Proportional Resonant-Based High Voltage Ride-Through Control Strategy for Permanent Magnet Direct-Drive Wind Turbine Systems (Postprint)

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Date: 2019-03-05T00:00:00+00:00

Abstract

This paper proposes a proportional-resonant-based high voltage ride-through control strategy for permanent magnet direct-drive wind turbine systems. According to the amplitude of grid voltage swell, the grid-side converter prioritizes delivering a certain proportion of inductive reactive current to the faulted grid. After the DC bus voltage exceeds its limit, the supercapacitor stores energy to stabilize the DC bus voltage. Compared with the traditional PI control strategy, the proposed strategy can achieve zero steady-state error control of AC input signals in the stationary coordinate frame. Meanwhile, this strategy reduces coordinate rotation transformations, eliminates coupling terms and feedforward compensation terms that are affected by temperature and circuit parameters, thereby simplifying the control algorithm. Simulation results demonstrate that this control strategy not only ensures that the permanent magnet direct-drive wind turbine system remains grid-connected and operates continuously during grid high-voltage faults, but also enables the system to provide a certain amount of inductive reactive power for grid voltage recovery.

Full Text

Preamble

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Abstract

This paper proposes a high voltage ride-through (HVRT) control strategy for direct-driven permanent magnet synchronous generator (PMSG) wind turbines based on proportional-resonant (PR) control. According to the magnitude of grid voltage swell, the grid-side converter prioritizes the injection of a proportional inductive reactive current into the faulted grid. When the DC bus voltage exceeds its limit, a supercapacitor absorbs excess energy to stabilize the DC bus voltage. Compared with traditional PI control strategies, the proposed approach enables static-error-free control of AC input signals in the stationary reference frame while reducing coordinate rotation transformations. It eliminates coupling terms and feed-forward compensation components that are susceptible to temperature and circuit parameter variations, thereby simplifying the control algorithm. Simulation results demonstrate that this control strategy not only ensures continuous grid-connected operation of direct-driven PMSG wind turbines during grid voltage swells but also provides inductive reactive power support for grid voltage recovery.

Keywords: Permanent magnet synchronous generator, high voltage ride-through, proportional-resonant

1 Introduction

Direct-driven permanent magnet synchronous generator (PMSG) wind turbines offer numerous advantages including low mechanical losses, high operational reliability, superior generation efficiency, and simplified maintenance, leading to their widespread adoption in modern wind farms. As wind turbine capacity continues to grow rapidly, the impact of grid voltage swell faults on the safe and stable operation of wind turbines has attracted significant attention.

Voltage swell is a common grid anomaly that typically occurs under conditions of excess reactive power. Common causes include delayed disconnection of capacitor banks, single-phase ground faults, sudden load shedding at wind farms, and energization of large compensation devices. During voltage swells, PMSG systems experience DC bus voltage rise due to instantaneous power imbalance. Since converters and DC bus capacitors have limited overvoltage and overcurrent withstand capability, this can trigger wind turbine tripping. Consequently, wind turbines must possess a certain degree of continuous grid-connected operation capability during voltage swells—known as high voltage ride-through (HVRT) capability.

In recent years, countries have gradually recognized the importance of HVRT for power generation equipment and established corresponding standards [1]. These standards vary according to national grid structures and renewable energy penetration levels. Australian grid codes require wind turbines to remain connected for 60 ms when grid voltage swells to 130% of rated voltage, for 0.4 s at 120% of rated voltage, and to maintain continuous operation at 110% of rated voltage. Germany’ s E.ON grid code stipulates that wind turbines must remain operational for 100 ms at 125% of rated voltage while absorbing a proportional amount of reactive current.

Current HVRT implementation methods for PMSG wind turbines fall into two categories: additional hardware circuits and improved control strategies. Auxiliary devices can be further classified as active or passive. Active devices primarily include static synchronous compensators (STATCOM), static var compensators (SVC), and dynamic voltage restorers (DVR), which isolate wind turbines from grid faults to ensure safe grid-connected operation. Passive devices mainly consist of AC crowbar resistors and DC chopper circuits that dissipate excess system energy through additional discharge paths during faults.

Dynamic voltage restorers have been primarily employed for fault ride-through of doubly-fed induction generators (DFIG) and fixed-speed induction generators (FSIG) [2-4]. DVRs are series-connected between the wind turbine terminals and the grid point of common coupling, providing series voltage compensation through transformers during grid faults. Reference [5] proposed a reactive voltage coordinated control scheme between variable-speed constant-frequency DFIG wind farms and STATCOM, allocating reactive power between rotor-side and grid-side converters and STATCOM during grid faults to achieve low voltage ride-through (LVRT). Reference [6] series-connected STATCOM through a reactor at the wind turbine’ s point of common coupling, employing a dual-loop feedback control strategy to absorb capacitive reactive power and compensate inductive reactive power during voltage swells, thereby achieving HVRT. Reference [7] proposed an HVRT control strategy that adjusts the DC bus voltage reference online based on grid voltage and generator-side load current information to increase control margin during high voltage faults. Reference [8] utilized a mode selector to set active and reactive current references according to grid voltage swell magnitude and DC bus voltage rise level, enabling HVRT capability for PMSG wind turbines. Reference [9] achieved improved HVRT functionality for PMSG through upgrades to dump resistors and optimization of grid-side converter control. Reference [10] presented a method combining emergency pitch control, parallel DC capacitor technology, and grid-side converter voltage control from active and reactive power perspectives to enhance fault ride-through capability. Reference [11] employed PR controllers for stator voltage control in the rotor synchronous reference frame, simplifying the control algorithm and improving robustness compared to traditional PI control. Reference [12] conducted a comparative analysis of PI and PR control, concluding that PR control can replace traditional PI control in inverter applications. Reference [13] utilized a PR controller-based grid-side converter control system to maintain DC voltage stability and regulate power factor, demonstrating easier implementation for low-order harmonic current compensation in DFIG systems.

This paper introduces PR controllers into the current regulation of grid-side converters in PMSG systems, proposing an HVRT control strategy based on proportional-resonant control. During grid voltage swells, the grid-side operating mode is altered to enable rapid injection of inductive reactive power into the grid. When DC bus voltage exceeds its limit, supercapacitors store excess grid energy to maintain constant DC bus voltage, thereby equipping PMSG with HVRT capability. The proposed control strategy is validated using a solid-state transformer-based PMSG grid-connected system [14].

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2 Wind Power System Grid-Connected Model

A solid-state transformer-based PMSG grid-connected system enables electrical isolation between rectification and inversion stages while significantly reducing grid-connection inrush currents, representing an effective grid integration method for PMSG wind turbines. The system structure is shown in [Figure 1: see original paper]. During normal operation, the wind turbine drives the PMSG to generate three-phase AC power, which is converted to low-voltage DC by the machine-side rectifier. A single-phase full-bridge inverter then modulates this into a high-frequency square wave, which is stepped up by a high-frequency transformer and converted back to DC by a single-phase full-bridge rectifier. Finally, the grid-side inverter converts the high-voltage DC into stable three-phase AC power delivered to the grid.

The PMSG control system comprises machine-side converter control, DC-DC converter control, grid-side converter control, and supercapacitor control systems. Both converters in the DC-DC stage employ PWM control [15], while the supercapacitor utilizes voltage-current dual-loop control. The machine-side converter employs decoupled PI control [16], and the grid-side converter uses voltage-oriented control based on proportional-resonant controllers. The control block diagram is shown in [Figure 1: see original paper], where i_s represents generator stator current; u_{sd}, u_{sq} denote stator voltage d- and q-axis components; i_{sd}, i_{sq} represent stator current d- and q-axis components; u_g, i_g are grid-side voltage and grid current; $u_{g\alpha}, u_{g\beta}$ denote grid-side converter output voltage α- and β-axis components; $i_{g\alpha}, i_{g\beta}$ represent grid current α- and β-axis components; and e_α, e_β denote grid voltage α- and β-axis components.

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3 Analysis of PMSG Transient Process Under Grid Voltage Swell

Direct-driven wind turbines using the grid-connected system shown in [Figure 1: see original paper] feature complete isolation between the generator stator terminals and the grid. Consequently, grid faults do not directly impact the generator, allowing the analysis of HVRT control strategies to focus primarily on the grid-side converter.

The steady-state equations of the grid-side converter in the synchronous rotating reference frame are:

$$u_{gd} = Ri_{gd} + e_d - \omega Li_{gq} \tag{1}$$

$$u_{gq} = Ri_{gq} + e_q + \omega Li_{gd} \tag{2}$$

where u_{gd}, u_{gq} are grid-side converter output voltage vector d- and q-axis components; i_{gd}, i_{gq} are grid-side converter output current vector d- and q-axis components; e_d, e_q are grid voltage vector d- and q-axis components; R is the grid-side converter line resistance; L is the grid-side converter line inductance; and ω is the grid angular frequency.

According to voltage space vector modulation theory, the modulation index m must satisfy:

$$m = \frac{\sqrt{u_{gd}^2 + u_{gq}^2}}{u_{dc}/2} \leq 1$$

where u_{dc} is the DC bus voltage.

Combining [Figure 2: see original paper] and equation (2) reveals that for a given power factor angle ϕ, the terminal of the output voltage vector u_g must lie on the hypotenuse of the impedance triangle, with its maximum value u_{gmax} strictly limited by the DC-side voltage U_{dc}.

When grid voltage orientation control is employed (d-axis aligned with grid voltage vector E), the grid voltage vector q-axis component $e_q = 0$ and $e_d = E$ (where E is the peak grid phase voltage). Substituting equation (1) into equation (2) and neglecting resistance R yields:

$$u_{gmax} = \sqrt{(E + \omega Li_{gd})^2 + (\omega Li_{gq})^2} \leq \frac{U_{dc}}{2}$$

From [Figure 1: see original paper], the PMSG main circuit power balance equation is:

$$P_{gen} - P_{grid} + P_{neg} = P_{dc} = U_{dc}I_{dc} = U_{dc}C\frac{dU_{dc}}{dt}$$

where P_{gen} is generator output active power; P_{grid} is active power injected into the grid; P_{neg} is reverse power flow from grid to turbine system; P_{dc} is converter DC bus power; U_{dc} is DC-side voltage; I_{dc} is DC-side current; and C_{dc} is DC-side capacitance.

Equation (3) indicates that DC bus voltage rises with increasing grid voltage. Equation (4) shows that during grid voltage swells, power cannot be normally delivered to the grid, causing reverse power flow into the converter and DC bus voltage rise, which directly threatens converter operation. Therefore, effective HVRT control measures are essential to ensure wind turbine operation during grid voltage swells.

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4 HVRT Control Strategy Based on Proportional-Resonant Controller

4.1 Proportional-Resonant Controller

The proportional-resonant (PR) controller consists of a proportional term and a generalized integral (GI) term, with the transfer function:

$$G_{PR}(s) = K_P + \frac{K_r s}{s^2 + \omega_0^2}$$

where ω_0 is the resonant frequency; K_p and K_r are the proportional and integral constants, respectively. When the input AC signal angular frequency is ω_0, the magnitude G_{PR} becomes infinite, enabling static-error-free tracking of AC signals.

Due to limitations in analog component parameters and digital system precision, ideal PR controllers are difficult to implement in practical systems. Therefore, this paper employs a quasi-PR controller with the transfer function [17]:

$$G(s) = K_P + \frac{2K_r \omega_c s}{s^2 + 2\omega_c s + \omega_0^2}$$

According to literature [18-19], the controller bandwidth ω_c reflects the ability to track input signals. To improve response speed, the system should have adequate bandwidth, but excessive bandwidth introduces high-frequency switching noise interference. Therefore, a compromise must be made in selection. ω_c affects both controller gain and bandwidth; as ω_c increases, both bandwidth and gain increase. According to GB/T 15945-2008, the allowable frequency deviation limit caused by user impact loads is ± 0.5 Hz, giving $\omega_c/\pi = 1.0$ Hz, which corresponds to 3.14 rad/s.

K_r affects only controller gain, not bandwidth, with gain proportional to K_r. K_p influences system bandwidth and stability; as gain increases, bandwidth and stability margin initially increase then decrease. Therefore, an optimal gain coefficient must be selected to maximize stability margins.

The quasi-PR controller design procedure is as follows: (1) Select controller bandwidth ω_c based on requirements; (2) Choose K_r according to required controller gain; (3) Select K_p based on optimal gain coefficient.

In grid-side converter control, active and reactive currents in the rotating reference frame are transformed to the stationary frame for regulation using quasi-PR controllers. The grid-side inverter quasi-PR control system is designed to achieve HVRT capability.

4.2 Grid-Side Converter Reactive Power Control

During grid voltage swells, wind turbine reactive power output primarily depends on the voltage swell magnitude, following German E.ON HVRT grid code requirements: when point-of-interconnection voltage swells to 1.1 pu or above, the turbine must provide at least 2% rated reactive current for each 1% voltage increase, prioritizing fault grid compensation:

$$i_{gq}^* = \begin{cases} 0, & U_{ref} \leq 1.1U_N \\ 2(U_{ref} - 1.1U_N)I_N, & U_{ref} > 1.1U_N \end{cases}$$

where i_{gq}^* is reactive current reference; U_{ref} is measured grid voltage RMS value; and I_N is rated current.

To prevent grid-side converter overcurrent, active current magnitude i_{gd}^* must satisfy:

$$i_{gd}^* \leq \sqrt{i_{max}^2 - i_{gq}^{*2}}$$

where i_{max} is the maximum allowable current for the grid-side converter.

The grid-side converter dynamic equations in the synchronous rotating frame are:

$$L\frac{di_{gd}}{dt} = u_{gd} - Ri_{gd} - e_d + \omega L i_{gq} \quad (3)$$

$$L\frac{di_{gq}}{dt} = u_{gq} - Ri_{gq} - e_q - \omega L i_{gd} \quad (4)$$

where u_{gd}, u_{gq} are grid-side converter output voltage d- and q-axis components; i_{gd}, i_{gq} are grid-side converter output current d- and q-axis components. The grid-side converter control block diagram is shown in [Figure 3: see original paper], where i_{gq1}^* and i_{gq2}^* serve as selector1 inputs, and i_{gd1}^* and i_{gd2}^* serve as selector2 inputs.

4.3 Proportional-Resonant Based Control System

Assuming balanced three-phase grid voltage, the three-phase grid inverter output current dynamic equations in the stationary $\alpha\beta$ frame are:

$$L\frac{di_{g\alpha}}{dt} = u_{g\alpha} - Ri_{g\alpha} - e_\alpha \tag{5}$$

$$L\frac{di_{g\beta}}{dt} = u_{g\beta} - Ri_{g\beta} - e_\beta \tag{6}$$

The grid-side converter control system is shown in [Figure 4: see original paper]. Comparing [Figure 4: see original paper] with [Figure 3: see original paper] reveals that the PR control approach eliminates coordinate rotation transformations for current and voltage control commands, removing the need for coupling terms $\omega Li_{gd}, \omega Li_{gq}$ and grid voltage disturbance terms u_d. This eliminates the influence of circuit parameters and grid voltage on system control.

When grid voltage pu value does not exceed 1.1, reactive current reference i^*_{gq} is set to zero while active current $i^*_{gd1} < i^*_{gd2}$, so active current reference selects i^*_{gd1}. When grid voltage pu value exceeds 1.1, reactive current reference selects i^*_{gq2}; if active current $i^*_{gd1} > i^*_{gd2}$, active current reference selects i^*_{gd2}. Simultaneously, DC bus voltage is monitored in real-time, and when it exceeds limits, energy is stored in the supercapacitor to ensure normal wind turbine operation.

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5 Simulation Analysis

5.1 System Parameters and Simulation Conditions

A simulation model of the grid-connected system shown in [Figure 1: see original paper] was built in MATLAB/Simulink, with the grid-side converter using the control system shown in [Figure 4: see original paper]. System parameters are as follows: wind turbine rated wind speed 12 m/s, blade radius 31 m, rated speed 20 r/min, optimal tip speed ratio 5.6, power coefficient 0.33; PMSG rated power 1 MW, generator terminal line voltage 690 V, permanent magnet flux 6.27 Wb, pole pairs 48, stator d- and q-axis inductances $L_d = L_q = 2$ mH, moment of inertia 2.5×10^4 kg $\cdot$ m^2.

Based on Australian grid codes, HVRT performance is analyzed under two different conditions:

Condition 1: Grid voltage swells to 1.3 pu at 0.5 s, lasting 60 ms until 0.56 s, then returns to normal.

Condition 2: Grid voltage swells to 1.2 pu at 0.5 s, lasting 400 ms until 0.9 s, then returns to normal.

5.2 HVRT Simulation Results

[Figure 5: see original paper] shows the grid fault voltage for Condition 1. [Figure 6: see original paper], [Figure 7: see original paper], and [Figure 8: see original paper] present DC bus voltage, grid-side converter output power, and grid-side phase current waveforms with and without HVRT control strategy, respectively.

[Figure 5: see original paper] Grid fault voltage

As shown in [Figure 6: see original paper], with HVRT control strategy, DC bus voltage during the fault swells to 1.3 pu then stabilizes at 1.01 pu, compared to sustained overvoltage without control. [Figure 7: see original paper] demonstrates that active power surges to 1.6 pu without control but drops to 0.8 pu before stabilizing at 1.0 pu with control; reactive power injection increases from 0.05 pu to 0.25 pu. [Figure 8: see original paper] shows that current fluctuations during faults are significantly reduced with the proposed control strategy.

[Figure 6: see original paper] DC bus side voltage

[Figure 7: see original paper] Active power and reactive power waveform of the converter

[Figure 8: see original paper] Phase current of grid side

[Figure 9: see original paper] shows the grid fault voltage for Condition 2. [Figure 10: see original paper], [Figure 11: see original paper], and [Figure 12: see original paper] present corresponding DC bus voltage, converter power, and phase current waveforms.

[Figure 9: see original paper] Grid fault voltage

As shown in [Figure 10: see original paper], with HVRT control, DC bus voltage swells to 1.3 pu then stabilizes at 1.03 pu. [Figure 11: see original paper] indicates active power surges to 1.3 pu then drops to 1.15 pu without control, but with control drops to 0.9 pu before stabilizing at 1.0 pu; reactive power increases from 0.05 pu to 0.1 pu. [Figure 12: see original paper] confirms that current fluctuations are significantly reduced with the proposed strategy.

[Figure 10: see original paper] DC bus side voltage

[Figure 11: see original paper] Active power and reactive power waveform of the converter

[Figure 12: see original paper] Phase current of grid side

Simulation results demonstrate that during grid voltage swells, modifying the grid-side converter control mode combined with supercapacitor energy storage to absorb excess DC-side energy can prevent DC bus overvoltage, ensure normal wind turbine operation, and enhance HVRT capability.

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6 Conclusion

This paper investigates grid-side converter control strategies for PMSG wind turbines during high voltage faults, analyzing both PI and PR control systems. The study details different control methods for grid-side converters before and after faults, utilizing mode selectors to set active and reactive current references. When DC bus voltage exceeds limits, the control strategy employs supercapacitors to maintain DC bus voltage stability. Simulation results validate that the proposed control strategy achieves HVRT capability, providing theoretical value for future grid-connected direct-driven wind power generation research.

References

[1] Gao Yaqiu, Xiao Peng, Zhang Jian, et al. Study on high-voltage ride through control strategy of direct drive converter[J]. Modern Electronic Technique, 2015, 38(9): 117-124.

[2] Hong Lucheng, Wei Yingdong, Jiang Qirong, et al. Low voltage ride through strategy for wind turbine based on dynamic voltage regulator[J]. Automation of Electric Power Systems, 2011, 35(16): 32-37.

[3] Umashankar Subramaniam. Improved fault ride through capability in DFIG based wind turbines using dynamic voltage restorer with combined feed-forward and feed-back control[C]. IEEE Access, 2017(99): 1-9.

[4] Gkavanoudis S I, Demoulias C S. FRT capability of a DFIG in isolated grids with dynamic voltage restorer and energy[C]. IEEE International Symposium on Power Electronics for Distributed Generation Systems, 2014: 1-8.

[5] Zhao Jingjing, Hu Xiaoguang, Lv Xue, et al. Research on coordination control strategy of DFIG wind farm with crowbar circuit[J]. Advanced Technology of Electrical Engineering and Energy, 2016, 35(10): 17-22.

[6] Ye Shengfeng, Wang Weiqing, Wang Haiyun. High voltage ride-through technology of wind generators based on STATCOM[J]. High Voltage Apparatus, 2017, 53(5): 35-40.

[7] Zheng Zhong, Geng Hua, Yang Geng. High voltage ride-through control strategy of grid-connected inverter for renewable energy systems[J]. Proceedings of CSEE, 2015, 35(6): 1463-1472.

[8] Ma Weina, Bai Kai, Song Peng, et al. The research on control strategy of high voltage ride through for PMSG based on dual-modes control[J]. Mordern Electric Power, 2015, 32(3): 13-18.

[9] Aisikaer, Zhu Yongli, Wang Hailong. Development and test of HVRT function for PMSG[J]. Electric Power Automation Equipment, 2016, 36(12): 18-23.

[10] Bian Xiaoyan, Tian Chunsun, Fu Yang. A coordinated control strategy for fault ride-though capacity of direct-drive permanent magnet wind power generating units[J]. Power System Protection and Control, 2016, 44(9): 69-74.

[11] Chen Sizhe, Zhang Yun, Wu Jie, et al. Proportional-resonant direct voltage control of DFIG wind power generation system[J]. Electric Power Automation Equipment, 2012, 32(2): 104-113.

[12] Liu Deng, Liu Jun, Tao Zhongzheng, et al. Proportional integral and proportional resonant on the research and simulation of single-phase inverter control[[J]. Journal of Electrical Engineering, 2015, 10(10): 64-68.

[13] Chen Wei, Chen Cheng, Song Zhanfeng, et al. Double PWM converter in doubly fed wind generation system[J]. Proceedings of CSEE, 2009, 29(15): 1-7.

[14] Zhang Mingrui, Li Na, Wang Zhixin. LVRT ability of PMSG wind power system[J]. Electric Power Automation Equipment, 2014, 34(1): 128-134.

[15] Zhang Mingrui, Lin Chengxin, Xu Ruixin. Grid-connected photovoltaic power generation technology based on SST[J]. Power System Protection and Control, 2012, 40(19): 133-138.

[16] Zhang Mingrui, Chen Jie, Wang Zhixin, et al. A new permanent magnet synchronous wind-power generation grid-connected system[J]. Power System Protection and Control, 2013, 41(14): 141-148.

[17] Yang Yong, Zhao Chunjiang. Proportional resonance controller of grid-connected inverter for distributed generation system[J]. Electric Power Automation Equipment, 2011, 31(11): 51-55.

[18] Zhao Qinglin, Guo Xiaoqiang, Wu Weiyang. Research on control strategy for single-phase grid-connected inverter[J]. Proceedings of CSEE, 2007, 27(16): 60-64.

[19] Sun Qiang, Wei Kexin, Wang Shasha, et al. A novel proportional resonant control strategy and robust design in rotary vector frames for PWM converters[J]. Proceedings of CSEE, 2016, 36(5): 1344-1356.

Note: Figure translations are in progress. See original paper for figures.