Transient stability enhancement of DC-connected DFIG and its converter system using fault protective device

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Abstract Transient stability of doubly-fed induction generators (DFIGs) is a major concern in both AC and DC grids, and DFIGs must stay connected for a time during grid faults according to the power grid requirements. For this purpose, this work proposes an overcurrent and overvoltage protective device (OCV-PD) to ensure that DC-based DFIG system can stay connected and operate well during the faults. Compared with a series dynamic braking resistor (SDBR), two aspects are improved. First, a two-level control strategy and DC inductor circuit are used to ensure that the OCV-PD can limit the current impulse to protect DFIG system during an overcurrent fault. Second, the OCV-PD can protect system from overvoltage fault which a SDBR cannot do. Simulation results verify its

validity and feasibility, finding that for overcurrent protection the OCV-PD outperforms a SDBR with an average decreased index of 3.29%, and for overvoltage protection it achieves an average index of 1.02%.

Keywords Transient stability, Doubly-fed induction generator (DFIG), Overcurrent and overvoltage protective device (OCV-PD), DC grid, Series dynamic braking resistor (SDBR)

1 Introduction

In recent years, the variable-speed wind turbine with doubly-fed induction generator (DFIG) has gained popularity as a smart renewable energy source, due to its operational flexibility and enhanced features [1, 2]. However, a DFIG system inevitably faces the problems of overvoltage and overcurrent in extreme situations [3]. During a short-circuit fault, a very high current flows through both stator and rotor windings, and the terminal voltage of the DFIG becomes very low [4]. A DFIG system is traditionally disconnected from AC grid when there is a short-circuit fault [5]. In the event of an open-circuit fault, the current flows are very low and the terminal voltage becomes very high, which threatens its operation and eventually burns the DFIG and its converters. However with more and more wind power integrating into the grid, it is necessary for DFIGs to stay connected during faults for a time according to the power grid requirements [6, 7]. DFIGs should therefore have good transient stability and fault ride-through capability [8]. The converter system can maintain its stability under some fault conditions [9, 10], however, its capacity alone is insufficient to ensure its

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stability in severe cases. Therefore, additional devices are required.

Different kinds of solutions have been proposed to overcome the issue of AC grid instabilities affecting connected wind farms. A static synchronous compensator can be applied to the wind farm AC bus to compensate the reactive power and stabilize AC voltage [11–13]. Circuit configurations including a fault current limiter (FCL) and energy storage systems such as flywheel energy storage (FES) and superconducting magnetic energy storage (SMES) can also improve the transient stability of DFIGs [14–16], but their high installation cost offsets their good performance [17]. A bridge-type fault current limiter (BFCL) has been proposed to enhance the transient stability of DFIGs, which is a promising application in an AC grid [18–21], but it only suits specific situations. A SDBR has a simple structure, which is applied in both AC and DC grids to enhance the transient stability and fault ride-through capability of generators [22–24], but it cannot overcome both overcurrent and overvoltage issues and current impulse usually occurs.

With the increasing use of DC transmission, DC-based DFIG systems have been widely applied in a DC grid [25–27]. A diode-based stator converter interfaces a DFIG with a DC grid, which simplifies its converter structure, reduces its cost and improves its efficiency [26, 28], however this diode-based converter has no protective ability and exposes the DFIG to DC grid faults. An IGBT-based stator converter is a promising DC-based converter which connects a DFIG to a DC grid directly with lower levels of current harmonics and higher power quality [27, 29–31], but its protective ability is insufficient during serious DC grid faults.

Few solutions are proposed in the literature to solve transient stability issues of DC-connected DFIGs. SMES with a FCL function can improve the low voltage ride-through capability and smooth the power fluctuations of a DFIG in a DC grid [32], but it only applies to traditional DFIG systems and its installation cost is high.

Thus it is important to protect DFIGs with DC-based converter systems from the full range of DC grid faults.

This paper focuses on a DC overcurrent and overvoltage protective device (OCV-PD) to enhance the transient stability of DC-based DFIG systems. Compared with a SDBR, the proposed OCV-PD could make DC-based DFIGs less influenced by overcurrent faults in the all power situations with less impulse currents; Moreover, it has overvoltage protective ability that SDBR does not possess. In this paper, a DC-based DFIG system is presented in Section 2; the design and control scheme of the OCV-PD are elaborated in Section 3; and simulation studies are carried out to

verify the effectiveness of OCV-PD in Section 4, where the results show that OCV-PD is effective and feasible.

2 DC-based DFIG system

The DC-based converter system adopted in this paper is shown in Fig. 1, and has been widely applied in DC-interfaced wind farms [27, 29–31]. It consists of a rotor side converter (RSC) and a stator side converter (SSC). The RSC is an IGBT-based converter that couples the rotor to the DC bus. The SSC interfaces the stator and the DC bus, which consists of an IGBT-based converter and a LC inductor. LC and du/dt filter inductors are added to the stator and rotor sides to prevent sharp changes in voltage caused by converters and to smooth the stator and rotor currents.

2.1 DC-based converter system model

RSC and SSC models are described as [29, 33, 34]:

$$\begin{cases} u_{rd} = R_r i_{rd} + \sigma L_r \frac{d}{dt} i_{rd} - s\omega_1 \sigma L_r i_{rq} + s \frac{L_m}{L_s} u_s \\ u_{rq} = R_r i_{rq} + \sigma L_r \frac{d}{dt} i_{rq} + s\omega_1 \sigma L_r i_{rd} \end{cases} \quad (1)$$

$$\begin{cases} L \frac{di_{Ld}}{dt} = u_{sd} - R_L i_{Ld} + \omega_1 L i_{Lq} - v_{sd} \\ L \frac{di_{Lq}}{dt} = u_{sq} - R_L i_{Lq} - \omega_1 L i_{Ld} - v_{sq} \end{cases} \quad (2)$$

$$\begin{cases} C \frac{du_{sd}}{dt} = i_{Ld} - i_{sd} + \omega_1 C u_{sq} \\ C \frac{du_{sq}}{dt} = i_{Lq} - i_{sq} - \omega_1 C u_{sd} \end{cases} \quad (3)$$

where u_{sd} , u_{sq} , i_{sd} , i_{sq} are the dq components of stator voltage and current; u_{rd} , u_{rq} , i_{rd} , i_{rq} are the dq components of rotor voltage and current; ω_1 is the synchronous angular frequency; L_s , L_r , L_m are the stator, rotor and mutual inductance; R_r is the rotor resistance; u_s is the stator voltage; v_{sd} , v_{sq} , i_{Ld} , i_{Lq} are the dq components of stator converter voltage and current; C and L are the capacitance and inductance of LC filter; σ is $1 - L_m^2/(L_s L_r)$.

Fig. 1 DFIG with its DC-based converter system in DC grid

2.2 Control scheme for DC-based DFIG system

The control equations can be derived from (1)–(3) as:

$$\begin{cases} u_{rd} = \left(k_{rp} + \frac{k_{ri}}{s}\right)(i_{rd}^* - i_{rd}) - s\omega_1 \sigma L_r i_{rq} + s \frac{L_m}{L_s} u_s \\ u_{rq} = \left(k_{rp} + \frac{k_{ri}}{s}\right)(i_{rq}^* - i_{rq}) + s\omega_1 \sigma L_r i_{rd} \end{cases} \quad (4)$$

$$\begin{cases} i_{Ld} = \left(k_{up} + \frac{k_{ui}}{s}\right)(u_{sd}^* - u_{sd}) - \omega_1 C u_{sq} + i_{sd} \\ i_{Lq} = \left(k_{up} + \frac{k_{ui}}{s}\right)(u_{sq}^* - u_{sq}) + \omega_1 C u_{sd} + i_{sq} \end{cases} \quad (5)$$

$$\begin{cases} v_d = \left(k_{sp} + \frac{k_{si}}{s}\right)(i_{Ld}^* - i_{Ld}) - \omega_1 L i_{sq} + u_{sd} \\ v_q = \left(k_{sp} + \frac{k_{si}}{s}\right)(i_{Lq}^* - i_{Lq}) + \omega_1 L i_{sd} + u_{sq} \end{cases} \quad (6)$$

Fig. 2 Whole control strategy of SSC and RSC

where n_r , n_{opt} , θ_m are the rotor speed, optimal speed, and rotor angle. From (4) to (6), the whole control scheme of converter system can be obtained, as shown in Fig. 2.

The RSC undertakes the stator power control task to track the wind power curve, and its control strategy consists of a power regulator and a current regulator. The SSC stabilizes stator voltage and converts AC power to DC power; its control strategy consists of a voltage regulator and a current regulator. The voltage and angle references come from an ideal AC voltage source. The parameters of an example DFIG system and controllers are provided in Tables 1 and 2 respectively.

3 Overcurrent and overvoltage protective device

3.1 OCV-PD configuration

The proposed OCV-PD consists of a serial inductor circuit (SIC), a shunt resistance (SR), a snubber circuit (SC), IGBTs (k_m and k_s), and a diode (D_{con}) as shown in Fig. 3. The overcurrent protective circuit (OCPC) includes the SIC, SC, SR, k_m and D_{con} . The overvoltage protective circuit (OVPC) consists of the SIC, SR and k_s . V_{busG} and V_{busF} are the voltages of the DC grid and the wind farm respectively. The SIC includes a reactor (L_{sic}), a resistance (R_{sic}), and a diode (D_{sic}), which smooths the DC current and limits the burst current. D_{sic} provides the path to discharge the stored reactor energy. R_{sic} is the internal resistance of the reactor. The SC consists of a reactor (L_{sc}) and a diode (D_{sc}), which protects k_m from a current impulse when the IGBT is turned on instantaneously. The SR consists of multi-branch resistances with DC switches ($k_1, k_2, \dots, k_n$) placed in series, which generate different equivalent resistance to adapt to variable power. D_{con} connects the SR to the DC bus and prevents the DC bus current from experiencing an overcurrent fault. It also separates the SR from the DC bus and protects the DC bus from overvoltage faults.

3.2 OCV-PD operation

During normal operation, k_m stays on and k_s stays off, therefore current flows through the SIC, SC and k_m . The

Table 1 Parameters for 1.5 MW DFIG system

Characteristic	Value	Characteristic	Value
Stator voltage	0.575 kV	Stator resistance	0.023 p.u.
Stator reactance	0.18 p.u.	Rotor resistance	0.016 p.u.
Rotor reactance	0.16 p.u.	Magnetic reactance	2.9 p.u.

0.003 m Ω and 0.01 mH for a practical solution, and R_{sic} is chosen to be 0.33 m Ω in the same way.

3.4 OCV-PD control strategy

The two-level control strategy shown in Fig. 4 is used to ensure that the OCV-PD can adapt to variable output power. The first level controller selects the applied quantity of DC switches ($k_1, k_2, \dots, k_n$) once every 10 s according to the output power of wind farm to approximate the required equivalent resistance. The second level controller determines k_m and k_s to get an accurate equivalent resistance in overcurrent and overvoltage fault situations. It consists of a hysteresis control unit, a pulse width modulation (PWM) generator, two selectors, and two IGBTs (k_m and k_s). In order to alleviate DC voltage fluctuations, V_{busF} is used as the feedback reference. A hysteresis controller is used to produce an appropriate signal for the PWM generator with a hysteresis bandwidth of 1 V. The PWM signals '0' and '1' are sent to IGBTs (k_s and k_m) via selector 2. The overcurrent (OC) and overvoltage (OV) flags are mentioned above.

3.5 SDBR design considerations

The performance of the OCV-PD can be compared with that of a SDBR to demonstrate its effectiveness. A SDBR consists of an IGBT (k_m) and a resistor (R_{sh}) [20, 22–24] as shown in Fig. 5.

During normal operation, k_m stays on. Therefore, the DC current flows through k_m and bypasses R_{sh} . During an overcurrent fault, the DC current increases very sharply. k_m is turned off and R_{sh} is switched into DC transmission to consume excess power. k_m is turned on when the overcurrent fault is cleared and the DC voltage recovers.

There is no DC inductor, so current impulses may occur. The resistor is chosen to be equal to the equivalent resistance to allow direct comparison. The working condition of SDBR is same as that of OCV-PD.

4 Simulation and discussion

A simulation platform has been developed to verify the effectiveness and feasibility of the OCV-PD in Fig. 6, which consists of six DFIG systems, protective devices

Fig. 5 SDBR circuit

Fig. 6 Test platform description

(OCV-PD and SDBR), fault scenarios, transmission line and DC grid. Protection devices are installed on the wind farm bus. The performance of the OCV-PD and the SDBR is compared when an overcurrent fault occurs, and the system performance is analyzed to validate the overvoltage protective ability of the OCV-PD during an open-circuit fault.

4.1 Simulation settings

The simulated DFIG systems operate at their rated speed steadily before faults occur at 0.05 s. Faults are cleared at 0.15 s. Three cases are considered when an overcurrent fault occurs:

- 1) Case A: with no protective device.
- 2) Case B: with an OCV-PD.
- 3) Case C: with a SDBR.

Since a SDBR cannot protect the DFIG systems from an overvoltage fault, two cases are considered:

- 1) Case A: with no protective device.
- 2) Case B: with an OCV-PD.

Simulation results and analysis are carried out in the following sections. The black and dot-dash lines are the curves for case A. The red and solid lines are the curves for case B. The blue and dotted lines are the curves for case C.

4.2 Transient stability analysis for short-circuit fault

Figures 7 and 8 show the responses of an OCV-PD and a DFIG system when an overcurrent fault occurs.

In Fig. 7a, V_{busG} is 1.0 p.u. initially, then falls down to 0.22 p.u. during 0.05 to 0.15 s. In Fig. 7b, V_{dcF} is lowest right after the fault occurs for case A, and has a big damped oscillation with amplitude of 0.2 p.u. for case C. Meanwhile the OCV-PD keeps V_{dcF} at 1.0 p.u. after a small transient regulation. When the overcurrent fault is cleared, V_{dcF} recovers most quickly for case B.

In Fig. 7c, the abrupt current is limited by the DC reactor for case B, and its current fluctuation is the

Fig. 7 Performance of protective device during short-circuit fault

Fig. 8 Performance of DFIG system during short-circuit fault

smallest. Power devices in the OCV-PD and DC-based converter system are safe during the overcurrent fault, however an abrupt current exists for cases A and C, which may damage the power devices.

In Fig. 7d, the OCV-PD consumes more appropriate active power and gives better transient stability than the SDBR during the overcurrent fault. Power is not consumed by the SR during normal operation for cases B and C.

Considering now the DFIG, in Fig. 8a, when the DC bus voltage drops, the wind farm and sator voltages decrease instantaneously since no protective device exists for case A, and then sator voltage is regulated by the SSC to a level that is below the normal value. For case C, since wind farm voltage is not influenced much due to the protection of the SDBR, the sator voltage decreases from 1 to 0.95 p.u. under the regulation of the SSC, and then recovers to 1.0 p.u.. For case B, the sator voltage is not influenced and stable wind farm voltage is achieved due to the protection of the OCV-PD.

In Fig. 8b and c, sator current varies with sator voltage, which would make the rotor current change similarly. The lower sator voltage causes a higher sator current. Therefore, the sator current becomes high for case A during an overcurrent fault, and the system may break down if the fault time is too long. For cases B and C, the OCV-PD limits the current's rising rate and ensures better transient stability with lower oscillation, which is more than the SDBR can achieve. The current responses of the sator and the rotor have similar waveforms.

Figure 8d and e show how the active and reactive power of the DFIG respond to the system current and voltage. With the drop in voltage and increase in current, the active power decreases to a very low level for case A during the overcurrent fault, and increases to a very high level when the fault is cleared, which may harm the DFIG and its converter system; and reactive power increases to a high level due to the big system current. For case B, active and reactive power remain stable at 1 and 0 p.u. respectively for the stable system voltage and current due to the protection of the OCV-PD. For case C, the active and reactive power have oscillations with amplitudes of 0.07 p.u..

In Fig. 8f, since wind power is approximately constant during the overcurrent fault, the rotor speed increases very quickly with the decrease in active power for case A. The rotor speed for case B is more constant than that for case C, and both are influenced slightly.

Simulation results indicate that the OCV-PD can protect the DC-based DFIG system from an overcurrent fault, and it can do so more effective than the SDBR.

Fig. 9 Performance of protective device during overvoltage fault

Fig. 10 Performance of DFIG system during overvoltage fault

4.3 Transient stability analysis for overvoltage fault

Figures 9 and 10 describe the responses of an OCV-PD and a DC-based DFIG system during an open-circuit fault that causes overvoltage.

In Fig. 9a, b, and c, V_{busF} and V_{busG} become high right after the overvoltage fault occurs, and the DC current decreases to zero with a sudden impulse for case A. The DC-based converter system should not be subjected to such a high voltage and current impulse, which may damage the capacitor and converter. On the other hand, the DC voltage and current remain close to their nominal values after a transient oscillation for case B, and recover quickly with the help of the OCV-PD when the fault is cleared.

In Fig. 9d, the OCV-PD consumes excess active power during the overvoltage fault, but does not consume wind power during normal operation.

The responses of the DFIG system for cases A and B are illustrated in Fig. 10. Since the DC wind farm voltage is not influenced by the overvoltage fault due to the protection of the OCV-PD, the sator voltage, sator current, rotor current, sator active and reactive power, and rotor speed remain essentially at their normal values during the overvoltage fault. Although the DFIG system is less affected in case A during the overvoltage fault than during the overcurrent fault, overvoltage in a wind farm would damage the DC-based converter system, so an overvoltage protection device is needed.

From the results, we can see that the DFIG system operates in a stable state with the lowest voltage fluctuation and limited current impulse for case B, which indicates that the OCV-PD can protect the DC-based DFIG system from overvoltage and overcurrent faults.

4.4 Index comparison

In order to illustrate the relative performances in a quantitative way, eight indices are defined as:

$$\begin{cases} sp = \int_{t_0}^{t_s} |\Delta p(t)| dt \\ sq = \int_{t_0}^{t_s} |\Delta q(t)| dt \\ sc\omega_r = \int_{t_0}^{t_s} |\Delta \omega_r(t)| dt \\ sU_{dc} = \int_{t_0}^{t_s} |\Delta U_{dc}(t)| dt \\ sI_s = \int_{t_0}^{t_s} |\Delta I_s(t)| dt \\ sV_s = \int_{t_0}^{t_s} |\Delta V_s(t)| dt \\ sI_r = \int_{t_0}^{t_s} |\Delta I_r(t)| dt \\ sI_{dc} = \int_{t_0}^{t_s} |\Delta I_{dc}(t)| dt \end{cases} \quad (10)$$

where $\Delta p(t)$, $\Delta q(t)$, $\Delta \omega_r(t)$, $\Delta I_r(t)$, $\Delta I_s(t)$, $\Delta V_s(t)$, $\Delta U_{dc}(t)$, $\Delta I_{dc}(t)$ are the deviations of the real and reactive power of

Table 3 Performance indices for short-circuit faults

Index parameters	Values of indices (%)		
	No protective device	SDBR	OCV-PD
sp	542.24	7.54	0.96
sq	194.61	12.57	1.08
$s\omega_r$	1.80	0.03	0.002
sI_s	44.08	1.43	0.16
sI_r	31.09	1.19	0.11
sV_s	32.95	0.36	0.03
sU_{dc}	35.95	2.63	0.11
I_{dc}	68.51	5.33	1.87
Average index	118.9	3.89	0.6

Table 4 Performance indices for open-circuit faults

Index parameters	Values of indices (%)	
	No protective device	OCV-PD
sp	9.93	1.00
sq	4.66	0.76
$s\omega_r$	0.003	0.001
sI_s	1.35	0.18
sI_r	0.98	0.11
sV_s	0.33	0.04
sU_{dc}	184.90	0.37
I_{dc}	64.66	5.69
Average index	33.3	1.02

the generator, the rotor speed, the rotor and stator current, the stator voltage, and the DC voltage and current, respectively. The integrals are calculated over the time range from 0.05 and 0.15 s, and the indices are expressed as a percentage of the average value of each parameter integrated over the same period, hence they measure the percentage average normalized deviation.

Tables 3 and 4 are obtained when the simulation results in Figs. 7–10 are substituted into (10). A lower index represents a better system performance regarding transient stability. The system performance for case A is the worst with the average indices of 119% and 33% during overcurrent and overvoltage faults. The indices for cases B and C are 0.6% and 3.89% during the overcurrent fault. The index for case B is 1.02% during the overvoltage fault.

Thus the OCV-PD makes a significant improvement and outperforms the SDBR by reducing the average normalized deviation from 3.89% to 0.6%; moreover, the OCV-PD can protect system from overvoltage fault with an average normalized deviation of 1.02%, while the SDBR cannot provide this protection.

4.5 Implementation feasibility

The OCV-PD would probably be located at the substation of wind farms and use local parameters without needing additional signal detection equipment. The OCV-PD incorporates power electronic devices that have made astounding advances in recent times and are readily available. Cascaded and parallel configurations could be used in situations of very large current and voltage. Thus the OCV-PD could be feasible both technically and financially.

5 Conclusion

Based on the simulation results and analysis, the following conclusions may be drawn.

- 1) The OCV-PD can effectively protect DC-based DFIG systems from overvoltage and overcurrent faults to enhance their transient stability.
- 2) The OCV-PD outperforms a SDBR during an overcurrent fault, reducing the average normalized deviation from 3.89% to 0.6% according to the graphical and numerical results from a simulated system.
- 3) The OCV-PD ensures that the DFIG can operate well during an overvoltage fault with an average normalized deviation of 1.02%.

In our future research, a prototype of the OCV-PD will be manufactured and tested to verify its effectiveness.

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