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Design of Fuzzy PI Load Frequency Controller for Hybrid Wind Diesel system with SMES unit

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Abstract

This paper attempts to study a wind-diesel hybrid power system. While studying the wind- diesel power system, various aspects of its design, wind penetration and, frequency and power deviations are studied. Based on the need, the work develops fuzzy, PID controllers which work in conjunction with an SMES unit.

The conventional controller is taken as the basic controller and its performances are compared with the hence, developed controllers. Developments in renewable energy systems have led to increased use of renewable/diesel hybrid systems to provide power to small remote communities where grid connections are not viable. This hybrid system consists of an isolated wind-diesel hybrid power system, the LFCs are designed to regulate the frequency deviation and power deviations.

Due to the sudden load changes and intermittent wind power, large frequency fluctuation problem can occur. The conventional Proportional Integral Derivative (PID) controller and a Fuzzy Logic (FL) controller with PI were designed separately to control the frequency and power fluctuations. To achieve acceptable power and frequency regulation, individual controllers have been designed and their performances are compared on the SIMULINK platform.

The load frequency control (LFC) deviates the frequency deviation and maintains dynamic performance of the system. In order to develop a robust LFC for the system, the fuzzy logic PI controller is considered. Based upon the above studies and their implementations, the PID and Fuzzy controllers working in conjunction with the SMES units are incorporated into the system. Simulation results explicitly show that the performance of the proposed Fuzzy Logic Controller is superior to the PID controller and the basic conventional controller in terms of overshoot, settling time against various load changes and variations of wind inputs.

Key Words: Superconducting Magnetic Energy Storage (SMES), Hybrid Wind-Diesel Power System, Load Frequency Control (LFC), Fuzzy Logic Controller (FLC), Proportional Integral (PI), Proportional Integral Derivative (PID).

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I.INTRODUCTION

The ever increasing demand for energy is one of the biggest challenges in the world today. There are several issues regarding large scale introduction of renewable energy sources. One of the issues is the quality of supply. More specific it is not possible to control the power output from a wind park or a wave power plant like it is for hydropower. There can also be variations within a relatively short time span. These variations can occur due to wind gusts, clouds shadowing for the sun or other random events. These phenomena present challenges which have to be solved before the new renewables can provide the base load. There are a number of problems in integrating a wind turbine to an existing diesel genset: voltage and frequency control, frequent stop–starts of the diesel, utilization of surplus energy, and the use and operation of a new technology. These problems vary by the amount of penetration.

Load Frequency Control (LFC) is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. Load fluctuations such as the generation outages cause the system frequency to decay from the desired value. To ensure the quality of the power supply, it is necessary to regulate the generator loads depending on the optimal frequency value with a proper LFC design. Therefore, in designing the controller, the non-linear effects due to the physical components of the system, the load change inherent characteristics and the parametric uncertainty and disturbances should be taken into account. For satisfactory operation of a power system the frequency should remain nearly constant.

A solution to this problem is the concept of energy storage coupled with a robust controller to attenuate the dynamic responses.

Load Frequency Control:

Wind energy is intermittent, and also, the real power demand of the isolated community changes frequently. It is, therefore, necessary to have a proper control strategy for maintaining the scheduled frequency and nullify the offset, if any, between generation and load. Different strategies can be adopted to reduce the mismatch between the generation and load and, thereby, control the system frequency deviations. The strategies are, namely, dump load control, priority switched load control, flywheel energy storage systems, superconducting magnetic energy storage systems and battery energy storage systems [3]. The load frequency control is to maintain the power balance in the system such that the frequency deviates from its nominal value to within specified bounds and according to practically acceptable dynamic performance of the system. An optimum load frequency controller is required for satisfactory operation of the system.

II. SYSTEM MODELLING

2.1 System Investigated:

The system considered is a 150-kW wind turbine generator (WTG) operated in parallel with a diesel generator (DG), which acts as a synchronous condenser to the wind turbine, to serve an average load of 350-kW. This system is configured as a linear and as a non-linear model with various controllers like PID, Fuzzy, and SMES, and their combinations. The controllers and their applications to the model are individually discussed in the following segments of this paper. These models' frequency deviations are simulated and their results are shown later. Initially considering the model with a program pitch conventional controller, the model is further replaced with PID, and, Fuzzy controllers which are modelled in conjunction with SMES units. It is to be noted throughout the thesis that the fuzzy controller so designed has a PI controller in conjunction.

The system is a linear, continuous – time dynamic system, and it can be represented by a set of linear differential equations of the form:

$$\dot{x} = [A]x + [B]u + [\Gamma]p \quad \text{------- (2.1)}$$

Where x, u and, p are the state, control and disturbance vectors, A, B and, Γ are real constant matrices, of the appropriate dimensions, associated with the above vectors. However, as response to a known load disturbance is analysed in the paper without any other control input being applied, then the above equation becomes:

$$\dot{x} = [A]x(t) + [\Gamma]p(t) \quad \text{------- (2.2)}$$

$$x(0) = -x_{ss} \quad and \quad x(\infty) = 0 \quad \text{------- (2.3)}$$

Where x_{ss} the steady –state value of the modified state is vector, and $x(0)$ is the vector of initial conditions. The time domain solution of equation 2.3 at a particular time *t* = *T* can be obtained as:

$$x(T) = e^{[A]T}x(0) + e^{[A]T}\int_0^T e^{-[A]t}[\Gamma]p(t)dt \quad \text{- (2.4)}$$

$$x(T) = [\phi]x(0) + [\Delta]p(0) \quad \text{------- (2.5)}$$

Where the Φ matrix is

$$[\phi] = [I + (A)T + (A)^2T^2/2! + (A)^3T^3/3! + ...] \quad \text{--- (2.6)}$$

and the Δ matrix is

$$[\Delta] = [IT + (A)T^2/2! + (A)^3T^3/3! + ...][\Gamma] \quad \text{--- (2.7)}$$

Wind energy system are already proven to be a viable alternative to fossil fuel based systems on isolated locations, such as the costal and island regions in many countries. Wind turbine generators are the most advanced among the alternative energy technologies and are expected to find their economically viable application in areas where electricity costs are high.

Power supply, using stand-alone wind energy systems, to isolated localities is a complex task because of the fluctuating nature of the wind speed and hence, of the turbine generator output power. Since wind power varies randomly, there must be a standby power source to meet the load demand [1]. A wind and diesel system is one of the hybrid systems utilizing more than one energy source. A hybrid wind and diesel system is quite reliable because the diesel acts as a cushion to take care of the variation in wind speed, and would always provide power equal to load power minus the wind power.

It provides the capability of simulating the steady and dynamic performance of the wind turbine generator, with blade angle pitch control, operated in parallel with a diesel engine generator on an isolated power system.

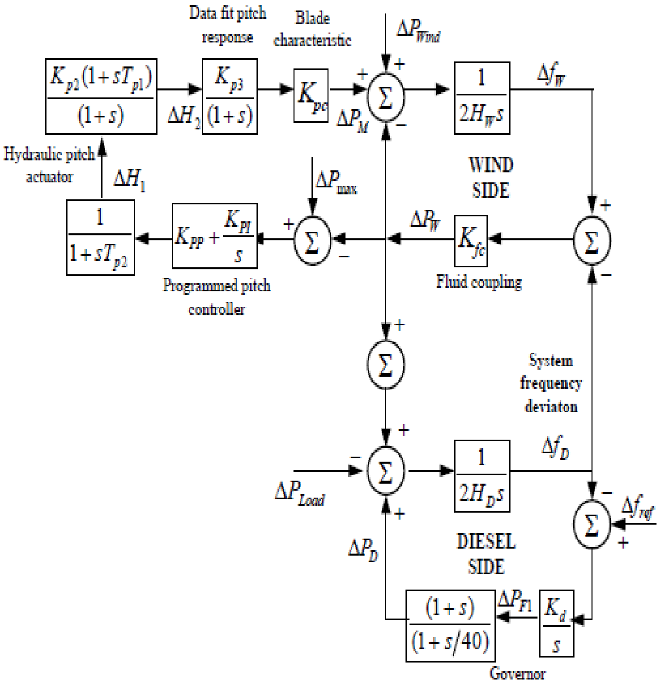


Figure 2.1-Transfer function block diagram representation of single area Wind-Diesel system

The LFC of Wind Diesel Hybrid Power System [3] using conventional controller time dynamic behavior of the load frequency control system is modeled by a set of state vector differential equations.

$$\dot{x} = Ax + Bu + \Gamma p \qquad \text{------- (2.8)}$$

Where x, u and, p are the state, control and disturbance vectors, respectively. A, B and Γ are real constant matrices, of the appropriate dimensions, associated with the above vectors described in previous section.

In order to achieve zero steady state error in frequency, designing of LFC for hybrid wind-diesel system is done by augmenting the equation 2.5.2 by two additional state variables x_{n+1} and x_{n+2} which are defined as

$$x_{n+1} = \int \Delta f_s dt \qquad \text{------- (2.9)}$$

$$x_{n+2} = \int \Delta f_r dt \qquad \text{------- (2.10)}$$

The additional state equations are,

$$\dot{x}_{n+1} = \Delta f_s \qquad \text{------- (2.11)}$$

$$\dot{x}_{n+2} = \Delta f_r \qquad \text{------- (2.12)}$$

The above equations in the matrix form can be written as,

$$\begin{bmatrix} \dot{x}_{n+1} \\ \dot{x}_{n+2} \end{bmatrix} = A_1 X \qquad \text{------- (2.13)}$$

The state vector in equation 2.11 is modified by including the state variables defined in equation 2.12 and 2.13. The augmented set of differential equations can be written as

$$\dot{\hat{X}} = \begin{bmatrix} A & 0_1 \\ A_1 & 0_2 \end{bmatrix} \hat{X} + \begin{bmatrix} B \\ 0_3 \end{bmatrix} u + \begin{bmatrix} \Gamma \\ 0_4 \end{bmatrix} P \qquad \text{------- (2.14)}$$

Where 0_1, 0_2, 0_3, 0_4 are null matrices of appropriate dimensions. The control vector u can be expressed in terms of the augmented state vector as

$$u = H\hat{X} \qquad \text{------- (2.15)}$$

Where,

The final augmented set of differential equations can be written as

$$\hat{X} = \hat{A}\dot{\hat{X}} + \hat{\Gamma}P \qquad \text{------- (2.16)}$$

Where,

$$\hat{A} = \begin{bmatrix} A & 0_1 \\ A_1 & 0_2 \end{bmatrix} \hat{X} + \begin{bmatrix} B \\ 0_3 \end{bmatrix} H \quad \text{and} \quad \hat{\Gamma} = \begin{bmatrix} \Gamma \\ 0_4 \end{bmatrix} P$$

2.1.1 Stand-Alone Hybrid Wind Diesel systems:

Stand-alone systems are generally used to power remote houses or remote technical applications (e.g. for telecommunication systems). The wind turbines used for these purposes can vary from between a few watts and 50kW. For village or rural electrification systems of up to 300 kW, wind turbines are used in combination with a diesel generator and sometimes a battery system. The key driver of many of these power quality issues is the power fluctuations from the wind turbines [11]. The power fluctuations create fluctuations in system voltage and impose fluctuations in the diesel output. Voltage fluctuations can create disturbances such as light flicker and low intensity. The power fluctuations depend not only on the amount of installed wind power capacity but also on the number of wind turbines. The decrease in power fluctuations with increasing number of wind turbines is a result of the stochastic nature of the turbulent wind: the power fluctuations from the individual wind turbines will, to some extent, be independent of each other and they will therefore even out some of the higher frequency fluctuations. Keeping power fluctuations small is a desirable feature in an isolated power system with a high penetration level.

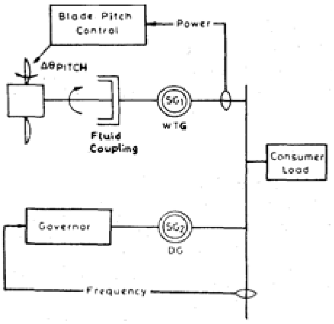


Fig. 2.2. Basic Wind-Diesel System

III. Controllers and Problem Formulation

The objective of control strategy in a power system is to generate and deliver power in an isolated hybrid power system as economically and reliably as possible while maintaining the frequency and voltage in permissible limits. The power system control has a hierarchical structure. The control system consists of a number of nested control loops that control different quantities in the system. The load in a given power system is continuously changing and consequently the system frequency and tie-line flows deviate from the desired nominal values. Therefore, to ensure the quality of power supply a load frequency controller (LFC) is needed to maintain the system frequency and inter-area flows at the desired nominal values.

The active power and frequency control is referred to as load frequency control (LFC). The main aims of the LFC systems are: (1) a zero steady errors in tie-line exchanges and frequency deviations. (2) Optimal transient performance and, (3) ensuring that the power generation levels should satisfy the optimal dispatch conditions in steady state conditions [10].

Electric power control systems such as LFC usually adopt classical PI and PID controllers to improve the dynamic response in addition to eliminating or reducing the steady-state error. The main goal of any controller in an LFC to be designed, when a disturbance occurs, is to control the frequency of the power system and the inter area tie-line power flows with good damping of oscillations, minimum steady-state error, good speed of response to reach a final value with a minimum settling time.

LFC systems basically use simple PI controller and I controller, whose parameters are usually tuned based on classical control or trial and error approaches. The controller provides zero steady-state frequency deviation but it exhibits poor dynamic performance. The basic approaches to design controllers are not effective to obtain good dynamic performance for various load changes scenarios and disturbances in an interconnected or an isolated power system. PI controllers are very often used in industry, especially when speed response is not an issue.

Control strategies used for LFC include linear feedback optimal control, artificial neural networks, fuzzy logic control techniques, adaptive self-tuning and decentralised control techniques.

Parameters	P	PI	PID
Rise time	Decreas	Decreas	Minor
Overshoot	Increas	Increas	Minor
Settling time	Small	Increas	Minor
Steady state	Decreas	Significa	No
Stability	Worse	Worse	Better

Table 3.1 Effects on Various O/P Parameter of P, PI and PID Controller w.r.t Variation in Rise Time.

Based on the above comparison, we can see there is a decrease in rise time, overshoot and settling time and there is no change in steady state error of PID it is clear that the PID controller offers the best performance among the lot.

System nonlinear characteristics, variations of system configuration due to unpredictable disturbances, loading conditions etc., cause various uncertainties in the power system. A controller which is designed without considering system uncertainties in the system modelling, the robustness of the controller against system uncertainties cannot be guaranteed [7]. As a result, the controller may fail to operate and lose stabilizing effect under various operating conditions. To enhance the robustness of power system damping controller against system uncertainties, the inverse additive perturbation (Gu et.al. 2005) is applied to represent all possible unstructured system uncertainties.

To make up for the above disadvantages, we use the SMES unit in series with a fuzzy controller and a PID controller as separate models. We, then make a comparison of them.

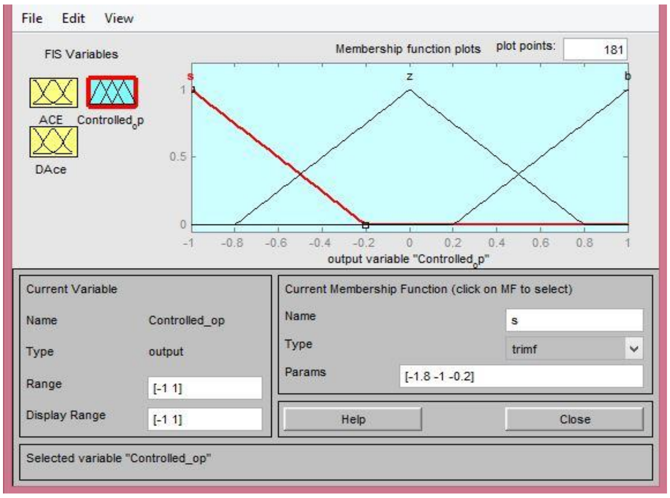
IV. Application of Controllers to the System

The effect of wind power is very important in autonomous power systems (here, isolated hybrid systems). In an autonomous grid, the spinning reserve is supplied by diesel engines, and it is usually small. This small spinning reserve will give rise to frequency fluctuations in case of a sudden wind rise or wind drop. Hence, in a wind–diesel system, voltage and frequency fluctuations will be considerably larger than in an ordinary utility grid. So, there is a definite necessity of having a robust controller to the system.

Rule based fuzzy logic controllers are useful when the system dynamics are not well known or when they contain significant non-linearity. The intermittency of wind introduces large turbulence. Fuzzy logic controllers apply intuitive reasoning, similar to how human beings make decisions, and thus the controller rules contain expert knowledge of the system. The big advantages of fuzzy logic control when applied to a wind turbine are that the turbine system neither needs to be accurately described nor does it need to be linear. Power smoothening is achieved which in turn enhances the power quality and increases the longevity of the generators protecting them against gust.

4.1 Implementation of the Fuzzy Controller:

Damping torque is produced to overcome rotor oscillation. To achieve better performance fuzzy logic can be implemented in a more effective way for load frequency controller. The fuzzy controller considered, has two phases, first being the fuzzy system unit where the Area Control Error (ACE) and its derivative (dACE) are set as input parameters. Before being connected to the output a rule base is created in the Mamdani controller. It is a common practice to build a rule base from terms such as s, z, and b representing labels of fuzzy sets. An input family may consist of those three terms. Consequently, with two inputs it is possible to build 3 x 3 = 9 rules. Nine rules is a manageable amount often used in practice, and the same is used here. The fuzzy codes are written in the .fis file in MATLAB using AND function in the Mamdani inference using triangular membership functions. The rules highly depend on the membership function, the rules are set in appropriate collection of input and output parameters. The fuzzy controller is implemented with and without an SMES unit. Both the results are separately shown in the results section.



plot points: 181

output variable "Controlled_op"

Current Variable

Name Controlled_op

Type output

Range [-1 1]

Display Range [-1 1]

Current Membership Function (click on MF to select)

Name s

Type trimf

Params [-1.8 -1 -0.2]

Selected variable "Controlled_op"

Fig. 4.1 Membership function plots on the GUI of a fuzzy controller

4.2 SMES Unit:

Superconducting Magnetic Energy Storage (SMES) is used as Energy Storage. It is able to compensate the fluctuation of wind power generation. The SMES unit is a device that stores energy in the magnetic field generated by the direct currents flowing through a superconducting coil [12]. Since energy is stored as a circulating current, energy can be drawn from the SMES unit with almost instantaneous response with energy stored or delivered over periods ranging from a fraction of a second to several hours (Ribeiro et.al, 2001). Because direct current flows with negligible losses in superconductors, the SMES unit can be used for small and large scale energy storage and rapid charge/discharge applications.

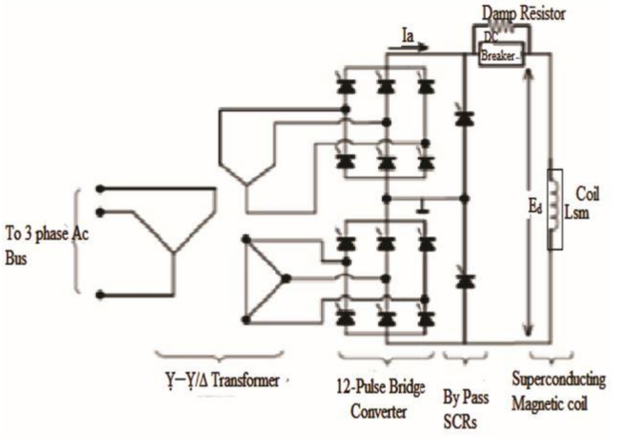


Fig.4.2 Circuit Diagram of SMES

A power conversion/conditioning system connects the SMES unit to an a.c. power system, which has an inverter that converts the dc output of the storage device to ac during discharge and the ac to dc for recharging the storage device (Schainker, 2004).

The SMES systems have several advantages. The SMES coil has the ability to release large quantities of power within a fraction of a cycle, and then fully recharge in just minutes. The SMES unit can store and discharge DC power at efficiencies of 98% or more and switch between charging and discharging within 17 milliseconds. This quick, high-power response is very efficient and economical. The SMES manufacturers cite controllability, reliability and no degradation in performance over the life of the system as prime advantages of SMES systems.

However, the robust stability of SMES units against uncertainties cannot be guaranteed. They may fail to operate and stabilize the power system when individually used, hence their use as an ancillary controller is justified.

4.3 Implementation of PID Controller:

For the system considered a PID controller is modelled into the system. The PID controller is implemented into the system along with an SMES unit and without it too. The various values of the P, I and, D are 0.9, 0.6, and 0.3, respectively.

V. RESULTS AND DISCUSSIONS

Case 1: Hybrid Wind Diesel Power System without SMES units.

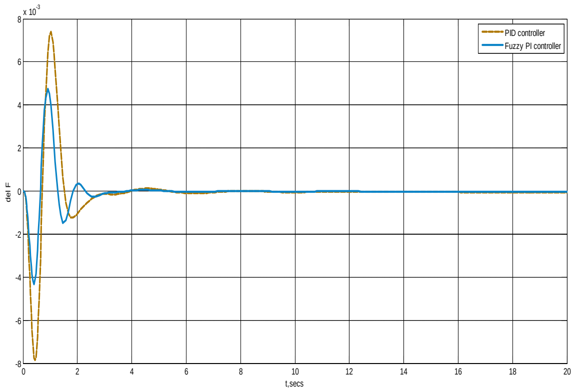


Fig 5.1 System frequency deviation without SMES

The above result shows us that the frequency deviation of the system when controlled with a fuzzy and PID controller, being very small, with the PID having a higher overshoot and relatively longer settling time, over the fuzzy controller. Showing us that, a fuzzy controller delivers a better performance for frequency settling.

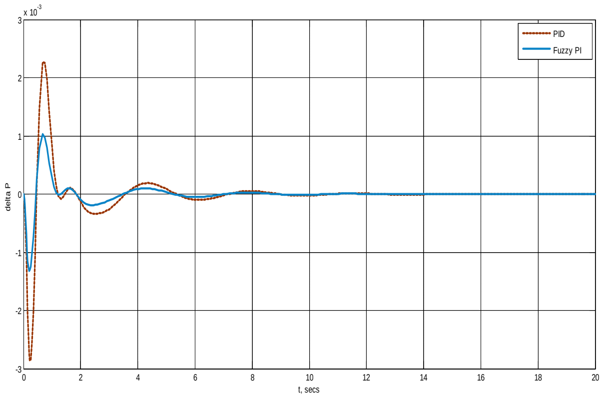


Fig. 5.2 System power deviation without SMES

The curve is smoother, with less overshoot about 50% less than its equivalent PID, and the settling is also accurate enough to settle back to zero.

Case 2: Hybrid Wind Diesel Power System LFC with SMES unit:

The curve is smoother, with less overshoot about 50% less than its equivalent PID, and the settling is also accurate enough to settle back to zero. In this set, the frequency and power deviations are compared for the Fuzzy, PID controllers (as Load Frequency Controller) modelled in conjunction with SMES, and the third controller being conventional PI controller. The set is divided into three different cases, relating to three different loading conditions. It must be noted that, the perturbations produced in the three cases are simultaneously done at the load and power ends of the model.

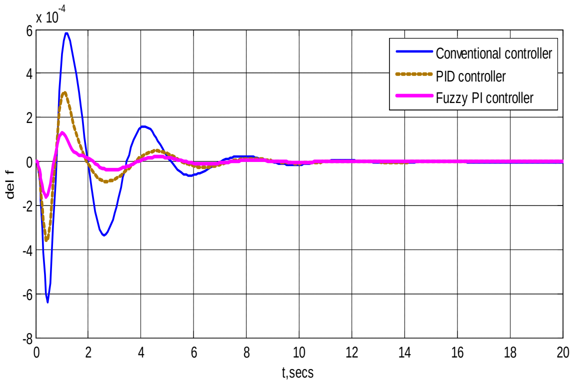


Fig.5.3. Frequency Deviation for case A

From the graph it can be analyzed, for a 10% loading case the fuzzy controller produces the least frequency deviation. The conventional controller has the highest overshoot and a slower settling time. It is followed by the PID controller. Again, the fuzzy controller is the best performer. It has negligible overshoot with a quick settling time of under 10 seconds.

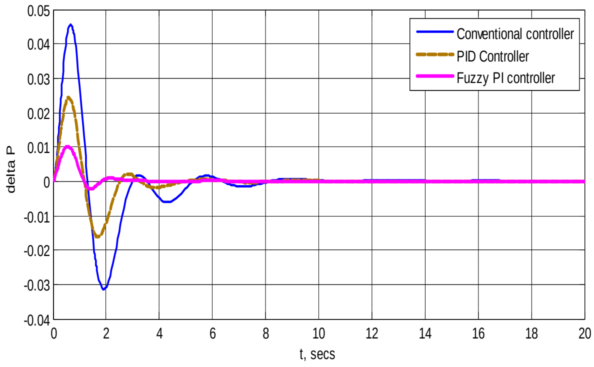


Fig. 5.4. Power Deviation curve for case A

The above power deviation curve depicts clearly, that the Fuzzy with the SMES unit provides the best power smoothening, and also settles more accurately. The PID coupled with the SMES unit provides the second better power smoothening, better than the conventional controller.

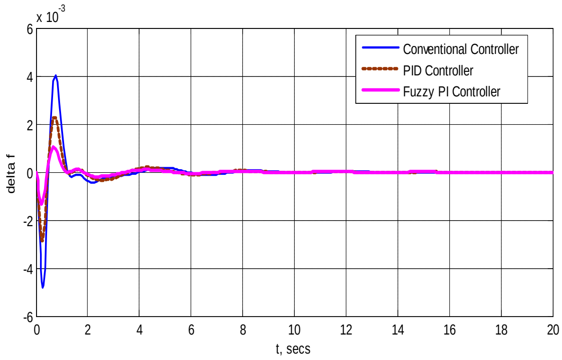


Fig. 5.5. Frequency Deviation Curve of case B

The above power deviation curve depicts clearly, that the Fuzzy with the SMES unit provides the best power smoothening, and also settles more accurately. Fuzzy being the best controller, over the PID and SMES unit. It can be concluded that the frequency attenuation of the frequency deviation of the fuzzy controllers is more distinct in the higher non-linear cases, i.e., at higher loading conditions.

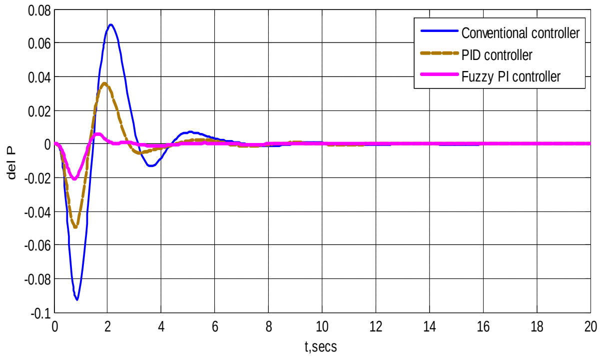


Fig 5.6. Power Deviation curve of case B

Again from the curve it is clear that the conventional controller is unable to settle at higher loads (here, 45% loading.) It is also evident that the PID controller cannot produce a smooth curve, which the fuzzy is able to. In this case the settling time of the curves are relatively increased owing to the increased loading.

VI.CONCLUSION

The implementation of the fuzzy logic controller (with a PI) and the PID controller in combination with and without an SMES unit and their comparisons with a conventional controller, with various controlling variables are carried out. Based on the simulations, it is concluded that the proposed controllers, i.e., the fuzzy controller and, the PID controller coupled with the SMES unit, provide efficient attenuation of the frequency and power deviations.

It is also evident that the power conditioning is better done by the fuzzy controllers than the PID counterparts which are slightly sluggish.

It can be concluded with reason that the fuzzy controller is best suited in all cases, and is a certain winner over the conventional controller, when the non-linearities in the system are increased. Since in all practical conditions the wind-diesel power systems work under heavy perturbations and exogenous disturbances, the proposed fuzzy controller working in combination with the SMES unit proves to be the essential controller.

SYSTEM DATA:

The system data is as follows:

Area Capacity, P_r =350 kW
H_W = Inertia constant on machine base is 3.5 for wind system
H_d = Inertia constant on machine base = 8.5 for diesel system

P=0.9, I=0.6, D= 0.3; 150kW generator.

SMES unit data:
I_{do} = 2.0 kA,
L = 10 H
K_o = 6000 kV/Hz
K_{Id} = 5.0 kV/kA

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