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Research on Super Capacitor Energy Storage System and Its Control of Wind Power System Based on Virtual Synchronous Technology

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High penetration of wind power in power grid would seriously affect the frequency safety. Synchronous generator can adjust system power and stabilize grid voltage and grid frequency. The inverter can be equivalently regarded to be synchronous generator with the help of super capacitor. Not only the wind turbines can participate in the frequency modulation and voltage regulation, but also the inertia of the system will be improved. On the basis of the analysis of virtual synchronous generator (VSG), a method of calculating the capacity of energy storage system (ESS) is proposed and a control strategy of the bi-directional converter is researched to improve the virtual inertia of wind turbines and suppress the fluctuation of power and frequency when load or wind speed is changed. This method makes the wind farm behave like a virtual synchronous generator, and effectively enhance the grid-connected performance of wind turbines. The simulation results based on Simulink show the feasibility of the control strategy.

1. Introduction

With the constant global consumption of fossil fuel, wind power generation receives a speedy growth worldwide. With large-scale wind farms being put into grid-connected operation, wind power is gaining an increasing proportion (Zhang et al., 2010). The randomness and fluctuation of wind power pose a certain threat to steady operation of power grid, which arouse widespread concern (Ak et al., 2013).

There is a constant relationship between rotor speed and output voltage frequency in synchronous generator (SG). When a sudden change in load causes a frequency change, a damping effect is produced by the SG system, resulting in the certain inertia of the SG system (Fang et al., 2013). Therefore, SG presents remarkable effect in maintaining system power balance and stabilizing frequency. If a control strategy is used to make the grid-connected inverter process the external characteristics of SG, the stability and reliability of grid-connected wind power generation system can be improved. The virtual synchronous generators (VSG) technology is proposed to solve this problem (Zhang et al., 2006). (Lu and Chu, 2015) apply the theory of virtual synchronous generators (VSG) to grid-connection realm of micro-grids and wind power farms. That is to say, by use of the parallel power storage devices on the dc bus side of distributed power generation systems (DPGS) and with the use of the grid-connected control strategy of simulation of SG's operation characteristics, the stability of system frequency is improved.

In recent years, energy storage technology has received a boost while increasing the incidence of renewables (Breschi et al., 2009). Energy storage system (ESS) devices are found wide applications in smoothing wind farm power fluctuation (Cui et al., 2008), increasing damping of wind turbines (Liu et al., 2012), enhancing low voltage ride-through (LVRT) capability (Zhang et al., 2012), compensating for virtual inertia of power generation system (Ji and Zhang, 2010), etc., and hence substantially improving wind power quality (Yuan et al., 2013). Whereas super capacity features high power density, quick response, etc., application of ESS in the control of wind farm's simulated SGs will not only effectively improve frequency stability of wind power, but also take part in maintaining power grid's power balance, which makes it has a good prospect for application.

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However, research of existing literatures focused more on “virtual synchronous” control strategy of grid-connected inverters while paid little attention to ESS devices including type, capacity and control method. On the analysis of virtual synchronous control of ESS used in wind power system, this paper probes into the scheme for configuring ESS capacities for compensating for virtual inertia of wind turbines, and proposes a systematic overall control strategy based on virtual synchronous technology. The energy control strategy of DC/DC converter for energy exchange between ESS and dc bus is also studied. By detecting system frequency signals, real-time adjustment of energy exchange between ESS and dc bus of generation system and dynamic compensation for virtual inertia of wind turbines, frequency fluctuation of system is effectively damped and dynamic characteristic of system is improved.

2. System Structure and Working Principle

The wind power system with VSG technology is commonly made up of distributed energy and energy storage devices, bi-directional DC/DC converter and grid-connected inverter with VSG technology. By the systematic overall control strategy of wind power generator and grid-connected inverter, the maximum power point tracking (MPPT) of wind energy is achieved, which makes most efficient use of wind energy. The system structure of wind power system with VSG technology is shown in Figure 1.

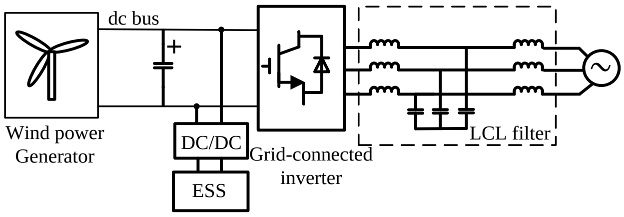


Figure1: The system structure of wind power system with VSG technology

The super capacity is deployed at the dc bus, thus making full use of its high power density and fast charging/discharging characteristics. As a result, it not only suppresses bus-side voltage fluctuation, but also enables fast throughput power and maintains balance between input and output powers. The energy exchange between ESS and bus, controlled by the bi-directional DC/DC converter, can directly suppress power fluctuation at the Dc bus while effectively enhances virtual inertia of power generation system, in comparison to deployment of super capacity ESS at the output portion of wind turbines.

3. VSG Model and Control

3.1 VSG Model

Comparison between the grid-connected inverter and synchronous generator reveals that the three-phase bridge arm voltages U_a, U_b, and U_c of the inverter can be regarded as internal potential of synchronous power generation, and that the inductance L can be deemed as internal inductance of synchronous motor, and that the circuit and inductance internal resistance R can be viewed as synchronous motor’s armature resistance. In this way, the grid-connected inverter of wind farm can be structurally equivalent to synchronous generator, as shown in Figure 2.

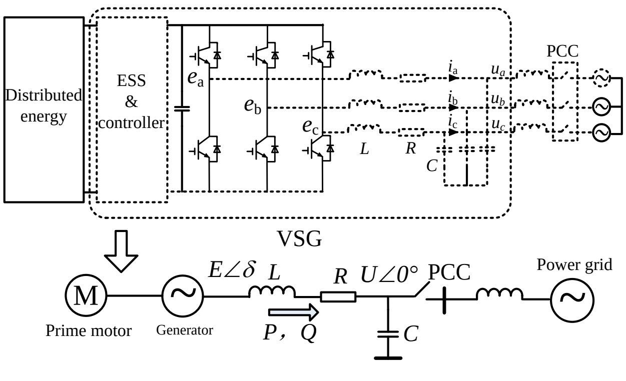


Figure 2: The equivalent circuit of VSG

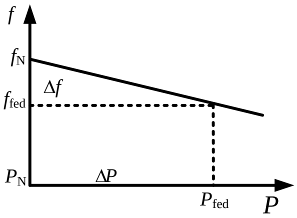
To show the operation characteristics of synchronous generator and reduce analysis difficulty, the second-order mathematic model of the synchronous generator is used,

$$\boldsymbol{E}_0 = \boldsymbol{U} + \boldsymbol{I}R_a + j\boldsymbol{I}X_s \tag{1}$$

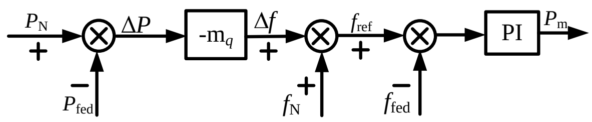
$$J\frac{d\omega}{dt} = T_m - T_e - T_d = T_m - D(\omega - \omega_0) \tag{2}$$

where E_0 is the exciting electromotive force, U and I are the generator output voltage and output current respectively, R_a and X_S are the armature resistance and synchronous impedance respectively; ω is the rotor synchronous angular frequency, T_e and T_d are the synchronous generator electromagnetic and damping torque respectively, T_m is the mechanical torque, D is the damping coefficient.
It shows that J in equation (2) enables grid- connected inverter to simulate the virtual rotation inertia during operation, and that D in equation (2) makes it possible for inverter to enable sudden change in damping grid frequency.

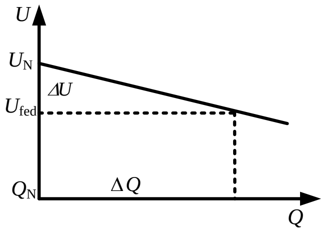
3.2 VSG Control Strategy
Figure 3(a) and 3(b) reflect the *P-f* sagging relationship of synchronous generator. When the system runs steadily, according to the theory of power balance, the active power output by generator should be the same as system active load, and when the load changes, the output power of generator will change accordingly. In detail, by comparing actual value of active power P_{fed} and the given value P_N ($\Delta P=P_N- P_{fed}$), and by calculating the sagging characteristic curve, Δf is got; the sum of Δf and f_N ($\Delta f=f_{ref}-f_N$) is the given value of frequency and is compared with feedback frequency F_{fed}, and then control the speed adjustment system to get the expected virtual mechanical power P_m.



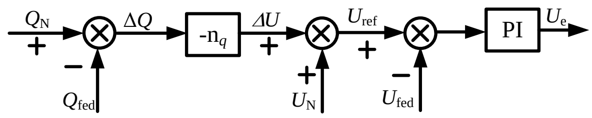
(a) Active-frequency Characteristic



(b) Block diagram of active-frequency control



(c) Reactive-voltage characteristic



(d) Block diagram of reactive-voltage control

Figure 3: Synchronous generator frequency and voltage control

Figure 3(c) and 3(d) show the *Q-U* sagging relationship of synchronous generator. The relationship in this figure shows that stability of voltage level can be realized by maintaining reactive power balance of the system. When reactive load changes, *Q* deviates from rated reactive power Q_N. The given terminal voltage value U_{ref} is then obtained using sagging characteristic curve. After comparison of it with actual value, the output voltage of synchronous motor and the given value are kept consistent by use of PI regulator.

4. Capacity Optimization of ESS and its Control

4.1 Configuration of ESS Capacity
When the system load change causes frequency fluctuation, ESS can help grid-connected inverter to generate varied virtual inertia by adjusting of ESS output volume. Under varying operation states, the volume of system inertia produces varying influence over power grid also. The excessively small inertia will result in poor damping effect of system over frequency fluctuation, while excessively large inertia will cause deterioration in dynamic performance of this system. Therefore, keeping system inertia constant within reasonable range is the only way to enhance system stability. With the reference to satisfied stability of regular synchronous generator and its adjusting frequency and voltage ability over power grid, energy storage output

is adjusted to enable wind farm to simulate inertia and damping characteristics similar to regular wind turbines, which reduces the adverse effect produced by wind farm connecting power grid.
Analysis result shows that the turning speed of synchronous generator is related to system frequency during the participation procedure of adjusting system dynamics. The power grid frequency only varies within a very small range, and therefore, only a very small amount of kinetic energy is released in the process of this participation in system frequency modulation. On the other hand, ESS can release almost all energy stored in it (to avoid ESS "over-discharge", value of state of charge (SOC) usually goes no less than 0.2). Therefore, a relatively small energy storage capacity is sufficient to make the grid-connected inverter simulate frequency modulation characteristics of synchronous generator by using ESS. Whereas the turning speed variation of synchronous generators generally falls within 0.95~1 pu, the maximum rotor kinetic energy to be released by the synchronous generator is

$$\Delta E_{\max} = \frac{1}{2}J(1-0.95^2)\omega_s^2 = 0.04875J\omega_s^2 \tag{3}$$

When the generator runs at rated speed, the kinetic energy stored by rotor is

$$E_s = \frac{1}{2}J\omega_s^2 = \frac{1}{2}P_{\mathrm{N}}T_{\mathrm{J}} \tag{4}$$

Suppose the energy released by ESS in time *t* equals that by generator rotor. Thus

$$\Delta E_{\mathrm{ESS}} = \Delta E_{\max} = P_{\mathrm{ESS}} \cdot \Delta t = 0.04875P_{\mathrm{N}}T_{\mathrm{J}} \tag{5}$$

In equations (3)~(5), ω_s is the rotor angular speed; T_j is the inertia time constant of generator; P_N is the rated power of generator; P_{ESS} is the energy storage power capacity.
(Zhang, 2014) shows that the time in which the power system participates in frequency control relying on inertia is about 10 s, so the time where the wind power participates in frequency modulation relying on inertia is not long. Suppose that this time equals the inertia time of synchronous generation, and then ESS power capacity is

$$P_{\mathrm{ESS}} = 0.04875P_{\mathrm{N}} \tag{6}$$

This shows ESS with about 5 % of rated capacity of wind turbines can just simulate the virtual inertia of synchronous generator with the same capacity. On the other hand, using ESS to assist in wind turbines' simulation of inertia control won't add difficulty in system control, thus improving reliability of control system.

4.2 Bi-directional DC/DC converter Control Strategy

The bi-directional DC/DC converter is the channel for power flow between ESS and Dc bus. The external wind speed fluctuation or power variation in power grid will cause violent fluctuation of Dc bus. If this fluctuation is not suppressed, a steady operation of inverter will be achieved. In this paper, by controlling the Buck/Boost bi-directional inverter, the stability of bus voltage is achieved. As shown in Figure 4, when the circuit runs under Buck state, the super capacitor is charged, and it is discharged vice versa. In this way, the application efficiency of ESS is enhance, and the ESS capacity is reduced as much as possible and thus the economy of this system is enhanced (Zhang et al., 2011).

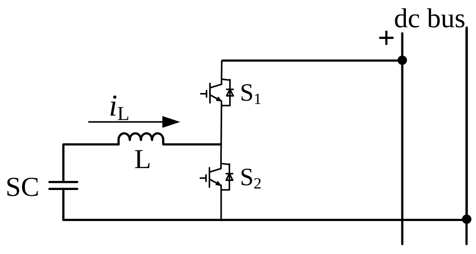


Figure 4: Super capacity and its controller

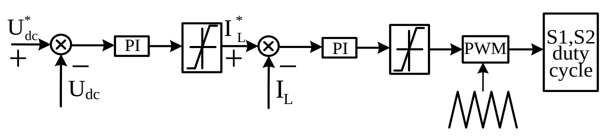


Figure 5: Control strategy of bi-directional DC/DC converter

The Buck/boost bi-directional inverter features simple structure, few power components and excellent control performance. It is controlled in two ways, that is, complementary PWM control and independent PWM control. In independent PWM control, it is necessary to control steady switch between Buck and Boost states in order to stabilize power exchange between two sides and protect power components. To achieve this objective, the hysteresis control is used for realization generally. In practical circumstance, the super capacity makes quick response to system state and needs fast throughput power to make full advantage of its high power density. So, independent PWM control is used to realize fast exchange between super capacity energy and bus power, thus enhancing the system stability and dynamic response speed.

The control of bi-directional inverter aims to stabilize bus voltage. In order to improve system stability and dynamic performance, capacity voltage and inductive current states serve as double-loop control strategy for volume control, the external loop serves as bus voltage and the internal loop serves as super capacity current. Control block diagram of system is shown in Figure 5.

Here U_{dc}^{*} is rated value of Dc-bus voltage. When actual value U_{dc} fluctuates, the deviation between these two values is processed by PI adjustor and then the inductive current demand is obtained subject to amplitude limiting. After the demand is compared with actual value of inductive current, it runs through current adjustor. After amplitude limiting, PWM generating module produces switching signals for Switches S_1 and S_2.

5. System Simulation

Based on the VSG and ESS control strategy, a wind power system simulation model with super capacity ESS is built in Matlab/Simulink environment, with the purpose of

(1) Verify the effectiveness of ESS in suppressing power fluctuation when input power fluctuates, by way of energy exchange between super capacity and bus side;

(2) Verify the damping effectiveness of wind turbines over system frequency variation, with the use of ESS, by way of virtual synchronous control algorithm.

5.1 Simulation Parameters

(1) Wind turbines with rated capacity is 25 kW, and super capacity is 1.5 kW. With installation of ESS, the whole is equivalent to a VSG with rated capacity 25 kVA.

(2) VSG parameters: R_a=0.01 Ω, X_s=0.2 Ω, J= 0.14 kg·m^2, filter inductance L=6 mH, filter capacity C=15 μF, line resistance R=0.2 Ω. To enable the optimal dynamic performance of the system, the foregoing parameters can be adjusted as required.

(3) Super capacity rated voltage is 220 V, 20 F, 0.1 Ω; Dc-bus voltage is 350 V, and bi-directional inverter's switch frequency is 10 kHz.

5.2 Simulation Results

The wind speed variation will cause fluctuation of power output by wind turbines, influencing the steady operation of power grid. When wind speed is varying, high power density characteristic of super capacity is used for fast throughput of power fluctuation of wind turbines and smoothing the active power fed by the wind turbines to the power grid. In Figure 6, P_{WT} and P_G respectively represent wind turbine output power and power fed by wind turbine into power grid.

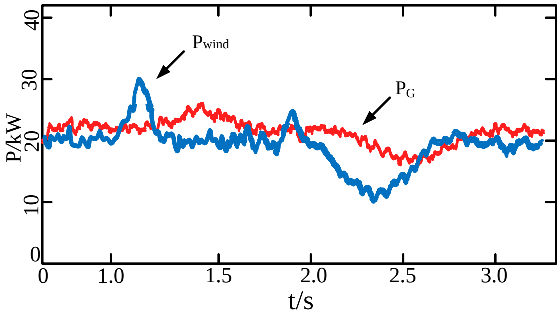


Figure 6: wind turbine output and grid-connection power

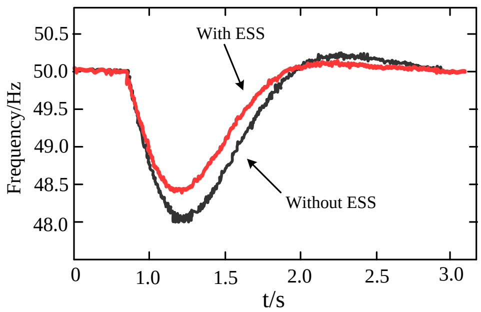


Figure 7: Frequency dip at sudden load increase

At 10.0 s, the active power of the system suddenly increases by 10 kW; comparison is made between wind turbines without ESS and that with super capacity ESS presents the simulation results as shown in Figure 7.

Figure 7 shows the comparison of system frequency response in such two cases. This shows that the wind power system without ESS and VSG algorithm falls to frequency 47.9 Hz, while that with super capacity ESS remarkably slows down in system frequency variation with the lowest value 48.7 Hz. This also shows that the large-scale connection of wind turbines into power grid will reduce the frequency stability of power grid, and pose certain threat to power grid. With the application of VSG control algorithm, ESS assists system to generate the virtual inertia which effectively improve dynamic performance of system frequency.

6. Conclusion

The large-scale connection of wind power into power grid reduces the moment of inertia in power grid to some extent, posing threat to its safe and steady operation. In this paper, the wind turbines configured with super capacity ESS is simulated into a VSG, so that it comes with good grid connection interfacing characteristics. This does not only reduces fluctuation of grid-connected power, but also presents good characteristics of synchronous generator to the power grid. During grid-connected operation, certain inertia support can be provided to power grid, thus enhancing the system ability of active participation in frequency modulation and voltage regulation and improving the ability of power grids to take in such distributed energy as wind power.

Acknowledgments

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