

# Control Scheme of Hybrid Wind-Diesel Power Generation System

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## 1. Introduction

Global warming is one of the most serious environmental problems facing the world community today. It is typified by increasing the average temperature of Earth's surface and extremes of weather both hot and cold. Therefore, implementing a smart and renewable energies such as wind power, photo voltaic etc are expected to deeply reduce heat-trapping emissions. Moreover, wind power is expected to be economically attractive when the wind speed of the proposed site is considerable for electrical generation and electric energy is not easily available from the grid (Ackermann, 2005). This situation is usually found on islands and/or in remote localities. However, wind power is intermittent due to worst case weather conditions such as an extended period of overcast skies or when there is no wind for several weeks. As a result, wind power generation is variable and unpredictable.

The hybrid wind power with diesel generation has been suggested (Hunter, 1994) and (Lipman, 1989) to handle the problem above. A hybrid wind diesel system is very reliable because the diesel acts as a cushion to take care of variation in wind speed and would always maintain an average power equal to the set point. However, in addition to the unsteady nature of wind, another serious problem faced by the isolated power generation is the frequent change in load demands. This may cause large and severe oscillation of power. The fluctuation of output power of such renewable sources may cause a serious problem of frequency and voltage fluctuation of the grid, especially, in the case of isolated microgrid, which is the a small power supply network consisting of some renewable sources and loads. In the worst case, the system may lose stability if the system frequency can not be maintained in the acceptable range.

Control schemes to enhance stability in a hybrid wind - diesel power system have been proposed by much researchers in the previous work. The programmed pitch controller (PPC) in the wind side can be expected to be a cost-effective device for reducing frequency deviation (Bhatti et. al ,1997) and (Das et. al, 1999). Nevertheless, under the sudden change of load demands and random wind power input, the pitch controller of the wind side and the governor of the diesel side may no longer be able to effectively control the system frequency due to theirs slow response. To overcome this problem, an Energy Storage (ES), which is able

to supply and absorb active power rapidly, has been highly expected as one of the most effective controller of system frequency (Tripathy et. al. 1997) and (Tripathy et. al. 1997).

In this chapter, 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. 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. The SMES system consists of a large superconducting coil at the cryogenic temperature. The coil is kept at cryogenic (superconductive) temperature by a refrigeration system designed to meet the superconducting properties of the special materials used to fabricate the magnetic coil. A power conversion/conditioning system connects the SMES unit to an ac 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. The estimated life of a typical system is at least 20 years (Schainker, 2004).

In power system, the SMES is capable of supplying both active and reactive powers simultaneously and quickly. Thus, it is able to enhance the power system stability and reliability dramatically (Jiang & Chu, 2001) and (Simo& Kamwa, 1995). Primarily, the SMES unit was aimed to store energy during the off-peak load period and release it in the peak load period. It has been shown that the SMES is able to supply the active and reactive power simultaneously and damp the oscillations in an power system (Simo& Kamwa, 1995) and (Wu & Lee, 1993). In fact, the SMES can also be used as a PSS, if the control scheme is suitably designed (maschowski & Nelles, 1992). Besides, the applications of the SMES also include load regulation, transmission stabilization, uninterruptible power supply, power compensation, voltage control and improving customer power quality, etc. (Buckles & Hassenzahl, 2000). Moreover, the SMES also has been successfully applied to solve many problems in power systems such as an improvement of power system dynamics (Rabbani et.al., 1998) and (Devotta & Rabbani,2000), a frequency control in interconnected power systems (tripathy,1997) and (Ngamroo,2005), an improvement of power quality (Chu et.al. 2001), a stabilization of sub-synchronous oscillation in the turbine-generator (Devotta et.al. 1999), a load leveling (Abdelsalam et.al. 1987) etc.

Several design methods to design SMES have been successfully proposed, such as a proportional control (Banerjee et.al. 1990), a digital control (Tripathy & Juengst, 1997), an adaptive control (Tripathy et.al. 1997), a neural network (Demiroren et.al. 2003) and a fuzzy control (Demiroren & Yesil 2004), etc. Despite the potential of modern control techniques with different structures, power system utilities still prefer the fixed structure controller. The reasons behind that might be the ease of on-line tuning and the lack of the assurance of stability related to some adaptive or variable structure techniques. On the other hand, various generating and loading conditions, wind power fluctuations, variation of system

parameters and system nonlinearities etc., result in system uncertainties. The SMES controllers in these works have been designed without considering system uncertainties. The robust stability of resulted SMES controllers against uncertainties cannot be guaranteed. They may fail to operate and stabilize the power system.

To enhance the robustness, many research works have been successfully applied robust control theories to design of PSS and damping controllers of flexible AC transmission systems (FACTS) devices. In (Djukanovic et.al. 1999) and (Yu et.al. 2001), the structured singular value has been applied to design robust PSS and static var compensator (SVC), respectively. In (Zhu et.al. 2003) and (Rahim & Kandlawala, 2004), the  $H_\infty$  control approach has been used to design robust PSS and FACTS devices. The presented robust controllers above provide satisfactory effects on damping of power system oscillations. Nevertheless, selection of weighting functions becomes an inevitable problem that is difficult to solve. Furthermore, an order of designed controller depends on that of the system. This leads to the complex structure controllers. In (wang et.al. 2002) and (Tan & wang, 2004), the robust non-linear control based on a direct feedback linearization technique has been applied to design an excitation system, a thyristor controlled series capacitor (TCSC) and a SMES. However, the drawback of this design method is a tuning of  $Q$  and  $R$  matrices for solving Riccati equation by trial and error. Besides, the resulted controllers are established by a state feedback scheme which is not easy to implement in practical systems.

This chapter presents a controller design of programmed pitch controller (PPC) and Energy storage (ES) to control frequency oscillation in a hybrid wind-diesel power generation. To take system uncertainties into account in the control design, the inverse additive perturbation is applied to represent all unstructured uncertainties in the system modeling. Moreover, the performance conditions in the damping ratio and the real part of the dominant mode is applied to formulate the optimization problem. In this work, the structure of the proposed controllers are the conventional first-order controller (lead/lag compensator). To achieve the controller parameters, the genetic algorithm (GA) is used to solve the optimization problem. Various simulation studies are carried out to confirm the performance of the proposed controller.

## 2. Proposed control design method

### 2.1 System uncertainties

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 modeling, the robustness of the controller against system uncertainties can not be guaranteed. 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. The concept of enhancement of robust stability margin is used to formulate the optimization problem of controller parameters.

The feedback control system with inverse additive perturbation is shown in Fig.1.  $G$  is the nominal plant.  $K$  is the designed controller. For unstructured system uncertainties such as various generating and loading conditions, variation of system parameters and

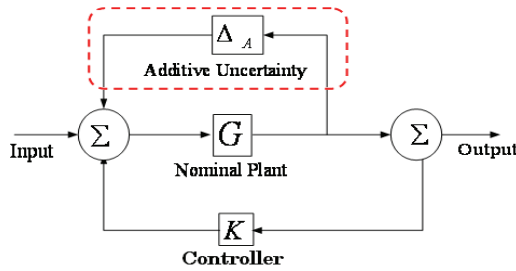


Fig. 1. Feedback system with inverse additive perturbation.

nonlinearities etc., they are represented by  $\Delta_A$  which is the additive uncertainty model. Based on the small gain theorem, for a stable additive uncertainty  $\Delta_A$ , the system is stable if

$$\|\Delta_A G / (1 - GK)\|_\infty < 1 \tag{1}$$

then,

$$\|\Delta_A\|_\infty < 1 / \|G / (1 - GK)\|_\infty \tag{2}$$

The right hand side of equation (2) implies the size of system uncertainties or the robust stability margin against system uncertainties. By minimizing  $\|G/(1 - GK)\|_\infty$ , the robust stability margin of the closed-loop system is a maximum or near maximum.

## 2.2 Implementation

### 2.2.1 Objective function

To optimize the stabilizer parameters, an inverse additive perturbation based-objective function is considered. The objective function is formulated to minimize the infinite norm of  $\|G/(1 - GK)\|_\infty$ . Therefore, the robust stability margin of the closed-loop system will increase to achieve near optimum and the robust stability of the power system will be improved. As a result, the objective function can be defined as

$$\text{Minimize} \quad \|G/(1 - GK)\|_\infty \tag{3}$$

It is clear that the objective function will identify the minimum value of  $\|G/(1 - GK)\|_\infty$  for nominal operating conditions considered in the design process.

### 2.2.2 Optimization problem

In this study, the problem constraints are the controller parameters bounds. In addition to enhance the robust stability, another objective is to increase the damping ratio and place the closed-loop eigenvalues of hybrid wind-diesel power system in a D-shape region (Abdel-Magid et.al. 1999). the conditions will place the system closed-loop eigenvalues in the D-shape region characterized by  $\zeta \geq \zeta_{spec}$  and  $\sigma \leq \sigma_{spec}$  as shown in Fig. 2.

Therefore, the design problem can be formulated as the following optimization problem.

$$\text{Minimize} \quad \|G/(1 - GK)\|_\infty \tag{4}$$

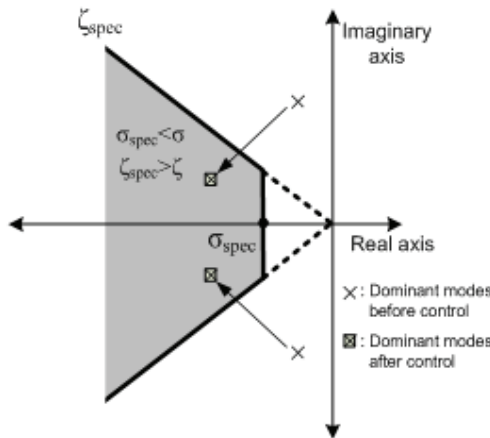


Fig. 2. D-shape region in the s-plane where  $\sigma \leq \sigma_{spec}$  and  $\zeta \geq \zeta_{spec}$

Subject to 
$$\zeta \geq \zeta_{spec}, \sigma \leq \sigma_{spec} \tag{5}$$

$$K_{min} \leq K \leq K_{max}$$

$$T_{min} \leq T \leq T_{max}$$

where  $\zeta$  and  $\zeta_{spec}$  are the actual and desired damping ratio of the dominant mode, respectively;  $\sigma$  and  $\sigma_{spec}$  are the actual and desired real part, respectively;  $K_{max}$  and  $K_{min}$  are the maximum and minimum controller gains, respectively;  $T_{max}$  and  $T_{min}$  are the maximum and minimum time constants, respectively. This optimization problem is solved by GA (GAOT, 2005) to search the controller parameters.

### 2.3 Genetic algorithm

#### 2.3.1 Overview

GA is a type of meta-heuristic search and optimization algorithms inspired by Darwin’s principle of natural selection. GA is used to try and solving search problems or optimize existing solutions to a certain problem by using methods based on biological evolution. It has many applications in certain types of problems that yield better results than the common used methods.

According to Goldberg (Goldberg,1989), GA is different from other optimization and search procedures in four ways:

1. GA searches a population of points in parallel, not a single point.
2. GA does not require derivative information or other auxiliary knowledge; only the objective function and corresponding fitness levels influence the directions of search.
3. GA uses probabilistic transition rules, not deterministic ones.
4. GA works on an encoding of the parameter set rather than the parameter set itself (except in where real-valued individuals are used).

It is important to note that the GA provides a number of potential solutions to a given problem and the choice of final solution is left to the user.

### 2.3.2 GA algorithm

#### A. Representation of Individual.

Individual representation scheme determines how the problem is structured in the GA and also determines the genetic operators that are used. Each individual is made up of a sequence of genes. Various types of representations of an individual are binary digits, floating point numbers, integers, real values, matrices, etc. Generally, natural representations are more efficient and produce better solutions. Encoding is used to transform the real problem to binary coding problem which the GA can be applied.

#### B. GA Operators.

The basic search mechanism of the GA is provided by the genetic operators. There are two basic types of operators: crossover and mutation. These operators are used to produce new solutions based on existing solutions in the population. Crossover takes two individuals to be parents and produces two new individuals while mutation alters one individual to produce a single new solution (S. Panda,2009).

In crossover operator, individuals are paired for mating and by mixing their strings new individuals are created. This process is depicted in Fig. 3.

|          |       |  |       |
|----------|-------|--|-------|
| Parent 1 | 11010 |  | 01100 |
| Parent 2 | 10110 |  | 11011 |
| Child 1  |       |  |       |
|          | 11010 |  | 11011 |
| Child 2  |       |  |       |
|          | 10110 |  | 01100 |

Fig. 3. Crossover operator

In natural evolution, mutation is a random process where one point of individual is replaced by another to produce a new individual structure. The effect of mutation on a binary string is illustrated in Fig. 4 for a 10-bit chromosome and a mutation point of 5 in the binary string. Here, binary mutation flips the value of the bit at the loci selected to be the mutation point (Andrew C et.al).

|          |       |  |       |
|----------|-------|--|-------|
| Parent 1 | 11010 |  | 01100 |
| Child 1  |       |  |       |
|          | 11010 |  | 11100 |

Fig. 4. Mutation operator

#### C. Selection for Reproduction

To produce successive generations, selection of individuals plays a very significant role in a GA. The selection function determines which of the individuals will survive and move on to the next generation. A probabilistic selection is performed based upon the individual's fitness such that the superior individuals have more chance of being selected (S. Panda et.al ,2009). There are several schemes for the selection process: roulette wheel selection and its extensions, scaling techniques, tournament, normal geometric, elitist models and ranking

methods. Roulette wheel selection method has simple method. The basic concept of this method is “ High fitness, high chance to be selected”.

### 2.3.3 Parameters optimization by GA

In this section, GA is applied to search the controller parameters with off line tuning. Each step of the proposed method is explained as follows.

**Step 1.** Generate the objective function for GA optimization.

In this study, the performance and robust stability conditions in inverse additive perturbation design approach is adopted to design a robust controller as mention in equation (4) and (5).

**Step 2.** Initialize the search parameters for GA. Define genetic parameters such as population size, crossover, mutation rate, and maximum generation.

**Step 3.** Randomly generate the initial solution.

**Step 4.** Evaluate objective function of each individual in equation (4) and (5).

**Step 5.** Select the best individual in the current generation. Check the maximum generation.

**Step 6.** Increase the generation.

**Step 7.** While the current generation is less than the maximum generation, create new population using genetic operators and go to step 4. If the current generation is the maximum generation, then stop.

## 3. Robust frequency control in a hybrid wind-diesel power system

### 3.1 System modeling

The basic system configuration of an isolated hybrid wind-diesel power generation system as shown in Fig. 5 (Das et.al. 1999) is used in this study. The base capacity of the system is 350 kVA. The diesel is used to supply power to system when wind power could not adequately provide power to customer. Moreover, The PPC is installed in the wind side while the governor is equipped with the diesel side. In addition to the random wind energy supply, it is assumed that loads with sudden change have been placed in this isolated system. These result in a serious problem of large frequency deviation in the system. As a result, a serious problem of large frequency deviation may occur in the isolated power system. Such power variations and frequency deviations severely affect the system stability. Furthermore, the life time of machine apparatuses on the load side affected by such large frequency deviations will be reduced.

### 3.2 Pitch control design in a hybrid wind-diesel power system

#### 3.2.1 Linearized model of hybrid wind-diesel power system with PPC

For mathematical modelling, the transfer function block diagram of a hybrid wind-diesel power generation used in this study is shown in Fig. 6 (Das et.al. 1999). The PPC is a 1<sup>st</sup> order lead-lag controller with single input feedback of frequency deviation of wind side.

The state equation of linearized model in Fig. 6 can be expressed as

$$\dot{\Delta X} = A\Delta X + B\Delta u_{PPC} \quad (6)$$

$$\Delta Y = C\Delta X + D\Delta u_{PPC} \quad (7)$$

$$\Delta u_{PPC} = K(s)\Delta f_W \quad (8)$$

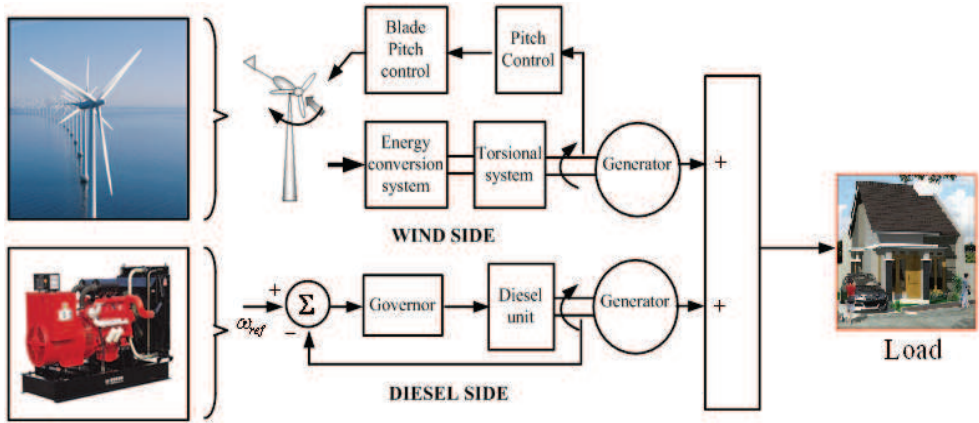


Fig. 5. Basic configuration of a hybrid wind-diesel power generation system.

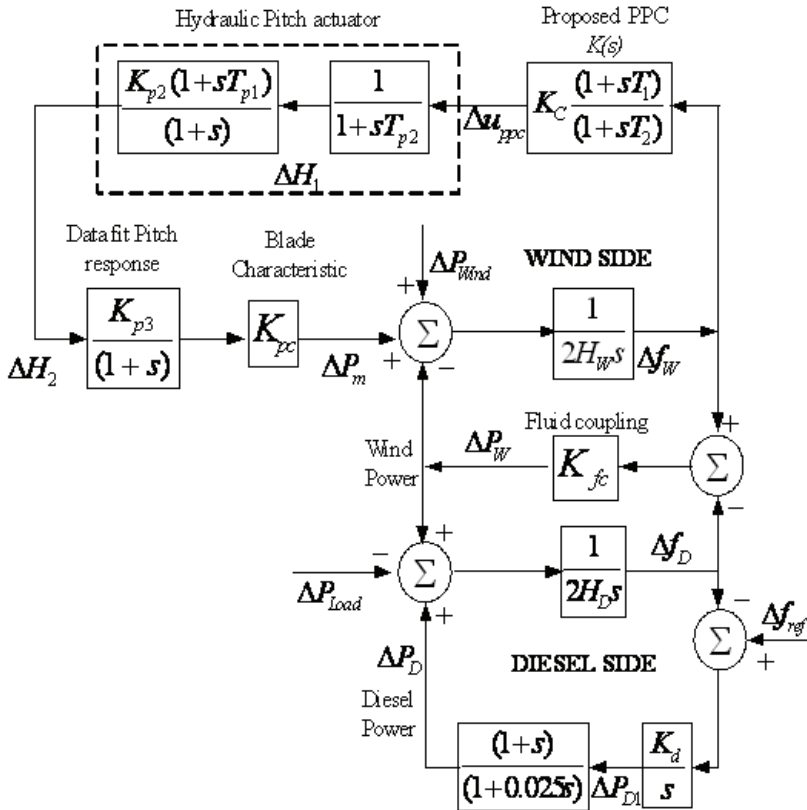


Fig. 6. Functional block diagram for wind-diesel system with proposed PPC.



Where the state vector  $\Delta X = [\Delta f_W \ \Delta f_D \ \Delta P_{D1} \ \Delta P_D \ \Delta H_1 \ \Delta H_2 \ \Delta P_m]$ , the output vector  $\Delta Y = [\Delta f_W]$ ,  $\Delta U_{PPC}$  is the control output of the PPC. The proposed control is applied to design a proposed PPC  $K(s)$ . The system in equation (6) is referred to as the nominal plant  $G$ .

### 3.2.2 Optimization problem formulation

The optimization problem can be formulated as follows,

$$\text{Minimize} \quad \left\| G/(1-GK) \right\|_{\infty} \quad (9)$$

$$\text{Subject to} \quad \zeta \geq \zeta_{spec}, \sigma \leq \sigma_{spec} \quad (10)$$

$$K_{min} \leq K \leq K_{max}$$

$$T_{min} \leq T \leq T_{max}$$

where  $\zeta$  and  $\zeta_{spec}$  are the actual and desired damping ratio of the dominant mode, respectively;  $\sigma$  and  $\sigma_{spec}$  are the actual and desired real part, respectively;  $K_{max}$  and  $K_{min}$  are the maximum and minimum controller gains, respectively;  $T_{max}$  and  $T_{min}$  are the maximum and minimum time constants, respectively. This optimization problem is solved by GA to search optimal or near optimal set of the controller parameters.

### 3.2.3 Designed results

In this section, simulation studies in a hybrid wind-diesel power generation are carried out. System parameters are given in (Das et.al. 1999). In the optimization, the ranges of search parameters and GA parameters are set as follows:  $K_C \in [1 \ 100]$ ,  $T_1$  and  $T_2 \in [0.0001 \ 1]$ , crossover probability is 0.9, mutation probability is 0.05, population size is 200 and maximum generation is 100. As a result, "the proposed PPC" is given automatically. In simulation studies, the performance and robustness of the proposed PPC is compared with those of the PPC designed by the variable structure control (VSC) obtained from (Das et.al. 1999). Simulation results under four case studies are carried out as shown in table 1.

| Cases | Disturbances                                    |
|-------|---|
| 1     | Step input of wind power or load change         |
| 2     | Random wind power input                         |
| 3     | Random load power input                         |
| 4     | Simultaneous random wind power and load change. |

Table 1. Operating conditions

#### Case 1: Step input of wind power or load change

First, a 0.01 pu kW step increase in the wind power input and the load power are applied to the system at  $t = 5.0$  s, respectively. Fig. 7 and Fig. 8 show the frequency deviation of the diesel generation side which represents the system frequency deviation. The peak frequency deviation is reduced significantly by both of the VSC PPC and the proposed PPC. However, the proposed PPC is able to damp the peak frequency deviation quickly in comparison to VSC PPC cases.

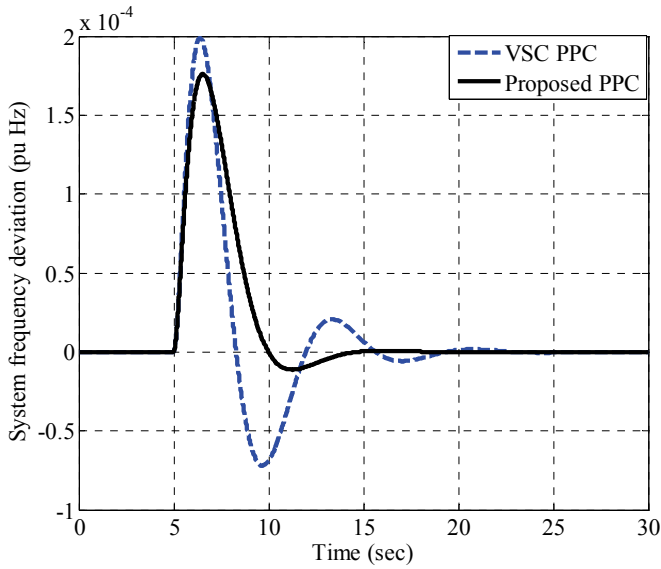


Fig. 7. System frequency deviation against a step change of wind power.

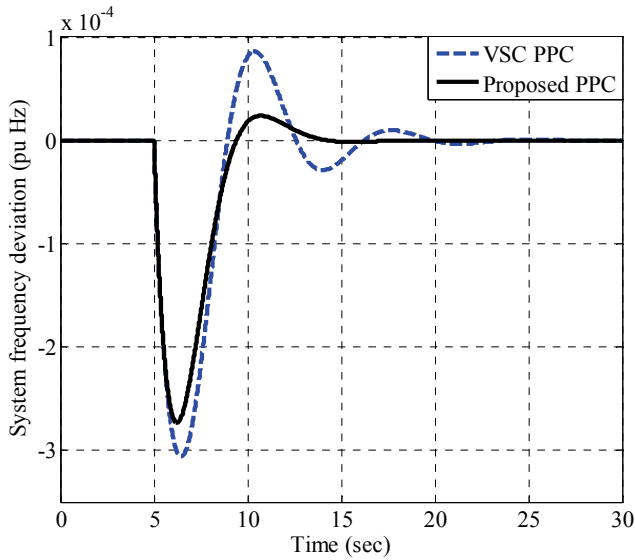


Fig. 8. System frequency deviation against a step load change.

**Case 2: Random wind power input.**

In this case, the system is subjected to the random wind power input as shown in Fig.9. The response of system frequency deviation is shown in Fig.10. By the proposed PPC, the frequency deviation is significantly reduced in comparison to that of the VSC PPC.

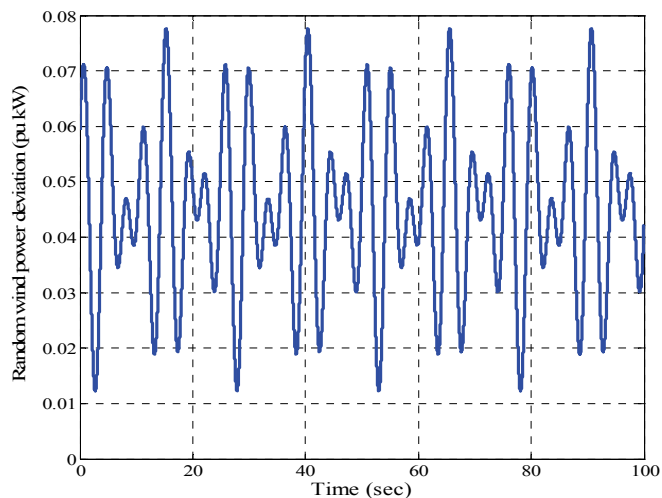


Fig. 9. Random wind power input.

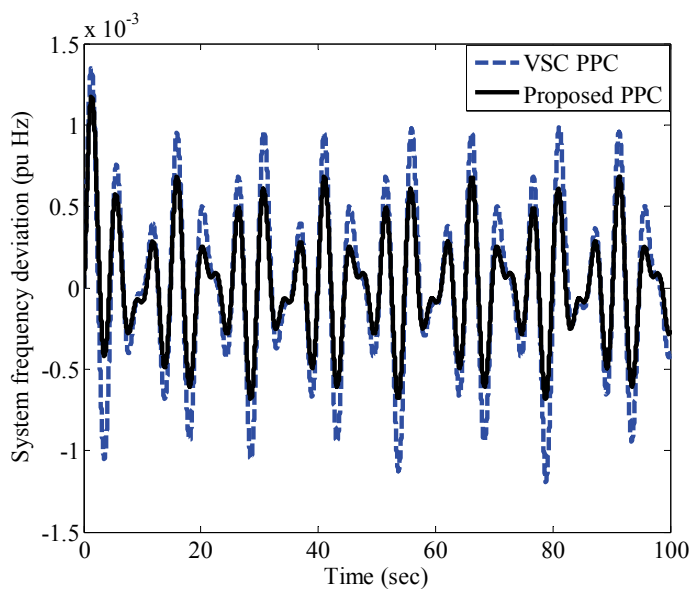


Fig. 10. System frequency deviation in case 2

### Case 3: Random load change.

Next, the random load change as shown in Fig.11 is applied to the system. Fig. 12 depicts the response of system frequency deviation under the load change disturbance. The control effect of the proposed PPC is better than that of the VSC PPC.

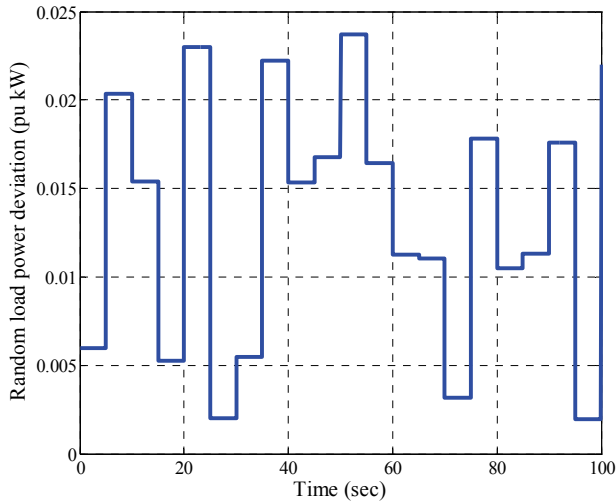


Fig. 11. Random load change

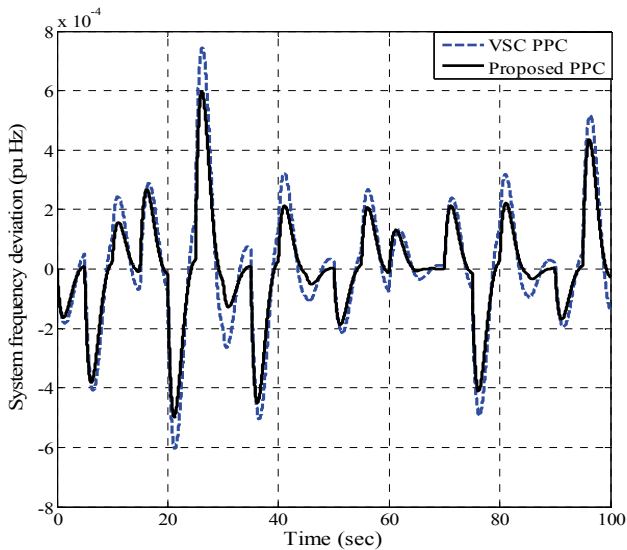


Fig. 12. System frequency deviation in case 3.

#### Case 4: Simultaneous random wind power and load change.

In this case, the random wind power input in Fig. 9 and the load change in Fig.11 are applied to the hybrid wind-diesel power system simultaneously. The response of system frequency deviation is shown in Fig. 13. The frequency control effect of the proposed PPC is superior to that of the VSC PPC.

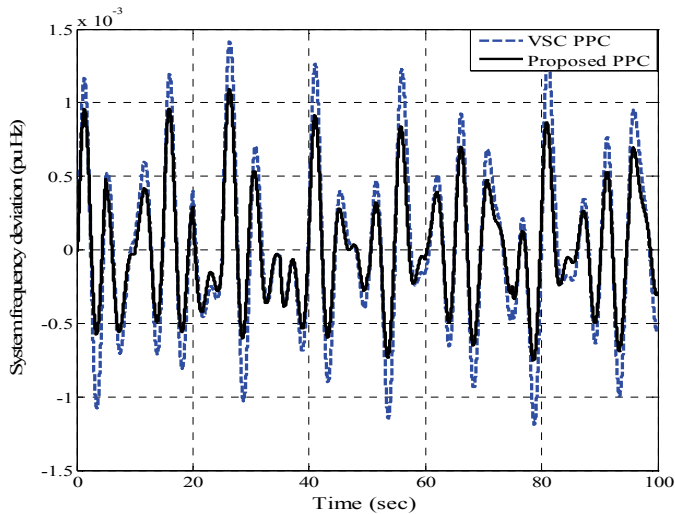


Fig. 13. System frequency deviation in case 4.

### 3.3 Frequency control in a hybrid wind-diesel power system using SMES

In this study, the system configuration in Fig. 5 is used to design frequency controller using SMES. In worst case, it is assumed that the ability of the pitch controller in the wind side and the governor in the diesel side to provide frequency control are not adequate due to their slow response. Accordingly, the SMES is installed in the system to fast compensate for surplus or insufficient power demands, and minimize frequency deviation. Here, the proposed method is applied to design the robust frequency controller of SMES.

#### 3.3.1 Linearized model of hybrid wind-diesel power system with PPC and SMES

The linearized model of the hybrid wind-diesel power system with Programmed Pitch Controller (PPC) and SMES is shown in Fig.14 (Tripathy, 1997). This model consists of the following subsystems: wind dynamic model, diesel dynamic model, SMES unit, blade pitch control of wind turbine and generator dynamic model. The details of all subsystems are explained in (Tripathy, 1997). As shown in Fig. 15, the SMES block diagram consists of two transfer functions, i.e. the SMES model and the frequency controller. Based on (Mitani et.al. 1988), the SMES can be modeled by the first-order transfer function with time constant  $T_{sm} = 0.03$  s. In this work, the frequency controller is practically represented by a lead/lag compensator with first order. In the controller, there are three control parameters i.e.,  $K_{sm}$ ,  $T_{sm1}$  and  $T_{sm2}$ .

The linearized state equation of system in Fig. 14 can be expressed as

$$\dot{\Delta X} = A\Delta X + B\Delta u_{SM} \quad (11)$$

$$\Delta Y = C\Delta X + D\Delta u_{SM} \quad (12)$$

$$\Delta u_{SM} = K_{SM}\Delta u_{IN} \quad (13)$$

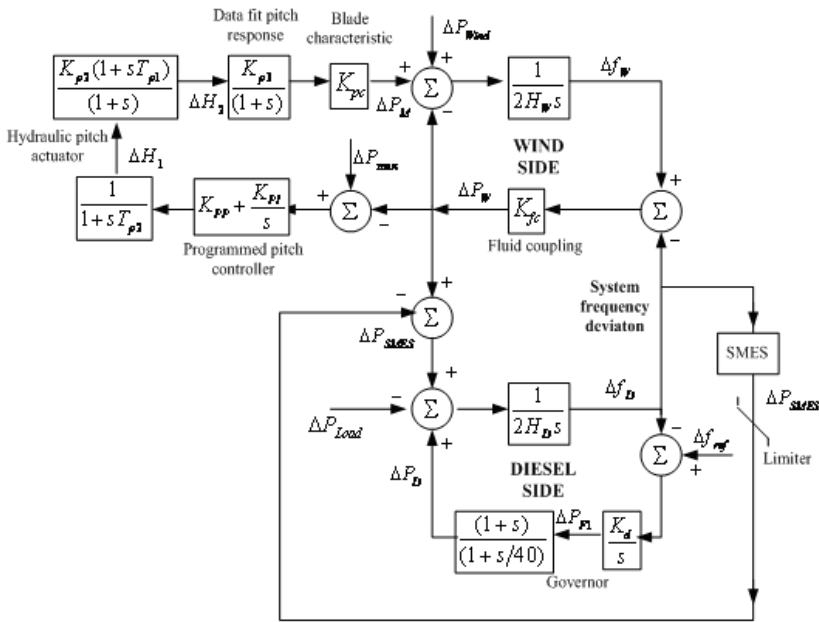


Fig. 14. Block diagram of a hybrid wind-diesel power generation with SMES.

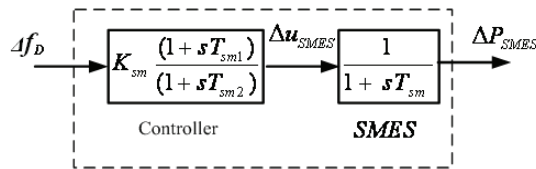


Fig. 15. Block diagram of SMES with the frequency controller.

Where the state vector  $\Delta X = [\Delta f_w \ \Delta f_D \ \Delta P_{F1} \ \Delta P_D \ \Delta H_0 \ \Delta H_1 \ \Delta H_2 \ \Delta P_M]^T$ , the output vector  $\Delta Y = [\Delta f_D]$ ,  $\Delta f_D$  is the system frequency deviation,  $\Delta P_{SMES}$  is the control output signal of SMES controller;  $\Delta u_{IN} = [\Delta Y]$  is the feedback input signal of SMES controller. Note that the system in equation (11) is a single-input single-output (SISO) system. The proposed method is applied to design SMES controller, and the system of equation (11) is referred to as the nominal plant  $G$ .

### 3.3.2 Optimization problem formulation

The optimization problem can be formulated as follows,

$$\text{Minimize} \quad \|G/(1-GK)\|_{\infty} \tag{14}$$

$$\text{Subject to} \quad \zeta \geq \zeta_{spec}, \sigma \leq \sigma_{spec} \tag{15}$$

$$K_{\min} \leq K \leq K_{\max}$$

$$T_{\min} \leq T \leq T_{\max}$$

where  $\zeta$  and  $\zeta_{spec}$  are the actual and desired damping ratio of the dominant mode, respectively;  $\sigma$  and  $\sigma_{spec}$  are the actual and desired real part, respectively;  $K_{\max}$  and  $K_{\min}$  are the maximum and minimum controller gains, respectively;  $T_{\max}$  and  $T_{\min}$  are the maximum and minimum time constants, respectively. This optimization problem is solved by GA to search optimal or near optimal set of the controller parameters.

### 3.3.3 Designed results

In the optimization, the ranges of search parameters and GA parameters are set as follows:  $\zeta_{spec}$  is desired damping ratio is set as 0.4,  $\sigma_{spec}$  is desired real part of the dominant mode is set as -0.2, and  $K_{\min}$  and  $K_{\max}$  minimum and maximum gains of SMES are set as 1 and 60,  $T_{\min}$  and  $T_{\max}$  are minimum and maximum time constants of SMES are set as 0.01 and 5. The optimization problem is solved by genetic algorithm. As a result, the proposed controller which is referred as "RSMES" is given.

Table 2 shows the eigenvalue and damping ratio for normal operating condition. Clearly, the desired damping ratio and the desired real part are achieved by RSMES. Moreover, the damping ratio of RSMES is improved as designed in comparison with No SMES case.

| Cases          | Eigenvalues (damping ratio)  |
|----------------|--|
| <b>NO SMES</b> | -39.0043<br>-24.4027<br>-3.5072<br>-1.2547<br>$-0.1851 \pm j 0.671, \xi = 0.266$<br>$-0.5591 \pm j 0.541, \xi = 0.719$                                       |
| <b>RSMES</b>   | -39.5266<br>-24.4006<br>-2.1681<br>-1.3325<br>$-17.782 \pm j 5.339, \xi = 0.958$<br>$-0.3050 \pm j 0.539, \xi = 0.492$<br>$-0.2012 \pm j 0.268, \xi = 0.600$ |

Table 2. Eigenvalues and Damping ratio

To evaluate performance of the proposed SMES, simulation studies are carried out under four operating conditions as shown in Table 1. In simulation studies, the limiter  $-0.01 \text{ pu kW} \leq \Delta P_{SMES} \leq 0.01 \text{ pu kW}$  on a system base 350 kVA is added to the output of SMES with each controller to determine capacity of SMES. The performance and robustness of the proposed controllers are compared with the conventional SMES controllers (CSMES) obtained from (Tripathy,1997). Simulation results under 4 case studies are carried out as follows.

### Case 1: Step input of wind power or load change

In case 1, a 0.01 pu kW step increase in the wind power input are applied to the system at  $t = 0.0$  s. Fig. 16 shows the frequency deviation of the diesel generation side which represents the system frequency deviation. Without SMES, the peak frequency deviation is very large. The frequency deviation takes about 25 s to reach steady-state. This indicates that the pitch controller in the wind side and the governor in the diesel side do not work well. On the other hand, the peak frequency deviation is reduced significantly and returns to zero within shorter period in case of CSMES and the RSMES. Nevertheless, the overshoot and setting time of frequency oscillations in cases of RSMES is lower than that of CSMES.

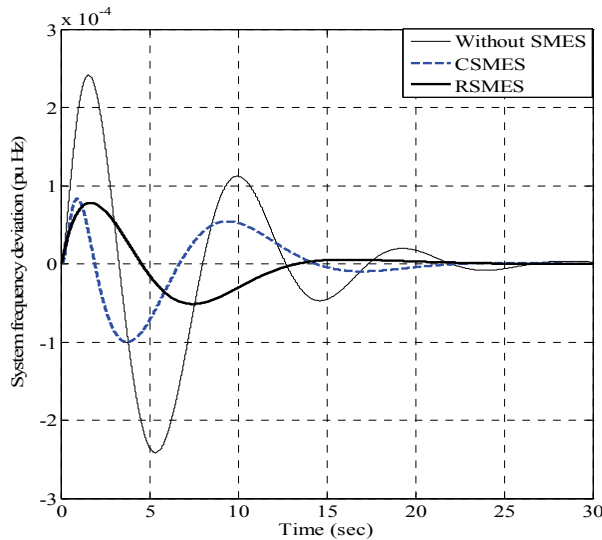


Fig. 16. System frequency deviation against a step change of wind power.

Next, a 0.01 pu kW step increase in the load power is applied to the system at  $t = 0.0$  s. As depicted in Fig. 17, both CSMES and RSMES are able to damp the frequency deviation quickly in comparison to without SMES case. These results show that both CSMES and RSMES have almost the same frequency control effects.

### Case 2: Random wind power input.

In this case, the system is subjected to the random wind power input as shown in Fig.18. The system frequency deviations under normal system parameters are shown in Fig.19. Normal system parameter is the design point of both CSMES and RSMES. By the RSMES, the frequency deviation is significantly reduced in comparison to that of CSMES.

Next, the robustness of frequency controller is evaluated by an integral square error (ISE) under variations of system parameters. For 100 seconds of simulation study under the same random wind power in Fig.18, the ISE of the system frequency deviation is defined as

$$\text{ISE of } \Delta f_D = \int_0^{100} |\Delta f_D|^2 dt \quad (16)$$



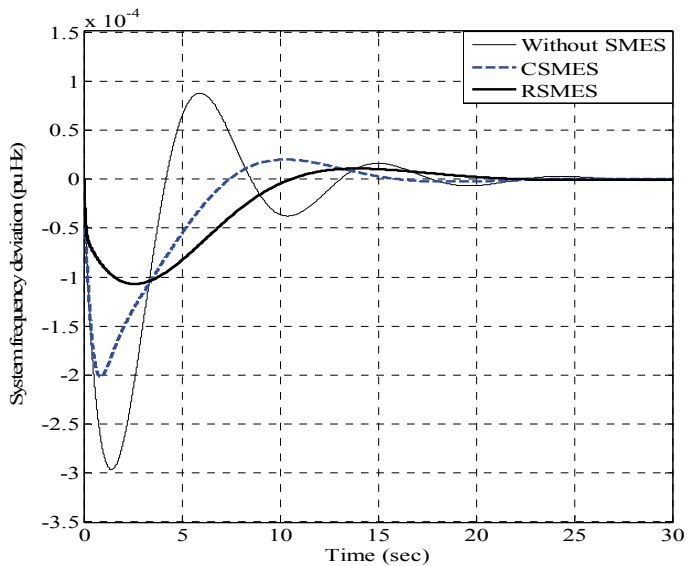


Fig. 17. System frequency deviation against a step load change.

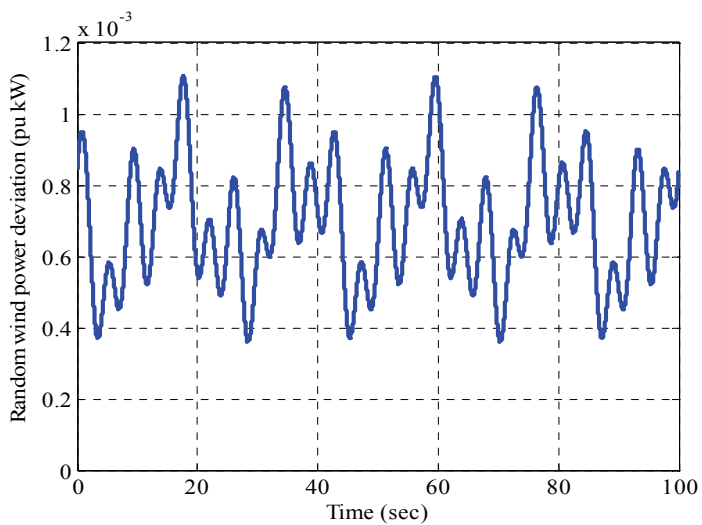


Fig. 18. Random wind power input.

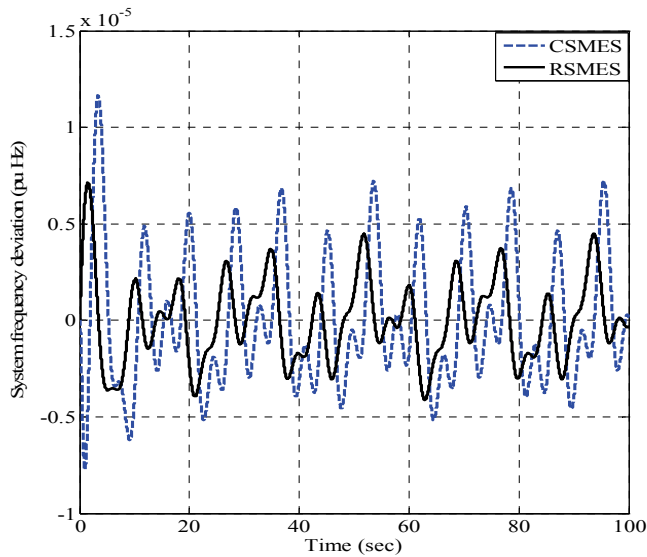


Fig. 19. System frequency deviation under normal system parameters.

Fig.20 shows the values of ISE when the fluid coupling coefficient  $K_{fc}$  is varied from -30 % to +30 % of the normal values. The values of ISE in case of CSMES largely increase as  $K_{fc}$  decreases. In contrast, the values of ISE in case of RSMES are lower and slightly change.

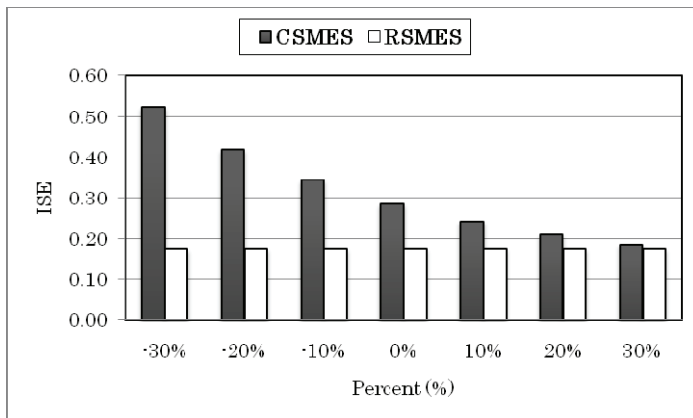


Fig. 20. Variation of ISE under a change of  $K_{fc}$ .

**Case 3: Random load change.**

Fig. 22 shows the system frequency deviation under normal system parameters when the random load change as shown in Fig.21 is applied to the system. The control effect of RSMES is better than that of the CSMES.

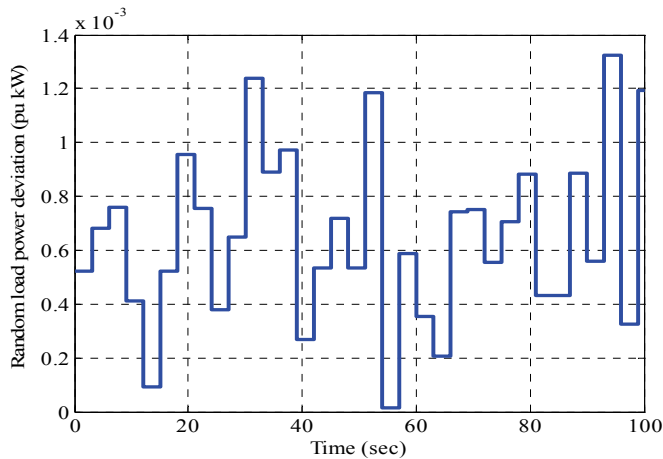


Fig. 21. Random load change.

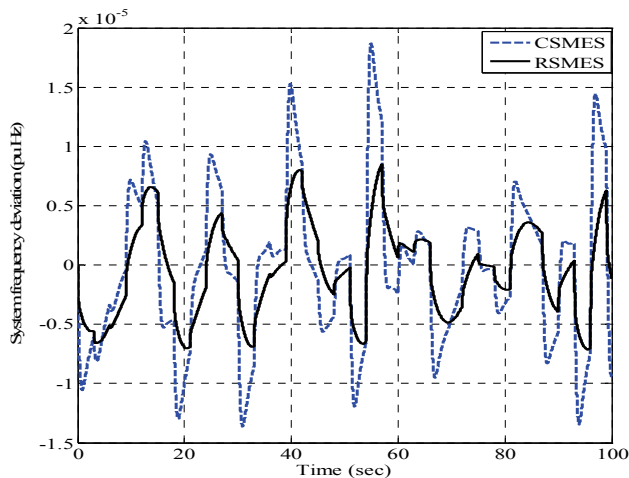


Fig. 22. System frequency deviation under normal system parameters.

#### Case 4: Simultaneous random wind power and load change.

In case 4, the random wind power input in Fig. 18 and the load change in Fig.21 are applied to the system simultaneously. When the inertia constant of both sides are reduced by 30 % from the normal values, the CSMES is sensitive to this parameter change. It is still not able to work well as depicted in Fig.23. In contrast, RSMES is capable of damping the frequency oscillation. The values of ISE of system frequency under the variation of  $K_{fc}$  from -30 % to +30 % of the normal values are shown in Fig.24. As  $K_{fc}$  decreases, the values of ISE in case of CSMES highly increase. On the other hand, the values of ISE in case of RSMES are much lower and almost constant. These simulation results confirm the high robustness of RSMES against the random wind power, load change, and system parameter variations.

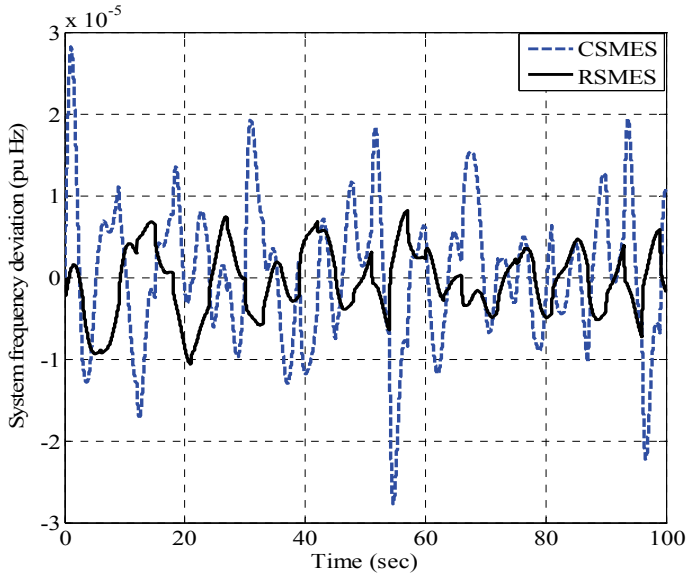


Fig. 23. System frequency deviation under a 30 % decrease in  $K_{fc}$

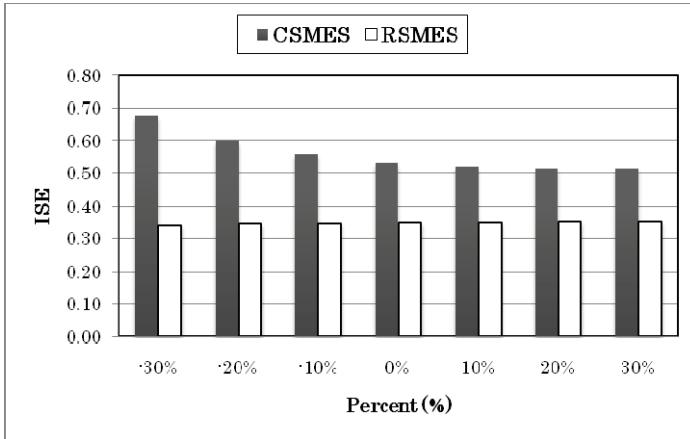


Fig. 24. Variation of ISE under a change in  $K_{fc}$ .

Finally, SMES capacities required for frequency control are evaluated based on simultaneous random wind power input and load change in case study 4 in addition to a 30 % decrease in  $K_{fc}$  parameters. The kW capacity is determined by the output limiter  $-0.01 \leq \Delta P_{SMES} \leq 0.01$  pu kW on a system base of 350 kW. The simulation results of SMES output power in case study 4 are shown in Figs. 25. Both power output of CSMES and RSMES are in the allowable limits. However, the performance and robustness of frequency oscillations in cases of RSMES is much better than those of CSMES.

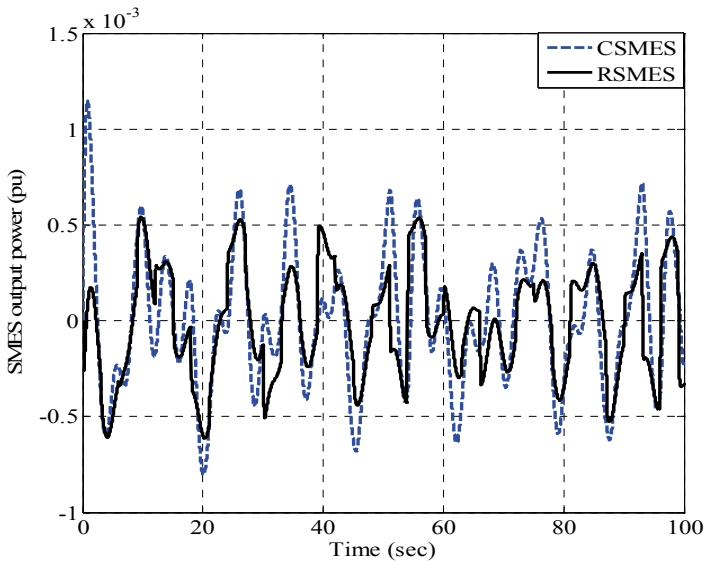


Fig. 25. SMES output power under a 30 % decrease in  $K_{fc}$

## 5. Conclusion

Control scheme of hybrid wind-diesel power generation has been proposed in this work. This work focus on frequency control using robust controllers such as Pitch controller and SMES. The robust controllers were designed based on inverse additive perturbation in an isolated hybrid wind - diesel power system. The performance and stability conditions of inverse additive perturbation technique have been applied as the objective function in the optimization problem. The GA has been used to tune the control parameters of controllers. The designed controllers are based on the conventional 1<sup>st</sup>-order lead-lag compensator. Accordingly, it is easy to implement in real systems. The damping effects and robustness of the proposed controllers have been evaluated in the isolated hybrid wind - diesel power system. Simulation results confirm that the robustness of the proposed controllers are much superior to that of the conventional controllers against various uncertainties.

## 6. References

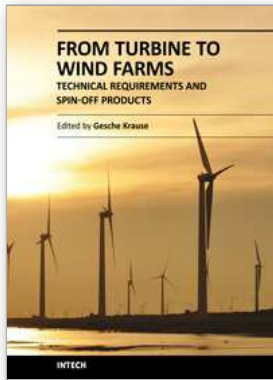
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