Intelligent Frequency Control Strategy of Wind Turbine Generation System with DFIG by Using PI and Fuzzy Logic Controllers

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Abstract: In today world's market; main disadvantage of Doubly fed induction generator is that under its operation mode, rotor speed decoupled from frequency of power grid resulted as not responding situation about changes of system frequency. With large-scale integration of DFIG; frequency stability of power system decreases and most significantly it creates disturbance in frequency regulation so its foremost priority to study control strategies for purpose of overall system frequency adjustment. The aim of this paper is to study and analysis of DFIG along with its frequency control strategy based on existing methods (PI traditional controller) as well as proposed new method based on Fuzzy control logic. Initially, establishes the mathematical model, build power decoupling control strategy, analyze response under varying system load. It is noticed that due to external performance of zero inertia, it changes characteristics of frequency response as well as reduces the equivalent inertia of power system. In order to cope this critical issue; theoretical and simulation-based analysis has performed. Furthermore, paper focuses on selection of control coefficients (Kp, Kd) in DFIG comprehensive inertial control strategy, analyzes the influence of inertial control coefficients and finally optimizes the control coefficient to meet the frequency regulation.

Keywords: Doubly-fed induction generator, PI traditional controller, fuzzy logic controller, inertial control coefficient

1. Introduction

The reduction of economic dependency on fossil fuel-based energy has been among the top priority goals of regulators and their governments around the world. During recent years fossil fuel resources are limited and have a significant adverse impact on the environment by raising the level of CO_2 in the atmosphere and contributing to global warming. Among renewable sources of energy, wind is one of the most promising technologies. It has already been in use for a significant period of time and, compared to other forms of alternative energy resources, has the greatest potential to reduce the conventional generation.

The proportion of wind-based generation in total energy production mix has been growing continuously in many parts of the world. It has been reported [1] that renewable energy will provide as much as 10% of the world's energy supply by 2020, and will increase to as much as 50% by 2050. Canada has outlined a future strategy for wind energy that would reach a capacity of 55,000 MW by 2025, fulfilling 20% of the country's energy needs [2].

In particular, country like Denmark has set its ambitious target to achieve 50% wind penetration by 2025 [3-4]. However, more penetration of wind energy into existing power networks raises concern for power system operators and regulators. Traditionally wind energy convertors do not participate in frequency regulation or Automatic Generation Control (AGC) services, and therefore large penetration of wind power into the power systems can result in a reduction of total system inertia and robustness of the frequency response to the disturbances.

2. Related Work

Some strategies for the frequency excursion of the wind energy conversion system have been proposed. One strategy was realized by shifting the operating point of a WT between the maximum power point tracking (MPPT) model and the de loaded model [6]. The disadvantage of the technique is that the gain of the droop control was adjusted based on an artificial pre-defined linear relationship. Reference [7] researched on the inertial response and the primary frequency control of a WTs. The impact of the gains of the droop control and inertia control on the effect of the frequency regulation was studied. A supervision algorithm for grid connected PMSG wind farms has been developed. In [8] to contribute to the frequency stability. Similar to [6], the adjusted active power is based on a predefined linear relationship between frequency and active power. Reference [9] deduce second frequency drop as an one critical constraint on large-scale usage of rotor inertia control in terms of DFIG-VSG, Also Influencing factors on inertia support time of DFIG-VSG is studied, followed by optimization of rotor recovery methods. Constant-value restoration and comprehensive restoration methods are also proposed respectively to improve performance of DFIG-VSG. The synchronous stability of DFIG-based WTG with SYNC under frequency deviations is studied using the derived synchronization characteristics in active power – rotor speed plane [10]. The author in [11] presented a novel model to control the frequency of the wind farm connected to conventional units, throughout the proposed frequency control, the integral controller, washout filter, and the PID controller could determine the active power variation value in

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different situations, PID coefficients are optimized based on a multi objective function using particle swarm optimization (PSO) algorithm. An optimization strategy of power deviation control (pitch angle control) is proposed in [12] in order to improve the DFIG based wind farm contribution to power system frequency regulation demand. The output power of wind turbines can be adjusted more rapidly, but it is limited by the amount of rotor kinetic energy that can be released, in order to make full use of the limited rotor kinetic energy to support system frequency, a variable parameters frequency control loop and the gain of the control loop is adjusted along with the change of wind speed and the size of power imbalance are proposed in [13]. On the other hand, authors in [14] are proposed method using the kinetic energy stored in the "hidden inertia" of the turbine blades to let variable-speed wind turbines emulate inertia and support primary frequency control.

Finally, the basic idea is to introduce a closed-loop frequency control into the active power control scheme. The active power output setting is modified according to the variation speed of frequency and its deviation compared to the nominal value, thus emulating inertia and offering primary frequency regulation respectively.

2. Methodology

3.1 The basic principle of DFIG

A mathematical model of the DFIG, including electromagnetic transients both in the stator and the rotor circuits, is typically used to analyze the transient performances. Based on a standard per-unit notation, in a reference frame rotating at synchronous speed and with the motor convention considered, the transient models of a grid-connected DFIG can be represented by the detailed differential equations of the flux linkages, as follows:

$$\begin{cases} u_{sd} = R_s i_{sd} + \dfrac{\mathrm{d}\psi_{sd}}{\mathrm{d}t} - \omega_s \psi_{sq} \\ u_{sq} = R_s i_{sq} + \dfrac{\mathrm{d}\psi_{sq}}{\mathrm{d}t} + \omega_s \psi_{sd} \\ u_{rd} = R_r i_{rd} + \dfrac{\mathrm{d}\psi_{rd}}{\mathrm{d}t} - s\omega_s \psi_{rq} \\ u_{rq} = R_r i_{rq} + \dfrac{\mathrm{d}\psi_{rq}}{\mathrm{d}t} + s\omega_s \psi_{rd} \end{cases}.$$

The equations of flux linkage are given as follows:

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = L_s i_{sq} + L_m i_{rq} \\ \psi_{rd} = L_r i_{rd} + L_m i_{sd} \\ \psi_{rq} = L_r i_{rq} + L_m i_{sq} \end{cases},$$

where ω_s is synchronous speed; u, ψ, i, R, and L are voltage, flux linkage, current, resistance, and inductance, respectively; L_m is the mutual inductance between rotor and stator; subscripts s and r indicate the stator and rotor of the electric machine, respectively; subscripts d and q indicate the d and q components, respectively; and s is the slip ratio of the DFIG. The electromagnetic torque of the DFIG can be expressed as follows:

$$T_e = -\frac{3L_m}{2L_s}\psi_s i_{rd}.$$

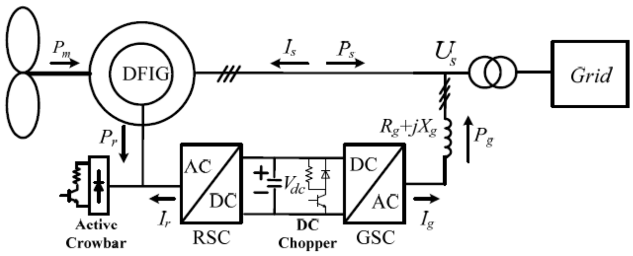

Fig:1 Schematic of a Grid connected DFIG WT

3.2 Description of Power System Model with DFIG-Based Wind Farm

The schematic diagram of doubly fed induction generator wind turbine has been illustrate in figure.2 The DFIG based WT models including two aspects, one is steam generator models, the other is DFIG wind farm, including wind turbine, drive train, pitch control, converter as well as DFIG machines as shown, is adapted from IEEE first benchmark model (FBM) for computer simulation of sub-synchronous resonance It is assumed that a 150 MW DFIG-based wind farm is connected to the network.

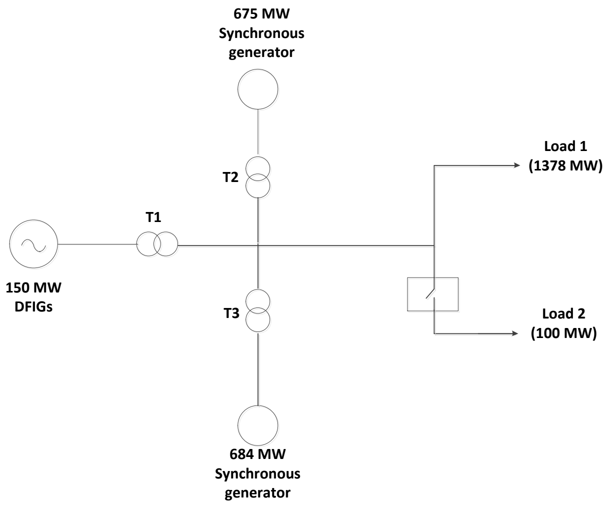

Figure:2 Simulation power system model

3.3 Traditional (PI controller) frequency control method

The stability of power grid frequency is very important for the power quality of the system to reach the standard, and its value will vary with the system when the active power supply-demand relationship changes, the frequency will fall when the active power of the system is insufficient, and when the active power is surplus, the frequency will fall can cause an increase in frequency. In the traditional power system, the large generator is usually synchronous generator, which is driven by prime mover the rotor winding with DC excitation generates rotating magnetic field, and the three-phase winding of rotor stator is cut in rotating magnetic field use it to generate induced electromotive force. When the stator of synchronous generator is connected with symmetrical load, the frequency will flow through the stator winding. It is the current of F, and then induces a rotating magnetic field whose rotating speed is synchronous with the rotor speed, which meets the following requirements:

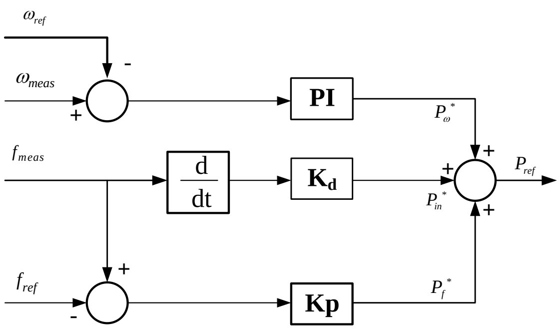

Fig:3 Active power controller with inertia emulation and frequency support control

3.4 The impact of traditional's method parameters on the frequency control response (K_d , K_p)

Where K_d is the inertial control coefficient.

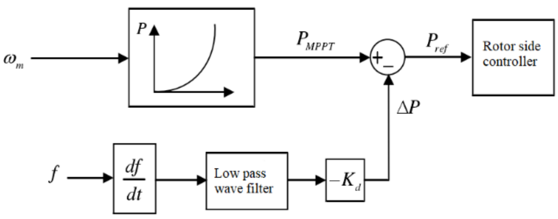

Fig:4 Virtual inertia control

The virtual inertia control of doubly fed wind turbine uses the kinetic energy of rotor to respond to the frequency change, which can suppress the frequency speed change. In addition, in order to make doubly fed wind turbines simulate the power frequency characteristics of similar synchronous generators, so that they can participate in the primary frequency control strategy, an additional value △ P, which is proportional to the frequency deviation, can be added to the given value of the rotor side power

$$\triangle \text{P}= -K_p \ \triangle f$$

Where K_p is the droop control coefficient

The virtual inertial control and droop control are combined, and the frequency deviation and the rate of change of frequency deviation are introduced into the rotor active power control loop on the side of the rotor is used to obtain the integrated inertial control strategy, which controls the release / absorption of the rotor speed in a short time rotation energy is used to provide power support. At this time, the additional value of frequency related power is:

$$\triangle \text{P}= -K_p \frac{d\triangle f}{\text{dt}} - K_p \triangle f$$

When the frequency changes, the virtual inertial link simulates the inherent inertial response of the synchronous machine to limit the frequency change rate, droop control link simulates the primary frequency control strategy response of the synchronous machine governor to reduce the amplitude of frequency change, and both of them improve together control block diagram of the wind turbine's ability to adjust the system frequency is shown in figure 5.

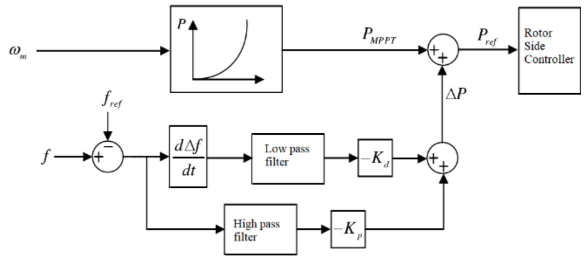

Fig:5 Comprehensive inertial control

In the wind turbine level control, additional controllers are installed on the converters of variable speed wind turbines or pitch controllers to relate the electromagnetic torque and frequency. The droop control simulates the similar frequency droop characteristics to that of synchronous generators. The deloading control enables the wind turbines to operate over deloading curves instead of the MPPT and saves the available power as reserves by using pitch control (pitching) or increasing the rotational speed from the MPPT value (over speeding). Synchronous generators and fixed speed wind turbines can automatically release the kinetic energy of the rotating mass for a sudden frequency change while variable speed wind the impact of traditional's method parameters on the frequency control response (K_d , K_p)

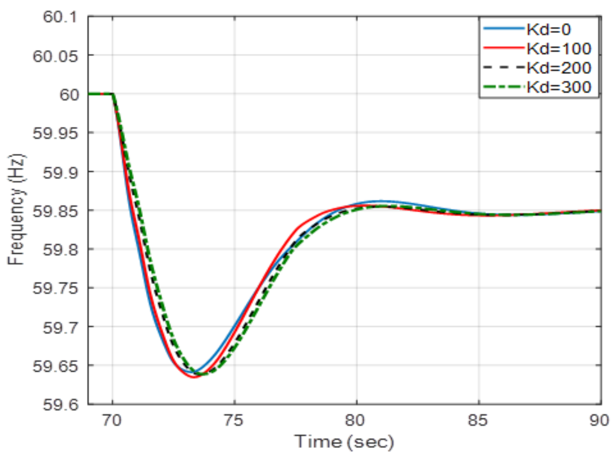

Fig:5 Effect of K_d on system frequency response

Tab:1 Lowest frequency corresponding to different inertia coefficients K_d

K_d	Frequency (Hz)	K_d	Frequency (Hz)
0		300	59.6440
100	59.6481		
200	59.6351		
	59.6431		

Tab:2 Lowest frequency corresponding to different droop coefficients K_p

K_p	Frequency (Hz)	K_p	Frequency (f/Hz)
0		5	
10	59.6001	15	59.6404
20	59.6143		59.6522
	59.6281		

From the above chart, it can be seen that the inertial link can improve the frequency response process of the system to a certain extent, with K_d when the value increases, the lowest frequency point is increased, the frequency deviation is reduced, and the time of the lowest frequency point is delayed. When 20 K_d, the lowest point of system frequency is 59.6531 Hz, and the lowest point of system frequency when DFIG does not participate in frequency control strategy compared with 59.6513 Hz, it increases by 0.018 Hz, but at the same time, the increase of K_d value intensifies the dynamic control of frequency.

Figure 6 shows that the control amplitude of the system frequency can reach 0.05Hz after the load changes, and the time required for frequency recovery significantly increased. Next, the influence of the droop control coefficient K_p value on the frequency change of the response system of the wind turbine is analyzed K_d is set to 0.

The simulation is carried out under the condition of different K_p values. The remaining parameters of the simulation model remain unchanged and the system frequency changes the simulation results are shown in figure: 6

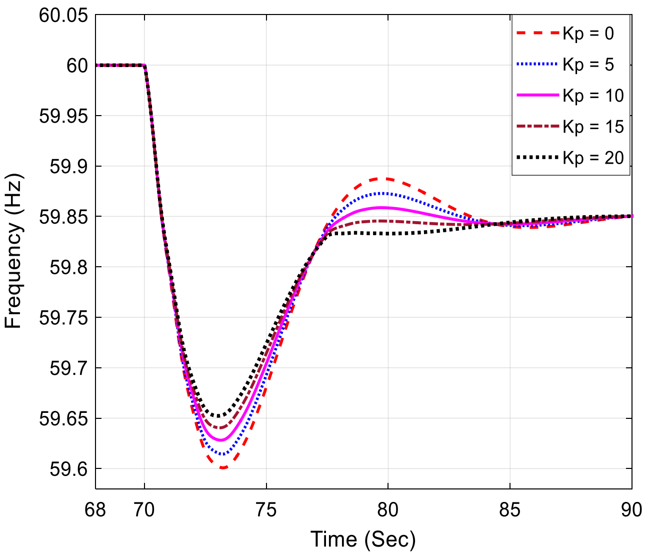

Fig:6 Effect of K_p on system frequency response

As can be seen from figure 6, with the increase of K_p, the lowest point of system frequency has been significantly increased, and its specific values shown in Table 3-2.

It can be seen from Table 3-2 that the maximum deviation of system frequency decreases with the increase of K_p, when K_p is 20, lowest point of the system frequency decrease is 59.6281 Hz, which is the lowest compared with the control loop without droop (i.e. K_p is 0) point increased by 0.028 Hz. However, when K_p is further increased, the frequency control strategy effect is no longer significantly improved, and there is rotor motion can release the excessive danger, and the dynamic control also occurs in the frequency recovery process, which is not conducive to the stability of the system. The simulation waveform is as follows:

3.4 Improved frequency control method (Fuzzy logic controller)

According to the previous simulation analysis the optimal control coefficient should be selected at different wind speeds, but it is still inevitable there is a contradiction between the lowest point of the frequency drop and the frequency control, to maximize the use of kinetic energy in the rotor, under the vertical control coefficient K_p can't be too small, However, if K_p is selected too large, delay Long frequency recovery time, and it may cause excessive release of rotor kinetic energy, which may cause the frequency drops twice, which can even cause the system to lose stability in severe cases. In this case, it is necessary to improve the control method of doubly-fed wind turbine participation in frequency control strategy so that the wind turbine can respond to the system frequency changes to the greatest extent, and avoid the control problem and frequency quadratic during the frequency control process. In this paper proposes an inertial control strategy with additional variable coefficient fuzzy control links.

Δ_f as E, The frequency deviation change rate $\frac{d\Delta_f}{dt}$ is EC.

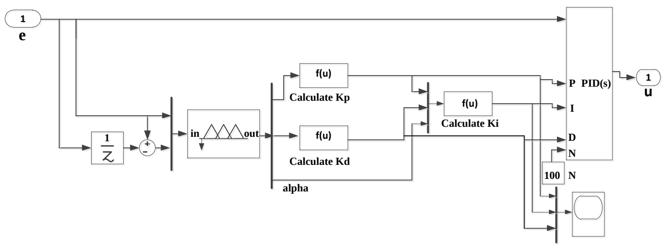

Fig:7 Simulink based Fuzzy Logic Controller

Because the droop control loop plays a major role in the frequency control strategy output of the wind turbine in the integrated inertia control strategy, Only the droop control loop is retained in the frequency-added control link, and the frequency deviation Δ_f and the frequency deviation change rate $\frac{d\Delta_f}{dt}$ are taken as the input of the fuzzy controller uses the output of the fuzzy control link as the control coefficient value of the droop control loop to obtain the conversion. The value of the additional power in the sub-side control. During the control process, the frequency deviation and the rate of change of the frequency deviation change in real time the droop control coefficient K_p is used to optimize the frequency regulation strategy of the wind turbine.

The control idea of the proposed improvement strategy is as follows: when the specified frequency starts to decrease to the maximum frequency deviation change rate is the first stage, in this stage, when the system load suddenly increases, the imbalance of supply and demand power in the system causes the frequency to start to decrease. In the initial stage of frequency reduction, the frequency change rate increases rapidly. At this time, we hope that the wind turbine can release as much as possible.

The rotational kinetic energy in the rotor responds to changes in the system frequency, that is, the control coefficient of the drooping link should be selected as much as possible. Therefore, the output of the fuzzy controller is set to be large. When the frequency deviation change rate reaches the maximum, the value of the control coefficient also reaches to the maximum; the second stage is specified from the maximum change rate of the frequency deviation to the lowest point of the frequency. In this stage, the amplitude of the frequency deviation change rate starts to decrease. In order to avoid excessive release of rotational kinetic energy in the rotor of the wind turbine, it should be set. The control coefficient of the drooping link gradually decreases; finally, the frequency returns to the steady state for the third stage, during which the system frequency start recovery, set the control coefficient of the droop link to decrease with the decrease of the frequency deviation, and keep as much rotor motion as possible yes, it can reduce the secondary frequency drop and frequency control during the speed recovery process.

In the fuzzy control process, the fuzzy sets of the frequency deviation and the frequency deviation change rate of the two input variables are set to {NB, NM, NS, ZO, PS, PM, PB}, the fuzzy set of fuzzy control link output is {ZO, PS, PM, PB}, as per above write the fuzzy control rules based on the control ideas, and the resulting control rule table is shown in Table 3.

Tab:3 Fuzzy control rules

ED	E: NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PS	ZO	ZO	ZO
NM	PB	PM	PS	PS	ZO	ZO	PS
NS	PM	PS	PS	PS	ZO	PS	PS
ZO	PS	PS	PS	ZO	PS	PS	PS
PS	PS	PS	ZO	PS	PS	PS	PM
PM	PS	ZO	ZO	PS	PS	PM	PB
PB	ZO	ZO	ZO	PS	PM	PB	PB

According to the fuzzy control rules in Table 3, a three-dimensional model diagram between the input and output can be obtained, as shown in the figure 8 shown

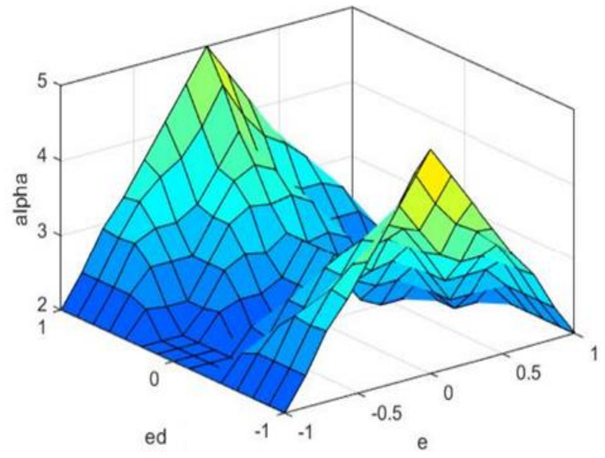

Fig:8 Fuzzy control three-dimensional map

4. Results and Discussion

Based on MATLAB / Simulink simulation platform, the improvement of the integrated inertial control link on the rotor side of doubly fed wind turbine, the basic parameters of the simulation model are consistent with the previous paper, No more details. Respectively observe that the wind turbine does not participate in frequency regulation, the frequency waveform of the system under the three conditions of frequency control strategy under the integrated inertial control link and the improved inertial control strategy, Wind turbine speed waveform and output power waveform.

When the wind speed is 8m/s, 9.3m/s, 10m/s. Frequency waveform of the system, the speed waveform and output power waveform of DFIG are shown in the figure below.

The system frequency waveform rotor speed and power (MWatt) waveform under the wind speed of 8m/s, 9.3m/s, 10m/s are mentioned below:

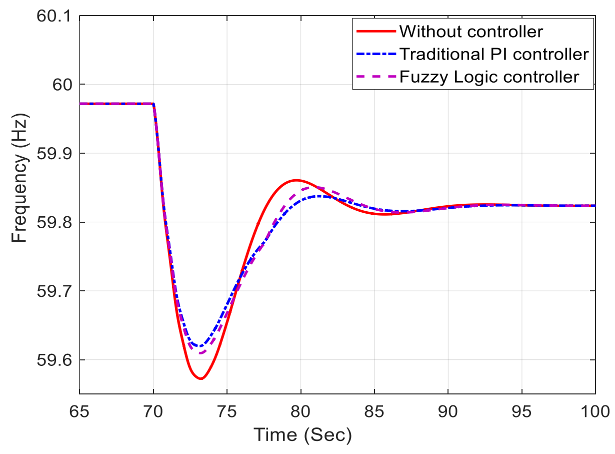

Fig:9 System frequency waveform at wind speed of 8 m/s

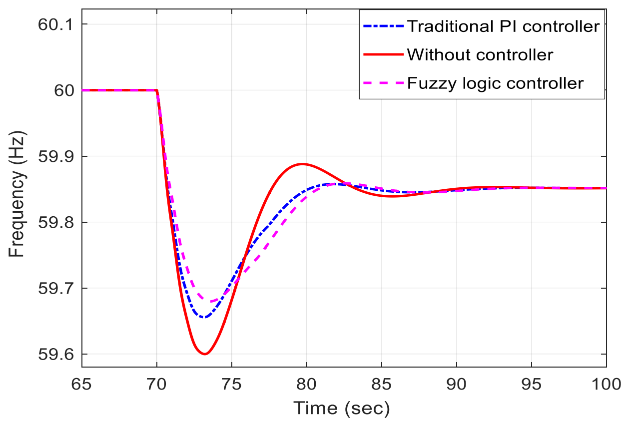

Fig:10 System frequency waveform at wind speed of 9.3m/s

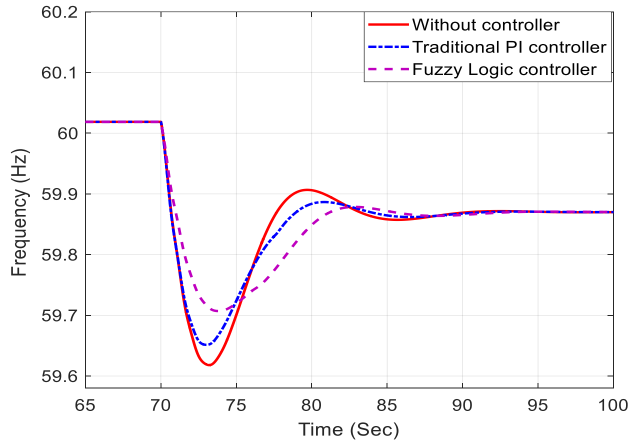

Fig:11 System frequency waveform at wind speed of 10 m/s

It can be seen from the above simulation waveform, When adopting the improved inertial control strategy, the lowest frequency point has been further improved, The minimum frequency is 59.6795Hz, which is 0.0302hz higher than that of DFIG, compared with the integrated inertial control strategy, the lowest frequency is increased by 0.0034hz, After improvement, although the amplitude of frequency increase is not obvious, However, it can make the system frequency quickly return to stable state and avoid the system frequency control. It can be seen from the speed waveform that, compared with the traditional strategy, the speed of DFIG decreases faster and the speed recovery is smoother in the initial period of frequency decrease. According to the output power waveform of DFIG, under the improved strategy, the wind turbine can release the rotational kinetic energy in the rotor more quickly to respond to the system frequency change, and can restore stability more quickly. It compared the improved inertial control strategy has better frequency control strategy effect at wind speeds of 9.3 m/s, the maximum frequency is 59.6795Hz we got with the used of fuzzy logic controller and also it compared with DFIG with without controller, PI traditional and fuzzy logic controller.

5. Conclusion

In this paper improving the frequency control strategy of power system using DFIG-based wind farm was investigated at three wind speeds of 8 m/s, 9.3 m/s and 10 m/s.

The IEEE first benchmark model for evaluating sub synchronous resonance was used as the study system. It was assumed a 150 MW DFIG-based wind farm was connected to this network. The MATLAB/Simulink software was used for modelling the wind farm and simulating. Whereas the dynamic performance of DFIG turbines are quite different at various wind speeds, all studies were done at three wind speeds of 8 m/s, 9.3 m/s and 10 m/s. But the principle of variable speed constant frequency operation at 9.3 m/s of DFIG is introduced, and the air of wind turbine is deduced and established the dynamic model and DFIG mathematical model in different coordinate systems are derived based on the mathematical model the power control strategy of DFIG rotor side, and under the condition of constant and variable wind speed on MATLAB / Simulink platform the power control strategy of DFIG is verified by simulation.

The influence of inertia control coefficient and droop control coefficient on DFIG frequency regulation performance the influence of droop control coefficient on the frequency control strategy performance of DFIG is analyzed deeply, and it is pointed out that droop control coefficient has more influence on the frequency control strategy performance of DFIG, with additional variable coefficient fuzzy control strategy is proposed, which only retains the drop of traditional PI inertial control strategy control loop, At last, the relevant model is built in MATLAB simulation environment, and the simulation results verify the validity of the model the effectiveness of the proposed strategy.

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