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Research Article

SYSTEM INERTIAL RESPONSE AND POWER OSCILLATION DAMPING OF PMSG-BASED WIND TURBINES BY USING FUZZY LOGIC CONTROLLER

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A B S T R A C T

In this paper deals with an improved active power control method for variable speed wind turbine to enhance the inertial response with fuzzy control and damping capability during transient events are analysed in this paper. According to the frequency deviation the optimized power point tracking (OPPT) controller, which shifts the turbine operating point from the maximum power point tracking (MPPT) curve to the virtual inertia control (VIC) curves, is proposed to release the "hidden" kinetic energy and provide dynamic frequency support to the grid. Compared to the conventional supplementary derivative regulator-based inertia control, the proposed control scheme can not only provide fast inertial response, but also increase the system damping capability during transient events. Thus, inertial response and power oscillation damping function can be obtained in a single controller by the proposed OPPT control. Here we are using the fuzzy controller compared to other controllers i.e. The fuzzy controller is the most suitable for the human decision-making mechanism, providing the operation of an electronic system with decisions of experts. In addition, using the fuzzy controller for a nonlinear system allows for a reduction of uncertain effects in the system control and improves the efficiency. By using the simulation results we can analyze the proposed control strategy on providing rapid inertial response and enhanced system damping.

INTRODUCTION

The renewable energy contribution in total power generation gaining more importance in present scenario because of its no maintenance cost. The main conventional resources are fossil fuel resources and they exist in a limited quantity. Over usage these fossil fuels causing us lookup on the renewable energy sources for generation of electricity.

Wind energy is a one form of renewable energy source which is widely used for power generation. All generating stations and the load centresare interconnected. As wind power generation depends upon on wind penetration the inertial response and power damping capability of wind turbine is important parameter for grid connected operation. The reduced inertial response and power damping capability as the result of increased wind power penetration in ac networks, have been receiving considerable attention from wind turbine manufactures and system operators [1]-[3]. The wind turbines should have the ability to participate in frequency and power regulation during faults so as to make the wind farms grid-friendly power generation sources.

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This purpose of this study is to investigate new system control to simultaneously provide inertial response and positive damping during frequency and oscillation events. So an improved active power controls method for variable speed wind turbine to enhance the inertial response and damping capability during transient events.

The power system stabilizer (PSS) is normally equipped in the traditional synchronous generators to provide power damping during and after large disturbances. With increased wind penetration, it also becomes essential for wind turbines to provide power oscillation damping [4], [5]. The optimized power point tracking (OPPT) controller is used to with Virtual inertia control (VIC) curves. This OPPT controller shifts turbine operating point from MPPT curves to VIC curves. Thus, inertial response and power oscillation damping function can be obtained in a single controller by the proposed OPPT control.

Normally the auxiliary controllers equipped with frequency feedback to provide system frequency response, such as P/*f* droop controller, PD controller, and deloading controller by shifting the maximum power point tracking (MPPT) curves [6]-[10]. OPPT controller with PI controller is also used. OPPT controller with Fuzzy logic controller is used in the proposed system. By the use of Fuzzy logic controller smooth recovery of wind turbine operation after inertia response can also be achieved. Due to the increase popularity of PMSG-based wind turbine for applications in large wind farms [9]-[11]. The damping capability of the proposed virtual inertia controller is analysed to ensure positive damping coefficient.

Compared to the conventional supplementary derivative regulator-based inertia control, the proposed control scheme can not only provide fast inertial response, but also increase the system damping capability during transient events.

Block diagram for proposed system

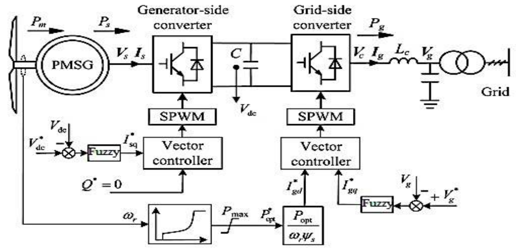

Fig 1 Schematic control diagram of a PMSG-based wind turbine

This paper is organized as follows. The operation of PMSG is introduced first then VIC of PMSG-based variable speed wind turbines and Fuzzy logic controller is presented. The damping capability of the proposed virtual inertia controller is analysed to ensure positive damping coefficient. The network containing two synchronous generators and a PMSG-based wind turbine are presented to demonstrate the effectiveness of the proposed schemes on providing inertia response and oscillation damping.

PMSG (Permanent magnet synchronous generator)

The proposed inertia and damping control methods are developed considering the power regulation of PMSG-based wind turbine.

Basic control of PMSG

There are two converters (a) Generator side converter (b) Grid side converter as shown in Fig 1. The electromagnetic power of the generator can be controlled using either the generator-side converter or the grid-side converter. In this paper, the grid-side converter directly controls the generated active power, whereas the generator-side converter is used to maintain a constant dc-link voltage. Whenever there is a fault like voltage dip with reduced power transmission. The grid-side converter can fall into current limit the generator side converter as the dc voltage control station automatically reduces power generation in order to maintain a constant dcvoltage. The surplus power in the turbine during such disturbances is stored as the kinetic energy of the large rotating masses but only results in a relatively small speed fluctuation of the PMSG. This control scheme provides automatic power balanceduring ac fault and simplifies fault ride through controlof the PMSG.

The wind turbines do not naturally response to frequency change or provide power system oscillation damping. In order to emulate the dynamic response of synchronous generators using PMSG-based wind turbines, advanced control schemes considering grid frequency deviation need be added to the grid-side converter's power control loops. Thus, the rotor speed of the PMSGs is regulated to release/store the kinetic energy to make the "hidden inertia" available to the connected grid, and its flexible power control can also be utilized to participate in power system oscillation damping.

Under normal operation, the generated power of the wind turbine is controlled under the MPPT according to its rotor speed, and is independent of the grid frequency due to the fast converter control. The reactive power of the PMSG can be controlled to zero or be regulated to maintain the stator voltage or minimize the power loss of the generator.

Virtual Inertia Control

Principle of Virtual Inertia Control (VIC)

The inertia constant H_{tot} of a power system with synchronous generators and variable speed wind turbines can be expressed as

$$H_{\text{tot}} = \left[\sum_{i=1}^{m}\left(J_{s\_i}\omega_e^2/2p_{s\_i}^2\right) + \sum_{j=1}^{n}E_{w\_j}\right] \Big/ S_N \qquad \text{…….(1)}$$

Where m and n are the numbers of connected synchronous generators and wind turbines in the grid, respectively. $P_{s\text{-}I}$ and $J_{s\text{-}I}$ are the numbers of pole pairs and moment of inertia for synchronous generator i, respectively. E_w is the effective kinetic energy of the wind turbine available to the power system. S_N is the total nominal generation capacity of the power system. As the stored kinetic energy in variable speed wind turbines cannot be automatically utilized during frequency changes as that of conventional synchronous generators [i.e., E_w=0 inEq.(1), replacing conventional plants with large numbers of variable speed wind turbines under MPPT control can significantly reduce the effective inertia of the whole system. This can have significant implications for power system operation and could lead to large frequency deviation. Therefore, it is important to make full use of the stored energy in the wind turbines. To better describe kinetic energy in wind turbines' rotating masses, the definition of the virtual inertia of variable speed wind turbines is given first. The mechanical characteristics of a wind turbine generator can be expressed as

$$\begin{cases} P_m - P_e = J_w\omega_r\dfrac{\mathrm{d}\omega_r}{p_w^2\mathrm{d}t} = \dfrac{J_w\omega_r\mathrm{d}\omega_r}{\omega_s\mathrm{d}\omega_s}\times\dfrac{\omega_s\mathrm{d}\omega_s}{p_w^2\mathrm{d}t} = J_{\text{vir}}\omega_s\dfrac{\mathrm{d}\omega_s}{p_w^2\mathrm{d}t} \\ J_{\text{vir}} = J_w\omega_r\mathrm{d}\omega_r/(\omega_s\mathrm{d}\omega_s) \end{cases} \qquad \text{…..(2)}$$

Where$\omega_r$is the rotor electrical angular speed and $p_w$is the number of pole pairs of the wind turbine generator. P_m and $P_e$are the mechanical and electromagnetic powers of the wind turbine, respectively. J_w is the combined natural inertia of the wind turbine system. J_{vir} is defined as the virtual inertia of the wind turbines. If the wind turbine is controlled to provide dynamic support using its kinetic energy during a frequency change, the released kinetic energy ΔE_k can be obtained fromEq.(2) as

$$\Delta E_w = \int (P_m - P_e)\mathrm{d}t = \int (J_{\text{vir}}\omega_s/p_w^2)\mathrm{d}\omega_s. \qquad \text{……(3)}$$

If the converter controls J_{vir} to be constant by adjusting the rotor speed and to move away from the MPPT point, the effective kinetic energy of the wind turbine compared with asynchronous generator can be expressed as

$$E_w = (1/2)J_{\text{vir}}(\omega_e/p_w)^2 \qquad \text{…..(4)}$$

According to Eq.(1) and Eq.(4), the inertia constant $H_{\text{tot}}$of the power system with synchronous generators and wind turbines can be expressed as

$$H_{tot} = \left[\sum_{i=1}^{m}(J_{s\_i}/2p_{s\_i}^2) + \sum_{j=1}^{n}(J_{vir\_j}/2p_{w\_j}^2)\right]\omega_e^2 \Big/ S_N \quad \text{……(5)}$$

Where p_{wj} and J_{virj} are the numbers of pole pairs and virtual inertia for wind turbine j, respectively. It can be seen from (3) that the kinetic energy of the wind turbine can be utilized for inertial response by regulating the generated power, and the equivalent inertia of the wind turbine can be described as

$$\begin{cases} J_{vir} = \dfrac{J_w \omega_r d\omega_r}{\omega_s d\omega_s} \approx \dfrac{\Delta\omega_r}{\Delta\omega_s}\cdot\dfrac{\omega_{r0}}{\omega_e}J_w = \lambda\dfrac{\omega_{r0}}{\omega_e}J_w \\ \lambda = \Delta\omega_r/\Delta\omega_s = (\omega_e/\omega_{r0})\times(J_{vir}/J_w) \end{cases} \quad \text{……(6)}$$

Where $\Delta\omega_s$and $\Delta\omega_r$ are the changes of the grid and rotor angular speed during a frequency event, respectively, $\lambda$is defined as the virtual inertia coefficient, and ω_{r0} is the pre-disturbance rotor speed.

It can be observed from Eq.(6) that the virtual inertia of the wind turbine is determined not only by its natural inertia, but also by the predisturbance rotor speed ω_{r0} and the virtual inertia coefficient λ. Different to synchronous generators, whose rotor speeds are coupled directly to the system frequency, i.e.,λ= 1, the speed variation of the variable speed wind turbine can be much greater than the system frequency variation due to the asynchronous operation, i.e., $\Delta\omega r>\Delta\omega e$ and thus λ >1. Therefore, the virtual inertia of the PMSG-based wind turbine can be several times of its natural inertia. However, the stored energy in the wind turbine changes with its rotor speed and is dependent on the wind velocity. Thus, the available virtual inertia also depends on the pre-disturbance rotor speed of the wind turbine.

OPPT Controller for Inertial Response

When system frequency deviation is detected, the generated power is regulated rapidly by switching the turbine operating point from the MPPT curve to the defined VIC curves. By this way, the kinetic energy in the wind turbines can be fully utilized to emulate the inertia response. The generated power based on the conventional MPPT control can be expressed as

$$P_{opt}^* = \begin{cases} k_{opt}{\omega_r}^3, & (\omega_0 < \omega_r < \omega_1) \\ \dfrac{(P_{max} - k_{opt}{\omega_1}^3)}{(\omega_{max} - \omega_1)}(\omega_r - \omega_{max}) \\ \quad +P_{max}(\omega_1 < \omega_r < \omega_{max}) \\ P_{max}, & (\omega_r > \omega_{max}) \end{cases} \quad \text{…….(7)}$$

Where k_{opt} is defined as the MPPT curve coefficient and ω_0 is the cut-in angular speed. To avoid an abrupt power change around the maximum speed ω_{max}, droop characteristic ofP $-\omega$ is used for the constant speed stage, and ω_1 is the initial angular speed in this stage. P_{max} is the maximum active power output of the PMSG.

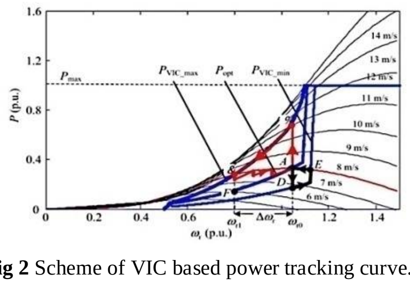

Fig 2 Scheme of VIC based power tracking curve.

From Eq.(7), it can be observed that different curve coefficients will generate a series of power tracking curves, defined as VIC curves. Thus, the regulation of the PMSG's operation point can be achieved by moving it from the MPPT curve with coefficient k_{opt} to the VIC curve with coefficient k_{VIC}.In the event of a system frequency drop, the wind turbine needs to decelerate to release the stored kinetic energy. Thus, the coefficient k_{opt} is increased and the power tracking curve is switched to the VIC curve. The operating point moves from the initial point A to B and then along the P_{VIC_max}curve to C. The rotor speed at point C (ω_{r1}) can be expressed using the frequency deviation as

$$\omega_{r1} = \omega_{r0} + \Delta\omega_r = \omega_{r0} + \lambda\Delta\omega_s = \omega_{r0} + 2\pi\lambda\Delta f. \quad \text{…….(8)}$$

If the wind speed remains constant, the captured active power at point A can be considered to be similar to that at point C for small rotor speed range. Thus, the VIC curve coefficient k_{VIC} can be calculated as

$$k_{VIC} = \left[{\omega_{r0}}^3/(\omega_{r0} + 2\pi\lambda\Delta f)^3\right]k_{opt} \quad \text{…….(9)}$$

According to Eq.(9), the VIC curve coefficient k_{VIC} is the function of the frequency deviation and replaces the constant coefficient k_{opt} of the MPPT curve. As illustrated in Fig. 3, in the event of a frequency drop, the dynamic response of the VIC can be divided into two stages: 1) fast dynamic frequency support stage (A → B → C) and 2) slow rotor speed recovery stage (C → A). Once the frequency decreases, k_{VIC} increases from the original value k_{opt} and rapidly reaches its upper limit during the first stage. According to Eq.(7) and Eq.(9), the corresponding power reference curve will then be shifted from P_{opt} to $P_{vic_max}$and the turbine's operating point is shifted from A to B with its output power changed from P_A to P_B. Since the generated power is greater than the captured mechanical power, the rotor decelerates and the operating point moves along the P_{vic_max}curve to the operating point C. Consequently, the kinetic energy stored in the rotating mass is released to support the grid frequency.

After the initial dynamic frequency response, the frequency gradually tends to stabilize with the power system's primary frequency regulation. If the power reference curve is switched from $P_{vic_max}$to P_{opt} directly, a large power step from P_C to P_F will be injected to the grid, which may result in further frequency oscillation during this recovery progress. The VIC curve coefficient is continuously changed from k_{max} to k_{opt} during the frequency recovery due to the continuous variation of the frequency deviation. In order to ensure wind turbine stability at any wind velocities, the rotor speed needs to be limited within the range [ω_{min} ω_{max}], and the upper and lower limits of the VIC curves ($P_{VIC_max}$and P_{VIC_min}) can be defined accordingly.

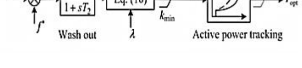

Fig 3 Structure diagram of the OPPT regulator based VIC

The block diagram of the OPPT-based VIC is shown in Fig.3. A wash out filter is used to eliminate the steady-state dc component of the frequency error.

OPPT controller for output power generation

For the proposed OPPT control, according to Eq.(9), the output power of the PMSG can be expressed as

$$P_g = \left[k_{opt}\omega_{r0}^3/(\omega_{r0} + \lambda(\omega_s - \omega_e))^3\right]\omega_r^3 \quad \text{……(10)}$$

During power oscillations, the regulation of Pg mainly depends on the variation of coefficient k_{VIC}. Neglecting the small rotor speed variation, the small perturbation quantity of Pg can be obtained as

$$\Delta P_g \approx -\frac{3\lambda k_{opt}\omega_{r0}^6}{[\omega_{r0}+\lambda(\omega_{s0}-\omega_e)]^4}\Delta\omega_s \approx -3\lambda k_{opt}\omega_{r0}^2\Delta\omega_s. \quad \text{……(11)}$$

Substituting

$$\Delta P_G = (E'V_G/x_1)\cos\theta_0\Delta\theta.$$

and Eq.(11) into below equation

$$[V_G V\cos(\delta_0-\theta_0)/x_2]\times(\Delta\delta-\Delta\theta) = \Delta P_G + \Delta P_g.$$

$\Delta\theta$ is obtained as

$$\Delta\theta = a_0\Delta\delta + [3\lambda k_{opt}\omega_{r0}^2 a_0 x_2/(V_G V\cos(\delta_0-\theta_0))]p\Delta\delta \quad \text{……. (12)}$$

Where $a_0 = x_1 V\cos(\delta_0-\theta_0)/(x_2 E'\cos\theta_0 + x_1 V\cos(\delta_0-\theta_0))$

Thus, the linear differential equations of the rotor motion can be obtained by substituting Eq.(12) and(ΔP_G) into

$$H_G p^2\Delta\delta + Dp\Delta\delta + \Delta P_G = 0$$

Then

$$H_G p^2\Delta\delta + (D+D_p)p\Delta\delta + (a_0 E'V_G/x_1)\cos\theta_0\Delta\delta = 0 \quad \text{…... (13)}$$

Where $D_p = 3\lambda k_{opt}\omega_{r0}^2 a_0 x_2 E'\cos\theta_0/(x_1 V\cos(\delta_0-\theta_0)) > 0$.

According to Eq.(13), system damping is increased from D to D+D_p, by the wind turbine's fast power regulation. This indicates that the OPPT controller can also provide power oscillation damping to the connected network. As can be seen from the above analysis and design, compared with the conventional supplementary derivative control, which results in reduced system damping, the OPPT control with VIC curves can realize both inertial response and improved power oscillation damping.

Fuzzy Logic Controller for Proposed System

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree.

The general structure of the FLC is shown in Fig. 4. The FLC is composed of fuzzification, membership function, rule base, fuzzy inference, and defuzzification.

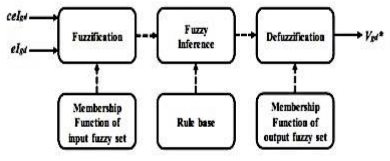

Fig 4 Block diagram of FLC

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.

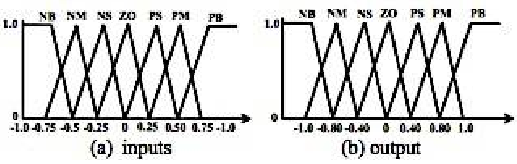

Fig 5 Membership functions

Table 1 Fuzzy rules

V_{gd}^*		ceI_{gd}						
		PB	**PM**	**PS**	**ZO**	**NS**	**NM**	**NB**
eI_{gd}	**PB**	PB	PB	PB	PM	PM	PS	ZO
	PM	PB	PB	PM	PM	PS	ZO	NS
	PS	PB	PM	PM	PS	ZO	NS	NM
	ZO	PM	PM	PS	ZO	NS	NM	NM
	NS	PM	PS	ZO	NS	NM	NM	NB
	NM	PS	ZO	NS	NM	NM	NB	NB
	NB	ZO	NS	NM	NM	NB	NB	NB

For fuzzification, the triangular membership functions with overlap are used for the inputs and output fuzzy sets as shown in figure 5, in which linguistic variables are represented as NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive small) PM (Positive Medium), and PB (Positive Big). The rules of fuzzy mapping of the input variables to the output are represented as the following form:

IF <eIgd is PB> and <ceIgd is NS> THEN <Vgd* is PM>The entire rule base is given in Table I. There are total 49 rules in the table. The Membership Function Editor is used to define the shapes of all the membership functions associated with each variable. The Rule Editor is for editing the list of rules that defines the behavior of the system. The Rule Viewer and the Surface Viewer are used for looking at, as opposed to editing, the FIS. They are strictly read-only tools. The Rule Viewer is a MATLAB-based display of the fuzzy inference diagram shown at the end of the last section. Mamdani type fuzzy inference is used in this study. The center of gravity method is used for defuzzification to obtain Vgd*. The normalized output function is given as [12],[13].

$$V_{gd}^* = \frac{\sum_{i=1}^{N}\mu_i C_i}{\sum_{i=1}^{N}\mu_i} \quad \text{…...(14)}$$

Where, N is the total number of rules, μ_i is the membership grade for i^{th} rule and C_i is the coordinate corresponding to the maximum value of the respective consequent membership function.

Simulationanalysis &Results

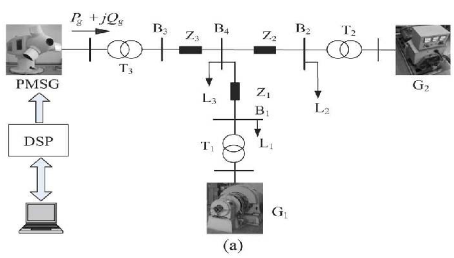

Fig 6 Schematic diagram of complete system

Circuit consists of two synchronous generators (G1 and G2), a PMSG-based wind turbine with the mechanical turbine and drive chain emulated using a controlled machine set, and three aggregated loads (L1, L2, and L3). G1and G2 are rated at 15 and 6.8 kVA, respectively[14]. The wind turbine is rated at 10 kVA, which gives a wind power penetration level of around 31% for the tested system. The three loads L1, L2, and L3 can be varied during tests and their maximum ratings are 10, 4, and 4 kW, respectively. The ac common coupling voltage is 500 V. The sampling time of the control system is 50 μsand the PWM frequency for the PMSG converters is 10 kHz. In this case, G1 regulates frequency by its governor with 4% droop setting, whereas G2 operates at constant active power modeand does not participate in frequency regulation.

For Analysing the Inertial Responses Following Cases Are Considered

Inertial Responses under Sudden Load Change

Case(a): Load L_1 was increased from 5.2 to 6.2 kW causing a temporary fall of the system frequency. The wind velocity was set as 8 m/s by the motor-based emulator and the PMSG-based turbine initially operated at the maximum power point. In Fig. 7-9, the dynamic responses of the network frequency, the PMSG's active power P_g, G1's active power output P_{G1}, and G2's active power output P_{G2} are compared for different control methods and different virtual inertia coefficients λ. The comparison between with and without the VIC-FLC scheme as shown in Fig 7.

Without Fuzzy logic controller With Fuzzy logic controller

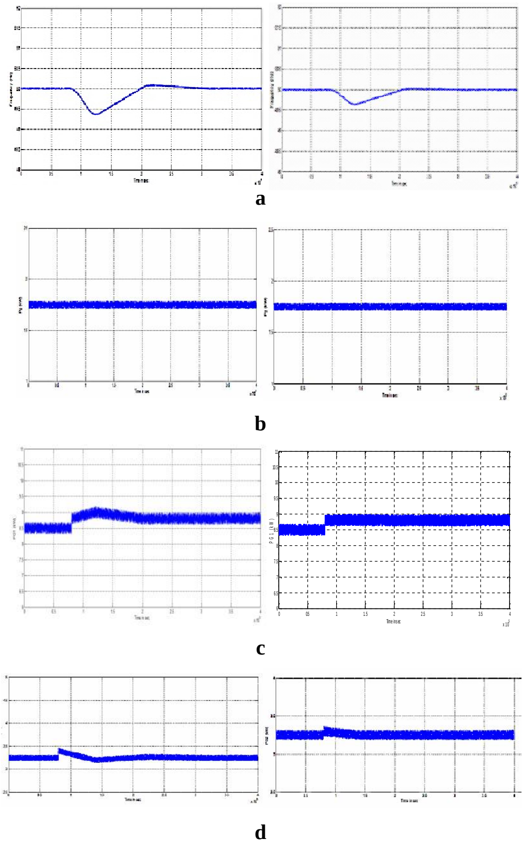

Fig 7 Without VIC& Without VIC-Fuzzy a) Frequency(Hz) b)Pg (kW) c)PG1 (kW) d) PG2 (kW)

The active power of the wind turbine remains almost constant at 1.7 kW. A large frequency drop of 0.55 Hz can be observed due to the small system inertia.

For the OPPT control scheme, the virtual inertia responses of the PMSG can be regulated by adopting different value of the virtual inertia coefficient λ. The wind turbine switches the control mode from the MPPT control to the VIC control when the frequency deviation occurs. VIC shown in Fig. 7. With G1's primary frequency regulation, the frequency deviation gradually reduces and the system frequency recovers to its normal value after 16s.

Case(b): Dynamic responses of network during load L1with VIC curves λ=1

For the results shown in Fig.8 with λ = 1, the active power of the wind turbine is increased by 0.25 kW and a reduced frequency drop of 0.45 Hz is observed compared to system without VIC.

Without Fuzzy logic controller With Fuzzy logic controller

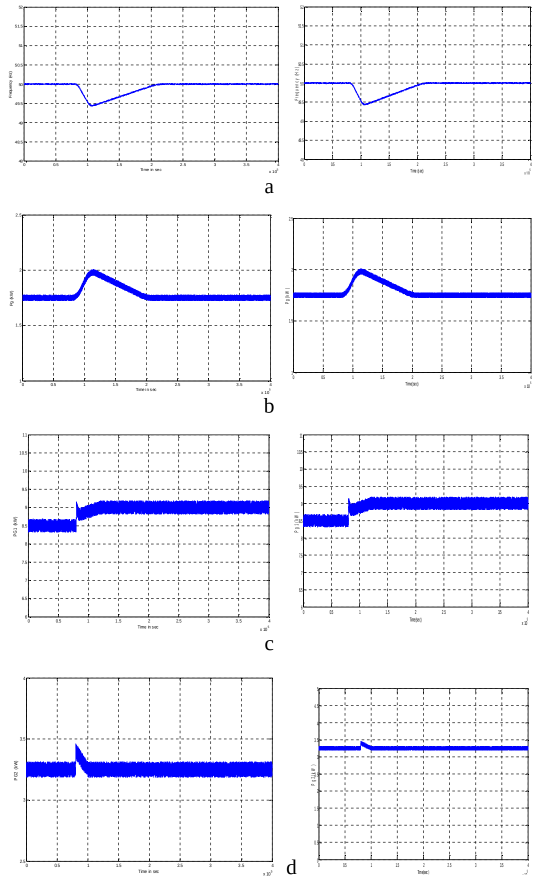

Fig 8 With VIC PI controller for λ=1 & VIC With FLC. a) Frequency(Hz) b)Pg (kW) c)PG1 (kW) d) PG2 (kW)

Case(c):: - Dynamic responses of network during load L1 sudden increase of 1kW with VIC λ=9

To further increase the virtual inertia of the wind turbine **λ**= 9 is used and the results are shown in Fig 9.

Without Fuzzy logic controller With Fuzzy logic controller

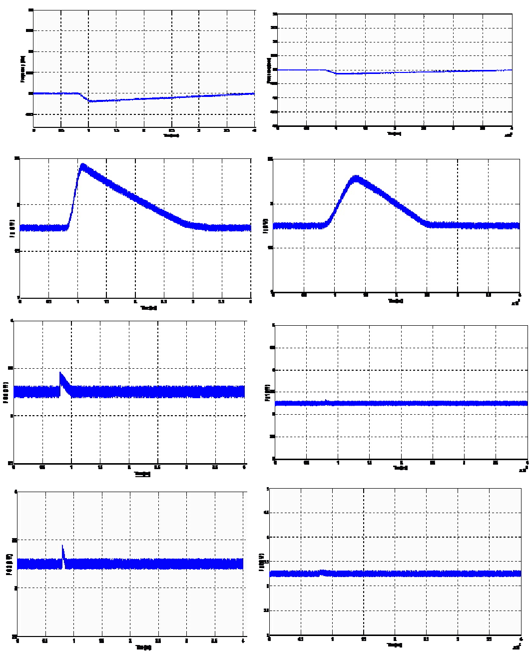

Fig 9 With VIC PI controller for λ=9& with VIC FLCa) Frequency(Hz) b)Pg (kW) c)PG1 (kW) d) PG2 (kW)

It can be seen that the wind turbine output active power is increased by 0.63 kW, which results in a much smaller frequency drop of 0.21 Hz. This represents 61.8% reduction infrequency deviation compared to system without VIC.

During the recovery progress, the output power of the PMSG decreases slowly to avoid unnecessary disturbances and provides a smooth recovery even with the large λ of 9.As evident from the analysis and test results, greater virtual inertia (i.e., higher λ) helps to reduce the rate of change of frequency. However, it is observed that as λ increases, the frequency recovery rate becomes slightly slower. This is due to the slower power increase from G1 since frequency deviation now is smaller as the result of increased inertia support from the wind turbine.

Comparison with Supplementary Derivative Control during Load Increase

L1 was increased from 5.2 to 6.2 kWAs shown in Fig 10-12, compared to Fig 10, the frequency nadir and the change rate are reduced when inertia control is applied in fig 10 &11. Furthermore, fig 12 with the proposed VIC has the smallest frequency drop and smoothest recovery. This can be explained by observing the wind turbine power outputs between the proposed OPPT controller and the supplementary controller.

Without Fuzzy logic controller With Fuzzy logic controller

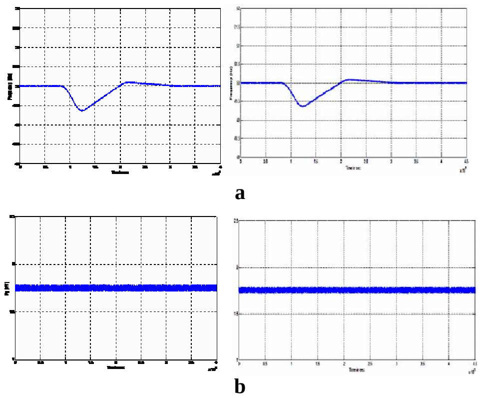

Fig 10 With No inertia control & Fuzzy a) Frequency(Hz) b)Pg (kW)

As shown, the output power of the wind turbine with the supplementary inertia control shown in Fig.11 only provides frequency support for the initial 5s, while the duration of the more effective power support in Fig 12 is about 10 s. In contrast to fig 11 where significant oscillations are observed during recovery, Fig 12 provides a stable and smooth recovery after inertia support. In fact, the impaired power response in fig 11 is mainly caused by the variation of P_{opt} of the MPPT controller.

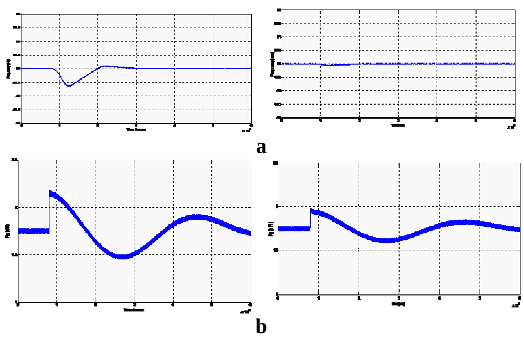

Fig 11 With supplementary control& Fuzzy a) Frequency(Hz) b)Pg (kW)

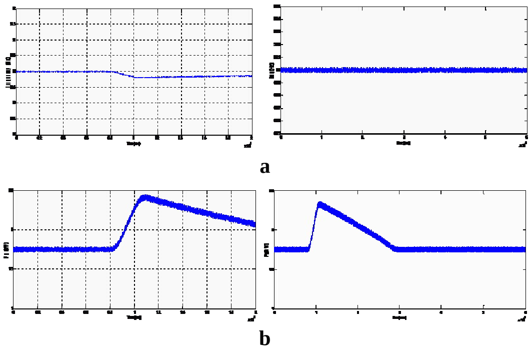

Fig 12 With VIC PI controller & with VIC FLC a) Frequency(Hz) b)Pg (kW)

Comparison with supplementary derivative control on power oscillation damping after short circuit fault

In order to compare the effects of the OPPT control and the supplementary derivative control on power system oscillation damping, a 0.1-s three-phase short-circuit fault at Bus B2 was applied. The initial wind speed was 8 m/s and λ was set to an intermediate value of 7. The severity of the three-phase short-circuit fault can be seen from the AcVoltage waveforms shown in Fig. 13 (a).

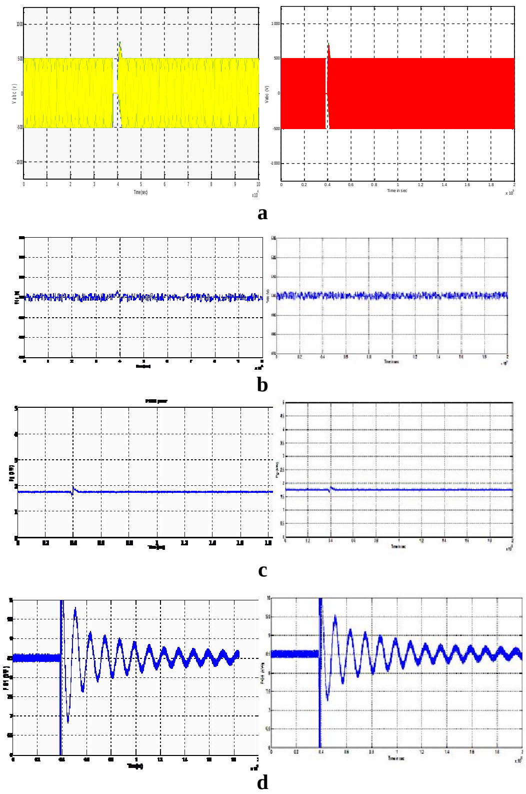

Fig 13 With No inertia control& Fuzzy a) Ac voltage b)Vdc (V) c)Pg (kW) d) PG1 (kW)

When the short-circuit fault occurred, the grid-side converter goes into current limit and its active power export to the grid is reduced. Since the generator-side converter controls the dc-link voltage, it automatically reduces power output from the PMSG and consequently the dc-link voltage remains stable with only less than 5% increase. During the fault period, the surplus mechanical power in the wind turbine is stored as kinetic energy in the wind turbines rotating masses. However, the power oscillation in this weak network cannot be damped effectively, since the wind turbine makes no contribution to system damping under this basic control scheme as shown in Fig.14 , the fast active power response from the wind turbine to the network frequency variation is generated by the supplementary derivative controller. Due to the adverse effect of this control resulting in reduced system damping, the system oscillates for a prolonged period after fault clearance. Compared to Fig 13, the increased dclink voltage and power oscillations can seriously affect the wind turbine operation and grid stability in Fig. 15, with the OPPT control, power oscillations in G1 are significantly reduced. Compared to Fig 13, the amplitude of G1's power oscillation is much lower and its duration is reduced from around 6 to 3s. This proves that the active power fluctuation of the wind turbines generated by the proposed controller helps damp the power oscillation. The dc-link voltage is also well maintained. Therefore, Case C achieves the best power oscillation damping performance among the three cases.

By the usage of VIC-FLC the magnitude and duration were reduced as compared to VIC-PI.

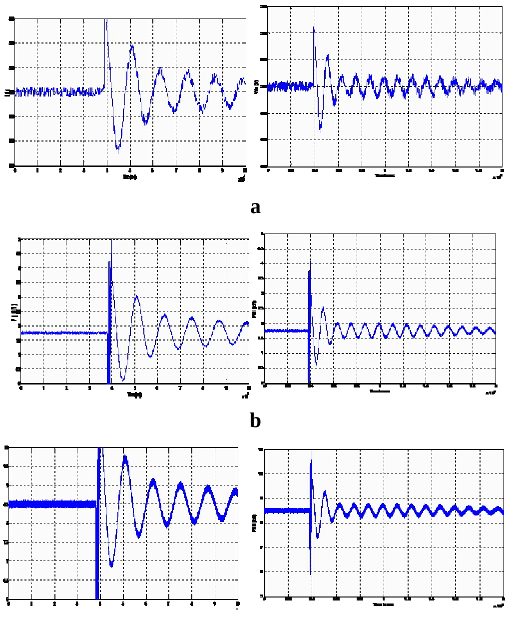

Fig 14 With supplementary derivative control& Fuzzy a)Vdc (V) b)Pg (kW) power generated by PMSG c) PG1 (kW)

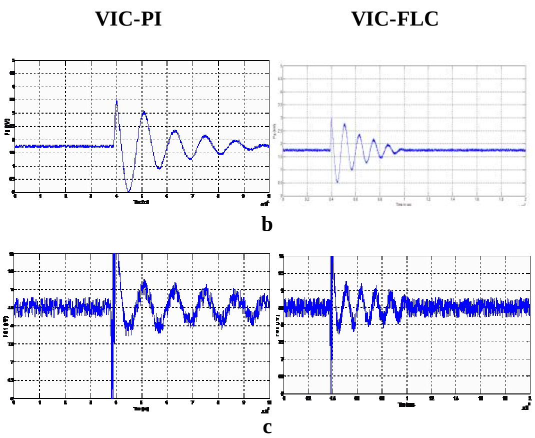

Fig 15 WithVIC PI controller & VIC FLC a)Pg (kW) power generated by PMSG b) PG1 (kW)

Comparison with Supplementary Derivative Control after Short-Circuit Fault and Load Increase

System operation during a 0.1-s three-phase short-circuit fault at Bus B2 immediately followed by a 1-kW load increase is tested to further illustrate the performance of the proposed OPPT control. The initial frequency change and power oscillations are generated by the short-circuit fault. The system frequency then decreases due to load increase. The dynamic response of the network frequency with supplementary derivative control is better than that with no inertia controlas evident from Fig. 16 and 17. However, the power oscillations are not effectively suppressed in Case B due to the lack of system damping.

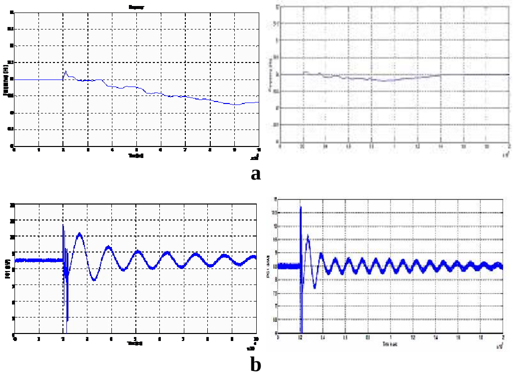

Fig16 WithNo inertia control& withFuzzy a) Frequency(Hz) b)Pg (kW)

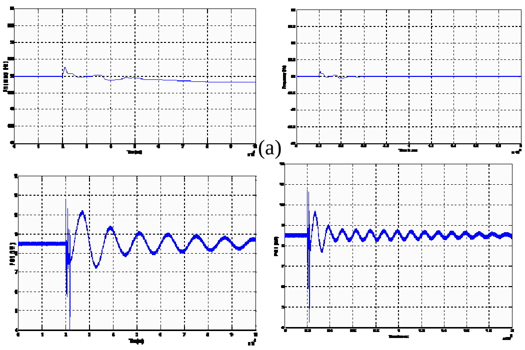

Fig 17 With supplementary control& with Fuzzy a) Frequency(Hz) b)PG1(kW)

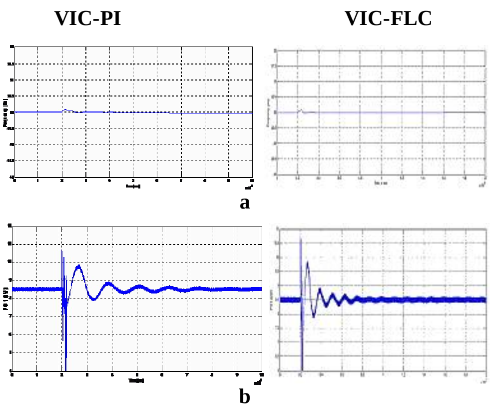

Fig 18 WithVIC PI controller & with VIC FLC a) Frequency(Hz) b)PG1 (kW)

Again the proposed OPPT control has the best performance of frequency support and power oscillation damping among the three cases. This is due to the fact that the proposed OPPT control provides simultaneous inertia response and system damping.The controller can provide additionalbenefit for dynamic stability of power systems and is well suited for wind power applications. By the usage of VIC-FLC the magnitude and duration were reduced as compared to VIC-PI.

Here We Are Considering L-L Fault Along With 3-Ø Short Circuit and 1kw of Load L1 Increment

Inthis case an L-L fault occurred at Bus B1 along with 3-Ø short circuit fault and 1kW of load L1 increment. Two conditions are considered i.e. with VIC-PI & with VIC-FLC, the power generated by PMSG and generator 1 & 2 are compared for both cases.

L-L fault without VIC-PI **L-L fault with VIC FLC**

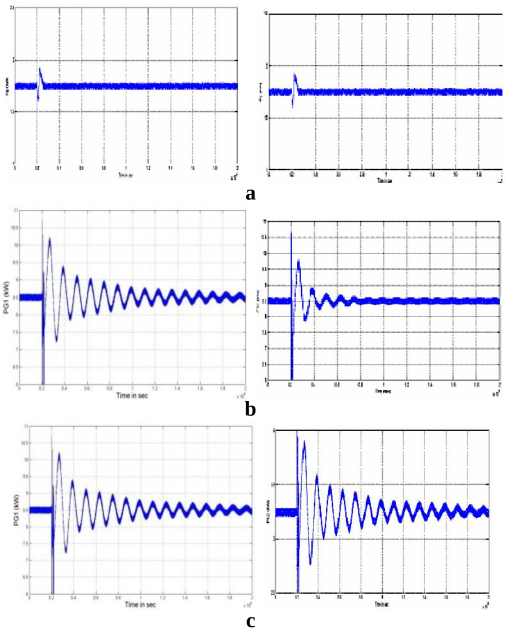

Fig 19 a) Pg (kW)b) PG1 (kW) c) PG2 (kW).

CONCLUSION

This paper scrutinizesthe power regulation of PMSG-based wind turbines during transient events for enhancing the grid inertial response and damping capability. VIC-FLC based on OPPT for PMSG-based wind turbine is proposed to provide inertial response and power oscillation damping.AC networks with high wind power penetration are likely to have reduced effective inertia and damping capability Thus, wind turbines equipped with virtual inertia and oscillation damping functions become increasingly necessary for ensuring system stability. By using the Fuzzy logic controller along with VIC based OPPT the amplitude of power oscillations are much reduced and its duration also reduced by comparing with VIC-PI. The usage of VIC-FLC results an improved active control scheme for variable speed wind turbines which provides both inertial response and positive damping function and an enhanced active power support for improved system stability.

Future Scope

Artificial neural network (ANN) can be used for providing inertial response and better damping capability for high wind penetration networks.

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