Enhanced low voltage ride-through control of multilevel flying capacitor inverter based wind generation

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ABSTRACT

This paper introduces a cost-effective control method to enhance the low voltage ride-through (LVRT) capability and smooth the output power of a three-phase multilevel flying capacitor inverter (FCI) in wind turbine-based permanent magnet synchronous generator (PMSG). The proposed approach utilizes the energy storage capability of flying capacitors to mitigate wind power fluctuations and address short-duration outages and deep voltage sags. Additionally, a nonlinear controller based Lyapunov theory is developed to regulate capacitor voltages, improve power factors, and balance DC-link voltage. Numerical simulations are conducted in MATLAB/SimPower systems environment to validate the effectiveness of this comprehensive control strategy across different grid operation scenarios.

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1. INTRODUCTION

The substantial rise in atmospheric carbon dioxide levels is strongly linked to the industrial revolution and the increasing energy demand [1]. With the energy sector accounting for approximately two-thirds of emissions, the integration of renewable energies into electricity grid infrastructure will be pivotal in reducing carbon emissions in the near future [2], [3]. Wind power, both onshore and offshore, has already taken a prominent role in our electricity system [4], [5]. In recent years, there has been significant exponential growth in the installed capacity of commercial wind turbines, making wind energy an attractive choice for enhancing the incorporation of renewables into hybrid energy systems, as emphasized in reference [6].

The wind turbine system must be appropriately controlled to meet specific criteria, including optimizing power extraction [7], [8], managing generator speed and torque [9], correcting power factors correction (PFC) [10], smoothing power output, and sustaining operation during grid faults. Among these, ensuring low voltage ride-through (LVRT) capability [11] is regarded as the most difficult aspect in the conception of wind turbine. Voltage sags resulting from various factors, such as lighting or short circuit failures, are common grid faults. Consequently, many grid regulations mandate that generating units, including wind power, remain connected to the utility grid and withstand grid faults [12] to maintain power system stability and prevent abrupt power loss.

Transmission system operators (TSOs) in different countries establish varying grid connection requirements for both conventional and renewable electricity generation plants, based on the specific attributes of their electricity systems. These requirements include resistance to voltage dips, wherein the wind turbines should provide reactive power to the grid during voltage dips [13], while the injection of active power can be dispatched to comply with this connection condition. As a result, any surplus active power generated must be stored and subsequently returned back to the grid during normal operation.

In the literature, numerous strategies have been put forward to enhance the LVRT capacity and mitigate active power fluctuations during grid faults. A dissipative resistor (breaking chopper) was suggested in [14]. During the grid fault period, the dissipative resistor circuit is turned on to absorb the excess wind energy, which can effectively protect the inverter against overvoltage caused by the increase in DC-link voltage. However, it cannot return the energy back to the grid [15]. Another method, proposed in [16], [17], suggests utilizing the inertia of the permanent magnet synchronous generator (PMSG) rotor to address LVRT requirements. This approach involves storing excess active power within the inertia of the rotating mass system. However, as wind speeds increase, the surplus power becomes more pronounced, potentially leading to severe rotor overspeed due to the delayed response of pitch regulation [18]. Additionally, an LVRT strategy involves the use of outboard devices such as battery energy storage (BES) or flywheel systems to smooth out the variation in output power are proposed in [19], [20]. Employing BES enhances LVRT capability for wind turbine systems and results in power stabilization. However, the incorporation of BES into wind turbines leads to an overall system cost increase [21].

Motivated by concerns about hardware requirements and associated costs, we introduce an innovative approach to enhancing LVRT for wind turbine systems that obviates the need for external devices. This strategy achieves power smoothing and fulfills LVRT criteria solely by utilizing the flying capacitors in the grid-side inverter. Moreover, a nonlinear backstepping control is developed based on the averaged model to ensure the balance of flying capacitor voltages, improve power factor, and regulate DC-link voltage. This paper is structured as fellow: Section 2 provides a description of the system and the mathematical model of flying capacitor inverter (FCI). Section 3 details the controller design. Section 4 presents the simulation results under different grid fault conditions. Lastly, section 5 draws a conclusion.

2. SYSTEM MODELING

Figure 1 illustrate the studied system of energy conversion from wind to electricity. The main components employed in wind turbine system are. A rotor with turbine blades (possibly with gearbox) to capture the wind energy, an electric generator PMSG to convert shaft mechanical power (P_m) into electrical power (P_e), a three-phase uncontrolled rectifier to change the generator's AC output into DC voltage, and lastly, a four-level FCI to reconvert the DC voltage into AC voltage at the specified grid frequency.

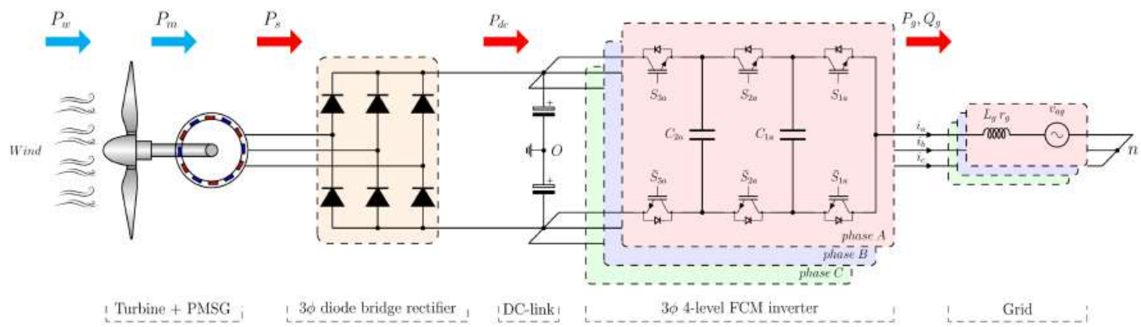


Figure 1. Schematic illustration of a PMSG-based wind energy conversion system

The four-level FCI is used in this study as a grid-side converter. It comprises three cells connected in a series configuration, with each cell incorporating a flying capacitor and two power switching devices (e.g., IGBT), composing one inverter leg. To prevent short-circuits, the upper and lower switches within each cell are operated in a complementary manner. To reduce collector-emitter voltage stress, all cell voltages must be the same [22]. The averaged model describing the leg j ($j \in \{a, b, c\}$) of the FCI can be obtained by applying Kirchhoff's law, leading to the (1)-(3) [23]:

$$C_{1j}\frac{dv_{c1j}}{dt} = \Delta u_{1j} i_{gj} \tag{1}$$

$$C_{2j}\frac{dv_{c2j}}{dt} = \Delta u_{1j} i_{gj} \tag{2}$$

$$L_{gj}\frac{di_{gj}}{dt} = -r_{gj}i_{gj} - \Delta u_{1j}v_{c1j} - \Delta u_{2j}v_{c2j} + (u_{3j} - \frac{1}{2})v_{dc} - v_{nO} - v_{gj} \tag{3}$$

where v_{c1j} and v_{c2j} are the flying voltages of capacitor C_{1j} and C_{2j} respectively, $\Delta u_{1j} = u_{2j} - u_{1j}$, $\Delta u_{2j} = u_{3j} - u_{2j}$ and u_{3j} are the average value of control signals,v_g and i_{gj} are the grid voltage and current, respectively, v_{nO} is the common mode voltage.

3. NONLINEAR CONTROL DESIGN

The nonlinear controller design is conducted to fulfill the following control objectives: i) Maximum power extraction of wind energy and regulation the voltages across dc-link capacitor. ii) Control the injected grid current to satisfy PFC. iii) Regulate the voltages across each flying capacitor. iv) Ensure uninterrupted operation during grid faults.

3.1. Maximize power extraction

To maximize the available wind power, it is crucial to maintain the rotor speed near its optimal reference, generated by the maximum power point tracking (MPPT) algorithm. In this study, a sensorless MPPT techniques, utilizing only the DC-link variables, is employed to establish the optimal DC-link voltage reference v_{dc}^*. Additionally, a DC-link voltage regulator is designed to track the optimal DC-link voltage reference and produce the reference current to ensure the injection of extracted wind energy into the grid [24]. By neglecting the inverter losses, the following differential equation of DC-link is obtained.

$$C_{dc}v_{dc}\frac{dv_{dc}}{dt} = P_g - P_{dc} \tag{4}$$

Where $P_{dc} = v_{dc}i_{dc}$ is the DC output power, and $P_g = 1.5v_g i_{gd}$ is the injected active power [25]. Our interest in this subsection is to design an effective control, so that the subsystem $e_{v_{dc}} = v_{dc} - v_{dc}^*$ converges to zero. To this end, a sub-Lyapunov function is chosen as $V = \frac{1}{2}e_{v_{dc}}^2$ and its differentiation yields;

$$\dot{V} = \left(\frac{1.5}{C_{dc}v_{dc}}V_g i_{gd} - \frac{i_{dc}}{C_{dc}} - \dot{v}_{dc}^*\right) e_{v_{dc}} \tag{5}$$

the virtual control signal i_{gd}^* which stabilizes the subsystem $e_{v_{dc}}$, is obtained from (5) by ensuring that $\dot{V}$ becomes a negative definite function and if the gain $k_{v_{dc}}$ are chosen such that $k_{v_{dc}} > 0$, the stabilizing function is expressed as (6).

$$i_{gd}^* = \frac{C_{dc}v_{dc}}{1.5V_g}\left(-k_{v_{dc}}e_{v_{dc}} + \frac{i_{dc}}{C_{dc}} + \dot{v}_{dc}^*\right) \tag{6}$$

3.2. Flying capacitor voltage regulation

To enhance the inverter's efficiency and reduce voltage stress on its power switches, it is crucial to keep the flying capacitor voltages within their specified reference levels. Our current control objective is to design an effective control strategy in which capacitor voltages track a variable desired reference. In this context, let's designate the following state errors.

$$e_{v_{c1j}} = v_{c1j} - v_{c1j}^*, \;\; e_{v_{c2j}} = v_{c2j} - v_{c2j}^* \tag{7}$$

The stabilization of the state subsystem $x = \begin{pmatrix} e_{v_{c1j}} & e_{v_{c2j}} \end{pmatrix}^T$ can be achieved by developing a control law that ensures the convergence of the subsystem variable x to zero. To this end, we choose the Lyapunov function $V = 0.5e_{v_{c1j}}^2 + 0.5e_{v_{c2j}}^2$, and its derivative is given as;

$$\dot{V} = \left(\frac{\Delta u_{1j}}{C_{1j}} i_{gj} - \dot{v}^*_{c1j}\right) e_{v_{c1j}} + \left(\frac{\Delta u_{2j}}{C_{2j}} i_{gj} - \dot{v}^*_{c2j}\right) e_{v_{c2j}} \tag{8}$$

hence, under the control law defined by (9), the system achieves global uniform asymptotic stability when the gains are selected to satisfy $k_{v_{c1j}} > 0$ and $k_{v_{c2j}} > 0$.

$$\begin{cases} \Delta u_{1j} = \dfrac{C_{1j}}{i_{gj}} \left(-k_{v_{c1j}} e_{v_{c1j}} + \dot{v}^*_{c1j}\right) \\ \Delta u_{2j} = \dfrac{C_{2j}}{i_{gj}} \left(-k_{v_{c2j}} e_{v_{c2j}} + \dot{v}^*_{c2j}\right) \end{cases} \tag{9}$$

3.3. Power factor correction

Maintaining the power factor at the point of common coupling (PCC) is crucial for preserving the power quality and stability of the entire system. Therefore, it is necessary to shape the grid current i_{gj} into a pure sine wave and have it track the instantaneous current i^*_{gj} command reference [26]. For this purpose, a control law based on the Lyapunov approach can be applied to zero the error $e_{i_{gj}} = i_{gj} - i^*_{gj}$ between the reference and the measured value. By using (3), the time derivative of $e_{i_{gj}}$ can be expressed as;

$$\dot{e}_{i_{gj}} = \frac{1}{L_{gj}}\big(- r_{gj} i_{gj} + \Delta u_{1j} v_{c1j} + \Delta u_{2j} v_{c2j} + (u_{3j} - 0.5) v_{dc} - v_{nO} - v_{gj}\big) - \frac{di^*_{gj}}{dt} \tag{10}$$

the sub-Lyapunov function is chosen as $V = 0.5 e^2_{i_{gj}}$. It can be verified that $\dot{V}$ can become a negative definite under the control law (11) if the design parameter $k_{i_{gj}}$ is selected to satisfy $k_{i_{gj}} > 0$.

$$\begin{aligned} u_{3j} = \frac{1}{v_{dc}}\Big(& - L_{gj} k_{i_{gj}} e_{i_{gj}} + r_{gj} e_{i_{gj}} + \frac{C_{1j}}{i_{gj}}(-k_{v_{c1j}} e_{v_{c1j}} + \dot{v}^*_{c1j}) v_{c1j} \\ & + \frac{C_{2j}}{i_{gj}}(-k_{v_{c2j}} e_{v_{c2j}} + \dot{v}^*_{c2j}) v_{c2j} + 0.5 v_{dc} + v_{nO} + r_{gj} i^*_{gj} + L_{gj} \frac{di^*_{gj}}{dt} + v_{gj}\Big) \end{aligned} \tag{11}$$

3.4. LVRT control algorithm

Voltage sags are the most common type of transient power quality issue, and they can impact protection systems. Therefore, it is necessary for the RMS value of the grid current to remain below an upper limit ($I_{ga}, I_{gb}, I_{gc} \leq I_{gmax}$) to ensure the safe operation of the inverter [27]. The mitigation technique employed in this study suggests that any excess power resulting from grid fault disturbances can be compensated by the flying capacitors within the FCI. Thus, the energy absorbed by the two flying capacitors of phase j during a fault period $t_1 - t_0$ and the energy released from both capacitors during a recovery period $t_2 - t_1$ is outlined as (11) and (12).

$$E_{c,charge} = \frac{1}{3}\int_{t_0}^{t_1} \big(P_{dc}(t) - P_g(t)\big) dt \tag{12}$$

$$E_{c,discharge} = \frac{1}{3}\int_{t_1}^{t_2} \big(P_g(t) - P_{dc}(t)\big) dt \tag{13}$$

The proposed control algorithm generates voltage references for C_{1j} and C_{2j}, where $v^*_{c2j} = 2v^*_{c1j}$ to ensure the correct allocation of energy between these capacitors. Figure 2 depicts the flowchart of the suggested LVRT control algorithm. Figure 3 illustrates the block diagram of a comprehensive controller for an FCI-based PMSG wind turbine. The MPPT block regulates the DC-link voltage to follow the optimum power point, while the LVRT algorithm supplies reference variables to the nonlinear controller for power control and system stability during grid fault conditions.

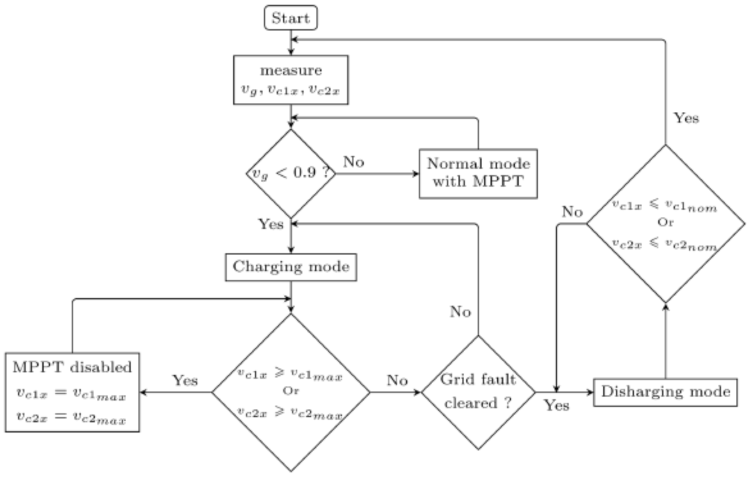


Figure 2. Proposed LVRT control algorithm

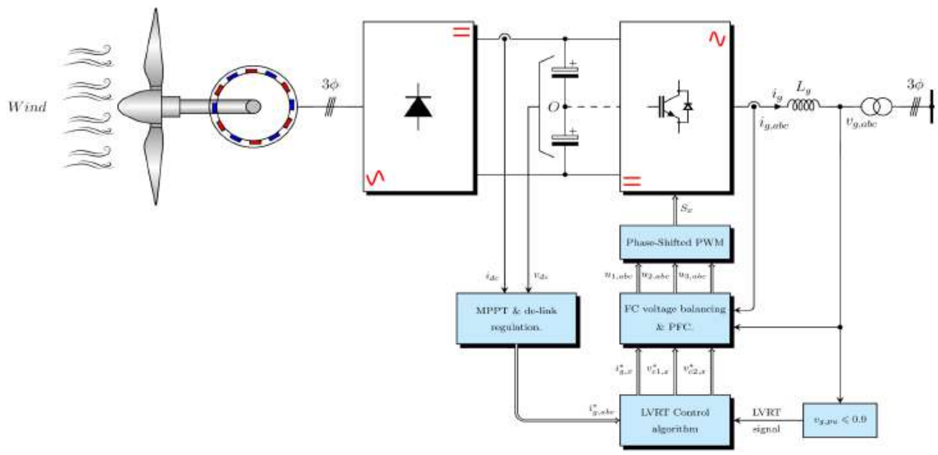


Figure 3. Schematic diagram of the proposed controller for wind energy conversion system

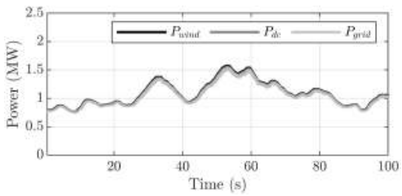
4. RESULTS AND DISCUSSION

The controller's performance is evaluated using Matlab/Simulink software in two grid operation modes: normal mode and symmetrical fault. The simulation model includes a PMSG-based wind turbine connected to the utility grid through a diode bridge and four-level FCI. Table 1 presents the system parameters employed in the simulations. To meet the control objectives, the control parameters are designed as: $k_{v_{dc}} = 100$, $k_{v_{c1j}} = k_{v_{c2j}} = 10^3$, $k_{i_{gj}} = 17.10^3$.

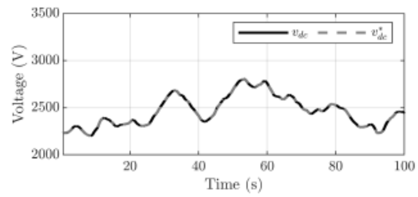
Table 1. System parameters

Subsystems	Parameters	Description	Values
Wind turbine	P_T	Rated power (MW)	2
	D_T	Rotor diameter (m)	86.6
	β	pitch angle $(degree)$	2
FCMI	C_1, C_2	Flying capacitance (mF)	250
	C_{dc}	DC-link capacitance (mF)	500
Electrical grid	v_g	Phase voltage (V)	1700
	r_g	Grid-side resistance (Ω)	0.025
	L_g	Grid-side inductance (mH)	1.65
	f_g	Grid frequency (Hz)	50

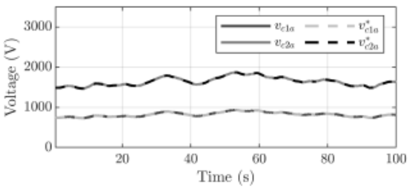
Figure 4 displays the simulation outcomes during normal mode operation. In Figure 4(a), the power P_{wind} generated by the wind turbine and the active power P_{grid} delivered from the dc-link to the grid are presented. The graph in Figure 4(b) illustrates the behavior of the dc-link voltage V_{dc}, which closely follows its reference value V_{dc}^*, successfully achieving the MPPT objective. Figure 4(c) shows the flying capacitor voltages for phase a, indicating satisfactory tracking of the desired references. Lastly, Figure 4(d) depicts the grid current, which exhibits a sinusoidal pattern, indicating compliance with the PFC requirement.



(a)



(b)



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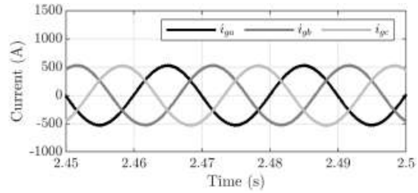
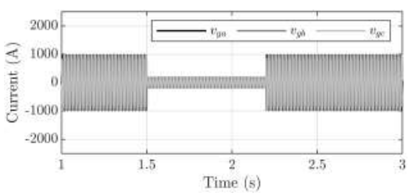


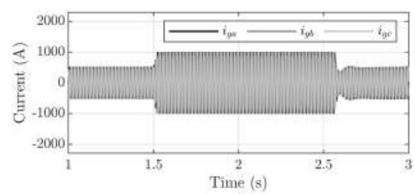
(d)

Figure 4. Results obtained from simulations under normal grid operating conditions; (a) Generated and injected power, (b) DC-link voltage, (c) Flying capacitor voltages, and (d) Grid current waveform

In the second mode, a grid voltage dip (about 0.2 p.u) was triggered at $t = 1.5s$ and resolved $0.7s$ later. Figure 5 displays the simulation results depicting the system's capability to withstand grid voltage dips. Figure 5(a) illustrates the phase voltage during the grid disturbance, while Figure 5(b) indicates that the grid current reached its limit $I_{g_{max}}$. Figure 5(c) illustrates the voltage dynamics across the flying capacitor during a grid disturbance, demonstrating the accurate tracking of the references generated by the LVRT algorithm. The wind turbine's generated power and the injected active power are presented in Figure 5(d). Notably, the generated power remains constant since the surplus power is absorbed by the flying capacitors, demonstrating that the proposed algorithm can prevent energy loss without the need for a battery storage device.



(a)



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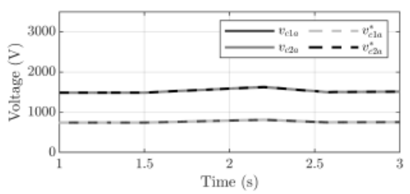
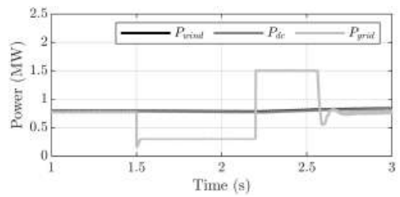


(c)



(d)

Figure 5. Results obtained from simulations under grid symmetrical fault; (a) Phase grid voltages, (b) Grid current, (c) Flying capacitor voltages, and (d) Power transferred to the grid

5. CONCLUSION

This research explores a novel LVRT control strategy for PMSG-based wind turbine using four-level FCI. The proposed approach involves the utilization of flying capacitors storage capacity to store surplus power generated during grid faults. The controller's design objectives encompass, optimizing power extraction from the turbine while regulating the DC-link voltage, maintaining precise control over the flying capacitor voltages, implementing PFC, and Enhanced resilience to voltage dips during a symmetrical fault. Simulation results demonstrate that the suggested control strategy effectively accomplishes these objectives in both normal and LVRT grid operating conditions.

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