Fig. 10(c) shows that the ripple of SM capacitor voltage increases from 5.6% to 9.9% when the fault happens. While the ripple of SM capacitor voltage is always 5.4% when taking the proposed control method, as can be seen in Fig. 11(c).

The test results confirm the validity of the proposed control method. Compared with the conventional control method under asymmetrical grid faults, the proposed control method can greatly reduce the capacitor voltage fluctuation by suppressing the 2nd output power harmonic of wind power generation system.

Fig. 10. Test results under the conventional control method (a) Line to line voltage \( u_{m12} \) and phase current \( i_{m1} \) of the PMSG, (b) Phase currents of the grid, (c) Capacitor voltage of the first SM in arms 1,2,3,4

Fig. 11. Test results under the proposed control method (a) Line to line voltage \( u_{m12} \) and phase current \( i_{m1} \) of the PMSG, (b) Phase currents of the grid, (c) Capacitor voltage of the first SM in arms 1,2,3,4

---

**Fig. 11 Test results under the proposed control method**

(a) Line to line voltage $u_{a12}$ and phase current $i_{a1}$ of the PMSG, (b) Phase currents of the grid, (c) Capacitor voltage of the first SM in arms 1,2,3,4

7 Conclusion

In this paper, the H-MMC is applied for MV WECS, which has the advantages of low costs, low ripple of capacitor voltage and transformer-less grid connection. The power transmission characteristics of the system under asymmetrical grid faults is analyzed in detail. To eliminate the 2nd harmonic component of the output power delivered to the grid, the positive and negative sequence current references of the grid are obtained, and then the bridge arm current references of H-MMC are determined. Afterwards, the double quasi-PR controller is used to track the bridge arm currents without steady error. With the proposed control method, the ripple of capacitor voltage decreases from 9.9% to 5.4%; the ripple of loop current of the H-MMC converter decreases from 106A to 29A; and the 2nd harmonic component of the output power decreases from 42.1% to zero. Simulation and HIL test results show that the proposed control method can eliminate power harmonics, reduce capacitor voltage fluctuation under asymmetrical grid faults.

8 Acknowledgment

This work was supported by the Natural Science Foundation of China (NSFC) under Grant 51937004.

9 References


---

The fault happens
switch count multilevel AC/AC converter', Iranian Conference on Electrical Engineering. IEEE, Tehran, Iran, May 2011, pp. 1-5


