# QFT DESIGN FOR LOAD FREQUENCY CONTROL OF WIND DIESEL SYSTEM USING CES

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***Abstract:*** *In an isolated wind-diesel system, the variable power consumptions as well as the intermittent wind power may cause a large fluctuation of system frequency. If the system frequency cannot be controlled and kept in the acceptable range, the system may lose stability. Further to reduce system frequency fluctuation, CES which is able to supply and absorb active power quickly, can be applied. In addition, variation of system parameters, unpredictable power demands and fluctuating wind power etc., cause various uncertainties in the system. A CES controller which is designed without considering such uncertainties may lose control effect. In this paper quantitative feedback theory method is used for LFC control problem in Wind-Diesel system with system parametric uncertainties like parameter variations ±25% from their nominal value, ±30% load variations and wind variations. To show effectiveness of proposed method, a classical PI controller is designed for LFC for comparison with QFT.*

***Keywords****: Capacitive Energy Storage, Load Frequency control, QFT control, System Uncertainties, Wind-Diesel System.*

## 1. Introduction

Wind power systems are considered economically for supply of electrical energy to remote and isolated areas where utility lines are uneconomical to install due to high costs, right of way difficulties or environmental impacts in [1,2]. Since wind power sources are naturally fluctuating or intermittent, they are generally integrated with the diesel generation [3,4]. The hybrid wind-diesel power generation provides high reliability of the system to supply power to the isolated load. Nevertheless, the active power demands of the isolated community change frequently, the mismatch between the generation and load causes the large and severe deviation of system frequency. If the frequency deviation cannot be controlled and kept in the acceptable range, system equipments may get damaged. Furthermore, the system may lose stability [5,6]. Different technologies such as flywheel [7], battery energy storage [8], superconducting Magnetic Energy Storage (SMES) [9], etc., can be adopted to alleviate system frequency fluctuation in isolated systems [10] and a grid connected systems [11, 12]. Among of them, a CES unit which is able to supply and absorb active power rapidly, has been highly expected as one of the most effective controller of system frequency [17].

In the 1960's, as a continuation of the pioneering work of Bode, Isaac Horowitz introduced a frequency domain design methodology [14] that was refined in the 1970’s to its present form, commonly referred to as the Quantitative Feedback Theory (QFT) [15,16]. The QFT is an engineering method devoted to practical design of feedback systems. Control design necessary to accomplish performance specifications in the presence of uncertainties is a key consideration in any real feedback design. In QFT, one of the main objectives is to design a simple, low-order controller with minimum bandwidth. Minimum bandwidth controllers are a natural requirement in practice in order to avoid problems with noise amplification, resonances and unmodeled high frequency dynamics. In most practical design situations iterations are inevitable, and QFT offers direct insight into the available trade-off between controller complexity and specifications during such iterations. QFT can be considered as a natural extension of classical frequency-domain design approaches. The objective of this research is to investigate the Wind-Diesel power system taking into consideration the uncertainties in the parameters of system. A robust decentralized control scheme is designed using QFT method. The proposed controller is simulated for a Wind - Diesel system with CES.

## 2. Wind-Diesel Power System

Fig. 1 shows the configuration of the wind-diesel system which includes a CES unit in [17, 18]. In addition to the random wind energy supply, it is assumed that loads with sudden change have been placed in this isolated system. Variation of wind power and load change results in a serious problem of large frequency fluctuation in the system. Such frequency fluctuation severely affects the system stability. To tackle this problem, the CES is installed in the system to compensate for power variations and minimize frequency fluctuation.

The state equation for Wind-Diesel with CES

$$\Delta f_w = \frac{1}{2H_w}\left[\Delta P_{wind} + \Delta P_M - \Delta P_W\right] = \frac{1}{2H_w}\left[\Delta P_{wind}\right] + \frac{\Delta P_M}{2H_W} - \frac{K_{fc}(\Delta f_D)}{2H_W} \quad (1)$$

$$\Delta f_D = \frac{1}{2H_D}(K_{fc}\Delta f_W - K_{fc}\Delta f_D - \Delta P_{load} + \Delta P_d - \Delta P_{CES}) \quad (2)$$

$$\Delta P_M = (K_{PC} \times K_{P3})\Delta H_2 - \Delta P_M \quad (3)$$

$$\Delta P_{f1} = K_D(\Delta f_{ref} - \Delta f_o) \quad (4)$$

$$\Delta P_D = 40\Delta P_D - 40\Delta P_{D1} + 40\Delta P_{F1} \quad (5)$$

$$\Delta H_1 = \frac{1}{T_{P2}}\Delta x_1 - \frac{1}{T_{P2}}\Delta H_2 \quad (6)$$

$$\Delta H_2 = (K_{P2} - K_{P2}\frac{K_{P2}T_{P1}}{T_{P2}})\Delta H_1 - \Delta H_2 + K_{P2}\frac{T_{P1}}{T_{P2}}\Delta x_1 \quad (7)$$

$$\Delta x_1 = (-\frac{K_{PP}K_{fc}}{2H_W}\Delta P_{wind} - \frac{K_{PP}K_{fc}}{2H_W}\Delta P_M + \frac{K_{PP}K_{fc}}{2H_W}\Delta P_W + \frac{K_{PP}K_{fc}}{2H_D}\Delta P_W - \frac{K_{PP}K_{fc}}{2H_D}\Delta P_{LOAD} + \frac{K_{PP}K_{fc}}{2H_D}\Delta P_D - \frac{K_{PP}K_{fc}}{2H_D}\Delta P_{CES} - K_{PI}\Delta P_W \quad (8)$$

$$\Delta x_2 = \frac{K_{CES}}{T_{CES2}}\Delta f_W - \frac{\Delta x_2}{T_{CES1}} + \frac{K_{SM}T_{CES1}(\Delta P_{wind})}{2H_W T_{CES2}} + \Delta P_M - K_{fc}(\Delta f_W - \Delta f_D) \quad (9)$$

$$\Delta P_{CES} = \frac{1}{T_{CES}}\Delta x_2 - \frac{1}{T_{CES}}\Delta P_{CES} \quad (10)$$

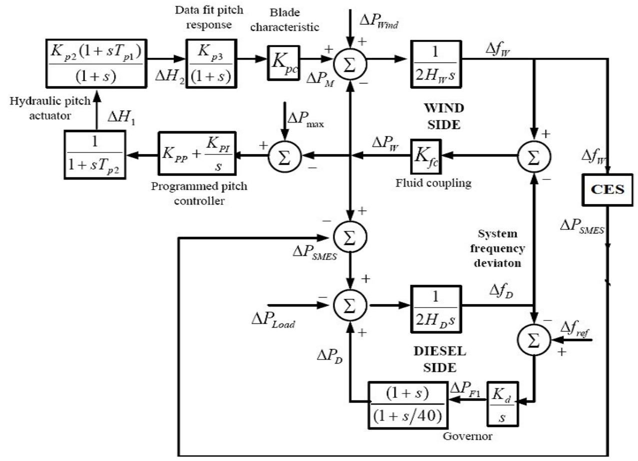

**Fig. 1.** Transfer Function Model of a W-D power generation with CES.

## 3. Capacitive Energy Storage

Capacitor is an electro chemical device consisting of two porous electrodes, an ion exchange membrane separating the two electrodes and a potassium hydroxide electrolyte in [19,20]. The operation of CES units, that is, charging, discharging, the steady state model and the power modulation during dynamic oscillatory period, is controlled by the application of the proper voltage to the capacitor so that the desired current flows in to or out of the CES. This can be achieved by controlling the firing angle of the converter bridges. Fig 2 shows the transfer function model CES in this, incremental change in CES current is expressed as.

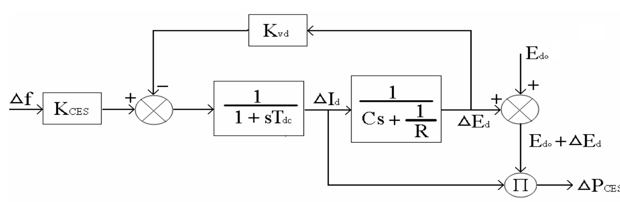
**Fig. 2.** Tranfer Function Model of CES.

$$\Delta I_{di} = \left[\frac{K_{cfi}}{(1+ST_{dci})}\right]\Delta f \quad (11)$$

Where $\Delta I_{di}$ is the incremental change in current of CES unit(KA), $T_{dci}$ is the converter time delay(second),$K_{cfi}$ is the gain of the control loop(KA/Hz),S is the Laplace operator(d/dt) and i denotes the area. The gains constant $K_{ci}$ (KA/unit Area) would be totally different from $K_{cf}$, the gain constants for frequency as control signal. So a signal proportional to area control error ($\Delta f_i$ + (1/$B_i$) $\Delta P_{ij}$) is used in such a scheme. Then,

$$\Delta I_{di} = \frac{K_{cai}}{(1+ST_{dci})}(\Delta f_i + \frac{1}{B_i} * \Delta P_{ij}) \quad (12)$$

The capacitor voltage deviation can be sensed and used as a negative feedback signal in the CES control loop to achieve quick restoration of voltage then, that with frequency deviation as control signal,

$$\Delta I_{di} = \frac{1}{(1+ST_{dci})}(K_{cfi}\Delta f_i \text{-} K_{vdi}\Delta E_{di}) \quad (13)$$

Where $K_{vdi}$ (kA/kV) is the gain corresponding to the $\Delta E_d$ feedback.

## 4. QFT Design Methodology

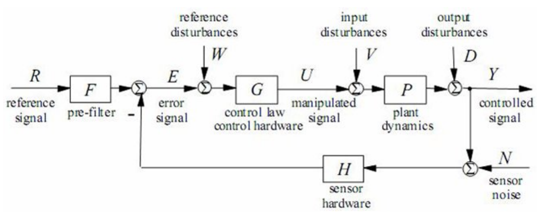


**Fig. 3.** SISO QFT bounds for the feedback system.

This section discusses the methodology behind QFT design procedure. Fig 3 shows an outline of the QFT algorithm. Then a brief description of each step is discussed. The QFT method involves the following steps:

### 4.1 Generation of Templates

First step involves generation of templates. Templates are nothing but variation in magnitudes and phases of the transfer function. These variations graphically reflect the uncertainty and these may be used to compute QFT bounds with the aid of different algorithms.

### 4.2 Computation of QFT Bounds

The next step is computation of QFT bounds .This is done by choosing a nominal plant which may be even chosen outside the parametric space. The performance specifications to be met in the control problem are translated into the Nichols chart. These are called QFT bounds. They may of different types like robust tracking bounds, disturbance rejection bounds and these depend on the control problem.

### 4.3 Loop Shaping

Loop shaping is the process of shaping the open loop transmission so that it satisfies all the bounds. The process involves choosing an initial controller and then adding by trial and error. Various functions like lag, lead, zero, pole etc to make the transmission function satisfy its bounds.

### 4.4 Design of prefilter

The prefilter is designed to aid tracking of input by the output. The controlled plant response may satisfy all the performance specifications at the same need not lie between the extremes of the frequency domain responses. So a prefilter is designed with the aid of prefilter shaping, a trial and error method similar to loop shaping is done to get the prefilter transfer function.

## 5. Problem Formulation

This section makes use of QFT to design controller and prefilter for some typical problems. Here QFT conventional design algorithm is followed to get the design of controller accomplished. Here SISO single loop problems are discussed.

### 5.1 Computation of QFT Bounds

Consider a system with plant transfer function as P(s) It is desired to satisfy the following stability, performance and disturbance rejection specifications: (Stability specifications).

1. Robust margins

$$\left|\frac{P(j\omega)G(j\omega)}{1+P(j\omega)G(j\omega)}\right| \le 1.2 \quad (14)$$

(Disturbance Rejection Specifications)

2. Robust output disturbance rejection

$$\frac{Y(j\omega)}{D(j\omega)} < 0.2.\frac{(j\omega)^3 + 64(j\omega)^2 + 748(j\omega) + 2400}{(j\omega)^2 + 14.4(j\omega) + 169}, \omega < 10 \quad (15)$$

3. Robust input disturbance rejection

$$\frac{Y(j\omega)}{D(j\omega)} < 0.01, \omega < 10 \quad (16)$$

All the bounds are combined to get collective bounds which are the exact constrain of the open loop transfer function.

### 5.2 Loop Shaping

It is a process of shaping the open loop transmission so that it satisfies all the bounds. The loop shaping is done with the pre-designed controller value.

### 5.3 Controller Design Using QFT

- Computing uncertainty plant matrix ( P )

$$P(s) = [P_{ij}](s) \tag{17}$$

- Computing diagonal compensation matrix ( G)

$$G(s) = \text{diag}\{ g_i(s) \} \tag{18}$$

- Computing controller value ( K )

$$Q = \frac{1}{(P_{ij})^{-1}} \tag{19}$$

$K = \frac{L_i}{Q'}$, where $L_i$ is a second order equation of the system.

## 6. Result Discussion

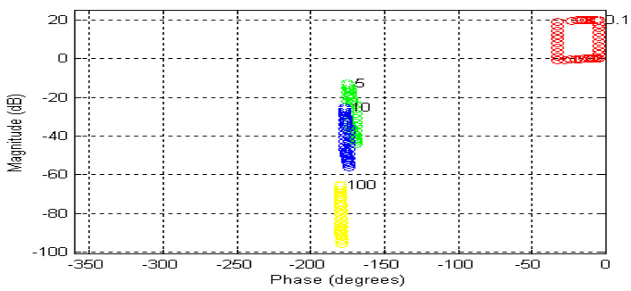


**Fig. 4.** Plant Template for W-D.

This section discusses the results obtained after applying QFT design to the above single input single output linear time invariant systems. The results are discussed for the order SISO in detail as an illustration for other similar systems having the same linear time invariant minimum phase stable nature. The results here are grouped under the headings like templates, bounds, loop shaping, prefilter shaping and time responses are shown in Fig (4-9).

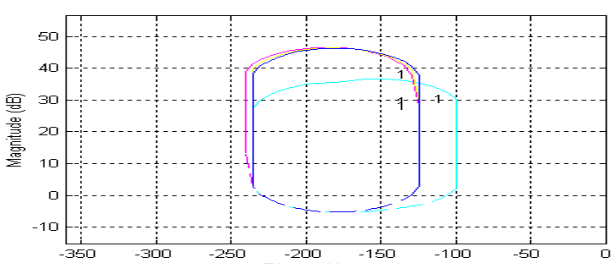


**Fig. 5.** Robust Stability Bounds for W-D.

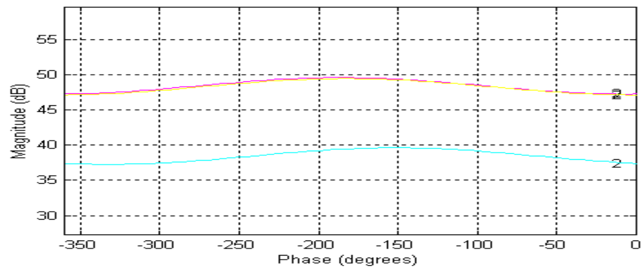


**Fig. 6.** Output Rejection Bounds for W-D.

Fig 4 shows the template for a single system namely wind- diesel as an illustration. These templates show the depth of parametric uncertainty. The width of templates increases as frequency increases and finally it thins down to a straight line

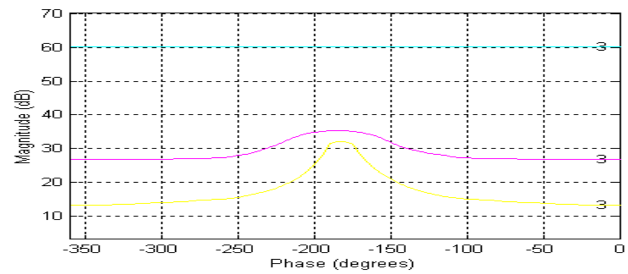


**Fig. 7.** Input Rejection Bounds for W-D.

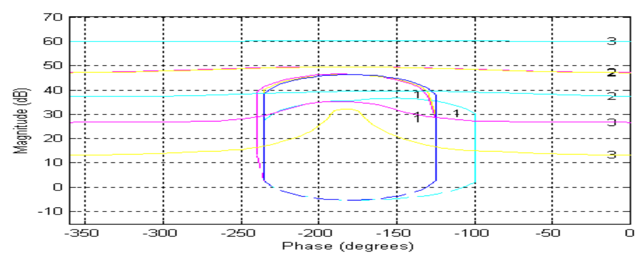


**Fig. 8.** All Bounds for W-D.

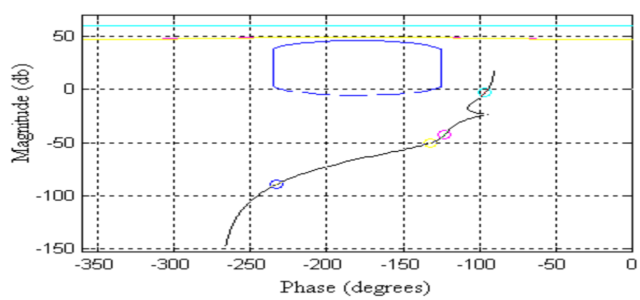


**Fig. 9.** Loop Shaping for W-D

Bounds are generated for the SISO System for wind-diesel as illustrated. The above bounds are derived from performance specifications by modeling the tracking control ratios for them and by repositioning templates after choosing one among the various sets of plants as the nominal plant $P_0(s)$ which is used in synthesizing the open loop transmission $L_0(s)=G(s)P_0(s)$.The magnitude of the bounds should decrease with increase in frequency for the ease of shaping the open loop transmission.

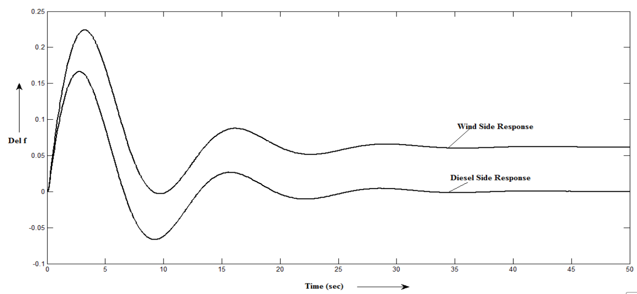


**Fig.10.** Open loop response of Wind Diesel power system

The nominal parameters of wind diesel and CES system data's are given in appendix-1. First, a 0.01 puKW step increase in the wind power input is applied to the system at t=0.0s, Fig. 10 shows the frequency deviation of the wind diesel generation, without controller and CES, the system frequency highly oscillates and peak frequency deviation is very large. The frequency oscillation takes about 60s and steady state error is also produced. This simulation results suggest that controller is required to reduce frequency oscillation and steady state error.

Fig 10 indicates the importance of pitch controller in the wind side and the governor in the diesel side is not able to work well. Fig 11 shows the response of wind diesel system with 0.01puKW step increase in the wind power input is applied to the system at t=0.0 s. with the help of pitch controller peak over shoot is reduced and steady state error is reduced to zero of both wind and diesel side.

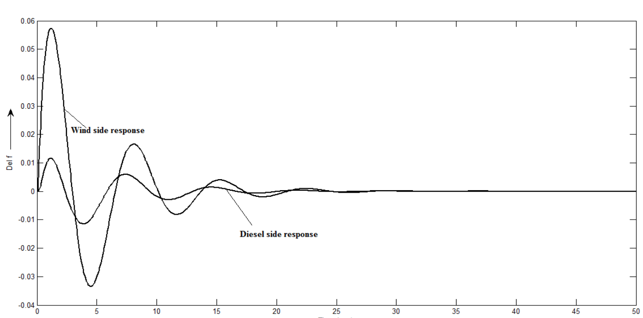


**Fig.11.** Closed loop response of Wind Diesel system

But this pitch controller is suitable for a particular operating condition when operating condition varies this fails to suppress the frequency of oscillation, again there is a stability problem in wind side. On the other hand, the peak frequency deviation is reduced significantly and returns to zero within shorter period in case of CES. The CES are able to damp the frequency deviation quickly in comparison to without CES case shown in fig 12.

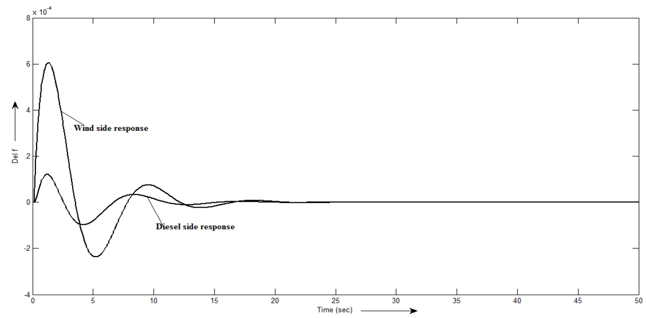


**Fig.12.** Closed loop response of Wind Diesel power system with CES

To show the performance of the suggested controller for different scenarios of load variations under various operating conditions as well as vast demands of load and its effectiveness and robustness against parametric uncertainties and un-contracted loads, simulation is performed for the W-D power system with CES.

Fig.13 illustrates the frequency deviation of W-D system, the simulation results show that the proposed robust controller suppresses the frequency fluctuation and peak overshoot better than the conventional type controller and W-D with CES. Fig 14 and 15 illustrates the comparative analysis of settling time and peak over shoot of different controllers, from the comparison it is clearly shows QFT controller based W-D with CES power system performance is better than other controllers and it is quit robust.

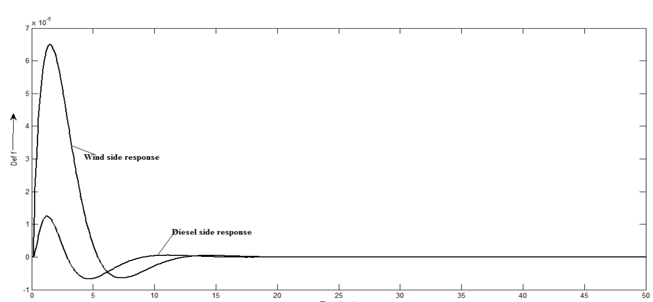


**Fig.13** QFT controller based closed loop response of Wind Diesel power system with CES

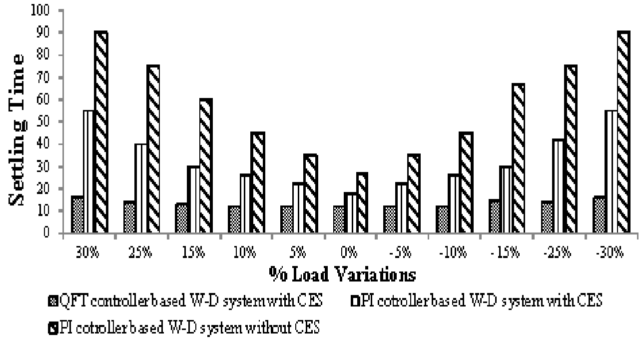


**Fig 14.** Comparative analysis of settling time of W-D system with different controllers

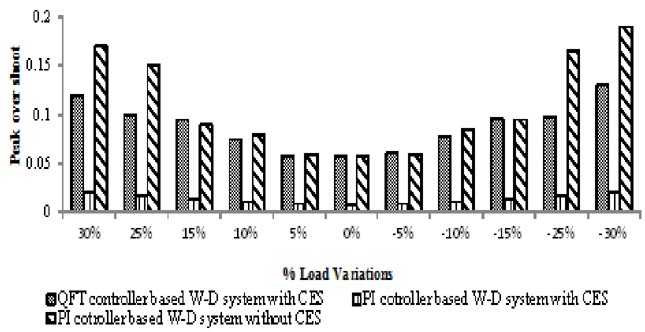


**Fig.15.** Comparative analysis of Peak over shoot of W-D system with different controllers

In this simulation studies, the proposed robust QFT controller based W-D with CES is compared with W-D system, W-D with SMES in [21,22]. Note that, to determine the kW capacity of CES, the limiter −0.01 pukW ≤ $\Delta P_{CES}$ ≤ 0.01 pukW on a system base kW is added to the output of CES. Simulation results under 2 case studies are carried out as follows.

Case-1: Step increase in wind power or load change First, a 0.01 pukW step increase in the wind power input is applied to the system at *t* = 0.0 s. Table 1 shows the frequency deviation of the diesel generation side which represents the system frequency deviation. Without SMES, the system frequency highly oscillates and the peak frequency deviation is very large. The frequency oscillation takes about 30 s. to reach zero. This indicates that the pitch controller in the wind side and the governor in the diesel side are not able to work well. On the other hand, the peak frequency deviation is reduced significantly and returns to zero within shorter period in case of SMES [21, 22] and the proposed SMES. The power output deviations of both SMESs are shown in Fig.10. The peak power output of the proposed robust QFT controller based W-D with CES is lower than that of the SMES [21, 22].

**Table 1**: System performance under 0.01pukW step load

| System | Frequency Deviation | | |
|---|---|---|---|
| | Steady state error ($e_{ss}$) | Settling time ($T_s$) | Peak Over shoot ($M_p$) |
| Wind-Diesel without controller | 0.05 | - | 0.225 |
| Wind-Diesel with pitch controller without SMES | - | 38 | 0.055 |
| Wind-Diesel with SMES in [21] | - | 27 | 0.0025 |
| Wind-Diesel with SMES in [22] | - | 19 | 0.0015 |
| Proposed Wind-Diesel with CES | - | 12 | 0.00065 |

Case 2: Random wind power input.

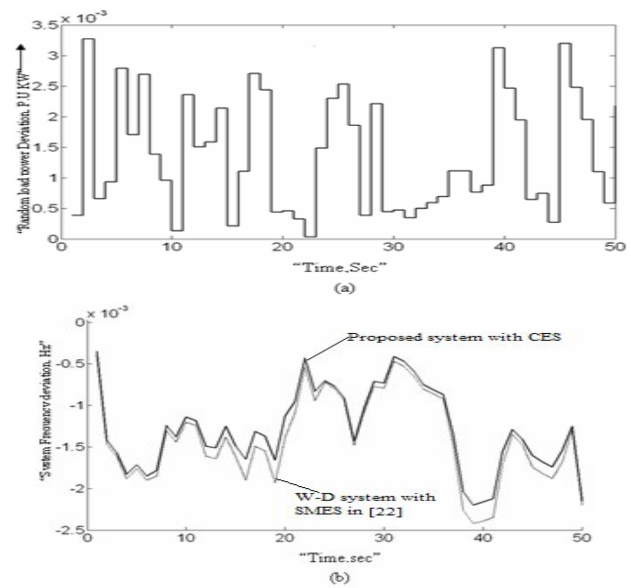


**Fig. 16.** (a) Random power input, (b) Comparative analysis of System frequency deviation under normal system parameters proposed system with SMES in [22]

In this case, the system is subjected to the random wind power input as shown in Fig.16 (a). The W-D system with SMES in [22] frequency deviations under normal system parameters are shown in Fig.16 (b). By the proposed W-D system with CES, the frequency deviation is lower than that in case of SMES [22].

*Sensitivity Analysis:* In this paper, the investigations are carried out to study the effect of power system by varying system parameters like $H_w$, $H_D$, $K_D$, $K_{pc}$ the parameters are varied by ± 25% from the nominal values. The dynamic response hardly changes by ± 25% variations in system parameters, for corresponding optimum PI gains. But the QFT controllers are quite robust for system parameter variations and it is tabulated in Table 2.

**Table.2.** Comparative analysis of different controller's performances

| Percentage Variation | | Value | QFT,W-D with CES | PI, W-D with CES | PI, W-D without CES |
|---|---|---|---|---|---|
| | | | Ts | Ts | Ts |
| $H_w$ | 100% | 3.5 | 13 | 22 | 30 |
| | 75% | 2.625 | 13 | 28 | 40 |
| | 125% | 4.375 | 13.2 | 63 | 90 |
| $H_D$ | 100% | 8.5 | 13 | 22 | 30 |
| | 75% | 6.375 | 12.8 | 25 | 48 |
| | 125% | 10.63 | 13.1 | 65 | 98 |
| $K_D$ | 100% | 6.5 | 13 | 22 | 30 |
| | 75% | 4.875 | 13 | 25 | 55 |
| | 125% | 8.125 | 12.9 | 65 | 95 |
| $K_{pc}$ | 100% | 0.08 | 13 | 22 | 30 |
| | 75% | 0.06 | 12.9 | 29 | 55 |
| | 125% | 0.1 | 13.1 | 55 | 105 |

## 7. Conclusion

In this research a new method for Load Frequency Control using QFT method in a W-D power system coordinated with CES has been proposed. Design strategy includes enough flexibility to setting the desired level of stability and performance, and considering the practical constraint by introducing appropriate uncertainties. The proposed method was applied to a typical W-D power system with system uncertainty parametric and various loads conditions. Simulation results demonstrated that the designed controller capable to guarantee the robust stability and robust performance such as precise reference frequency tracking and disturbance attenuation under a wide range of parameter uncertainty and area load conditions. Also, the simulation results show that the proposed method is robust to change in the parameter of the system and has good performance in compare to conventional PI controller in all of the operation conditions.

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## Appendix 1

**Wind – Diesel Data:** $P_R = 350$ kW, $H_W = 3.5$ s, $H_D = 8.5$ s, $K_{fc} = 16.2$ Hz/pu kW, $K_D = 16.5$ Hz/pu Kw, $K_{P2} = 1.25$, $K_{P3} = 1.4$, $T_{P1} = 0.6$ s, $T_{P2} = 0.041$ s, $K_{PC} = 0.08$, $K_{PI} = 4.0$, $K_{PP} = 1.5$.

**Capacitive Energy Storage Data:** C=1farad, R=100 ohm, Tdc=0.05s, Kace=70KA/unit MW, Kvd=0.1KA/KV, Vdo=2KV.

State space matrix (A):

$$\begin{vmatrix} -2.314 & 2.314 & 0.143 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.953 & -0.953 & 0 & 0 & 0.059 & 0 & 0 & 0 & 0 & -0.058 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0.112 & 0 & 0 & 0 \\ 0 & -16.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -660 & 0 & 40 & -40 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -24.39 & 0 & 24.39 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -17.04 & -1 & 18.29 & 0 & 0 \\ 14.59 & -14.59 & -3.471 & 0 & 1.429 & 0 & 0 & 0 & 0 & -1.429 \\ -99.25 & 183.16 & 11.306 & 0 & 0 & 0 & 0 & 0 & -1.716 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 33.33 & -33.33 \end{vmatrix}$$

Input matrix (due to wind disturbance):

$$\begin{bmatrix} 0.1428 & 0 & 0 & 0 & 0 & 0 & 0 & -3.4717 & 1.306 & 0 \end{bmatrix}$$

Input matrix (due to load disturbance):

$$\begin{bmatrix} 0 & -0.0588 & 0 & 0 & 0 & 0 & 0 & -1.4294 & 0 & 0 \end{bmatrix}$$

Output Matrix:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Feedback Matrix:

d= [0].