A Robust Decentralized Controller for Stand-Alone Wind Systems and Hybrid Wind-Diesel Systems Using Type-2 Fuzzy Approach

R. Vijaya Santhi and K. R. Sudha
Department of Electrical Engineering, Andhra University, Visakhapatnam, Andhra Pradesh, India
Email: {santhikanth, arsudhaa}@gmail.com, santhi_rajamahanthi@yahoo.co.in

A. Chandra Sekhar
Department of Mathematics, GITAM University, Visakhapatnam, Andhra Pradesh, India
Email: acs@gitam.edu

***Abstract*—In the present paper, a Non-Conventional source, wind system is considered for Load Frequency Control (LFC) problem. Modeling of a stand-alone wind system and a Hybrid wind-diesel system is done. In both the cases variable power consumptions as well as the intermittent wind power may cause a large fluctuation of system frequency. The system will lose stability, if the system frequency is not controlled. In addition, variation of system parameters, unpredictable power demands, fluctuating wind power etc., cause various uncertainties in the system. Literature shows Fuzzy controllers including Super Magnetic Energy Storage (SMES) units are suitable for highly chaotic systems. In the present paper, Fuzzy controller, which is termed as Type-1 Fuzzy including SMES units, is designed based on the analytical structure. Type-1 fuzzy can further be modified to Type-2 fuzzy by giving grading to the membership functions. Based on the same analytical structure, a robust decentralized control scheme is designed using Type-2 Fuzzy logic controlled SMES Controller. In the present paper it is observed that dynamic response with Type-2 Fuzzy controller for change in load and change in wind power is better when compared with conventional SMES controller and Type-1 fuzzy logic SMES controller.**

***Index Terms*—load frequency control (LFC), stand-alone wind system, hybrid wind diesel system, Type-2 fuzzy logic SMES controller**

I. Introduction

In a power system, Automatic Generation Control (AGC) plays an essential role to allow power exchanges and to supply better conditions for the electricity trading. Load frequency control in power systems is very important in order to supply reliable electric power with good quality. The goal of the LFC is to maintain zero steady state errors in a multi area interconnected power system [1].

In addition, the power system should fulfill the proposed dispatch conditions. The objectives of LFC [2], [3] are tominimize the transient deviations in these variables (area frequency and tie-line power interchange) and to ensure their steady state errors to be zeros. When dealing with the LFC[4], [5] problem of power systems, unexpected external disturbances, parameter uncertainties and the model uncertainties of the power system pose big challenges for controller design. A lot of studies have been made in the past about the load frequency control. In the literature, some control strategies have been suggested based on the conventional control theory [6], [7]. The system frequency variations must be held within acceptable tolerances so that consumer equipment may operate satisfactorily and efficiently.

In future, many countries in the world, including India are likely to install wind power system, as wind power is being increasingly considered not only to reduce CO_2 but also an interesting economic alternative in areas with appropriate wind speeds. The integration of high penetration levels of wind power into power systems that were originally designed around large-scale synchronous generators may require new approaches and solutions. This gave rise to new approach of isolated wind systems. When integrating wind power, wind-diesel systems, however, have the advantage of being able to neglect existing large and sometimes not very flexible, generation units. Wind energy is intermittent, and also, the real power demand of the isolated community changes frequently [8]. It is, therefore, necessary to have proper control strategy for maintaining the scheduled frequency.

In past, most of the works in the area of LFC pertain to interconnected thermal systems and relatively lesser attention has been devoted to the AGC of stand-alone wind system and Hybrid wind-diesel system [9] involving and wind subsystem of widely different characteristics. As frequency is a common factor throughout the system, a change in active power demand at one point is reflected throughout the system. Wind energy systems are already proven to be a viable alternative to fossil fuel based systems on isolated locations, such as coastal and island regions in many countries. Power supply, using stand-alone wind energy systems, to isolated localities is a

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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. 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 cushion to take care of the variation in wind speed, and would always provide power equal to the load power minus wind power [10]. Hence, Wind Diesel power systems are considered economically viable in many cases for supplying electrical energy where the wind speed is considerable for electric generation [11]. In the past decades, Fuzzy Logic Controllers (FLCs) have been successfully developed for analysis and control of nonlinear systems [12], [13]. The fuzzy reasoning approach is motivated by its ability to handle imperfect information, especially uncertainties in available knowledge. Stimulated by the success of FLCs, Talaq [14], Yesil [15] and Chang [16] proposed different adaptive fuzzy scheduling schemes for conventional PI and/or PID controllers [17]. These methods provide good performances but the system transient responses are relatively oscillatory.

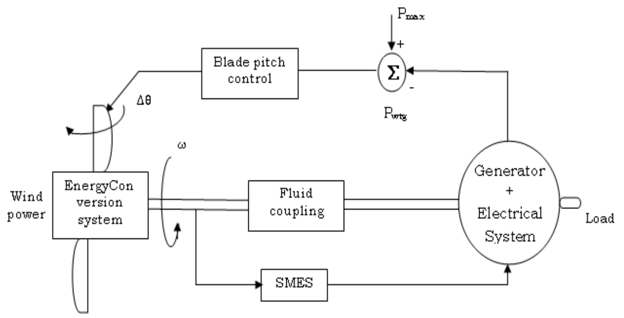


Figure 1. Basic configuration of a wind stand-alone power system with SMES

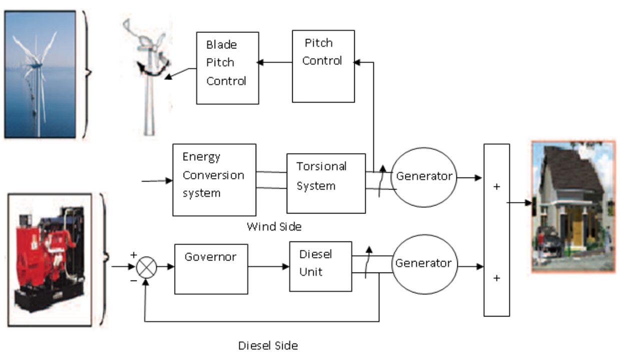


Figure 2. Basic configuration of hybrid wind-diesel power system

The objective of this research is to investigate the Load Frequency Control and inter-area tie line Power control problem for stand-alone wind system and hybrid Wind diesel power system shown in Fig. 1 and Fig. 2. To take care of these uncertainties many authors have proposed fuzzy logic based SMES controllers to power systems. This fuzzy logic, also called as Type-1 fuzzy, can further be modified to Type-2 fuzzy by giving grading to the membership functions which are themselves fuzzy. Or in other words, in Type-2 fuzzy sets, at each value of the variable the membership is a function but not just a point value. Therefore, a Type-2 fuzzy set can be visualized as a three dimensional.

The advantage of the third dimension gives an extra degree of freedom for handling uncertainties. Taking this feature into consideration, a robust decentralized control scheme is designed using Type-2 Fuzzy logic systems [18], [19], [20].

The proposed Type-2 Fuzzy SMES controller is simulated for stand-alone wind power system and hybrid wind-diesel system and was compared with conventional SMES controller [17] and Type-1 Fuzzy SMES controller. Results of simulation show that the Type-2 fuzzy SMES controllers guarantee the robust performance.

II. System Modeling

While modeling with wind systems, the power system operation should be independent of wind power penetration levels and has to supply an acceptable voltage to consumers and continuously to balance production and consumption [1].

The generated power of the Wind Turbine Generator (WTG) depends upon the wind speed, V_w. The mechanical power output of the wind turbine is expressed as:

$$P_W = \frac{1}{2}\rho A_r C_p V_w^{\ 3} \qquad (1)$$

ρ: The air density (kg/m^3);
A_r: The swept area of blade (m^2)
C_p: Power co-efficient which is a function of tip speed ratio (l) and blade pitch angle (b)

Standby Diesel Engine Generator (DEG) works autonomously to supply the deficit power to the hybrid system to meet the supply-load demand balance condition.

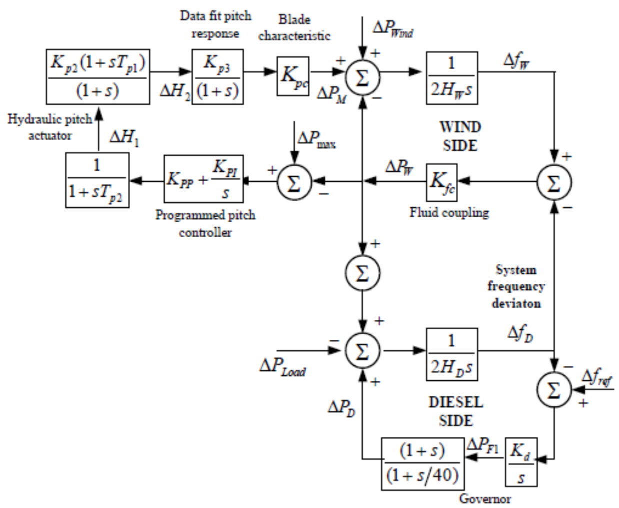


Figure 3. Transfer function block diagram representation of hybrid wind-diesel system

The LFC of Hybrid Wind Diesel Power System Using Conventional Controller time dynamic behavior of the load frequency control system is modeled by a set of state vector differential equations and transfer function block diagram representation of Hybrid Wind Diesel system is shown in Fig. 3.

$$\dot{x} = Ax + Bu + \Gamma p \tag{2}$$

where *x*, *u* and pare the state, control and disturbance vectors, respectively. *A*, *B* and *Γ* are real constant matrices, of the appropriate dimensions, associated with the above vectors.

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) by two additional state variables x_{n+1} and x_{n+2} which are defined as

$$x_{n+1} = \int \Delta f_s dt \tag{3}$$

$$x_{n+2} = \int \Delta f_r dt \tag{4}$$

The additional state equations are,

$$\dot{x}_{n+1} = \Delta f_s \tag{5}$$

$$\dot{x}_{n+2} = \Delta f_r \tag{6}$$

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

$$\begin{bmatrix} \dot{x}_{n+1} \\ \dot{x}_{n+2} \end{bmatrix} = A_1 X \tag{7}$$

The state vector in equation (2) is modified by including the state variables defined in equation (3) and (4). The augmented set of differential equations can be written as

$$\dot{\hat{X}} = \begin{bmatrix} A & 0_1 \\ A_1 & 0_2 \end{bmatrix} \hat{X} + \begin{bmatrix} B \\ 0_3 \end{bmatrix} u + \begin{bmatrix} \Gamma \\ 0_4 \end{bmatrix} P \tag{8}$$

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

$$u = H\hat{X} \tag{9}$$

where

$$H = \begin{bmatrix} -K_{DP} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{DI} & 0 \\ K_{IG}K_{PP} & 0 & 0 & 0 & -K_{IG}K_{PP} & 0 & 0 & 0 & K_{IG}K_{PI} & -K_{IG}K_{PI} \end{bmatrix} \tag{10}$$

The final augmented set of differential equations can be written as

$$\hat{X} = \hat{A}\dot{\hat{X}} + \hat{\Gamma}P \tag{11}$$

where

$$\hat{A} = \begin{bmatrix} A & 0_1 \\ A_1 & 0_2 \end{bmatrix} \hat{X} + \begin{bmatrix} B \\ 0_3 \end{bmatrix} H \text{ and } \hat{\Gamma} = \begin{bmatrix} \Gamma \\ 0_4 \end{bmatrix} P \tag{12}$$

III. Fuzzy Systems

A. Type-1 Fuzzy System

Fuzzy Logic Control Technique has been a good replacement for conventional control Techniques. Many researchers have suggested that these controllers have the potential for robust control in the face of system parameter and load uncertainties. It is realized that fuzzy logic control can perform very effectively when the operating conditions change rapidly. These features make up very attractive for power system applications since power system is a highly non-linear and chaotic system [4], [18].

A classical FLS, also denoted as Type-1 FLS, can be represented as in Fig. 4. As shown, rules play a central role in the FLS framework. Rules can be provided by experts or can be extracted from numerical data. The IF-part of a rule is an antecedent while the THEN-part of a rule is its consequent. Fuzzy sets are associated with terms that appear both in the antecedent and in the consequent, while Membership Functions (MFs) are used to describe these fuzzy sets.

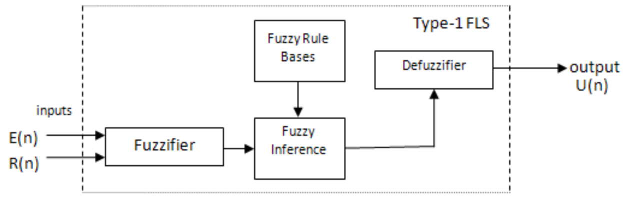


Figure 4. Type-1 FLS scheme

A Type-1 fuzzy setA, can be represented, in terms of a single variable x∈X, as

$$A = \{(x, \mu_A(x)) \mid \forall x \in X\} \tag{13}$$

where Type-1 MF, $\mu A(x)$, belongs to the range [0, 1], for all $x \in X$ and it is a 2D function, that depends on both *x* and *A*.

When the membership of an element in a set as 0 or 1 cannot be determined, Type-1fuzzy sets are employed. Similarly, when circumstances are so fuzzy that determining the membership degree even as a crisp number in [0, 1] is a difficult task, Type-2 fuzzy sets are employed. Thus, when something is uncertain (e.g. a measurement), there is trouble in determining its exact value, in such case there is a need of Type-1 fuzzy sets, instead of crisp sets. But, if there is uncertainty in determining its exact value, it will be difficult to determine exact membership in a fuzzy set. So, ideally there is a need to use Type-infinity fuzzy sets to completely represent uncertainty, but in practice we use some finite-type sets, just like Type-2 fuzzy sets a concept that was first introduced by Zadeh in 1975 [21].

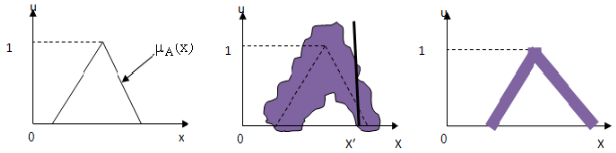
B. Type-2 Fuzzy System

A fuzzy system that uses Type-2 fuzzy sets and/or fuzzy logic and inference is called a Type-2 (T2) fuzzy system. In contrast, a fuzzy system that employs ordinary fuzzy sets, logic, and inference is called Type-1 (T1) fuzzy system [9]. T1 fuzzy systems, especially fuzzy controllers and fuzzy models, have been developed and applied to practical problems. A Type-1 fuzzy set (T1 FS) has a grade of membership that is crisp, whereas a Type-2 fuzzy set (T2 FS) has a grade of membership that is fuzzy, so T2 FS are 'fuzzy-fuzzy' sets.

By imagining blurring of Type-1 membership function depicted in Fig. 5(a) by shifting the points on the triangle either to the left or to the right and not necessarily by the same amounts, as in Fig. 5(b). Then at a specific value of x, x0, there no longer is a single value for the membership function, whereas the membership function takes on values wherever the vertical line intersects the blur. Those values need not all be weighted the same, and so it can be assigned with an amplitude distribution to all of those points. So a three dimensional membership function can be created, a Type-2 MF that characterizes a Type-2 fuzzy set. Thus a Type-2 fuzzy set can be defined $\tilde{A}$ as follows

$$\tilde{A} = \{(x,u), \mu_{\tilde{A}}(x,u) / \forall x \in X, \forall u \in J_x \subseteq [0,1]\} \quad (14)$$

where $\mu_{\tilde{A}}(x, u) \in [0, 1]$.



(a) (b) (c)

Figure 5. (a) Type-1 MF, (b) Blurred Type-1 MF, (c) FOU

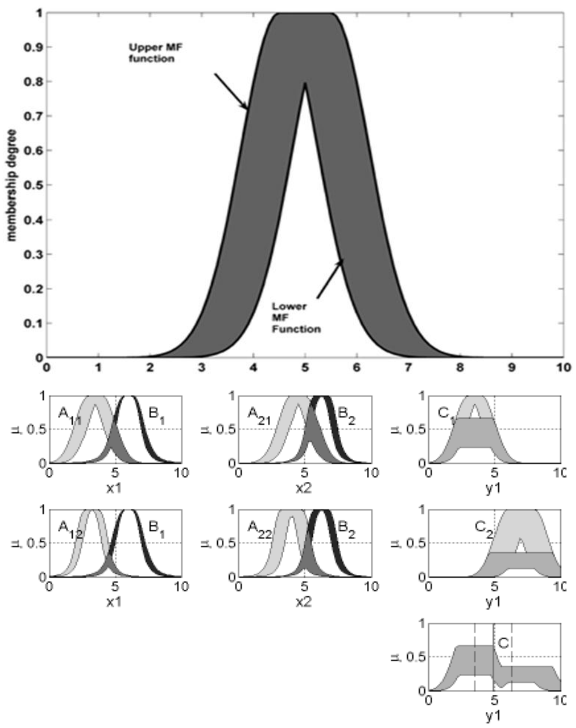


Figure 6. Interval Type-2 membership function and fuzzy reasoning

From this definition it follows that fixed $x = x'$ we have a set of possible values, even with different weights, that we call secondary MF, $\mu_{\tilde{A}}(x', u)$, while the domain of this secondary membership function is called primary membership of x, Jx in the expression above. Consequently there is a primary and secondary degree of membership to a fuzzy set. Fig. 5(c) represent the set of all possible primary MFs embedded in a Type-2 fuzzy set, also denoted as Footprint of Uncertainty (FOU). This term seems very useful because it provides a convenient way to describe the entire support of the secondary grades and in many applications allows to correctly choosing appropriate MFs by first thinking about their appropriate FOUs. The FOU can be also described through the concepts of lower and upper MFs [22] that represent respectively two Type-1 MFs that are bounds for the FOU of a Type-2 fuzzy set $\tilde{A}$ shown in Fig. 6.

One way of representing the fuzzy membership of fuzzy sets is to use the footprint of uncertainty (FOU), which is a 2-D representation, with the uncertainty about the left end point of the left side of the membership function, and with the uncertainty about the right end point of the right side of the membership function. Operation of Type-2 fuzzy set is identical with an operation of Type-1 fuzzy set, however on interval fuzzy system; fuzzy operator is done as two T1 membership functions which limit the FOU, UMF and LMF to produce firing strength. Defuzzification is a mapping process from fuzzy logic control action to a non-fuzzy (crisp) control action. Defuzzification on an interval Type-2 Fuzzy Logic System (T2FLS) using centroid method is shown in Fig. 7.

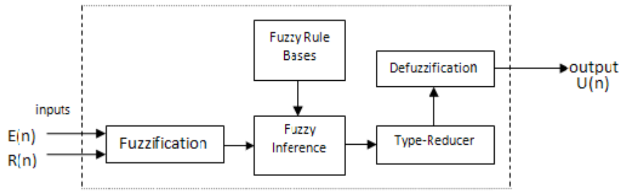


Figure 7. The structure of the T2FLS scheme

In Type-2 fuzzy set, at each value of primary variable the membership is a function and it is not just a point value; the secondary membership function whose domain, i.e., the primary membership is in the interval [0, 1], then their range, the secondary grades may also be in the interval [0, 1]. Since, the foot of membership functions is not a single point but designed over an interval, therefore Type-2 fuzzy logic controller can also be referred as Interval Type-2 fuzzy logic controller.

The design of Interval Type-2 membership functions and operators are implemented in the IT2FLS toolbox [19], [20]. An Inference Fuzzy System is a rule base system that uses fuzzy logic, instead of Boolean logic that is utilized in data analysis [4], [18].

IV. Robust Type-2 Fuzzy Logic SMES Control Approach to System Stabilization

Improving primary frequency control for power systems with high wind power penetration is an active area of research. One approach to improve frequency performance in the face of increased wind generation is to introduce robust control on the conventional generators. Type-2 fuzzy SMES controllers can be used to achieve robust performance and/or stability in the presence of bounded uncertainties, disturbances and noises.

The frequency spectrum of wind power fluctuation is then used in the problem formulation as the characterization of exogenous disturbance. The resulting robust controller can effectively narrow the band of frequency deviation caused by wind power fluctuations as shown by the response of the system frequency.

A. Stand-Alone Wind System

For the best performance of the system, the wind turbine generator should participate in the short as well as long term adjustment of generated power that occurs when there is a change in load. The system incorporates use of turbine blade angle pitch control to control wind turbine speed and shaft torque. Variable pitch turbines operate efficiently over a wide range of wind speeds [23]. Prime mover speed is kept constant using turbine blade angle pitch control. A total power set point is selected in which it can be adjusted from zero to its maximum value. This power set point will also be taken into account of SMES unit capacity [24]. When wind power rises above the power set point and the SMES unit is fully charged, the pitch control system begins operating to maintain the average power equal to the set point. The pitch control system consists of a power measurement transducer, manual power set point control, a proportional plus integral feedback function, and a hydraulic actuator which varies the pitch of the blades. Turbine blade pitch control has a significant impact on the dynamic behavior of the system.

Case 1: Step increase in wind load change

In this case, a 0.1pu step increase in the wind load input is applied to the system. The frequency oscillation for all the controllers is shown in below Fig. 8. From the figure, it is clear that though the frequency oscillations settle at almost nearby time for all the controllers, but the peak overshoot and undershoot of the proposed Type-2 Fuzzy with SMES controller shows its robustness.

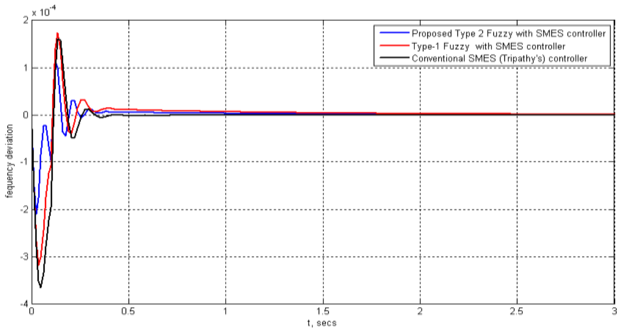


Figure 8. Frequency deviations due to change in wind load

Case 2: Step increase in wind power

Step increase in wind power ΔP_W is applied. The frequency deviation for all the controllers is shown in below Fig. 9.

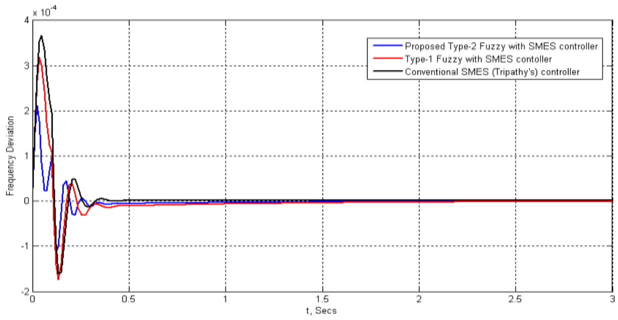


Figure 9. Frequency deviations due to change in wind power

Using proposed method, the frequency deviation is quickly driven back to zero and SMES units using Type-2 fuzzy controller [4], [18] has the best performance in control and damping of frequency in all responses when compared with conventional SMES controller [24] and Type-1 Fuzzy with SMES controller.

Case 3: Random wind power input

In this case, the system is subjected to the random wind power input as shown in Fig. 10.

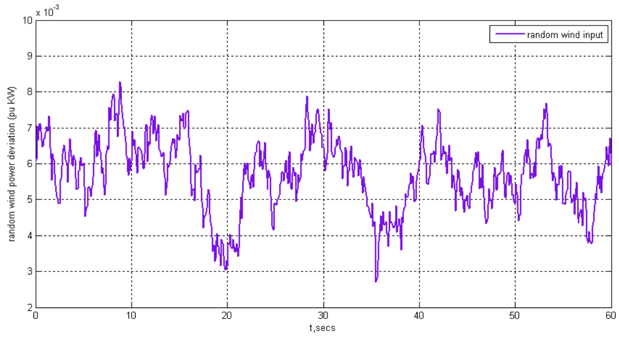


Figure 10. Random wind power input

As depicted in Fig. 11, both Type-1 Fuzzy with SMES controller and the proposed Type-2 Fuzzy with SMES controller are able to damp the frequency deviation quickly in comparison to conventional SMES controller case. The results show that both the Fuzzy controllers have almost the same frequency control effects under this condition.

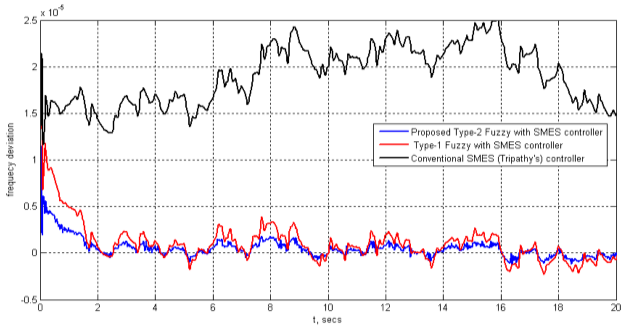


Figure 11. Frequency deviation due to change in random wind power

B. Hybrid Wind-Diesel Systems

When diesel generators are operating in parallel to wind turbines then, clearly, as the standard deviation of the wind power increases so will the standard deviation of diesel power since the diesel is required to fill any difference between the required load and the wind generation. This is an especially important point when considering the retrofit of existing diesel plants with wind energy as care will have to be taken to ensure that the current diesel controls can cope with the expected wind power fluctuations.

Case 1: Step change in wind load

In this case, a 0.1pu step increase in the wind load input is applied to the system. The frequency oscillation for all the controllers is shown in below Fig. 12. The frequency oscillations for conventional controller and Type-1 Fuzzy with SMES controller will take more than 5secs to settle to zero when compared with proposed

Type-2 Fuzzy with SMES controller. The peak overshoot and undershoot of the proposed Type-2 Fuzzy with SMES controller shows its robustness.

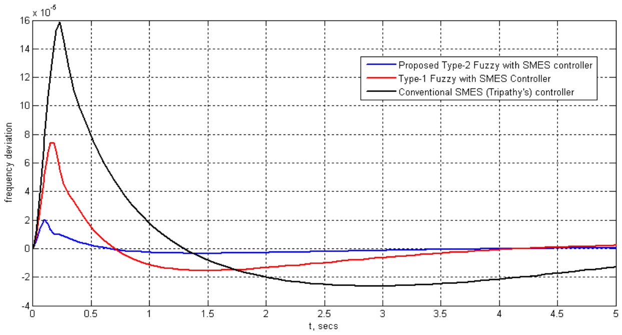


Figure 12. Frequency deviations due to change in wind load

Case 2: Step increase in wind power

When Step increase in wind power ΔP_W is applied, the frequency deviation is shown in Fig. 13. Using proposed controller, the frequency deviations are quickly driven back to zero and controller using Type-2 fuzzy with SMES controller [4], [18] has the best performance in control and damping of frequency when compared with conventional controller [24] and Type-1 Fuzzy with SMES controller.

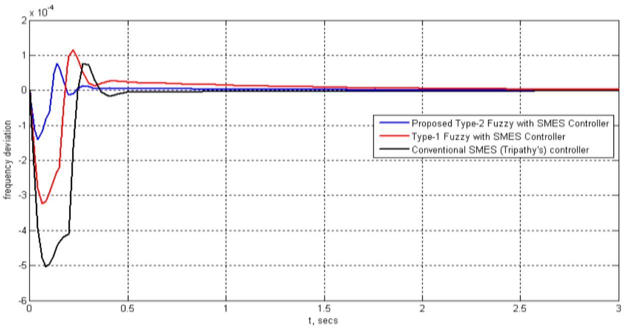


Figure 13. Frequency deviations due to change in wind power

Case 3: Random wind power input

In this case, the system is subjected to the random wind power input. As shown in Fig. 14, both Type-1 Fuzzy controller and the proposed Type-2 Fuzzy controller are able to damp the frequency deviation quickly in comparison to conventional controller case. These results show that both the Fuzzy controllers have almost the same frequency control effects under this condition.

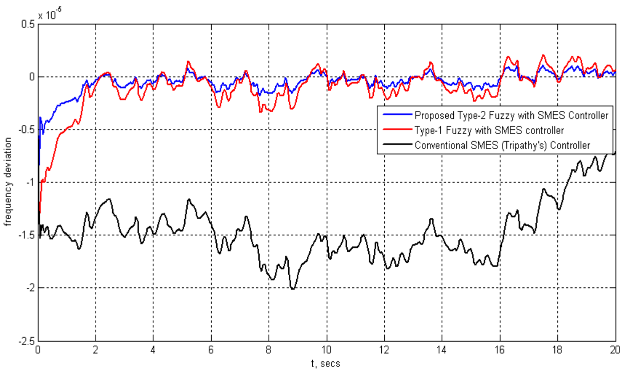


Figure 14. Frequency deviation due to change in random wind power

V. CONCLUSION

In this paper a dynamic performance of the stand-alone wind system and Wind Diesel hybrid power system with load frequency controller installed on the Diesel unit and the wind turbine unit equipped with a blade pitch control mechanism has been presented. The results obtained shows that for changes in wind power, the transient performance of the system is better when it is equipped with a blade pitch control mechanism, but for changes in load, the transient performance of the system remains unaffected, as it is accomplished by the load frequency controller in both the cases. Performance comparison of the proposed paper indicates that the system response of the Load Frequency Control with Type-2 Fuzzy controller has a quite shorter settling time. It has been also identified that the proposed controller is effective and provides significant improvement in system performance. Therefore, the proposed LFC using Type-2 Fuzzy Logic SMES controller is recommended to generate good quality and reliable power for the stand-alone wind system and Wind Diesel hybrid power system.

APPENDIX

Wind power co-efficient:

$\frac{1}{2}\rho_{Air}\pi R^2 = 0.00145$, $K_b = 69.5$

Parameters of wind-diesel system:

$H_W = 3.5$, $H_D = 8.5$, $K_{fc} = 16.2$, $K_d = 16.5$, $K_{p2} = 1.25$, $K_{p3} = 1.4$, $T_{p1} = 0.6$, $T_{p2} = 0.041$, $K_{pc} = 0.08$, $K_{PI} = 4.0$, $K_{PP} = 1.5$

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Dr. R. Vijaya Santhi was born in Andhra Pradesh, India on 31st August 1982. She received her B.Tech. degree in Electrical and Electronics Engineering from S.V.H Engineering College, Machilipatnam, Nagarjuna University in 2003. She did her M.Tech in Power systems, from JNTU Kakinada in 2008. She was awarded her Doctorate in Electrical Engineering in 2014 by Andhra University.
Presently she is working as Assistant Professor in the Department of Electrical Engineering, Andhra University, Visakhapatnam, India.

Dr. K. R. Sudha was born in Andhra Pradesh, India on 17th July 1970. She received her B.E. degree in Electrical and Electronics Engineering from GITAM, Andhra University in 1991. She did her M.E in Power Systems in 1994. She was awarded her Doctorate in Electrical Engineering in 2006 by Andhra University. During 1994-2006, she worked with GITAM Engineering College.
Presently she is working as Professor and Head in the Department of Electrical Engineering, AUCE (W), Andhra University, Visakhapatnam, India.

Dr. A. Chandra Sekhar was born in Andhra Pradesh, India on 24th November 1964. He is a Gold-Medalist in his post graduation. He received his M.Phil. degree in Mathematics from Andhra University in 2000. He was awarded his Doctorate in Mathematics in 2008from J.NT. University, Hyderabad. His areas of interest are cryptography and algebraic number theory.
Presently he is working as Professor and Head in the Department of Mathematics, GITAM University, Visakhapatnam, India.