

## Robust Decentralized Load Frequency Control Using Multi Variable QFT Method in Deregulated Power Systems

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**Abstract:** The Load Frequency Control problem has been a major subject in electrical power system design/operation and is becoming more significant recently with increasing size, changing structure and complexity in interconnected power systems. In practice LFC systems use simple proportional-integral controllers. However, since the PI control parameters are usually tuned based on classical or trial-and-error approaches, they are incapable of obtaining good dynamic performance for a wide range of operation conditions and various load changes scenarios in multi-area power system. For this problem, in this paper quantitative feedback theory method is used for LFC control in multi-area power system with system parametric uncertainties. The system parametric uncertainties are obtained by changing parameters by 40% simultaneously from their typical values. A two-area power system example with a wide range of parametric uncertainties is given to illustrate proposed method. To show effectiveness of proposed method, a classical I type controller optimized by genetic algorithm is designed for LFC for comparison with QFT. The validity of the proposed method was confirmed by comparing it results with those of traditional methods (I controller optimized by genetic algorithm) has been confirmed.

**Key words:** Load Frequency Control, robust control, quantitative feedback theory, and decentralized control deregulated power system

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### INTRODUCTION

For large-scale power systems, which normally consist of interconnected control area, Load Frequency Control (LFC) is important to keep the system frequency and the inter-area tie power as close as possible the scheduled values. The mechanical input power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. In a deregulated power system, each control area contains different kinds of uncertainties and various disturbances due to increased complexity, system modeling errors and changing power system structure. A well designed and operated power system should cope with changes in the load and with system disturbances, and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits<sup>[1-5]</sup>.

Several strategies for Load Frequency Control of power systems have been proposed by researchers over the past decades<sup>[1-17]</sup>. This extensive research is due to fact that LFC constitutes an important function on power system operation where the main objective is to

regulate the output power of each generator at prescribed levels while keeping the frequency fluctuations within pre-defined limits. Robust adaptive control schemes have been developed<sup>[4-6]</sup> to deal with changes in system parametric under LFC strategies. A different algorithm has been presented<sup>[7]</sup> to improve the performance of multi-area power systems. Viewing a multi-area power system under LFC as a decentralized control design for a multi-input multi-output system, it has been shown<sup>[8]</sup> that a group of local controllers with tuning parameters can guarantee the overall system stability and performance. The result reported in<sup>[4-8]</sup> demonstrates clearly the importance of robustness and stability issues in LFC design. In addition, several practical points have been addressed in<sup>[9-14]</sup> which include recent technology used by vertically integrated utilities, augmentation of filtered area control error with LFC schemes and hybrid LFC that encompasses an independent system operator and bilateral LFC. The applications of artificial neural networks, genetic algorithms, fuzzy logic and optimal control to LFC have been reported in<sup>[15-17]</sup>.

The objective of this research is to investigate the Load Frequency Control and inter-area tie power

control problem for a multi area power system taking into consideration the uncertainties in the parameters of system. A robust decentralized control scheme is designed using quantitative feedback theory (QFT) method. The proposed controller is simulated for a two area power system. To show effectiveness of proposed method, the proposed method is compare to a classical I type controller optimized by genetic algorithm. Results of simulation show the QFT controllers guarantee the robust performance for a wide range of operating conditions and have best performance in compare to classical controllers.

**MATERIALS AND METHODS**

A two-control area power system, shown in Fig. 1 is considered as a test system<sup>[13]</sup>. The state-space model of foregoing system is as (1)<sup>[13]</sup>.

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (1)$$

Where:

$$\begin{aligned} u &= [\Delta P_{D1}, \Delta P_{D2}, u_1, u_2] \\ y &= [y_1, y_2] = [\Delta f_1, \Delta f_2, \Delta P_{tie}] \\ x &= [\Delta P_{G1} \quad \Delta P_{T1} \quad \Delta f_1 \quad \Delta P_{tie} \quad \Delta P_{G2} \quad \Delta P_{T2} \quad \Delta f_2] \end{aligned}$$

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{M_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{M_2} \\ \frac{1}{T_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{T_{G2}} & 0 & 0 \end{bmatrix}$$

$$A = \begin{bmatrix} -\frac{1}{T_{G1}} & 0 & -\frac{1}{r_1 T_{G1}} & 0 & 0 & 0 & 0 \\ \frac{1}{T_{T1}} & -\frac{1}{T_{T1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{M_1} & -\frac{D_1}{M_1} & -\frac{1}{M_1} & 0 & 0 & 0 \\ 0 & 0 & T_{12} & 0 & 0 & 0 & -T_{12} \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{G2}} & 0 & -\frac{1}{r_2 T_{G2}} \\ 0 & 0 & 0 & 0 & \frac{1}{T_{T2}} & -\frac{1}{T_{T2}} & 0 \\ 0 & 0 & 0 & \frac{1}{M_2} & 0 & \frac{1}{M_2} & -\frac{D_2}{M_2} \end{bmatrix}$$

The parameters of model, defined as follow:

- $\Delta$  : Deviation from nominal value
- $M = 2H$  : Constant of inertia
- $D$  : Damping constant
- $R$  : Gain of speed droop feedback loop
- $T_t$  : Turbine time constant
- $T_G$  : Governor time constant

The typical values of system parameters for nominal operation condition are given in appendix<sup>[11]</sup>. The system parametric uncertainties are obtained by changing parameters by 40% simultaneously from their typical values. Based on this uncertainty, 6 different operating conditions are defined and shown in appendix.

Many practical systems are characterized by high uncertainty which makes it difficult to maintain good stability margins and performance properties for the closed-loop system. There are two general design methodologies for dealing with the effects of uncertainty: (i) adaptive control, in which the parameters of the plant are identified online and the information obtained is then used to tune the controller and (ii) robust control, which typically involves a

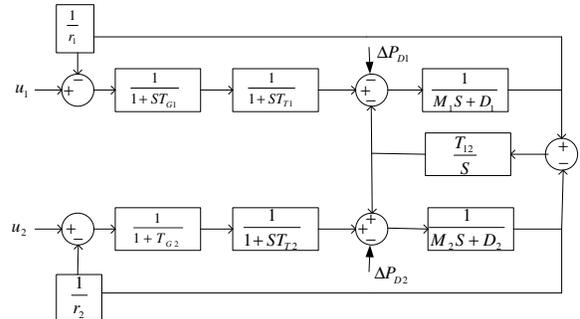


Fig. 1: Block diagram of two-area power system without LFC

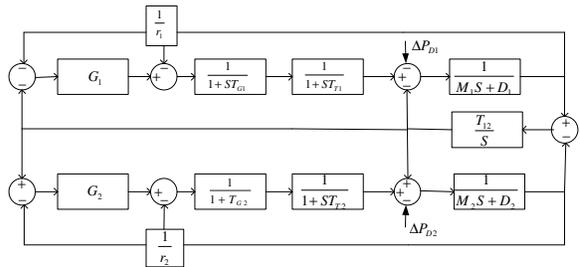


Fig. 2: Block diagram of two-area power system with controllers

worst-case design approach for family of plants (representing the uncertainty) using a single fixed controller.

In this paper a robust control method based on QFT is used for LFC and tie-power control. QFT is a robust control method developed during the last two decades which deals with the effects of uncertainty systematically. It has been successfully applied to the design of the both SISO and MIMO systems. It has also been extended to the nonlinear and time-varying cases. QFT often results in simple controllers which are easy to implement<sup>[18-21]</sup>. In this paper the goals are control of frequency and inter area tie-power with good damping of oscillation, also obtaining a good performance in all operating conditions and various loads and finally designing a low-order controller for easy implementation. The structure of system with controllers is shown in Fig. 2.

### CONTROLLER DESIGN USING QFT

In this section the goals are design of  $G_1$  and  $G_2$  simultaneously based on QFT technique, for control of frequency and inter area tie-power in Fig. 2.  $G_1$  is controller of first area and  $G_2$  is controller of second area. Because two controllers must be designed simultaneously, therefore, there is a  $2 \times 2$  MIMO system and the technique of design for MIMO systems is necessary. According to QFT method and using fixed point theory<sup>[21]</sup> the MIMO problem for a  $2 \times 2$  system can be separated into 2 equivalent single-loops MISO systems. Each MISO system design is based upon the specifications relating its output and all of its inputs. The basic MIMO compensation structure for a  $2 \times 2$  MIMO system is shown in Fig. 3. That consist of the uncertain plant matrix  $P$  and the diagonal compensation matrix  $G$ . These matrices are defined as (2).

$$P(s) = [P_{ij}](s) = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \quad G(s) = \text{diag}\{g_i(s)\} = \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \end{bmatrix} \quad (2)$$

Fixed point theory develops a mapping that permits the analysis and synthesis of a MIMO control system by a

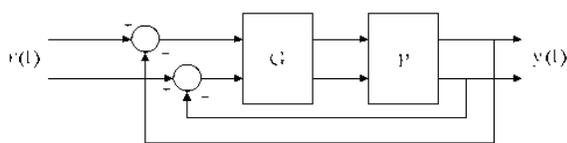


Fig. 3: The MIMO control structure ( $2 \times 2$ ) system

set of equivalent MISO control system. For  $2 \times 2$  system, this mapping results in 2 equivalent systems, each with two inputs and one output. One input is designated as a desired input and the other as a disturbance input. The inverse of the plant matrix is represented by (3).

$$P(s)^{-1} = \begin{bmatrix} P_{11}^* & P_{12}^* \\ P_{21}^* & P_{22}^* \end{bmatrix} \quad (3)$$

The 2 effective plant transfer function are formed as (4).

$$q_{ij} = \frac{1}{p_{ij}^*} = \frac{\det \cdot p}{\text{adj} \cdot p_{ij}} \quad (4)$$

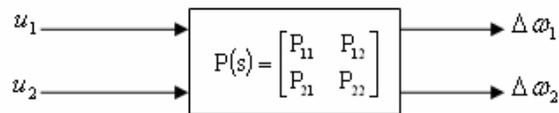


Fig. 4: Open-loop system for Load Frequency Control

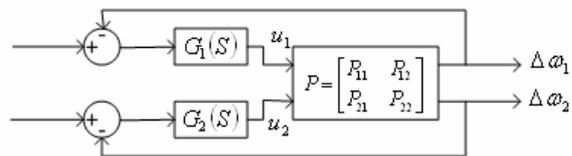


Fig. 5: Closed-loop system for load frequency control

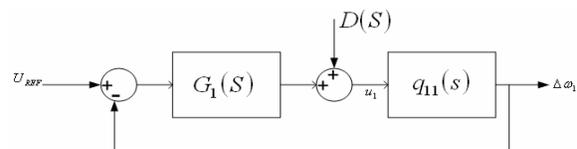


Fig. 6: Structure of closed-loop system for control of the first area

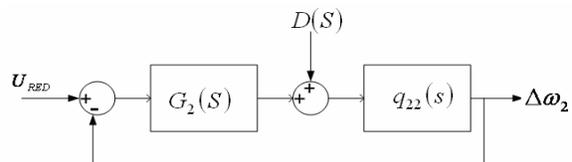


Fig. 7: Structure of closed-loop system for control of the second area

There is a requirement that det. P be minimum phase. The Q matrix is then formed as (5).

$$Q = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix} = \begin{bmatrix} \frac{1}{P^*_{11}} & \frac{1}{P^*_{12}} \\ \frac{1}{P^*_{21}} & \frac{1}{P^*_{22}} \end{bmatrix} \quad (5)$$

The matrix  $p^{-1}$  is partitioned to the following form:

$$P^{-1} = [P^*_{ij}] = \begin{bmatrix} 1 \\ q_{ij} \end{bmatrix} = \Lambda + B \quad (6)$$

Where  $\Lambda$  is diagonal part, and  $B$  is the balance of  $p^{-1}$ .

The system control relation relating  $r$  to  $y$  is  $T = [I + PG]^{-1} PGF$ . Pre multiplying of system control relation by  $[I + PG]$  yields:  $[I + PG]T = PGF$ .

When  $P$  is nonsingular, pre multiplying both sides of this equation by  $P^{-1}$  yields:  $[P^{-1} + G]T = GF$ .

Using (6), and with  $G$  diagonal,  $[P^{-1} + G]T = GF$  can be rearranged as (7).

$$T = [\Lambda + G]^{-1} [GF - BT] \quad (7)$$

This equation is used to define the desired fixed point mapping where each of the 4 matrix elements on the right side of this equation can be interpreted as a MISO problem. Proof of the fact that design of each MISO system yields a satisfactory MIMO design is based on the Schauder fixed point theorem<sup>[21]</sup>.

Based on this description, in  $2 \times 2$  system that we need to design of 2 controllers for two area, the plant matrix  $P$  is a  $2 \times 2$  matrix and the diagonal compensation matrix  $G$  contains two compensators of  $G_1$  and  $G_2$ .

Using dynamic state-space model for system presented in (1), one can obtain plant matrix  $P$  shown in Fig. 4 as an uncertain plant. According to QFT method and Fig. 4, the structure of control system may be shown as in Fig. 5.

$P$  is the plant transfer function matrix which contains uncertainty parameters and can be obtained using state space form (1) for any operating point,  $G_1$  and  $G_2$  are cascading compensators which to be designed so that the variation of  $\Delta\omega_1$  and  $\Delta\omega_2$  to uncertainty in the plant matrix  $P$  are within desired tolerances.

In section (II) system uncertainty and operating conditions in this area of uncertainty were defined. According to this operating points and corresponding

plant transfer functions, the effective plant transfer functions,  $q_{11}$  and  $q_{22}$  defined in (5), can be obtained. Then according to fixed point theory, first area controller ( $G_1$ ) was designed based on the effective plant transfer function of  $q_{11}$ . Similarly the second area controller ( $G_2$ ) was designed based on the effective plant transfer function of  $q_{22}$ .

**Design of two area controllers ( $G_1$  and  $G_2$ ):** The structure of control systems for the first area and the second area controllers are shown in Figs. 6 and 7. It can be seen clearly that the systems are MISO systems and compensator  $G_1$  will be designed based on  $q_{11}$  and compensator  $G_2$  will be designed based on  $q_{22}$  (based QFT technique and fixed point theory).

In QFT technique, the first design step, is plant uncertainty plot in Nichols diagram. This diagram is known as system templates. Templates of  $q_{11}$  and  $q_{22}$  for various operating points were obtained by using Matlab software<sup>[22]</sup> in some frequencies and shown in Fig. 8 and 9.

Next step is obtaining QFT tracking and disturbance rejection bounds. In this system, the design goal is driving back frequency and tie-power deviations to zero value and such systems are called regulatory systems. In fact, step change in input (demand of areas) is considered as disturbance and controller must reject this disturbance from output. So, controllers must have disturbance rejection property and tracking property is unnecessary. Therefore, we consider just disturbance rejection bounds for design, and the tracking models are unnecessary for this design. Output responses are acceptable if the magnitude of the output to be below

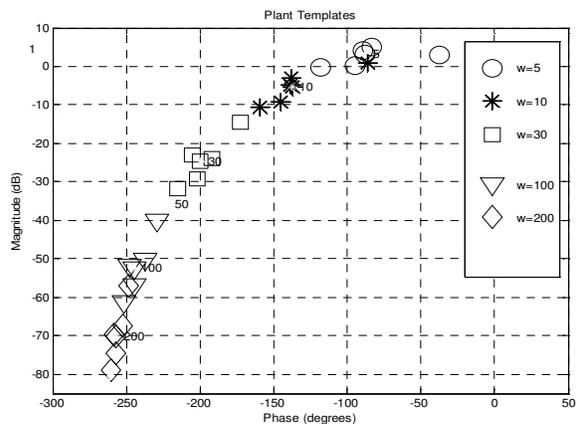


Fig. 8: Templates of effective plant transfer function of  $q_{11}$

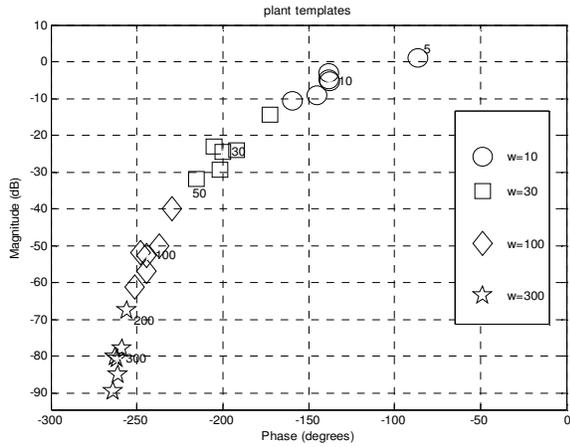


Fig. 9: Templates of effective plant transfer function of  $q_{22}$

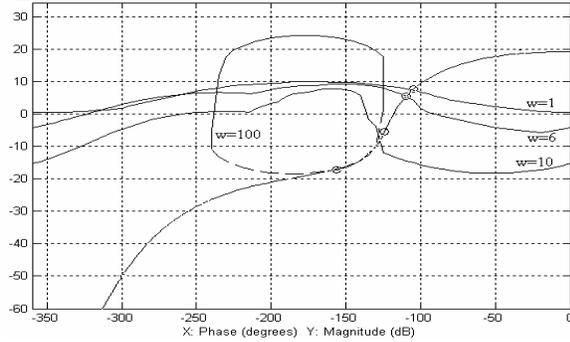


Fig. 10: Disturbance rejection bounds and loop shaping for  $q_{11}$

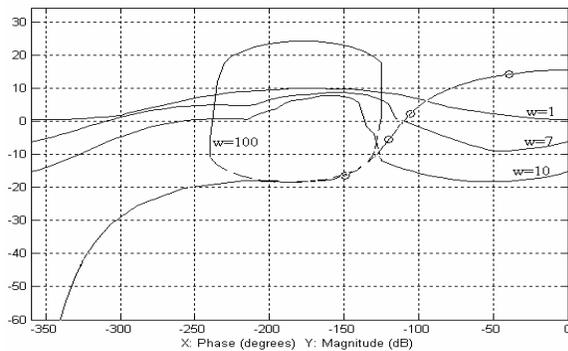


Fig. 11: Disturbance rejection bounds and loop shaping for  $q_{22}$

the limits given by disturbance rejection models. Based on desired performance specification, we can obtain disturbance rejections bounds according to QFT method

[18-21]. In this case, because tracking bounds are not considered, therefore, the disturbance rejection bounds or  $B_D(j\omega)$  were considered as composite bounds  $B_o(j\omega)$ . And also, minimum damping ratios  $\xi$  for the dominant roots of the closed-loop system is considered as  $\xi = 1.2$ , this amount, on the Nichols chart establishes a region which must not be penetrated by the template of loop shaping (Lo) for all<sup>10</sup>. The boundary of this region is referred to as U-contour. The U-contour and composite bound  $B_o(j\omega)$  and an optimum loop shaping ( $L_1$  and  $L_2$ ) based on these bounds, are shown in Fig. 10 and 11. The transfer functions for  $L_1$  and  $L_2$  is as (8).

$$L_1 = \frac{152444.5111 (S+18.8) (S+4.134)}{S (S+33.33) (S+6.44) (S+4.755) (S^2+14.49S+2300)} \quad (8)$$

$$L_2 = \frac{22772.9454 (S+10.21) (S+12.5) (S+3.618)}{S (S+7.306) (S^2+3.892S+5.376) (S^2+19.98S+3468)}$$

Therefore, the compensators ( $G_1$  and  $G_2$ ) obtained as (9).

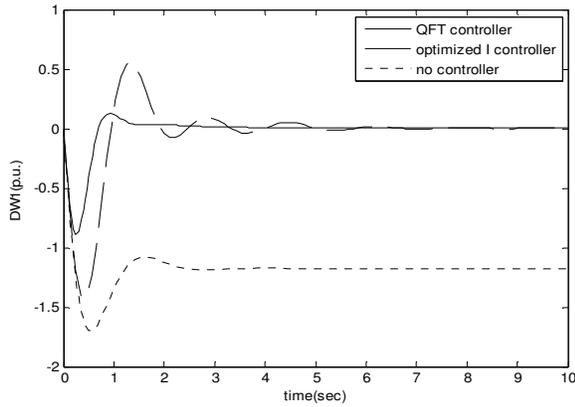
$$G_1 = \frac{L_1}{q_{11}} = \frac{60.99 (S+18.8) (S+4.134)}{S (S^2+14.49S+2300)} \quad (9)$$

$$G_2 = \frac{L_2}{q_{22}} = \frac{303.7 (S+10.21) (S+3.618)}{S (S^2+19.98S+3468)}$$

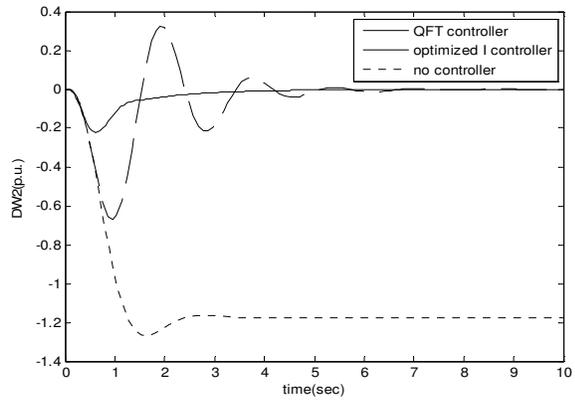
It can be observed clearly in Figs. 10 and 11, that the process of designing a nominal open-loop transfer function (loop-shaping) exactly based on QFT bounds, can met the design objectives.

## RESULTS AND DISCUSION

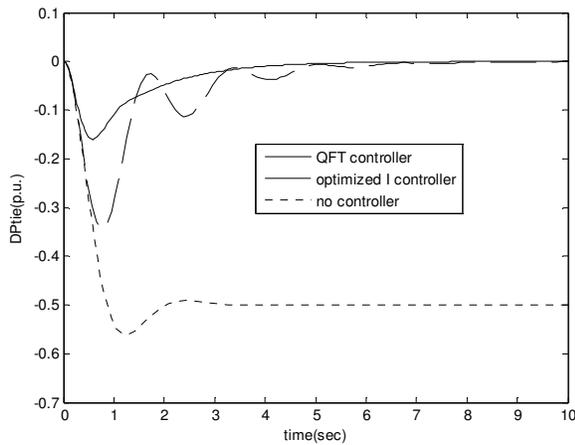
In this section different comparative cases are examined to show the effectiveness of proposed QFT controllers. These cases have been evaluated extensively by time domain simulation, using commercially available software package<sup>[22]</sup>. To compare and show effectiveness of proposed method, a classical I type controller optimized by genetic algorithm (GA) is designed for LFC. The parameter of conventional I type controller optimized using genetic algorithm<sup>[23]</sup>, and optimum value of the integral gain setting of the controller is obtained as  $K_{i=}$  1.0601. Therefore, I controller is as follow:



a



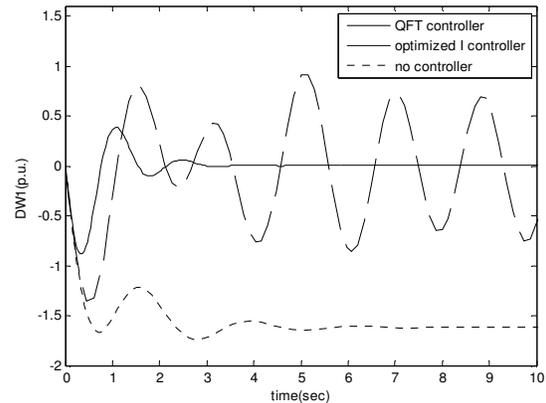
b



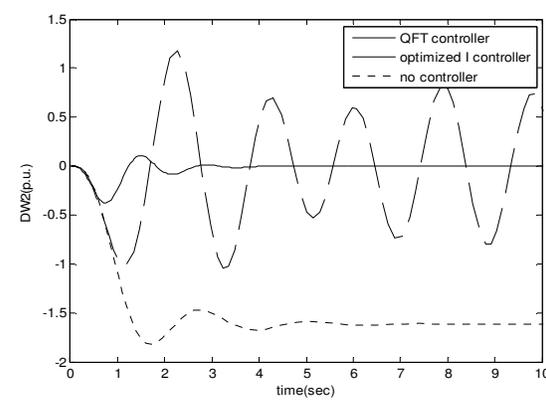
c

Fig. 12: Dynamic response at nominal load (operating point 1), following step change in demand of the first area ( $\Delta P_{D1}$ )

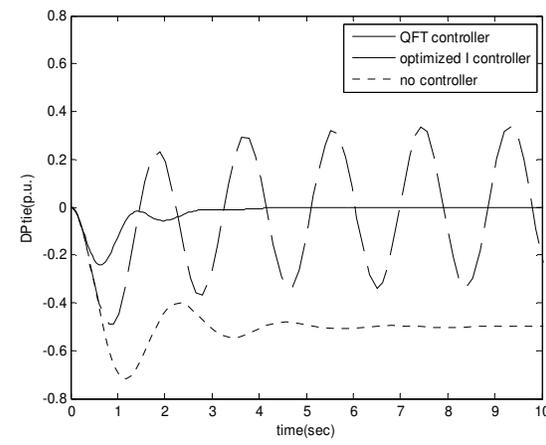
- a: Frequency deviation of the first area  $DW_1$ ,
- b: frequency deviation of the second area  $DW_2$  and
- c: inter area tie-power



a



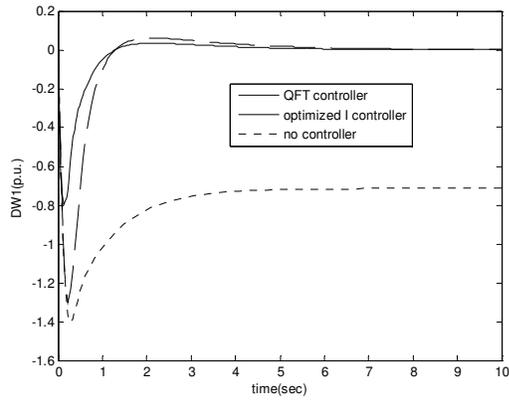
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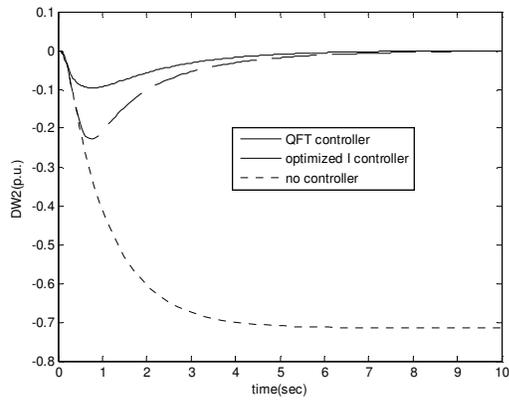
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Fig. 13: Dynamic response at operating point 2, following step change in demand of the first area ( $\Delta P_{D1}$ )

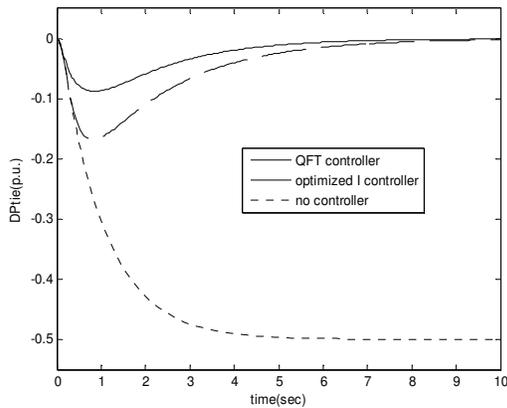
- a: frequency deviation of the first area  $DW_1$ ,
- b: frequency deviation of the second area  $DW_2$  and
- c: inter area tie-power



a



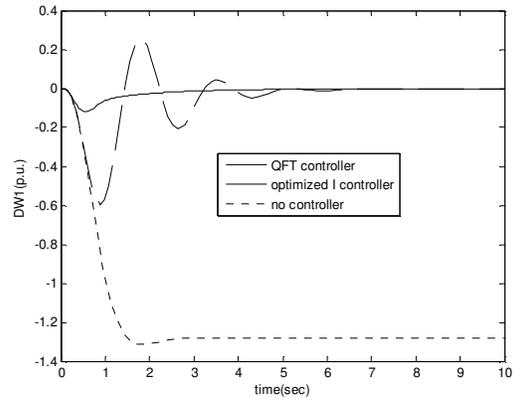
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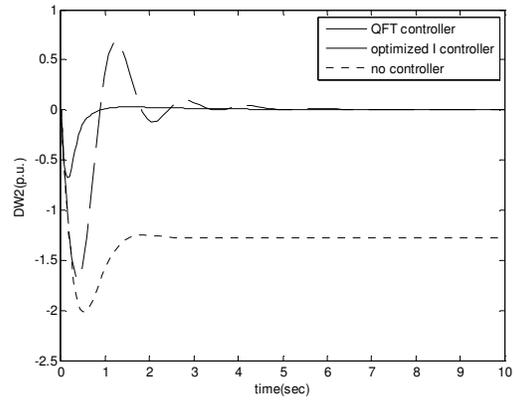
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Fig. 14: Dynamic response at operating point 3, following step change in demand of the first area ( $\Delta P_{D2}$ )  
a: frequency deviation of the first area  $DW_1$ ,  
b: frequency deviation of the second area  $DW_2$  and

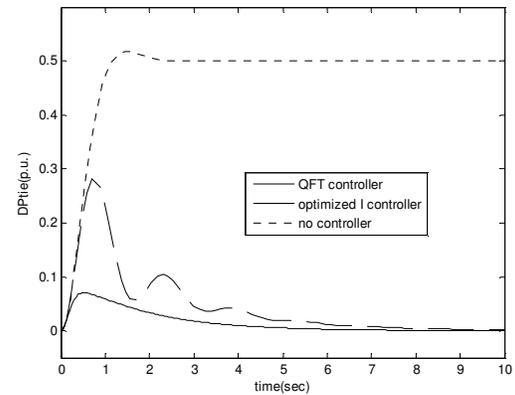
c: inter area tie-power



a



b



c

Fig. 15: Dynamic response at operating point 4, following step change in demand of the second area ( $\Delta P_{D2}$ )  
a: frequency deviation of the first area  $DW_1$ ,  
b: frequency deviation of the second area  $DW_2$  and  
c: inter area tie-power

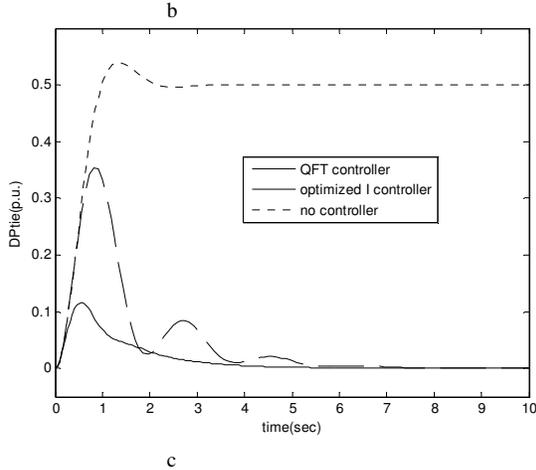
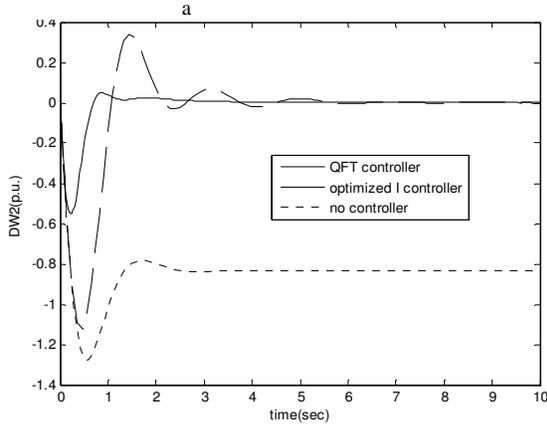
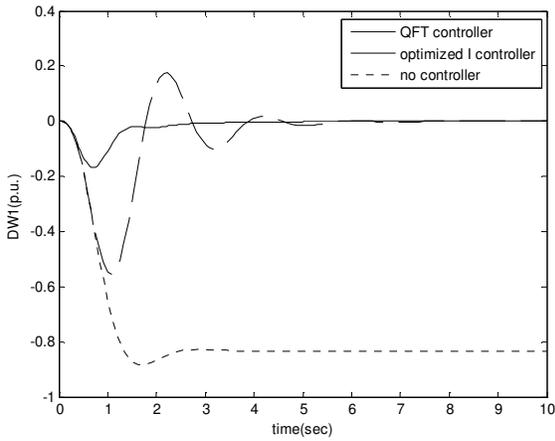


Fig. 16: Dynamic response at operating point 5, following step change in demand of the second area  $\Delta P_{D2}$   
 a: frequency deviation of the first area  $DW_1$ ,  
 b: frequency deviation of the second area  $DW_2$  and  
 c: inter area tie-power

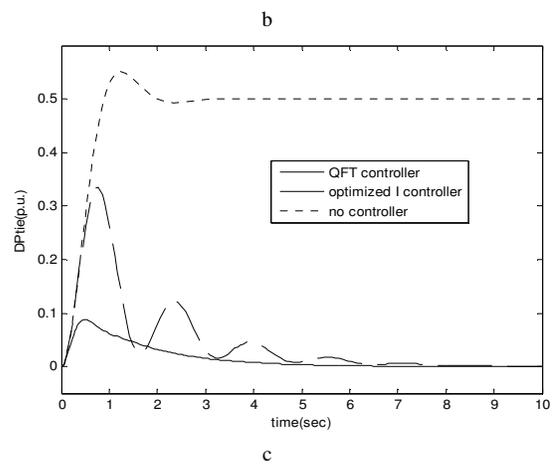
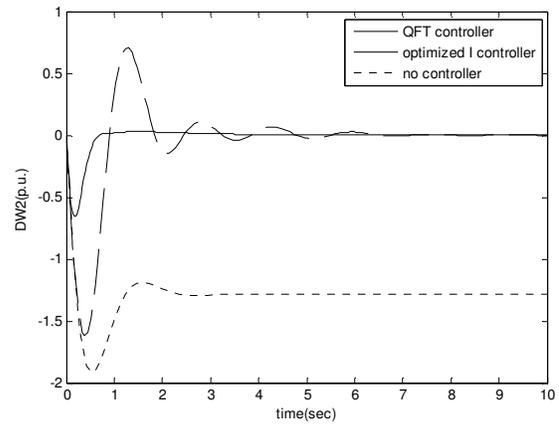
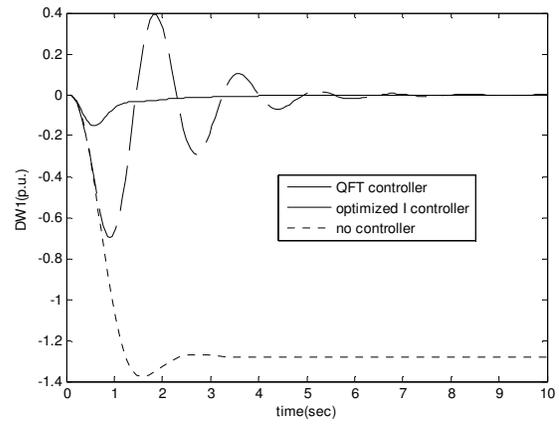


Fig. 17: Dynamic response at operating point 6, following step change in demand of the second area  $\Delta P_{D2}$   
 a: frequency deviation of the first area  $DW_1$   
 b: frequency deviation of the second area  $DW_2$

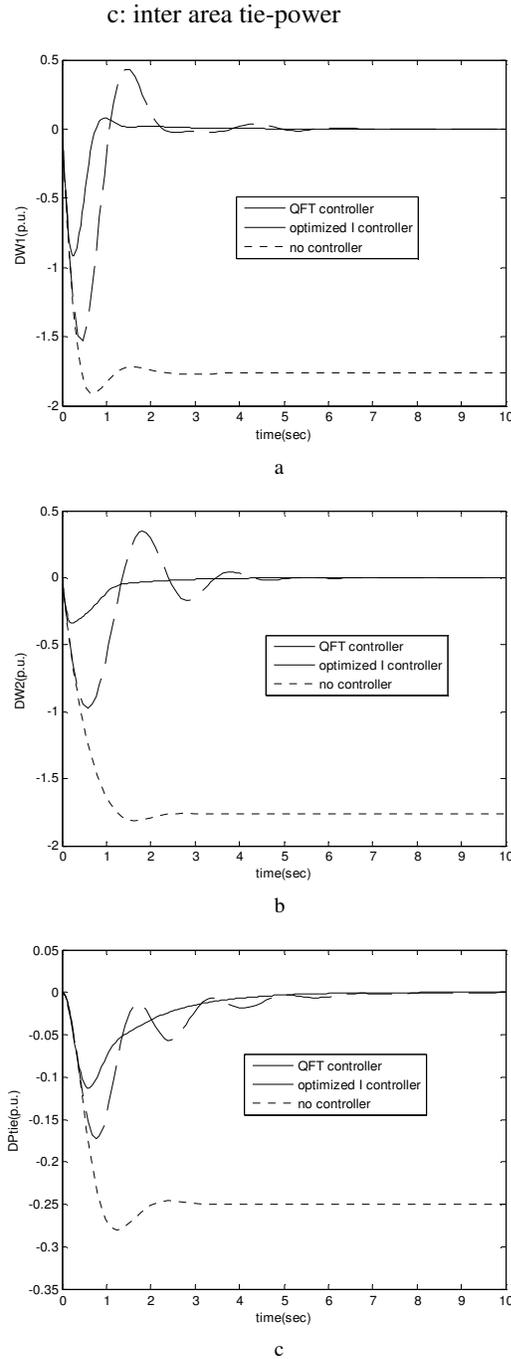


Fig. 18: Dynamic response at operating point 1, following step change in demand of the first area and 0.5 step change in demand of the second area simultaneously  
 a: frequency deviation of the first area  $DW_1$ ,  
 b: frequency deviation of the second area  $DW_2$  and

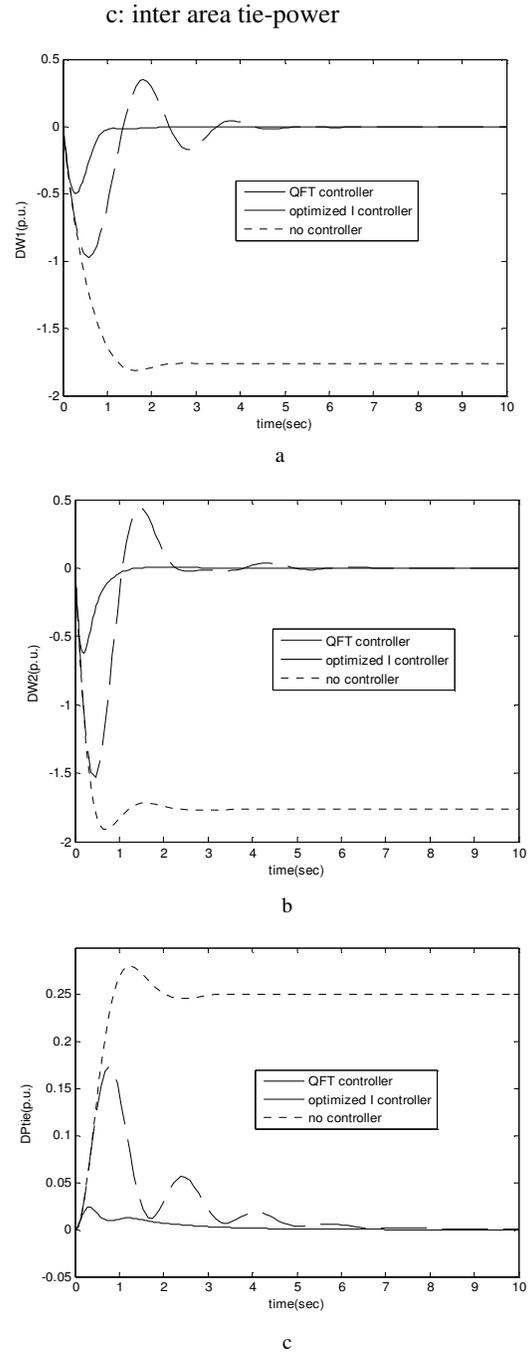


Fig. 19: Dynamic response at operating point 1, following 0.5 step change in demand of the first area and step change in demand of the second area simultaneously  
 a: frequency deviation of the first area  $DW_1$ ,  
 b: frequency deviation of the second area  $DW_2$  and

c: inter area tie-power

$$I \text{ controller} = \frac{Ki}{S} = \frac{1.0601}{S} \quad (10)$$

It should be noted that because the parameters of first area and second area are the same, therefore, foregoing I type controller optimized by GA and shown in (11), was used for two area with the same structure. Therefore:

$$G_1 = G_2 = \frac{Ki}{S} = \frac{1.0601}{S} \quad (11)$$

**Step increase in demand of the first area  $\Delta P_{D1}$ :** In this case, step increase in demand of the first area  $\Delta P_{D1}$  at operating points 1-3 are applied. As the first test case, a step increase in demand of the first area  $\Delta P_{D1}$  is applied. The frequency deviation of the first area,  $DW_1$ , and the frequency deviation of the second area,  $DW_2$ , and inter area tie-power signals of the closed-loop system are shown in Figs. 12-14. Using proposed method, the frequency deviations and inter area tie-power quickly driven back to zero and QFT has the best performance in control and damping of frequency and tie-power in all responses. Also in this case, because the step change applied to the input of the first area, therefore, based on QFT technique in MIMO systems, the output of the second area is known as disturbance and must driven back to zero quickly in compare to output of the first area. The simulation results clearly show this subject and the output of the second area has damping with smaller amplitude and settling time in compared with output of the first area. Also responses without any controller can not be driven back to zero and have a steady-state error.

At operating point 2, with conventional I controller, system goes to unstable situation and controller can not achieve the control objectives.

**Step increase in demand of the second area  $\Delta P_{D2}$ :** In this case, a step increase in demand of the second area  $\Delta P_{D2}$  at operating conditions 4-6 are applied. The frequency deviation of the first area  $DW_1$  and the frequency deviation of the second area  $DW_2$  and inter area tie-power signals of the closed-loop system are shown in Figs. 15-17. Using proposed method, the frequency deviations and inter area tie-power quickly driven back to zero and QFT has the best performance in control and damping of frequency and tie-power in all responses.

**Step increase in demand of the first area and the second area simultaneously:**

**Case 1:** In this case, a step increase in demand of the first area  $\Delta P_{D1}$  and 0.5 step increases in demand of the second area  $\Delta P_{D2}$  simultaneously are applied at

operating condition 1. The system outputs are shown in Fig. 18. Using QFT method, the frequency deviations and inter area tie-power quickly driven back to zero in compared to optimized I controller.

**Case 2:** In this case, a 0.5 step increase in demand of the first area  $\Delta P_{D1}$  and step increases in demand of the second area  $\Delta P_{D2}$  simultaneously are applied in operation condition 1. The system outputs are shown in Fig. 19. Using QFT method, the frequency deviations and inter area tie-power quickly driven back to zero in compare to optimized I controller. Also responses without any controller can not be driven back to zero and will have a steady state error.

## CONCLUSION

In this research a new method for Load Frequency Control using QFT method in a two area power system 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 two generator 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 I controller in all of the operation conditions.

## APPENDIX

The typical values of parameters of system for nominal operating condition are as follow

$$\begin{aligned} T_{T1} = T_{T2} &= 0.03; T_{G1} = T_{G2} = 0.08; T_{P1} = T_{P2} = 20 \\ R_1 = R_2 &= 2.4; K_{P1} = K_{P2} = 120; T_{12} = 0.545 \\ B_1 = B_2 &= 0.425; K_1 = K_2 = 1; a_{12} = -1 \end{aligned}$$

Where, the footnote 1 indicates the first area parameters and footnote 2 indicate the second area parameters. It should be note that, the parameters of two areas are equal. By changing parameters by 40% from their typical values the system uncertainty obtained. In this uncertainty area, 6 different operating conditions are defined as follow:

Operating point 1	$r_1 = 2.4$	$T_{T1} = 0.03$	$T_{G1} = 0.08$
	$T_{12} = 0.545$	$M_1 = 0.1667$	$D_1 = 0.0083$
Operating point 2	$r_1 = 3.36$	$T_{T1} = 0.112$	$T_{G1} = 0.042$
	$T_{12} = 0.763$	$M_1 = 0.2334$	$D_1 = 0.0116$
Operating point 3	$r_1 = 1.44$	$T_{T1} = .018$	$T_{G1} = 0.048$
	$T_{12} = 0.327$	$M_1 = 0.1$	$D_1 = 0.005$
Operating point 4	$r_1 = 2.64$	$T_{T1} = .039$	$T_{G1} = 0.072$
	$T_{12} = 0.3815$	$M_1 = 0.1334$	$D_1 = 0.0116$
Operating point 5	$r_1 = 1.68$	$T_{T1} = .027$	$T_{G1} = 0.1040$
	$T_{12} = 0.654$	$M_1 = 0.2334$	$D_1 = 0.005$
Operating point 6	$r_1 = 3$	$T_{T1} = .0195$	$T_{G1} = 0.1$
	$T_{12} = 0.479$	$M_1 = 0.1467$	$D_1 = 0.0011$

For any operating point, the parameters of the second area are equal to parameters of the first area and operating point 1 is nominal operating condition.

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