Improvement of Transient Stability using Fuzzy Logic Controller for Permanent Magnet Wind Generator Connected to the Grid

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***Abstract* -** In this paper, a design fuzzy logic controller for a variable speed permanent magnet wind generator connected to a grid system through a LC-filter is proposed. A new current control method of grid side conversion is developed by integrating the fuzzy controller, in which both active and reactive power, delivered to a power grid system, is controlled effectively. The fuzzy logic controller is designed to adjust the gain parameters of the PI controllers under any operating conditions, so that the transient stability is enhanced. To evaluate the controller system capabilities, simulation analyses are performed on a small wind farm model system including an induction wind generator connected to an infinite bus. Simulation results show that the proposed control scheme is more effective for enhancing the stability of wind farms during network disturbances.

***Keywords* - Wind farms, fuzzy logic control, permanent magnet synchronous generator, AC/DC/AC converter, LC filter, transient stability.**

1. Introduction

Due to the problem of global warming, utilization of distributed generation systems, which are connected with a distribution grid system, has been of interest and has received considerable attention in recent years. As the distributed generation can be located close to load consumers, it can have some merits: increasing the available power, improving the overall system reliability, lowering cost, reducing emissions and expanding energy options [1]. It is well known that wind power is one of the distributed resources. However, connecting wind turbine generators to a distribution grid system leads to stability problems due to the output power fluctuation. Therefore, it is very important to analyze a suitable control system for wind generators connected to the grid. The wind turbines can be Fixed Speed Wind Turbines with Induction Generator (FSWT-IG) or Variable Speed Wind Turbines with Permanent Magnet Synchronous Generator (VSWT-PMSG). The FSWT-IG has the advantages of mechanical simplicity, low specific mass, robust construction, and cost efficiency [2]. However, its disadvantages are a limited ability for power quality control and terminal voltage fluctuation under steady state condition, due to the uncontrollable reactive power consumption [3]. The VSWT-PMSG is a promising and attractive type of wind turbine concept, in which PMSG can be directly driven by a wind turbine and is connected to the power grid system through the AC/DC/AC power converter. The advantages of VSWT-PMSG are: (1) No gearbox and no brushes, and thus higher reliability; (2) No additional power supply for excitation; (3) The converter permits very flexible control of active and reactive power in cases of normal and disturbed grid conditions [4,5]. Therefore, a combined installation of VSWT-PMSG and FSWT-IG in a wind farm can be efficient due to reduced system investment cost. However, the PMSG has a more complex generator construction and more complicated controller system compared with FSWT-IG. Hence, the design and analysis of the power converter controller system still needs to be improved. The AC/DC/AC converter of PMSG consists of a stator side converter and a grid side converter linked by dc circuit.

The grid side converter has an important role in ensuring the active and reactive power delivered to the network effectively. Parameter change in the grid system can lead to a significant impact on the stability of the control system performance, especially under fault conditions. The deviation of grid system impedances can cause change in the stability gain margin and phase margin of the control system. In addition, the converter is operated at high switching frequencies between 2–15 kHz resulting in high order harmonics, which can disturb sensitive load on the grid and generate power losses [6,7]. To reduce harmonic currents injected to the grid, LC filter is an attractive solution because of its many potential advantages, such as higher harmonic attenuation and smaller inductances compared with an LC filter [8]. However, the resonance frequency of the filter can cause stability problems in the control system performance. Hence, determination of gain parameters should be performed carefully in the design process. Traditionally, the conventional PI controller is a very common in the control of the power converter of PMSG because of its simple structure and good performance in a wide range of operating conditions. PI controllers are simple but cannot always effectively control systems with changing parameters or strong nonlinearities, and they may need frequent online retuning of their parameters [9]. Integration of a fuzzy logic control with a conventional PI controller could be an effective way to solve the problem of system parameter change. The fuzzy logic control can be used to adjust the gain parameters of the PI controller for any operating conditions. Hence, a good control performance can be achieved. However, the membership function of the fuzzy set should be carefully determined in the controller design. It is difficult to achieve an optimal controller performance by using a trial and error method. Based on the view above, design fuzzy logic controller for the grid side converter of PMSG is proposed, in order to enhance the dynamic stability of a small wind farm including FSWT-IG connected to a grid system. To reduce harmonics injected into the grid, the installation of an LC filter is also considered.

2. Model

The model system used in this study is shown in Fig. 1. Here, Wind Farm with PMSG (1.5 MVA) is connected to an infinite bus through a frequency converter, and a step up transformer and a double circuit transmission line. In the figure, the double circuit transmission line parameters are numerically shown in the form of R+jX, where R and X represent the resistance and reactance, respectively.

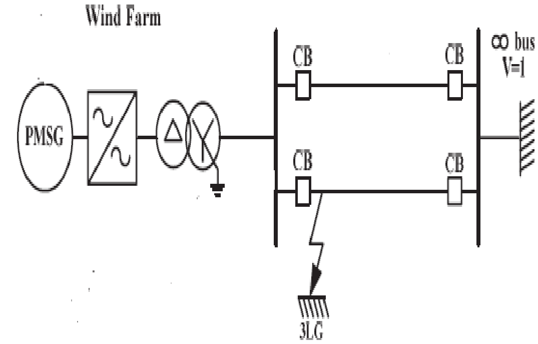


Fig. 1. Wind Farm Model System

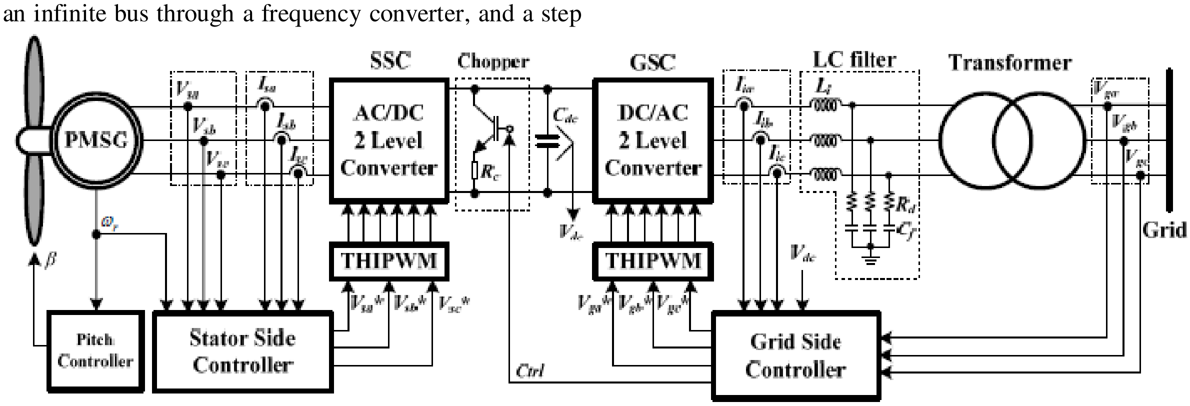


Fig.2 Block diagram of control system for VSWT-PMSG

3. The VSWT-PMSG Control System

The VSWT-PMSG system consists of the following components: a direct drive PMSG, blade pitch controller, AC/DC/AC converters based on two levels of IGBT which are composed of stator side converter (SSC) and grid side converter (GSC), a DC-link circuit composed of a chopper with a resistance (*Rc*) and a capacitor (*Cdc*), two voltage source converter controllers (stator side controller and grid side controller), and LC filter with passive damping resistance.

The SSC is connected to the stator of PMSG, and it converts the three-phase AC voltage generated by PMSG to DC voltage. The three-phase voltage and current of PMSG are detected on the stator terminal. The rotor speed of PMSG is detected from the rotor of the generator. All outputs of the sensors are fed to the stator side controller as input signals in order to control the voltage references of the stator side converter for modulation. In the GSC, the converter converts the DC voltage into the three-phase AC voltage of the grid frequency. The converter is connected to the grid system through an LC filter and a step up transformer. The grid current and the grid voltage sensors are detected on the converter side of the LC filter and the high voltage side of the transformer, respectively. The DC voltage (*Vdc*) is detected on the DC capacitor. Using the grid side controller controls the voltage reference of grid side voltage source converter for modulation. When a fault occurs in the grid, the *Vdc* increases significantly due to power unbalance between SSC and GSC. In order to protect the DC-link circuit, the controller activates the chopper by a trigger command (*Ctrl*). Output power of a wind generator always fluctuates due to the wind speed variations. To maintain the output power of generator under the rated level, a pitch controller is used to regulate rotational speed of PMSG under its rated value. In modulation technique, Third Harmonic Injection Pulse Wave Modulation

(THIPWM) is used in this work. Injection of the third harmonic in the reference voltage makes it possible to utilize the voltage reference without over modulation. In addition, the THIPWM can maximize fundamental amplitude of the output voltage [10].

3.1 Stator Side Converter

The aim of the stator side controller is to control the active and reactive power output of the PMSG. Details of the stator side controller system are presented in a block diagram shown in Figure7. The rotor angle position (θr) used in the transformation between abc and dq variables is obtained from the rotor speed of generator. The active power (*Ps*) and reactive power (*Qs*) of the generator are controlled by the d-axis current (*Isd*) and the q-axis current (*Isq*), respectively. For unity power factor operation, the reactive power reference (*Qs**) is set to zero. The cross couplings $Isd\omega eLd$ and $Isd\omega eLq$ should be compensated by the output of the current controllers in order to improve the tracking capability of the control system. Finally, *Vsd** and *Vsq** are voltage reference outputs of the current controller, which is used to generate the three phase reference voltage (*Vsa**, *Vsb**, *Vsc**) to control stator currents of the PMSG.

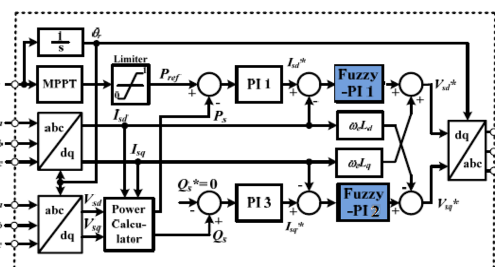


Fig.3 Stator side controller system

3.2 Grid Side Converter

Figure 4 shows a block diagram of the grid side controller system. In this control strategy, the control system based on the d-q rotating reference frame is implemented, which has the same rotational speed as the grid voltage. The three phase grid currents (*Iga*, *Igb*, *Igc*) and the grid voltages (*Vga*, *Vgb*, *Vgc*) are transformed into the d-q rotating reference frame by using Park transformation. The Phase Locked Loop (PLL) [11] is used to extract the grid side phase angle (θg).

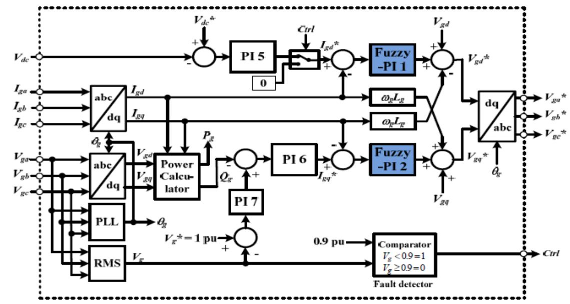


Fig.4 Grid side controller system

The controller is divided into two cascade loop control, one for active power and the other is for the reactive power. When grid voltages on the stationary reference frame are transformed into the d-q rotating reference frame, *Vgd* is set to constant and *Vgq* is set to zero. Therefore, the active and reactive power delivered to the grid can be controlled separately by the d-axis current (*Igd*) and the q-axis current (*Igq*), respectively. To improve the tracking capability of control system, the cross coupling should be canceled by adding $Igd\omega Lg$ and $Igq\omega Lg$ at the output of the current controllers. For d-axis and q-axis current loop regulation, in this paper, the Fuzzy-PI controllers are applied. The output of current controller (*Vgd** and *Vgq**) is transformed into the stationery reference frame (*Vga**, *Vgb**, *Vgc**), which is used as a reference signal for pulse wave modulation. Under normal operating conditions, the voltage of DC-link capacitor (*Vdc*) is maintained constant in order to transfer the active power generated by PMSG to the grid. The d-axis current reference signal (*Igd**) is determined from the output of the DC-voltage controller, and the q-axis current reference signal (*Igq**) is obtained from reactive power controller output. The reactive power reference (*Qg**) is set so that the terminal voltage at the high voltage side of the transformer remains constant. In grid fault condition, the fault detector is activated when the grid voltage decreases under 0.9 pu. The detector sends the control signal command (*Ctrl*) to trigger the DC link protection. At the same time, the active power transfer to the grid is set to zero.

3.3 Fuzzy-PI Controller Design

In order to design a fuzzy logic controller (FLC) for the current control loop, the block diagram of LC filter in the d-q rotating reference frame is considered as a plant system. The plant system can be modelled by using the d-axis component only where the cross coupling and the grid voltage are neglected. The control system is composed of a Fuzzy-PI controller, a processing delay, and a plant system, using the converter side voltage (*Vid*) as input and the converter side current (*Iid*) as output. The FLC is used to adjust the PI parameters according to the input signal error (*er*). To determine a control signal for proportional signal control (*Per*) and integral signal control (*Ier*), an inference engine with rule base having if-then rules in form of "If *er*, then *Per* and *Ier*" is used..

The fuzzification comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. For fuzzification, the three variables of the FLC—the error (*er*) and the outputs of *Per* and *Ier*—have five triangle membership functions. The variables fuzzy subsets for input are Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB). Figure 14 shows the membership function for input *er*. The interval input of the membership function is set at [−1 to 1] due to the variation of the d-axis or q-axis current between −1 to 1 pu.

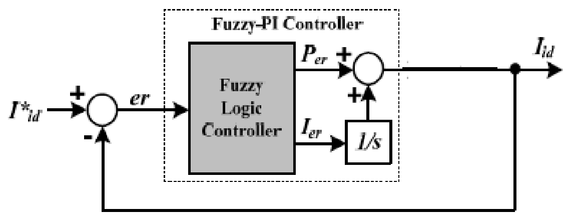


Fig.5 Block Diagram Of Fuzzy Logic Controller

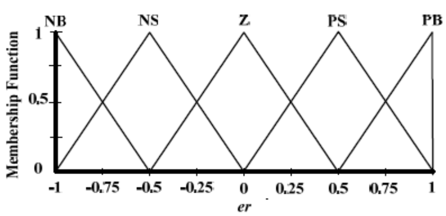


Fig.6 The membership function for input *er*.

Figures 6 and 7 show the membership functions of output for *Per* and *Ier*, respectively. The membership functions are designed based on frequency response of the bode diagram of the current control loop. In this paper the initial gain *Kp* is obtained by using optimum modulus criterion. The integral time constant (*Ti*) usually set equal to the plant system time constant (*Ltot*/*Rtot*) [6], where *Ltot* and *Rtot* are total of series inductances and its parasitic resistances of the plant system, respectively. The integral gain can be calculated by using $Ki = K_p/T_i$.

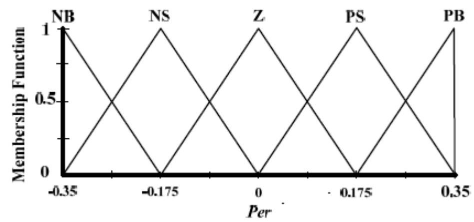


Fig.7 The membership function for output *Per*.

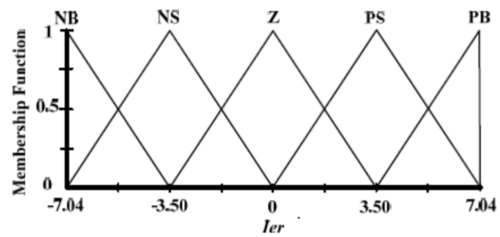


Fig.8. The membership function for output *Ier*.

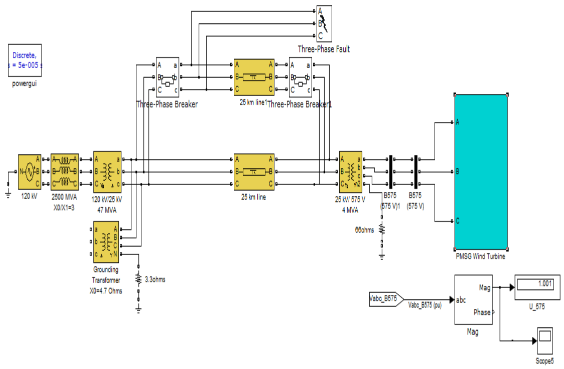
The rules are set based upon the knowledge and working of the system. The values of *Per* and *Ier* for Fuzzy-PI controller of the current regulator are calculated for the changes in the input of the FLC according to the rule base. The number of rules can be set as desired. A rule in the rule base can be expressed in the form:
If (*er* is NB), then (*Per* is NB) and (*Ier* is NB)
If (*er* is NS), then (*Per* is NS) and (*Ier* is NS)
If (*er* is ZE), then (*Per* is ZE) and (*Ier* is ZE)
If (*er* is PS), then (*Per* is PS) and (*Ier* is PS)
If (*er* is PB), then (*Per* is PB) and (*Ier* is PB)

The rule base includes five rules, which are based upon the five membership functions of the input variables to achieve the desired *Per* and *Ier*.

4. Simulation Study

4.1 Transient Stability Analysis

In the transient stability analysis, a symmetrical three line to ground (3LG) fault at the transmission line is considered as network disturbance, as shown in Figure 8. The fault occurs at 14 s; the circuit breakers (CBs) on the faulted line are opened at 14.1 s, and at 14.5 s the CBs are re-closed. In this transient analysis, the wind speeds for the wind generators are kept constant at the rated speed (12 m/s), assuming that the wind speed does not change in short time duration. The simulation results for the transient stability analysis are shown through Figures 9–11. Figures 9 show responses of reactive power output of PMSG. It is seen that, by using the proposed controller for PMSG, converter of PMSG can provide necessary reactive power during 3LG fault. Figures 10 and 11 show responses of the active power output of PMSG and Rotor speed response. The active power can be controlled more effective by using Fuzzy-PI Controller.. From these results, it is clear that the stability of performance of the wind farms can be improved more effectively in the case



of PMSG with the Fuzzy-PI controller than that with just PI controller.

Fig.8. Simulation Model

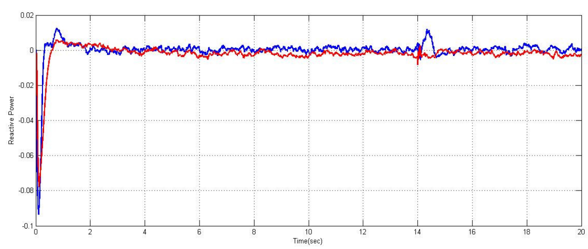


Fig.8 Reactive Power of PMSG

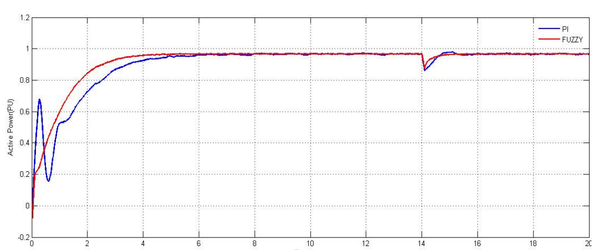


Fig.9 Active Power of PMSG

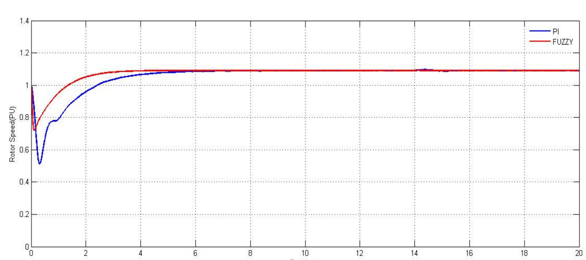


Fig.10 Rotor Speed Of PMSG

5. Conclusion

In this paper, a new Fuzzy-PI controller for variable speed permanent magnet wind generators connected to a power grid through a LC filter is proposed and investigated in order to enhance its transient stability. The controller combines fuzzy logic with a classical PI controller in order to adjust the PI gains online. The results show that the proposed Fuzzy-PI controller is very effective in improving the transient stability of overall wind farm systems during fault conditions. The significant effect of the proposed control system has been demonstrated

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