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Estimating PMSG Wind Turbines by Inertia and Droop Control Schemes with Intelligent Fuzzy Controller in Indian Development

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Abstract – This paper presents an exploration on the effect of wind turbine contribution to the frequency control of individual systems that can be used for efficient power production in India. The research includes the study of Permanent Magnet Synchronous Generator (PMSG), in wind farms. The WTs are tested for inertia and for droop responses with intelligent fuzzy logic controllers (FLC) that choose Double Input Single Output (DISO) strategy that automatically sets gain constants, as well as combined responses for the WTs. Quantitative analyses are presented for the WTs for benefits and drawbacks including appropriate selection parameters. The analysis includes inertia, droop and combined inertia, droop schemes. The reconnaissance also incorporates inertia with FLC, droop with FLC, inertia and droop with FLC schemes for detailed study of WTs, so as to forecast and achieve proper frequency control. Moreover, the analysis provides the best suited method for frequency control in PMSG.

Keywords: Droop control, Frequency control, Fuzzy logic controller, Inertia control, PMSG

1. Introduction

India was the first country in Asia to develop wind power on a commercial scale. The Danish International Development Agency (DANIDA) got involved with the Indian wind energy sector to explore the Indian market and set up two 10MW pilot projects, one at Porbandhar in Gujarat and other at Muppandal in Tamil Nadu, India. These model projects have 200 kW wind turbines and the study in our research also includes this 200kW wind turbine for the frequency control. As wind power penetration increases, a variety of technical, economic and control issues arise. Hence power system operators set technical requirements for wind turbines, which include the frequency control as a central feature [1, 2]. Autonomous power systems are characterized by very large frequency disturbances often in excess of ±1Hz, mainly due to their overall inertia [3]. Hence to avoid such instability and guard against excessive frequency deviations, controller schemes are included. Controllers have been proposed in the literature for variable speed wind turbines (VSWTs) in order to enhance their frequency response and achieve good contribution to frequency control [4-8]. Controllers' with inertial response in doubly fed induction generator (DFIG) WTs are proposed in [4] and [5]. In [6] the concept of droop control is added to the proposed scheme. In [9] pitch control is additionally used to provide frequency response in DFIG WTs. Relevant studies are majorly based on simple models for either the power system or the WTs and the responses are mainly studied for disturbances on the DFIG scheme [8-15]. The basic issues of parameter selections are usually ignored; as is the matter of the required primary reserves to be maintained in order for the wind farms (WFs) to provide the expected response.

In this paper, standard frequency controller is introduced to the control system of VSWTs based on or a permanent magnet synchronous generator (PMSG). The frequency controller includes the two fundamental frequency response theories, i.e., the transient inertial response and the permanent droop centered response. The WTs and the schemes proposed in the system are simulated in detail using the simulation software MATLAB and fuzzy logic is encompassed. The contribution of the paper lies first in the fact, where frequency regulation is more challenging. Then the effectiveness is evaluated of alternative frequency controller implementations (inertia and droop response), which are not just related to a specific WT type. The analysis includes different controllers for varying wind speeds by including fuzzy logic for transient inertial and permanent droop responses. With the existing literature, it is clear that researchers solve the frequency disturbance problems with basic PI implementations. In this response, ingenious work related to fuzzy logic is incorporated along with droop and inertia theories. Hence this conception of including soft computing technique with basic droop and inertia is novel.

In section 2, the modeling of PMSG, is examined. Also frequency controller designed such that, though the load changes drastically the frequency response is maintained within tolerance limits. Section 3 encompasses the frequency

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control concepts related to active power for the proper operation of the wind energy systems are studied. Section 4 describes frequency control executions for comprehending inertia, droop unaccompanied and combined concepts. Section 5 includes frequency control for the specified WTs integrates fuzzy logic controller (FLC) technique for inertia, droop with individual and collective schemes. Section 6 provides the comparison for with/without fuzzy logic schemes for PMSG type VSWTs. Section 7 summarizes the conclusions.

2. Modeling and control of VSWTs

2.1 Modeling and control of PMSG WTs

The typical configuration of VSWTs based multipole PMSG as shown in Fig. 1. Type D1, direct drive with large diameter variable speed multipole self-excited PMSG is chosen. As the PMSG speed has to match the slow rotating wind turbine rotor, they are multi-polar and of large diameter. Like the wound rotors, the PMSG has a three phase symmetrically distributed stator winding wound for a large number of poles to accommodate to the speed of the slow moving rotor. The difference is that the excitation is not by electromagnets as in wound rotors but is replaced by permanent magnets. The controller structures are employed as in [16]. In addition to back to back PWM voltage source converters, a dc chopper is also present in order to enhance the necessary fault ride through (FRT) capability [17]. The model for the mechanical, aerodynamic, drive train, pitch controller for PMSG WT are similar to that of DFIG [17]. The damping controller ensures damping of the torsional oscillations excited in the drive train and reflected in the generator speed, by providing the reference value for dc voltage and stator voltage to its rated value in the stator voltage reference frame. The GSC controller controls independently the active and reactive power, in the grid voltage reference frame. The system can be used with various wind turbines; the interest in the potential for wind turbines to provide regulation services has motivated new opportunities in control system research and development. Wind turbines do not inherently provide these services, but they can be synthesized through designed control actions. Ongoing research is focused on determining the upper bound of frequency regulation capability of wind turbines, as it seems possible that wind turbines could be more effective at providing some of these services than traditional power plants. The possible benefits of continuing the development of these methods present good opportunities for both grid operators and wind plant owner/operators.

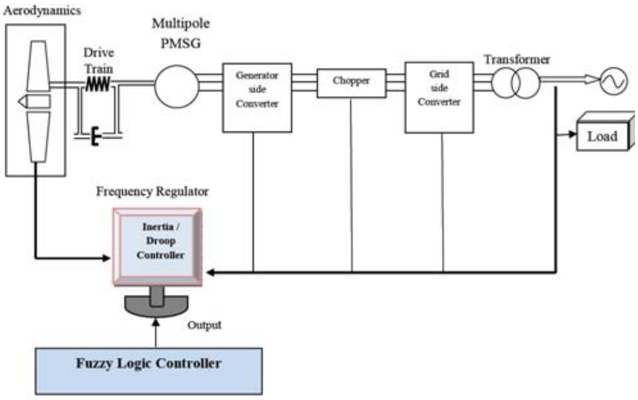

Fig. 1. PMSG WT Configuration of the proposed scheme

3. Frequency Control and Response of WTs in Frequency Disturbances

During normal operating conditions, variations in system frequency are very small. While power system frequency deviations are not uncommon, but adhere to reliability standards and practices, many a time the distributed system does not settle down to a stable operating point after the momentary disturbance. However, situations do occur, where the mismatch between the load and generation can become significant, leading to tripping of very large generating plants or an entire power station or the loss of a major transmission line leading to undesirable significant frequency variations until the protective systems operate to take corrective actions. So based on their configurations, different WTs present different response characteristics to frequency deviations. The frequency control of the system designed, is related to the active power demand and the power produced minus the losses, i.e. $P_{produced} = P_{demanded} + P_{losses.}$ Imbalance between the left-hand side and right-hand side of the power produced equation causes frequency drift. Generated power is short of demand and it led to frequency decrease (<50 Hz). The work is progressed only in a condition of deficient power production. In all the cases, for various wind turbines, the frequency drift continued till the power production is satisfied. Frequency control is achieved by switching on new power plants (or switching off some loads) or stopping some power plants according to the need. Here the demand and generation are predicted to ensure that the match is kept within tolerance.

3.1 Frequency control concept related to active power

Recalling that the active and reactive power transmitted across a lossless line, the real and reactive power is given as

$$P = \frac{V_1 V_2}{X} \sin\delta \tag{1}$$

$$Q = \frac{V_2}{X}(V_2 - V_1 \cos\delta) \tag{2}$$

Since power angle δ is typically small, we can simplify this further by using the approximations $\sin\delta \approx \delta : \cos\delta \approx 1$.

Hence the Eq. (1) and Eq. (2) becomes

$$\delta \approx \frac{PX}{V_1 V_2} \tag{3}$$

$$(V_2 - V_1) \approx \frac{QX}{V_2} \tag{4}$$

From Eq. (3) and Eq. (4), we can see that the active power has large influence on the power angle and reactive power has large influence on the voltage difference. Restating, by the control of active and reactive power, power angle and voltage can also be controlled. Also from the swing equation it is known that frequency is related to the power angle, so by controlling the active power, frequency can be controlled. This forms the basis of frequency and droop control where active power is adjusted according to linear characteristics based on the control equation as shown in Eq. (5).

$$f = f_o - K_{droop}(p - p_o) \tag{5}$$

Where f is the system frequency,

f_o is the base frequency,
K_{droop} is the frequency droop control setting,
P is the active power of the system,
P_o is the base active power of the system,

The Eq. (5) is plotted in the characteristic and shown in Fig. 2. When frequency falls from f_o to f, the power output of the generating unit is allowed to increase from P_o to P. A falling frequency indicates, increase in loading and requirement for more active power. Multiple parallel units with the same droop characteristics that, responds to fall in frequency by increasing their active power output simultaneously. The increase in active power output will offset the reduction in frequency and the units will settle at active power outputs and frequency at steady-state point on the droop characteristic. The droop characteristic therefore allows multiple units to share load without the units fighting each other to control the load.

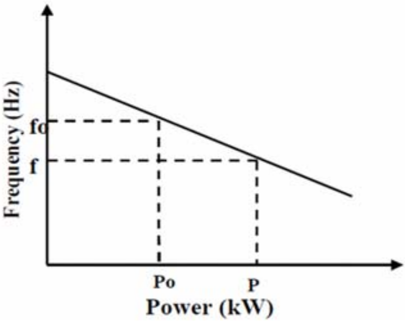

Fig. 2. Frequency control using active power control

4. Frequency Control with Droop and Inertia Only Schemes

Inertial response control, which is referred as inertial emulation or kinetic energy control, is required to help regulate the grid frequency. This response is implemented in a wind turbine or wind plant by measuring the frequency of the utility grid and using a controller to vary the output power to compensate for deviations in grid frequency. The inertial control is performed over a short time scale typically by the generator torque control to emulate the built-in response of a conventional generator. Wind turbines have the capability of providing more inertial frequency regulation than conventional generators per unit of spinning inertia, due to the speed at which the power electronics can actuate the torque command signal. Inertial response emulation typically provides fast increases (or decreases) in the power production through sudden increases (or decreases) in the generator torque. It is more common to have a conventional generator fail than for a large load to drop from the grid, so here we look at the case where there is a demand for a sudden increase in turbine power.

While conventional synchronous generators automatically provide inertial control and have governors for primary control, the distinction between inertial and primary responses is less clear for wind turbines without these governors. While patents for such technologies apparently exist and the researchers continue to explore the areas of inertial control, the methods by which primary response is achieved are generally not explicitly outlined as each control varies with respect to the specific application and it is unique. In a wind turbine, the gearbox and the blades contribute to the stored energy. Although the speed of the generator is 80 -100 times higher than the blades if a gearbox is present, most of the kinetic energy is coming from the blades due to their high inertia. This is comparable with the inertial constants of conventional power plants.

However when comparing the kinetic energy and their use in frequency control to conventional power plants, several differences should be mentioned: The kinetic energy stored in a wind turbine varies with time. When for instance the wind speed increases, the rotor speed will also increase to operate at maximum efficiency. A higher rotor speed results in an increase in stored kinetic energy. In a conventional power plant, the stored kinetic energy is virtually constant, since the generator speed is coupled with the system frequency.

In order for a wind turbine to participate in frequency control, the wind turbine may operate at reduced output, maintaining an amount of regulating power, to be reduced in the event of a frequency disturbance. The power reference block of the controller is shown in Fig. 3. It generates a power reference signal P_{ref0} based on WT $_{MPPT}$

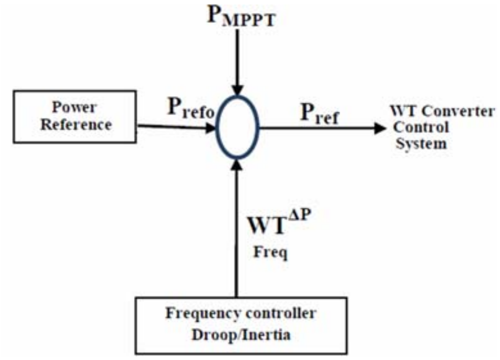

Fig. 3. Block diagram of reference value setting by the controllers as input to WT control system

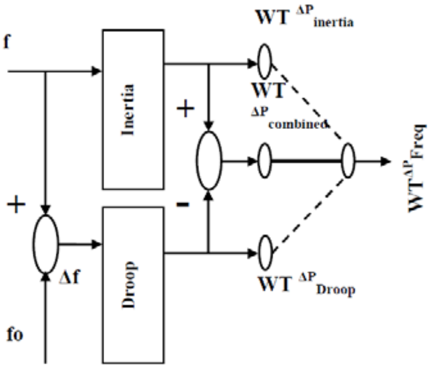

Fig. 4. Inertia only, Droop only and combined controller schemes

strategy. The output of frequency controller ΔP_{freq}^{WT} is superimposed to the output of power reference block, to determine the power reference signal as input to the WT converter controller. The frequency controller designed for VSWT incorporates two fundamental frequency response methods of inertia and droop control. Inertia only, Droop only or combined inertia and droop control are employed and shown in Fig. 4. According to the inertia principle, output power is proportional to $H_{WT}\frac{df}{dt}$ [4-6]. H is the inertia constant of a WT. In droop control, it consists in providing an output power term proportional to the deviations of frequency. Eq.5. can be written as Eq.6.

$$(P - P_0) = \Delta P \quad \text{and}$$
$$\Delta P = K_{droop}(f - f_0) \tag{6}$$

Where f_0 is the base or system frequency, parameter K_{droop} is 1/R.

$$R = \frac{f - f_0}{\Delta P} = \frac{\Delta f}{\Delta P} = \frac{1}{K_{droop}} \tag{7}$$

A dead band is included in the droop control, for which no frequency control is required in such region. Using the inertia and droop concepts, the controller behaves as PD controller, for which, due to virtual inertia the system provides fast output response, increasing the total inertia of the power system, but this is transient in nature. The droop behavior on the other hand is a permanent response waveform. It is found from the waveforms that, when the frequency falls below the limit of 50Hz, it means that production and consumption of electrical power are controlled by both primary and secondary control.

However, the frequency stabilizes not at pre-disturbance level, called primary control. These are fast frequency deviations and primary frequency control is activated for maintain the equilibrium between the instantaneous power consumption and production for the whole area.

To restore the frequency to its nominal value of 50 Hz, primary reserves are released and frequency controls are employed in a short time span, which is secondary control. Thereby secondary control results in slower increase or decrease of generation. These controls are automatic with inertia/droop schemes by power grid operator. These are relatively slow frequency variations and are aimed at keeping up the agreed exchange of power with other zones.

5. Frequency Control with Fuzzy Logic Controller Including Inertia and Droop

The values of K_{droop} and $K_{inertia}$ are tuned for frequency control. The goal of fuzzy controllers is to mimic a human operator's action or to make human like decisions by using the knowledge about controlling a target system without knowing its model [18]. So this can be achieved with fuzzy rules that constitute fuzzy rule base. For frequency control problems, rules set in this work may be sufficient to provide good control quality. Whatever form fuzzy rules may have, main concern in our research is how to interpret the meaning of each rule, that is, how to determine the influence produced by the antecedent part of the fuzzy rule or the consequent part of the rule. This procedure for assessing the influence is called fuzzy implication.

As the connotations of fuzzy propositions and fuzzy relations are expressed by membership functions it follows that fuzzy implications, related to rules formed of propositions and relations, also imply membership functions as a method of interpretation. There are many possible ways to define fuzzy implication but in control application two of them are preferred: a product (Larsen) implication and a min or Mamdani implication. In this research work, Mamdani implication is applied for frequency control. Here two input variables are chosen as input.

The fuzzy main implication is that one input variable is error frequency and the other is change in error frequency, based on the change in load (power) which is the output factor, the frequency parameter tunes as per fuzzy rules. In fuzzy inference part, there are 25 rules written. Hence

Table 1. Membership function for the fuzzy controller designed

CE Frequency Error	NB	NS	ZE	PS	PB
NB	ZE	NB	NB	NB	NB
NS	NB	ZE	NB	PS	PS
ZE	PS	ZE	ZE	ZE	PS
PS	PS	NS	NS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Table 2. Frequency response for PMSG type wind turbine with/without FLC

Control Type	Without FLC	With FLC
Inertia Control	48.1 Hz	48.8 Hz
Droop Control	48.4 Hz	49.1 Hz
Inertia & Droop Control	48.9 Hz	49.6 Hz

regarding the decision of rules to use in fuzzy controller, influences the control part. The result of fuzzy inference is a fuzzy output set. On the other hand, even control task will imply the existence of crisp value at the fuzzy controller output. This procedure which extracts crisp value from a fuzzy output set is called defuzzification. The output variable is power, when the load changes the frequency is maintained constant. The value ($f - f_0$) is set in fuzzy inputs as two separate inputs and membership functions are written for these inputs. The controlled process exhibits integral behavior, said as astatic, then a so-called non integral or PD type fuzzy controller whose crisp output value represents absolute control input value that could provide the required quality of control. The structure of a fuzzy controller is the double input-single output (DISO) structure. A convenient form of displaying the complete fuzzy rule base is fuzzy rule table shown in Table 1. Every rule in the fuzzy rule table is represented by an output set engaged in the THEN part of rule. The rule position within the fuzzy rule table is determined by co-ordinates of input fuzzy sets engaged in the IF part of the rule.

The tabular format also makes an elegant entry of new fuzzy rules possible. Table 2 clearly shows the variations of frequency that is maintained constant by using different controllers.

6. Comparison of PMSG Frequency Responses

PMSG WT of the proposed scheme employs a generic frequency controller that incorporates fuzzy logic controller. It can be seen from graphs that the frequency response of PMSG WT without frequency regulator shoots up to frequency of 95Hz. Table 2 lists the comparison for PMSG. From the simulations performed, it was found that for PMSG WT, in the 'droop only' condition the frequency is 48.4 Hz and maintained constant at 1.5 seconds, for 'inertia only' condition, the frequency is 48.1 Hz and reaches constant at 2 seconds and for the combined control the frequency reaches 48.9 Hz at 1.4 seconds. When the fuzzy control is incorporated, as shown in Fig. 5 the frequency reaches 48.8 Hz at 1.8 seconds for inertia controller, 49.1 Hz at 1.4 seconds for droop controller and 49.6 Hz for combined control.

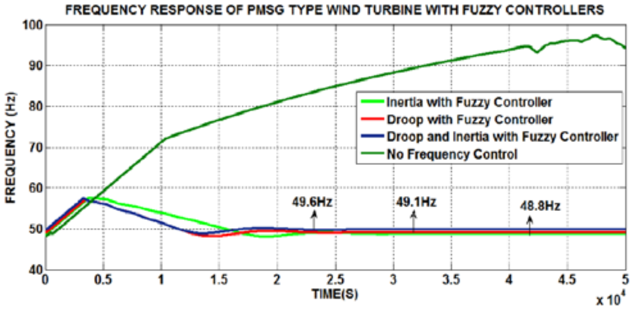

Fig. 5. Frequency response of PMSG wind turbines with FLC

It is clearly evident from the graphs that, with the inertia controller, there exists slight change is frequency response but with inclusion of droop controller, the waveform shows much better result with good frequency response. With both the controllers, the frequency response reaches a steady state at the earliest and henceforth provides enhanced performance. By adding fuzzy controller in to the system, the proposed scheme gives better-quality performance. It is noticeably seen that when both droop and inertia is included with FLC the frequency almost reaches 50Hz and maintains to be steady throughout.

7. Conclusion

In this paper, a frequency controller was proposed for VSWTs, which incorporates both the basic concepts of inertia and droop type of control. The controller is suitable for application in any type of VSWT and the implementation in PMSG WTs was investigated in this paper. The main purpose of this research was to measure the potential benefits of the WTs, considering frequency aspect. To assess the effectiveness of frequency controller implementations, simulations were performed for PMSG considering for three conditions namely inertia, droop, combined control, for with/without fuzzy logic controllers. From the analysis performed, it is evident that VSWTs can provide valuable active power during transient events that affect system frequency, as well as normal operation even under varying wind speeds. This virtual inertia controller provides transient response only and is most effective in fast frequency changes. Droop control on the other hand provides permanent response and is effective at slow events. Combined droop and inertia control with FLC provides optimal results rather than combined droop and inertia only control. The FLC with combined droop and inertia control reduces the transient excursions of one frequency and its steady state error. During normal operations, under wind fluctuations, droop control almost provides essentially the results that are near to combined control. Hence with fuzzy logic controllers, the power curtailments imposed in wind farms operating in grids constitute balanced type reserves and therefore be utilized to improve frequency response of wind farms with very low cost.

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