영구자석 동기발전기 시스템을 위한 회전자 관성에너지를 이용한 Sliding Mode제어 기반 LVRT 제어

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Use of Stored Energy in Rotor Inertia for LVRT of PMSG Wind turbine based on Sliding Mode Control

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Abstract - This paper describes a low-voltage ride-through method for the permanent magnet synchronous generator (PMSG) wind turbine system at a grid fault. The generator side converter regulates the DC link voltage instead of the grid side converter by storing the surplus active power in the rotor inertia during grid fault by the sliding mode controller. The grid side converter controls the grid active power keeping a maximum power point tracking. Simulation results for small scale PMSG wind turbine verify the efficiency of the control method.

1. 서 론

The wind power capacity has been increased significantly. Because of lager scale of wind turbine, one of important issue in wind turbine is the grid connection condition of the wind turbine. Therefore, the low-voltage ride-through (LVRT) method of the wind turbine system is necessary during grid fault. Various methods have been discussed for the LVRT method in the wind turbine systems. Typically the grid side converter controls the DC link voltage. However, the grid side converter could not efficiently control the DC link voltage during the grid fault. By exchanging of control role of the generator and grid side converter, the DC link voltage is regulated constant value during the grid fault. The nonlinear relationship between the DC link voltage and the generator power is derived. The sliding mode control method is applied to control the DC link voltage in the generator side converter. In other hand, the grid side converter controls power delivered to grid. The validity of the control method is verified by MATLAB/Simulink simulation results for the permanent magnet synchronous generator (PMSG) wind turbine.

2. PMSG Wind Power Systems

2.1 Modeling of Generator Side Converter

The output mechanical power of wind turbine, P_t, and the tip speed ratio, λ, are given by,

$$P_t = \frac{1}{2}\rho A C_p(\lambda,\beta) v_{wind}^3. \tag{1}$$

$$\lambda = \frac{\omega_m R}{v_{wind}}. \tag{2}$$

where ρ is the air density, v_{wind} is the wind velocity, A is the blade swept area, C_p is the power coefficient that is function of pitch angle, β, and the tip speed ratio, λ. The voltage equations of the PMSG, the torque, generator speed equation in d-q frame given by,

$$v_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} - \omega_s L_s i_{qs}. \tag{3}$$

$$v_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} + \omega_s L_s i_{ds} + \omega_s \lambda_f. \tag{4}$$

$$T_e = \frac{3}{2} p \lambda_f i_{qs}. \tag{5}$$

$$T_m - T_e = J\frac{d\omega_m}{dt}. \tag{6}$$

where v_{ds}, v_{qs} are stator voltage, i_{ds}, i_{qs} are stator current, L_s is stator inductance, R_s is stator resistance, ω_s is rotor flux electrical speed, λ_f is rotor flux, p is machine pole pairs, T_e is electromagnetic torque, T_m is mechanical torque, J is inertia of rotor, ω_m is generator mechanical speed.

2.2 Modeling of Grid Side Converter

The grid voltage equation are given by in d-q frame,

$$v_d = v_{id} - Ri_d - L\frac{di_d}{dt} + \omega L i_q. \tag{7}$$

$$v_q = v_{iq} - Ri_q - L\frac{di_q}{dt} - \omega L i_d. \tag{8}$$

where L is grid inductance, R is grid resistance , v_d, v_q are grid voltage, i_d, i_q are grid current, v_{id}, v_{iq} are the converter voltage. If d-axis of rotating frame is align with vector of grid voltage, the active and reactive power to grid can be expressed as,

$$P_{grid} = \frac{3}{2} v_d i_d. \tag{9}$$

$$Q_{grid} = \frac{3}{2} v_d i_q. \tag{10}$$

The active and reactive power to grid can be controlled by grid currents, i_d, i_q , respectively.

2.3 DC Link Voltage

Ignoring the converter loss, relationship of the DC link voltage and the generator, grid power is given by,

$$P_c = CV_{dc}\frac{dV_{dc}}{dt} = P_g - P_{grid}. \tag{11}$$

where P_g is the generator power, P_{grid} is the grid power, P_c is the DC link capacitor power, V_{dc} is the DC link voltage, and C is the DC link capacitor.

2.4 Generator Side Converter Control

We propose a generator side converter controller using the sliding mode control. The generator side converter controller is designed for the DC link voltage regulation. Sliding surface is designed as following equation.

$$e = V_{dc}^* - V_{dc}. \tag{12}$$

$$s = k_p e + k_{i1}\int e + k_{i2}\iint e. \tag{13}$$

where e is th DC link voltage error, V_{dc}^* is the DC link voltage reference. The derivation of sliding surface is given by,

$$\dot{s} = k_p\dot{e} + k_{i1}e + k_{i2}\int e = \frac{k_p}{CV_{dc}}P_{grid} - \frac{k_p}{CV_{dc}}u + k_{i1}e + k_{i2}\int e. \tag{14}$$

$$u_{eq} = P_{grid} + \frac{k_{i1}C}{k_p}V_{dc}e + \frac{k_{i2}C}{k_p}V_{dc}\int e. \tag{15}$$

The equivalent control input u_{eq} make the derivation of sliding surface come to be zero. Lyapunov function is selected by,

$$v = \frac{1}{2}s^2. \tag{16}$$

By taking time derivative of v, we could obtain,

$$\dot{v} = s\left(\frac{k_p}{CV_{dc}}P_{grid} - \frac{k_p}{CV_{dc}}u + k_{i1}e + k_{i2}\int e\right). \tag{17}$$

Taking a control law as,

$$u = u_{eq} + Ksgn(s), \tag{18}$$

$$\dot{v} = s\dot{s} = -\frac{k_p K}{CV_{dc}} s \cdot sgn(s) = -\frac{k_p K}{CV_{dc}} |s| < 0. \tag{19}$$

Lyapunov function v is satisfied positive definite and $\dot{v}$ is satisfied with negative definite. Therefore, the system trajectory reaches in boundary layer in finite time.

2.5 Grid Side Converter Control

The grid side converter controller is designed for a maximum power point tracking (MPPT). If air density and turbine radius are invariable, the wind turbine power depends on the generator speed. The maximum turbine power is expressed as,

$$P_t = \frac{1}{2}\rho A C_{P\max}\left(\frac{\omega_m R}{\lambda_{opt}}\right)^3 = K_{opt} \cdot \omega_m^3. \tag{20}$$

$$P^*_{grid} = \begin{cases} K_{opt}\omega_m^3 & (\text{if } normal\ operation) \\ P_{LVRT} & (\text{if } grid\ fault) \end{cases}. \tag{21}$$

During steady state, if electrical and mechanical loss are neglected, the grid power, generator power and turbine power are equal. Hence the maximum turbine power is selected as the grid power reference in normal operation. If the grid fault occur, LVRT requirement is selected as grid power reference. This control method allows to store the surplus active power in inertia of rotor during fault.

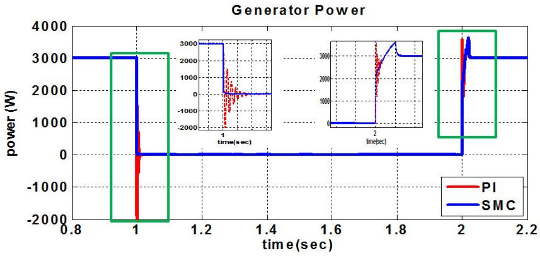
2.6 Simulation Result

To demonstrate the validity of the proposed method, simulation is carried out under MATLAB/Simulink. Parameters of wind turbine are expressed in Table 1.

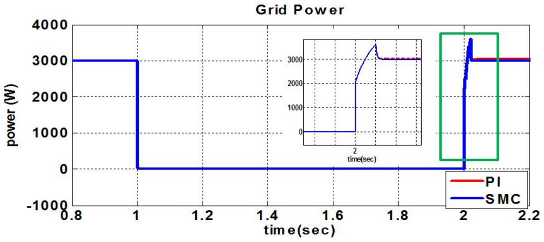
<Table 1> Parameter of Wind Turbine

P_{rated}	3 [kW]	v_{wind}	11 [m/s]
C	600 [μF]	p	8
V_{dc}	800 [V]	L,R (stator)	51 [mH] , 2.4 [Ω]

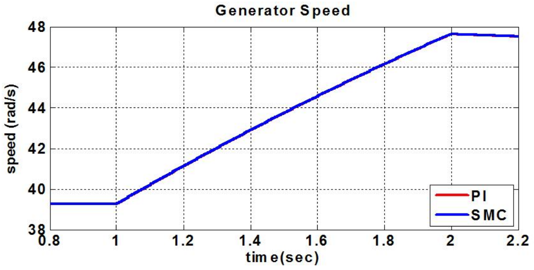
For 70% sag of the all grid fault occurs at 1 s, and grid fault is cleared at 2 s. Generator and grid power are described in Fig. 1 and Fig. 2. During the grid fault, the grid power is reduced because of low grid voltage and current limit. The generator power follows the grid power to regulate DC link voltage. Because of nonlinear relationship between the DC link voltage and the grid power, the sliding mode controller shows the better transient response than conventional PI controller. After the fault clearance, the grid and generator power are recovered. Fig. 3 shows generator speed variation. During the fault, the generator side converter forces the generator to reduce the active power. Hence the stator current and the generator electromagnetic torque is reduced. Because of a mismatch in torque, generator speed is increased. After the fault clearance, generator speed is reduced by a relationship of the electromagnetic and mechanical torque and the energy stored in the inertia of rotor is delivered to the grid. Fig. 4 shows the DC link voltage variation. When we use sliding mode control, the peak value of the DC link voltage variation V_{dc} is about 0.1025%. The sliding mode control shows better performance in transient response. The reason of occurrence overshoot of the DC link voltage is changing speed gap of generator and grid power in transient state.



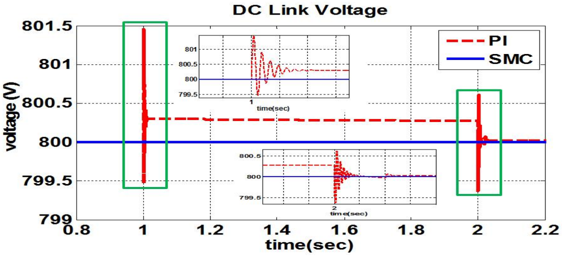
<Figure 1> Generator active power when voltage sag 70%.



<Figure 2> Grid active power when voltage sag 70%.



<Figure 3> Generator rotation speed when voltage sag 70%.



<Figure 4> DC link voltage when voltage sag 70%.

3. 결론

A sliding mode control was presented to regulate the DC link voltage during grid fault in a PMSG wind power system. The proposed control method allowed to regulate DC link voltage by storing the surplus energy in the rotor inertia during a grid fault. The simulation results verified the feasibility of control method. The sliding mode control showed better performance than PI control in transient state. With this control method, it was expected that the additional equipment like the DC link brake chopper is not necessary in balanced grid fault.

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