LVRT Research Based on Novel Energy Storage Control System

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Abstract: The energy storage system (ESS) with isolated bidirectional DC/DC converter based on parameter adaptive fuzzy PI control method is proposed to realize the low voltage ride through (LVRT) of the double fed wind power generation system. Firstly, the mathematical model of doubly fed wind power generation system and energy storage system are analyzed. Secondly, the coordinate control strategy of the rotor side converter and grid side converter is designed. The energy storage system used in grid normal condition or fault period is analysized. Parameter adaptive fuzzy PI control is used to replace traditional PI control to reduce the transient procession caused by the fault， shortening the adjusting time of the system, improving the dynamic performance. Finally the simulation researches of the system are carried out by Matlab/Simulink simulation software, and the feasibility and effectiveness of the proposed method are verified by comparing the simulation results of the parameters adaptive fuzzy PI with the traditional PI control, keeping the stability of DC bus voltage in the process of LVRT.

Introduction

In the current wind power generation system, doubly fed induction generator (DFIG) mainly provides slip power through dual PWM converter, so the converter capacity is only 30% of the whole power capacity, thereby reducing the cost and volume of the system. These advantages make it acclaimed in the wind power market. However, due to the stator side of the generator connected with the grid directly, once the short-circuit fault occurs in power grid side, the voltage of point of common coupling (PCC) usually drops, further causing adverse effects to the wind power system, such as rotor over current, torque ripple, power fluctuations, DC side over voltage or other issues[1]. To protect the converter connected with the wind turbine at LVRT, the wind power system is broken away from grid [2,3]. However, with the increasing of grid penetrating power of wind power system, the traditional method of wind turbine removal is no longer suitable for the reason that will lead to a large range of grid voltage/frequency fluctuations, further leading to the collapse of the entire power grid system. The new grid security criterion is shown that the wind power generation system must have the capability of LVRT, the grid code of wind power system for China is shown in Figure 1 [4].

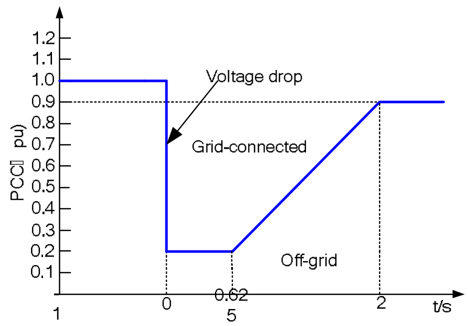


Fig.1 LVRT operation curve of wind generation system

As can be seen from Figure 1, when PCC voltage of wind farm drops to 0.2pu, the wind power system is required to keep 625ms operation, PCC voltage can be recovered to 90% of the rated voltage within 2 seconds, and the wind generator in the wind farm must ensure the continuous operation.

At present, there are two main forms of the LVRT implementation of the doubly fed wind power generation system: the first one is to improve the control strategy, which is usually suitable for small grid voltage sag. Once the voltage sag degree is large, this method is difficult to achieve good results. The second one is to add hardware circuits, some protection schemes, such as the crowbar circuit[5-7] or buffer circuit (SDR)[8,9]have been proposed in the existing domestic and international literatures. Crowbar protection is mainly divided into active and passive structure, the choice of the cast time and the size of the crowbar resistance will have a big impact on the protection effect. The advantage of which is that it can restrain well the rotor over current. The main shortcoming is that the rotor converter will be blocked during the crowbar circuit operation, so the doubly fed induction generator need to absorb a certain reactive power, which is not conducive to the restoration of the grid. The SDR protection scheme can suppress the over voltage of the DC bus, but can do nothing to deal with the drop of the DC bus voltage.With the increase of the storage capacity and the charge or discharge rate, the LVRT of wind power generator by the energy storage protection circuit becomes possible [10]. According to the different connecting positions of the energy storage system, which can be divided into two types: the first one is to access the PCC terminal [11], the second is DC bus terminal [12, 13]. The first method increases the cost of a DC/AC converter compared with the second, and the capacity of the storage system is larger, so the method is not practical. The second method uses mostly super capacitor energy storage system with non isolated bidirectional DC converter structure, where input and output terminals can not achieve electric isolation, voltage and current ratio can not be too big. To solve this problem, this paper adopts an isolation type push-pull full bridge (PFB) bi-directional converter to achieve LVRT control. The converter is suitable for high voltage and high power applications, it can provide good electrical isolation and improve the security of the system. So it has been used widely in the UPS system, electric vehicles, new energy power generation systems and aerospace power systems.

The model of DFIG system based on ESS

The topology structure of system

The double fed generation system topology based on energy storage is shown in Figure 2.

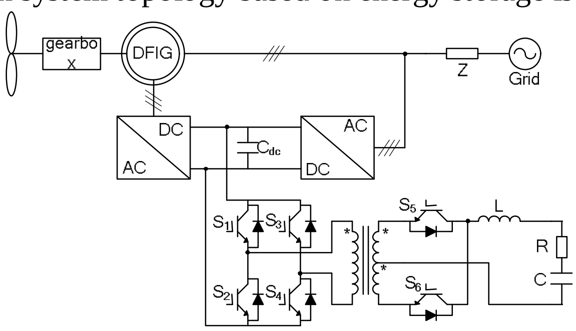
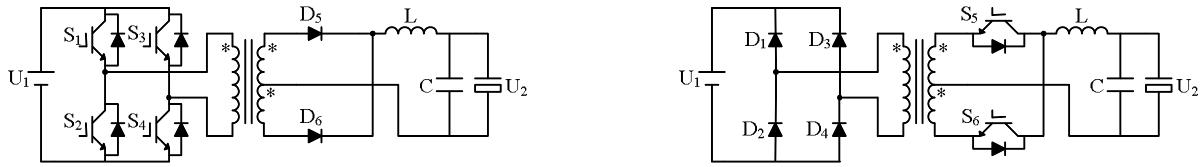


Fig.2 DFIG wind power system based on novel energy storage

The stator of doubly fed wind power generation system is directly connected with the grid, and the rotor side is connected with the dual PWM converter to adjust the slip power to achieve variable speed constant frequency (VSCF). Energy storage system is composed by the RC series circuit and isolated PFB bi-directional DC/DC converter. The converter is directly connected to DC bus link of the dual PWM converter. In the process of LVRT, the power grid voltage causes directly the impact on the DFIG, and leading to over-voltage and over current of the rotor side. The excess energy will make the DC link voltage rise, endangering the safe operation of the whole wind turbine system. Storage system is accessed to absorb the energy gathered on the DC bus capacitor, stabilizing DC bus voltage fluctuations during the fault.

The mathematical model of DFIG

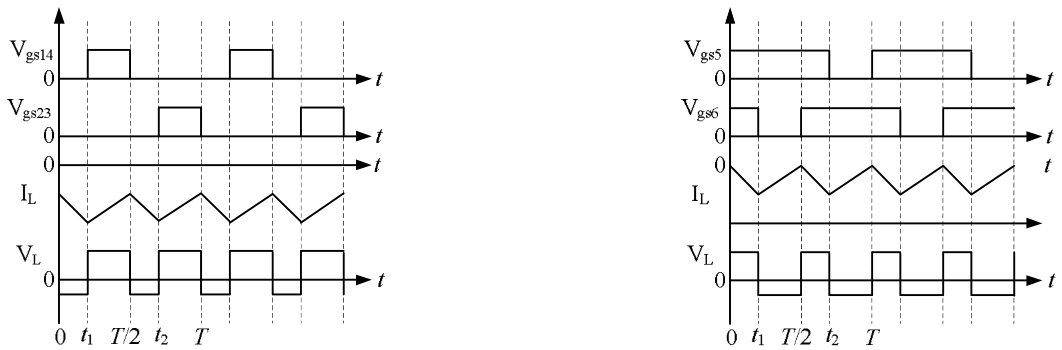
The mathematical model of doubly fed wind power generation system consists of four parts: the wind turbine, the grid side converter, the rotor side converter, and the ESS. In ESS, PFB bi-directional DC/DC converter includes boost and buck mode, the topology is shown in Figure 3 [14, 15].



(a) buck mode (b) boost mode

Fig.3 The topology structures of boost and buck mode

The energy storage system based on isolated bidirectional DC/DC converter is to achieve LVRT. During power grid fault, when the DC bus voltage is greater than the rated voltage, PFB bi-directional converter works in buck mode, switch tube S5 and S6 are equivalent to the diode, which plays the role of synchronous rectification, then by controlling the S1~S4 turn on and off, the excess energy of the DC bus is convened to the energy storage element in the right side. By conducting in turn of the switch tubes S1, S4 and S2, S3, Inductance L storage energy by single-phase full bridge and transformer. While when switch tubes S1~S4 turn off, the inductance L using S5 and S6 to hold current and release energy, working status is shown in Figure 4 (a). When the DC side voltage is smaller than the rated voltage, PFB bi-directional converter works in boost mode, switch tube S1~S4 is equivalent to the diode, which plays the role of synchronous rectification, the energy is transferred from the push-pull circuit to the DC side by controlling switch S5 and S6. On the process of switch tube S5 and S6 conducting in turn, the energy of storage element transmits to the DC bus by the push-pull converter and transformer, the inductance L storages energy, so the current rise. On the process of S5 and S6 conducts simultaneously, the inductance L using S5 and S6 to hold current and release energy, so the current falls, the working status is shown in Figure 4 (b). Therefore, the PFB bi-directional converter can operate at boost or buck mode according to the change of the DC side voltage during the grid fault period, controlling the DC link voltage within the allowable range,realizing LVRT.



(a) buck mode (b) boost mode

Fig.4 The main waveforms of boost and buck mode

The mathematical model of grid-side converter

The mathematic model of grid-connected converter can be expressed as formula (1) when d axis voltage vector orientation is applied. Where e_{dq}、 s_{dq} and i_{dq} are dq components of grid voltage, switching function and grid current respectively， w is angular frequency of fundamental wave, L is filter inductor, R is equivalent series resistor of filter inductor, C is dc-link capacitor, u_{dc} is dc-link voltage.

$$\begin{cases} C\dfrac{du_{dc}}{dt} = \dfrac{3}{2}\left(i_d s_d + i_q s_q\right) - \dfrac{u_{dc}}{R_L} \\ L\dfrac{di_d}{dt} + Ri_d - wLi_q = e_d - u_{dc}s_d \\ L\dfrac{di_q}{dt} + Ri_q + wLi_d = e_q - u_{dc}s_q \end{cases} \tag{1}$$

The mathematical model of rotor-side converter

The stator voltage and rotor voltage of rotor-side converter under two-phase synchronous rotary coordinate can be expressed as formula (2) and (3):

$$\begin{cases} U_{sd} = R_s i_{sd} + py_{sd} - wy_{sq} \\ U_{sq} = R_s i_{sq} + py_{sq} + wy_{sd} \end{cases} \tag{2}$$

$$\begin{cases} U_{rd} = R_r i_{rd} + py_{rd} - (w - w_r)y_{rq} \\ U_{rq} = R_r i_{rq} + py_{rq} + (w - w_r)y_{rd} \end{cases} \tag{3}$$

Where U_{sdq}, i_{sdq} and y_{sdq} are dq components of stator voltage, stator current and stator flux linkage respectively, U_{rdq}, i_{rdq} and y_{rdq} are components of rotor voltage, rotor current and rotor flux linkage respectively, w and w_r are synchronous angular speed and rotor angular speed respectively, R_s and R_r are stator resistor and rotor resistor, p is differential operator. The stator flux linkage and rotor flux linkage can be expressed as

$$\begin{cases} y_{sd} = L_s i_{sd} + L_m i_{rd} \\ y_{sq} = L_s i_{sq} + L_m i_{rq} \end{cases} \tag{4}$$

$$\begin{cases} y_{rd} = L_m i_{sd} + L_r i_{rd} \\ y_{rq} = L_m i_{sq} + L_r i_{rq} \end{cases} \tag{5}$$

Where y_{sdq} and y_{rdq} are dq components of stator and rotor flux respectively; i_{sdq} and i_{rdq} are dq components of stator and rotor current respectively; L_s is self-inductance of stator equivalent two-phase winding, $L_s = L_m + L_{ls}$; L_r is self-inductance of rotor equivalent two-phase winding, $L_r = L_m + L_{lr}$; L_m is mutual inductance of stator and rotor equivalent two-phase winding.

The electromagnetic torque can be expressed as formula (6):

$$T_e = n_p L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq} \right) \tag{6}$$

LVRT control strategy based on new ESS

The control strategy of ESS

The control block diagram of the energy storage system is shown in Figure 5. In grid normal operation period, the energy storage system is not working, and the DC bus voltage is controlled stable by the grid side converter (GSC). Once a short circuit fault occurs, voltage sag detection module sends a signal to control switch S connect to 2, the energy storage system starts to work, absorbing excess energy on DC bus capacitance, maintaining the stability of the DC bus voltage, and providing excitation voltage to RSC. When the power grid fault is cleared, the switch S switch to mode 3, the energy storage system uses constant current discharge mode, the super capacitor terminal voltage is restored to its initial state. Voltage and current double closed loop control is used in the control strategy, voltage outer loop uses parameter adaptive fuzzy PI control instead of traditional PI control to achieve the stability of DC bus voltage during fault, current inner control uses fast track instruction to improve the response speed of the system. The traditional PI control is controlled linearly, which has a large error gain because of definite integral constant [16], when the voltage deviation is large, the PI operation integral is accumulated, which caused large overshoot and oscillation of the system. The power electronic converter itself has a strong nonlinearity, so the parameters adaptive fuzzy PI control can be used to adjust the proportion and integral coefficient dynamically, reducing transient degree, shortening the adjusting time, and improving the dynamic performance of the system.When the DC side voltage exceeds the reference value, converter works in buck mode, charges the energy storage system on the right side. When the DC side voltage is lower than the reference value, converter works in boost mode, energy storage system is discharged, energy feeds back to the DC side and makse the DC link voltage rise.

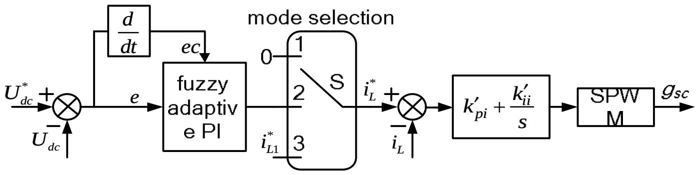


Fig.5 The fuzzy logic control strategy of PFB bidirectional DC/DC converter

In order to realize the fuzzy control much better, the membership function, fuzzy rule and quantization factor of the input error and the error differential are first need to be determined. In this paper, we select the voltage error signal E and error differential signal EC are {-6, -4, -2, 0, 2, 4, 6} and {NB, NM, NS, Z, PS, PM, PB}, triangular membership function is adopted, as shown in Figure 6.

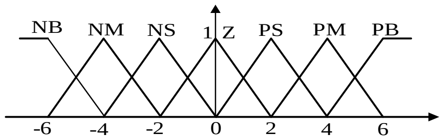


Fig.6 Membership function of fuzzy controller

According to the membership function, the fuzzy rules of the proportional coefficient Kp and the integral coefficient Ki are given, such as Table 1 and Table 2.

The double fed wind power generation system includes the grid side and the rotor side converter, the control method of the grid side converter is shown in Figure 7. The control objective of the grid side converter is to maintain the DC bus voltage constant, realize the bi-directional energy flow and the unit power factor operation. Grid side converter control method include voltage and current double closed loop control, the outer voltage reference value minus the feedback value, and send it into the PI regulator to obtain reference of the current inner loop. When the grid voltage is not falling, switch S connects to 1, the PI regulator output is the inner current instruction value, in order to achieve unity power factor operation, reactive current instruction value is 0; when the grid voltage drops to 0.9p.u, voltage sag module will send a signal to switch S to connect to 2, the grid side converter is running in STATCOM mode, the active current instruction value is 0, and the reactive power instruction value is $2Q^*/3e_d$. The current instruction value obtained after the switch S states, the value minus the dq axis current actual value, and send it into PI regulator, the decoupling and feed forward links are considered to eliminate the coupling between the dq axis and the grid disturbance, then the modulated signal is sent to the SPWM module to get the driving signal.

Table.1 The rule table of fuzzy for proportion coefficient

EC \ E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NS	NM	NM	NB	NB

Table.2 The rule table of fuzzy for integration coefficient

E / EC	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

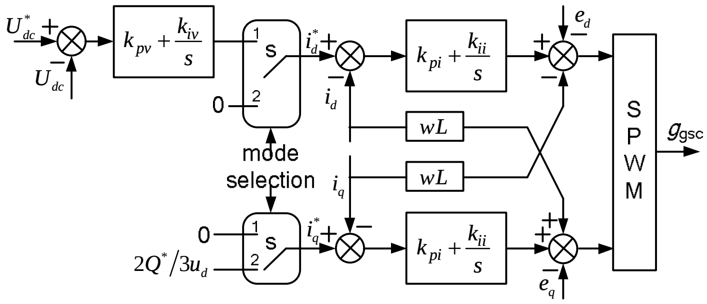


Fig.7 The control strategy of grid-side converter

The control block diagram of the rotor side converter is shown in Figure 8. Stator voltage oriented vector control is adopted, and the control system includes the speed outer loop, reactive power loop and the current inner loop. According to the characteristics of wind turbine, in certain case of wind speed, there is a unique speed corresponding to the maximum power point. According to the maximum power tracking algorithm, the optimal speed of the current wind speed can be obtained, which will injected to PI regulator after subtraction with the actual rotate speed, then the output is d axis current reference value. Under normal operating conditions, to achieve unity power factor operation, the reactive power instruction value Q* is set to zero. The subtraction between Q* and the reactive power Q will injected to PI regulator, then the output is q axis current reference value. Feedback value of the subtraction of d, q axis instruction value respectively will be send to PI regulator, and then get converter voltage signal. In order to achieve the coupling between the rotor voltage and current dq axis, the compensation quantum is added, which is represented as (7) and (8).

$$\Delta U_{rd}=-w_s\left(L_r-\frac{L_m^2}{L_s}\right)i_{rq}-\frac{L_m}{L_s}w_s y_s \tag{7}$$

$$\Delta U_{rq}=w_s\left(L_r-\frac{L_m^2}{L_s}\right)i_{rd} \tag{8}$$

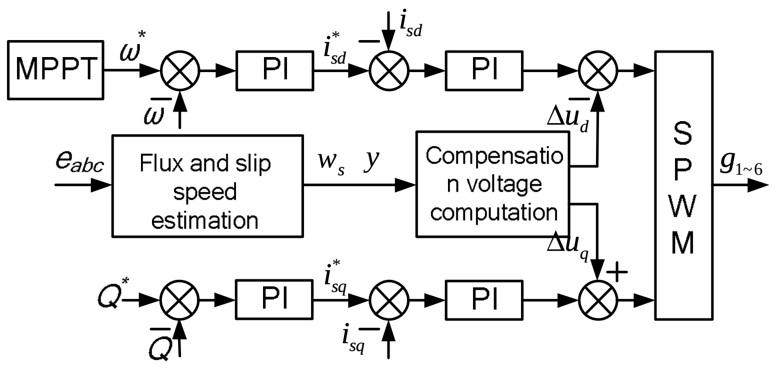


Fig.8 The control strategy of rotor-side converter

After Park and Clark transformation, the dq decoupling component of three-phase stator voltage is fed into the stator flux, stator power and rotor speed estimation module to get angular velocity and the active reactive power. The angular velocity and the active and reactive power with the dq decoupling component of the stator current after transformation can obtain the feed-forward compensation voltage through formula (7) and (8). Thus, the modulation signal is obtained by the superposition of the feed-forward compensation voltage and the output voltage of the current inner loop PI regulator, and the driving pulse of the rotor-side converter is obtained by the SPWM module.

Simulation research and results analysis

In order to verify the effectiveness of proposed control algorithm, the simulation experiment platform of system is built by Matlab/Simulink simulation software. The energy storage system is controlled by parameter adaptive fuzzy PI and traditional PI, and two results are contrasted. The systems parameters can be seen as Table.3~5.

Table.3 The main parameters of DFIG

name	value	name	value
rated capacity	1.5MW	stator voltage	690V
rated power	50Hz	stator winding	0.02Ω
stator leakage inductance	0.01mH	rotor winding	0.02Ω
rotor leakage inductance	0.02mH	mutual inductance	1.23mH
rotational inertia	$0.2kg.m^2$	pole-pairs	2
dc bus voltage	1200V	rated frequency	50Hz

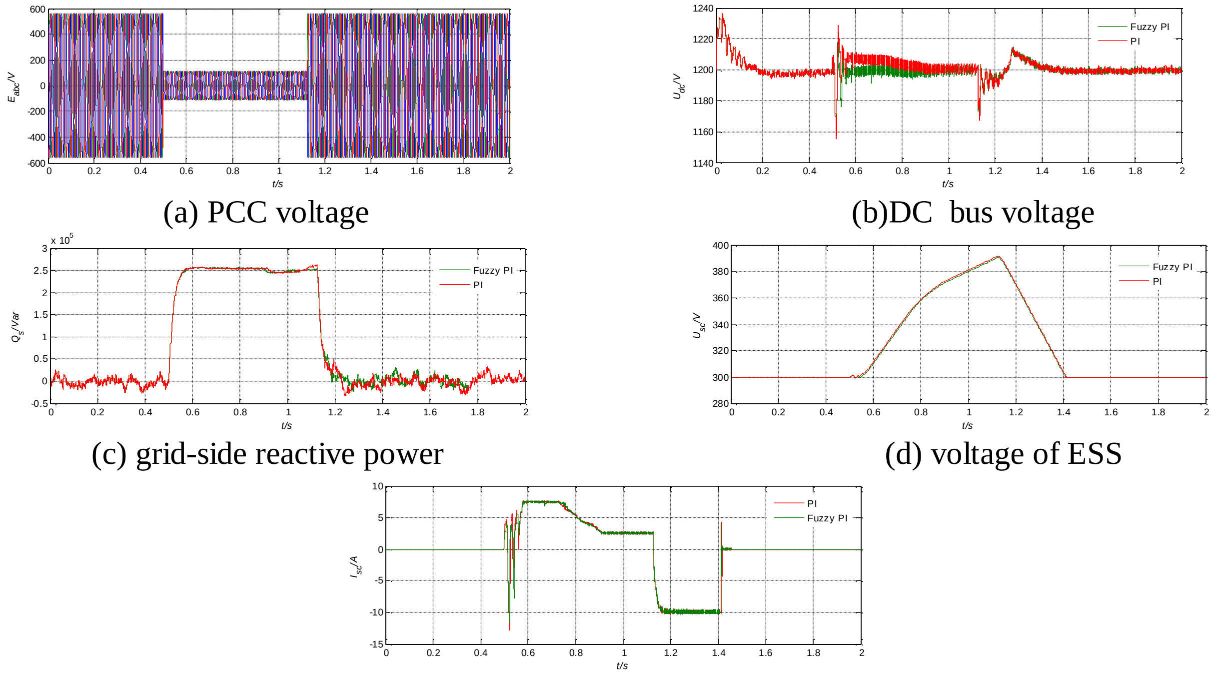
Table.4 The main parameters of wind turbine

name	value	name	value
rated wind speed	11m/s	blade radius	35m
optimal power coefficient curve	0.48	optimum tip-speed ratio	8.1
rated power	1.5MW	transmission ratio	90

Table.5 The main parameters of energy storage system

name	value	name	value
filter inductance	0.2H	transformer rated power	300MVA
Internal resistance	0.001Ω	ratio of transformer	2/1/1
value of supercapacitor	0.03F	excitation resistance of transformer	1.0805MΩ
initial voltage of supercapacitor	300V	excitation inductance of transformer	2866mH
outer voltage loop proportion coefficient	1	outer voltage loop integration coefficient	10
current inner loop proportion coefficient	0.1	current inner loop integration coefficient	10
error quantification factor	0.1	error differential quantification factor	4.2e-5
error output factor	0.05	error differential output factor	10

The Fig.9 shows simulation waveform results of parameter adaptive fuzzy PI control and traditional PI control strategy.



(a) PCC voltage (b)DC bus voltage

(c) grid-side reactive power (d) voltage of ESS

(e) current of ESS

Fig.9 The comparison simulation of traditional PI control and fuzzy adaptive PI control strategy

At the beginning of the normal operation of the power grid, the rated wind speed is 11m/s, the DC voltage stability in 1200V. In 0.5s, the power grid occur three phase symmetrical short circuit faults, the duration is 625ms, and PCC voltage drops to 0.2p.u. Energy storage system is put into use when the grid voltage drop is detected and over a certain threshold. The excess energy of the DC bus is absorbed by the super capacitor, the terminal voltage of the energy storage system continues to rise to stable the DC bus voltage, and the maximum peak of the DC voltage is only 1.03p.u, which can be seen from Figure 9 (b). The grid side converter is running in STATCOM mode to transmit reactive power to the power grid to help restore operation. With the recovery of the grid voltage, the energy storage system works in the constant current discharge mode, ESS will stop working when the voltage drops to the initial setting value of 300V. From Figure 9 (b), it can be seen that the DC voltage will not exceed the allowable operating range, meeting the requirements of the new power grid, and improving voltage ride through in fault period. And by comparing each other, it can be found that the voltage transient fluctuation of the adaptive fuzzy PI control strategy is smaller, and the time needed is shorter, and the system dynamic performance is better.

Table 6 shows the recovery time of DC link voltage from oscillation to stability of DC bus voltage under different voltage sag depth. It can be seen that the recovery time is lowed, and the stability and dynamic response performance of the system is improved with the energy storage system.

Table.6 The stable time under different drop depth

Drop depth	Without BES	With BES
20%	100ms	50ms
50%	200ms	90ms
80%	280ms	100ms

Conclusion

In this paper, isolated bidirectional DC/DC converter energy storage system based on parameter adaptive fuzzy PI control is proposed to realize the LVRT of the double fed wind power generation system. On the basis of analyze of the working principle and mathematical model of the double fed wind power generation system and energy storage system, the control strategy of the grid side converter and the energy storage system under normal and fault conditions is presented. By comparing with simulation results, the parameter adaptive fuzzy PI control strategy is proved to have advantages in suppressing DC bus voltage transient variation, improving the system dynamic performance and lowering the time of regulation. Energy storage system with isolated bidirectional DC/DC converter can be applied to the high voltage and high power, and the need for electrical isolation. The stability and security performance of the whole wind power system can be improved and has some application value on the double fed wind power generation system LVRT.

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