

A novel self-tuning fractional order PID control based on optimal model reference adaptive system

Mohamed. A. Shamseldin¹, Mohamed Sallam², A. M. Bassiuny³, A. M. Abdel Ghany⁴

¹Department of Mechatronics Engineering, Future University in Egypt, Cairo, Egypt

^{2,3}Department of Mechanical Engineering, Helwan University, Cairo, Egypt

⁴Department of Electrical Engineering, October 6 University (Helwan University Originally), Cairo, Egypt

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ABSTRACT

This paper presents a novel self-tuning fractional order PID (FOPID) control based on optimal Model Reference Adaptive Control (MRAC). The proposed control technique has subjected to a third order system case study (power system load frequency control). The model reference describes the requirements of designer. It can be first or second order system. The parameters of MRAC have obtained using the harmony search (HS) optimization technique to achieve the optimal performance. Sometimes, the tuning of the five parameters of FOPID control online at same moment consumes more calculation time and more processing. So, this study proposes three methods for self-tuning FOPID control. The first method has been implemented to tune the two integral and derivative parameters only and the rest of parameters are fixed. The second method has been designed to adjust the proportional, integral derivative parameters while the other fractional parameters are constant. The last method has developed to adjust the five parameters of FOPID control simultaneously. The simulation results illustrate that the third method of self-tuning FOPID control can accommodate the sudden disturbance compared to other techniques. Also, it can absorb the system uncertainty better than the other control techniques.

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Corresponding Author:

A. M. Abdel Ghany,
Department of Electrical Engineering,
October 6 University (Helwan University Originally), Cairo, Egypt.
Email: ghanyghany@hotmail.com

1. INTRODUCTION

The PID control has been applied to process control in most of engineering applications for decades [1]. The PID control has simple structure and linear behavior. Also, it gives acceptable performance for several industrial applications [2]. There are several methods to select the proper values for PID controller parameters [3]. The traditional methods for selecting these parameters such as try and error and Ziegler-Nichols which were became inappropriate to achieve a good performance [4]. So, the researchers have tended to use alternative methods such as optimization techniques (Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and Harmony Search (HS)) which are trying to reach the optimal solution for controller parameters [5]. Still, the behavior of PID control is linear and cannot deal with the high disturbance and high nonlinearity of complicated systems [6], [7].

The fractional order PID (FOPID) control has been widely used in control engineering in recent decades [8]. The FOPID considers the nonlinear copy of PID control where two more parameters (the fractional integral and derivative) added to the PID control parameters [9]. Hence, the task of designer selecting the proper values for the five parameters of the FOPID control [10]. The FOPID control can solve the nonlinearity problem but it cannot deal with the sudden disturbance due to its parameters which still fixed [11].

Different techniques have been proposed to tune the five parameters of FOPID control online but most of these techniques are based on the fuzzy logic control [12], [13]. The fuzzy logic control can solve the uncertainty problem and sudden disturbance but its design depends on the experience which sometimes is not available for some systems [14]-[16]. This study presents a novel technique to tune the FOPID control parameters online based on optimal model reference adaptive control (MRAC). It is known that the MRAC is high ranking adaptive control where it forces the overall system to follow the behavior of preselected model reference [17]. The preselected model can be first or second order system according to the point of view the designer and complicated degree of the system [18].

The task of model reference adaptive control is adjusting the FOPID control parameters online. The model reference contains the desired performance which can satisfy the designer. Moreover, to guarantee high performance the parameters of model reference optimized using the harmony search (HS) optimization technique according to a certain cost function.

The proposed technique will be subjected to a third order system as case study (power system load frequency control). Also, the proposed technique has been implemented with different methods. The first method has been designed to the MRAC will tune the two integral and derivative parameters only and the rest of parameters are fixed. The second method has been developed to adjust the proportional, integral derivative parameters while the other fractional parameters are constant. The last method fabricated to adjust the five parameters of FOPID control at the same time. The paper has organized as follows, firstly, the system model is presented. Secondly, the proposed control techniques are demonstrated. Thirdly, the simulation results are illustrated. Finally the conclusion is discussed.

2. THIRD ORDER CASE STUDY MODEL

Several nonlinear models for large power systems has to be established but all are complicated models. So, the linearized model has been used in our work. The power system represented by an equivalent turbine, governor and generator system [19], [20]. The transfer function of a single area power system model in a closed loop form as shown in Figure 1.

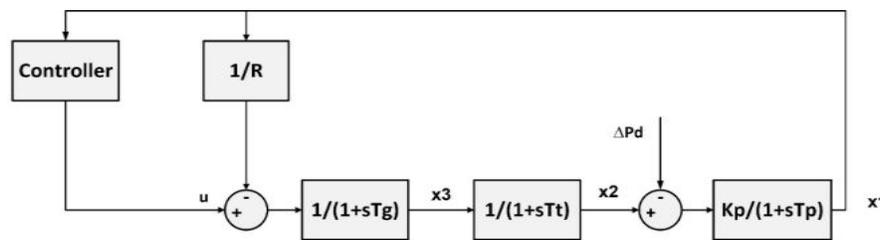


Figure 1. Block diagram of a single area power system

Where is u the control action, d is the disturbance vector (ΔPd), T_p is the plant model time constant, T_t is the turbine time constant, T_g is the governor time constant, K_p is the plant gain, R is the speed regulation due to governor action, x_1 is the change in system frequency, x_2 is the incremental changes in generator output and x_3 is the governor valve position. Table 1 present the values of system parameters that used in this work.

Table 1. System Parameters

Parameters	Value
K_p	120 pu
T_p	20 s
T_t	0.3 s
T_g	0.08 s
R	2.4 Hz/pu.MW

3. SELF-TUNING FOPID CONTROL

The Model Reference Adaptive Control (MRAC) is high-ranking adaptive controller [2], [5]. It may be regarded as an adaptive servo system in which the desired performance is expressed in terms of a

reference model. In this work the FOPID control parameters will be adjusted on-line using the model reference technique as shown in Figure 2.

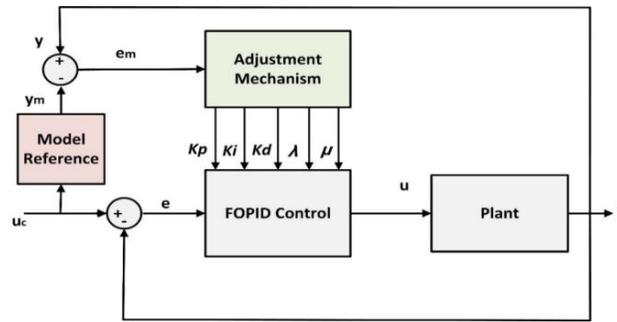


Figure 2. The overall system with self-tuning FOPID based on model reference technique

To adjust parameters using MIT rule which use the following loss function

$$j(\underline{\theta}) = \frac{1}{2} e_m^2 \tag{1}$$

To make j small, it is reasonable to change the parameters in the direction of the negative gradient of j , that is,

$$\frac{d\theta}{dt} = -\gamma \frac{\partial j}{\partial \theta} = -\gamma e_m \frac{\partial e_m}{\partial \theta} \tag{2}$$

where γ stand for the adaptation gain while $\underline{\theta}$ is the centroid vector of the output membership function. The transfer function of FOPID control can be described as follows.

$$\frac{u(s)}{e(s)} = k_p + k_i \frac{1}{s^\lambda} + k_d s^\mu \tag{3}$$

$$e = u_c - y \tag{4}$$

Assume that the plant can be simplified to a first order system as obvious in the following (5).

$$\frac{y(s)}{u(s)} = \frac{k}{Ts+1} \tag{5}$$

where k and T are unknown parameters. Also, assume that the model reference takes a form first order system as the following relationship.

$$\frac{y_m(s)}{u_c(s)} = \frac{k_m}{T_m s+1} \tag{6}$$

Where k_m and T_m are selected by designer. From (4-6) can conclude that

$$y = \frac{k}{Ts+1} (k_p + k_i \frac{1}{s^\lambda} + k_d s^\mu) (u_c - y) \tag{7}$$

$$\xrightarrow{\text{yields}} y = \frac{kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1} u_c - \frac{kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1} y$$

$$\left(1 + \frac{kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1}\right) y = \frac{kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1} u_c$$

$$\left(\frac{Ts+1 + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1}\right) y = \frac{kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1} u_c$$

$$y = \frac{kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1 + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu} u_c \quad (8)$$

$$e_m = y - y_m \quad (9)$$

$$e_m = \left[\frac{kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1 + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu} - \frac{k_m}{T_m s + 1} \right] u_c \quad (10)$$

3.1. Adaptation law of k_p parameter

This sub-section shows the steps of design of the adaptation law for proportional gain parameter (k_p). By deriving (10) respect to the proportional gain (k_p) to obtain the following relationship.

$$\frac{\partial e_m}{\partial k_p} = \left[\frac{k}{Ts + kk_p + kk_i \frac{1}{s^\lambda} + 1} - \frac{k(kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu)}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + 1)^2} \right] u_c \quad (11)$$

(11) can be rewritten;

$$\frac{\partial e_m}{\partial k_p} = \left[\frac{k(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1 - kk_p - kk_i \frac{1}{s^\lambda} - kk_d s^\mu)}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)^2} \right] u_c \quad (12)$$

$$\frac{\partial e_m}{\partial k_p} = \left[\frac{k(Ts+1)}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)^2} \right] u_c \quad (13)$$

$$\frac{\partial e_m}{\partial k_p} = \left[\frac{k(Ts+1)}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)(kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu)} \right] y \quad (14)$$

From (12) and (14);

$$\frac{\partial e_m}{\partial k_p} = \left[\frac{k^2 e}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)} \right] \quad (15)$$

To achieve the desired performance, the following condition must be hold.

$$Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1 = T_m s + 1 \quad (16)$$

$$\frac{\partial e_m}{\partial k_p} = \frac{k^2 e}{T_m s + 1} \quad (17)$$

From the MIT rule can obtain the following relationship

$$\frac{dk_p}{dt} = -\gamma \cdot e_m \cdot \frac{k^2 e}{T_m s + 1} \quad (18)$$

$$\frac{dk_p}{dt} = -\gamma_1 \cdot \frac{e_m \cdot e}{T_m s + 1} \quad (19)$$

$$\gamma_1 = \gamma \cdot k^2 \quad (20)$$

$$k_p)_{new} = \int \frac{dk_p}{dt} dt + k_p(0) \quad (21)$$

Where $k_p(0)$ is the initial value of proportional gain k_p .

3.2. Adaptation law of k_i parameter

This sub-section shows the steps of design of the adaptation law for integral gain parameter (k_i). By deriving (8) respect to the integral gain (k_i) to obtain the following relationship.

$$\frac{\partial e_m}{\partial k_i} = \frac{1}{s^\lambda} \left[\frac{k}{Ts + kk_p + kk_d s^\mu + kk_i \frac{1}{s^\lambda} + 1} - \frac{k(kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu)}{(Ts + kk_p + kk_d s^\mu + kk_i \frac{1}{s^\lambda} + 1)^2} \right] u_c \quad (22)$$

From (22) can be rewritten;

$$\frac{\partial e_m}{\partial k_i} = \frac{1}{s^\lambda} \left[\frac{k(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1 - kk_p - kk_i \frac{1}{s^\lambda} - kk_d s^\mu)}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)^2} \right] u_c \quad (23)$$

$$\frac{\partial e_m}{\partial k_i} = \frac{1}{s^\lambda} \left[\frac{k(Ts + 1)}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)^2} \right] u_c \quad (24)$$

$$\frac{\partial e_m}{\partial k_i} = \frac{1}{s^\lambda} \left[\frac{k(Ts + 1)}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)(kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu)} \right] y \quad (25)$$

From (23) and (25);

$$\frac{\partial e_m}{\partial k_i} = \frac{1}{s^\lambda} \left[\frac{k^2 e}{(Ts + kk_p + kk_i \frac{1}{s^\lambda} + kk_d s^\mu + 1)} \right] \quad (26)$$

To achieve the desired performance, the condition must be hold in (16).

$$\frac{\partial e_m}{\partial k_i} = \frac{1}{s^\lambda} \frac{k^2 e}{T_m s + 1} \quad (27)$$

From the MIT rule can obtain the following relationship

$$\frac{dk_i}{dt} = -\gamma \cdot e_m \cdot \frac{1}{s^\lambda} \frac{k^2 e}{T_m s + 1} \quad (28)$$

$$\frac{dk_i}{dt} = -\gamma_2 \cdot \frac{e_m \cdot e}{T_m s + 1} \quad (29)$$

$$\gamma_2 = \gamma k^2 \cdot \frac{1}{s^{\lambda(0)}} = \gamma_1 \frac{1}{s^{\lambda(0)}} \quad (30)$$

$$k_i)_{new} = \int \frac{dk_i}{dt} dt + k_i(0) \quad (31)$$

Where $k_i(0)$ is the initial value of proportional gain k_i .

3.3. Adaptation Law of k_d Parameter

This sub-section illustrates the steps of design of the adaptation law for derivative gain parameter (k_d). By deriving (10) respect to the derivative gain (k_d) to obtain the following relationship.

$$\frac{\partial e_m}{\partial k_d} = \left[\frac{k_s^\mu}{Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1}} - \frac{k_s^\mu (kk_p + kk_{i_{s^\lambda}} + kk_d s^\mu)}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})^2} \right] u_c \quad (32)$$

$$\frac{\partial e_m}{\partial k_d} = \left[\frac{k_s^\mu (Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1} - kk_p - kk_{i_{s^\lambda}} - kk_d s^\mu)}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})^2} \right] u_c \quad (33)$$

$$\frac{\partial e_m}{\partial k_d} = \left[\frac{k_s^\mu (Ts + 1)}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})^2} \right] u_c \quad (34)$$

$$\frac{\partial e_m}{\partial k_d} = \left[\frac{k_s^\mu (Ts + 1)}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})(kk_p + kk_{i_{s^\lambda}} + kk_d s^\mu)} \right] y \quad (35)$$

Also, from (33) and (35)

$$\frac{\partial e_m}{\partial k_d} = \left[\frac{k^2 \cdot s^\mu \cdot e}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})} \right] \quad (36)$$

$$\frac{\partial e_m}{\partial k_d} = \frac{k^2 \cdot s^\mu \cdot e}{T_m s + 1} \quad (37)$$

$$\frac{dk_d}{dt} = -\gamma \cdot e_m \cdot \frac{k^2 \cdot s^\mu \cdot e}{T_m s + 1} \quad (36)$$

$$\frac{dk_d}{dt} = -\gamma_3 \cdot \frac{e_m \cdot e}{T_m s + 1} \quad (37)$$

$$\gamma_3 = \gamma \cdot k^2 \cdot s^{\mu(0)} = \gamma_1 \cdot s^{\mu(0)} \quad (38)$$

$$k_d)_{new} = \int \frac{dk_d}{dt} dt + k_d(0) \quad (39)$$

Where $k_d(0)$ is the initial value of derivative gain k_d .

3.4. Adaptation Law of λ Parameter

This sub-section illustrates the steps of design of the adaptation law for fractional integral gain parameter (λ). By deriving (10) respect to the fractional integral gain (λ) to obtain the following relationship.

$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda} \left[\frac{(kk_p + kk_{i_{s^\lambda}} + kk_d s^\mu)}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})^2} - \frac{1}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})} \right] u_c \quad (40)$$

$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda} \left[\frac{kk_p + kk_{i_{s^\lambda}} + kk_d s^\mu - Ts - kk_p - kk_{i_{s^\lambda}} - kk_d s^{\mu-1}}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})^2} \right] u_c \quad (41)$$

$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda} \left[\frac{-(Ts + 1)}{(Ts + kk_p + kk_{i_{s^\lambda}} + kk_d s^{\mu+1})^2} \right] u_c \quad (42)$$

$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda} \left[\frac{-(Ts+1)}{(Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1)(kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu)} \right] y \quad (43)$$

Also, from (41) and (43);

$$\frac{\partial e_m}{\partial \lambda} = -\frac{k^2 k_i \ln(s)}{s^\lambda} \left[\frac{e}{(Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1)} \right] \quad (44)$$

$$\frac{\partial e_m}{\partial \lambda} = -\frac{k^2 k_i \ln(s)}{s^\lambda} \cdot \frac{e}{T_m s+1} \quad (45)$$

$$\frac{d\lambda}{dt} = \gamma \cdot e_m \cdot \frac{k^2 k_i \ln(s)}{s^\lambda} \cdot \frac{e}{T_m s+1} \quad (46)$$

$$\frac{d\lambda}{dt} = \gamma_4 \cdot \frac{e_m \cdot e}{T_m s+1} \quad (47)$$

$$\gamma_4 = \gamma \cdot \frac{k^2 k_i(0) \ln(s)}{s^{\lambda(0)}} = \gamma_2 \cdot k_i(0) \cdot \ln(s) \quad (48)$$

$$\lambda)_{new} = \int \frac{d\lambda}{dt} dt + \lambda(0) \quad (49)$$

Where $\lambda(0)$ is the initial value of fractional integral gain λ .

3.5. Adaptation law of μ parameter

This sub-section demonstrates the steps of design of the adaptation law for fractional derivative gain parameter (μ). By deriving the (8) respect to the fractional derivative gain (μ) to obtain the following relationship.

$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d \cdot s^\mu \cdot \ln(s)}{Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1} - \frac{kk_d \cdot s^\mu \cdot \ln(s) (kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu)}{(Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1)^2} \right] u_c \quad (50)$$

$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d \cdot s^\mu \cdot \ln(s) (Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1 - kk_p - kk_i \frac{1}{s^\lambda} - kk_d s^\mu)}{(Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1)^2} \right] u_c \quad (51)$$

$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d \cdot s^\mu \cdot \ln(s) (Ts+1)}{(Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1)^2} \right] u_c \quad (52)$$

$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d \cdot s^\mu \cdot \ln(s) (Ts+1)}{(Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1)(kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu)} \right] y \quad (53)$$

Also, from (51) and (53);

$$\frac{\partial e_m}{\partial \mu} = \left[\frac{k^2 k_d \cdot s^\mu \cdot \ln(s) \cdot e}{(Ts+kk_p+kk_i \frac{1}{s^\lambda}+kk_d s^\mu+1)} \right] \quad (54)$$

$$\frac{\partial e_m}{\partial \mu} = \frac{k^2 k_d \cdot s^\mu \cdot \ln(s) \cdot e}{T_m s+1} \quad (55)$$

$$\frac{d\mu}{dt} = -\gamma \cdot e_m \cdot \frac{k^2 k_d \cdot s^\mu \cdot \ln(s) \cdot e}{T_m s+1} \quad (56)$$

$$\frac{d\mu}{dt} = -\gamma_5 \cdot \frac{e_m \cdot e}{T_m s + 1} \quad (57)$$

$$\gamma_5 = \gamma \cdot k^2 \cdot k_d(0) \cdot s^{\mu(0)} \cdot \ln(s) = \gamma_3 \cdot k_d(0) \cdot \ln(s) \quad (58)$$

$$\mu)_{new} = \int \frac{d\mu}{dt} dt + \mu(0) \quad (59)$$

Where $\mu(0)$ is the initial value of fractional integral gain μ .

3.6. Harmony search (HS) optimization

The harmony search has been proposed in 2001. It is used lately in several engineering applications to obtain the optimal values of control parameters. In this study, the HS will be used to obtain the optimal parameters values of model reference adaptive control. The most effective parameter of MRAC is the adaptation gain for each adaptation law. Here, the harmony search tuning system will adjust the parameters of model reference adaptive system ($\gamma_1, \gamma_2, \gamma_3, \gamma_4$ and γ_5) according to the objective function as shown in (60).

$$f = \frac{1}{(1-e^{-\beta})(M_p + e_{ss}) + e^{-\beta}(t_s - t_r)} \quad (60)$$

Where M_p the overshoot of system response is, e_{ss} is the steady state error, t_s is the settling time and t_r is the rise time. Also, this objective function is able to compromise the designer demand by the weighting parameter value (β). The parameter is set larger than 0.7 to reduce over shoot and steady-state error. If this parameter is set smaller than 0.7 the rise time and settling time will be reduced.

The initial population of Harmony Memory (HM) is produced randomly. HM contains Harmony Memory Solution (HMS) vectors. The HM is filled with HMS vectors as follows:

$$HM = \begin{bmatrix} \gamma_{1(1,1)} & \gamma_{2(1,2)} & \gamma_{3(1,3)} & \gamma_{4(1,4)} & \gamma_{5(1,5)} \\ \gamma_{1(2,1)} & \gamma_{2(2,2)} & \gamma_{3(2,3)} & \gamma_{4(2,4)} & \gamma_{5(2,5)} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \gamma_{1(HMS,1)} & \gamma_{2(HMS,2)} & \gamma_{3(HMS,3)} & \gamma_{4(HMS,4)} & \gamma_{5(HMS,5)} \end{bmatrix} \quad (61)$$

Table 2 demonstrates the obtained values of MRAC parameters after the offline tuning using the harmony search tuning system.

MRAC	γ_1	γ_2	γ_3	γ_4	γ_5
Parameters	0.234	0.678	0.456	0.568	0.7043

Sometimes, some systems don't need adjust the five parameters of FOPID control online at same moment which will save the calculation time and make the overall system more ready to deal with the sudden disturbance. So, this study proposes three methods for self-tuning FOPID control. The first method considers k_p, k_i and k_d are constants while λ and μ are varying. The second method considers k_p, k_i and k_d are varying while λ and μ are constants. The third method tunes the five parameters of FOPID control online simultaneously.

4. SIMULATION RESULTS

This section presents the simulation results of the proposed different types of self-tuning FOPID control algorithms based on model reference. The first method, the adaptive mechanism will adjust the fractional integral and derivative parameters only while the other parameters are fixed. The second method, the fractional integral and derivative parameters are fixed while the other three parameters will be tuned using the adaptive mechanism. The third method, the five parameters of FOPID control will be adjusted simultaneously. Figure 3 demonstrates the Simulink diagram of the overall system with self-tuning FOPID based on optimal model reference technique.

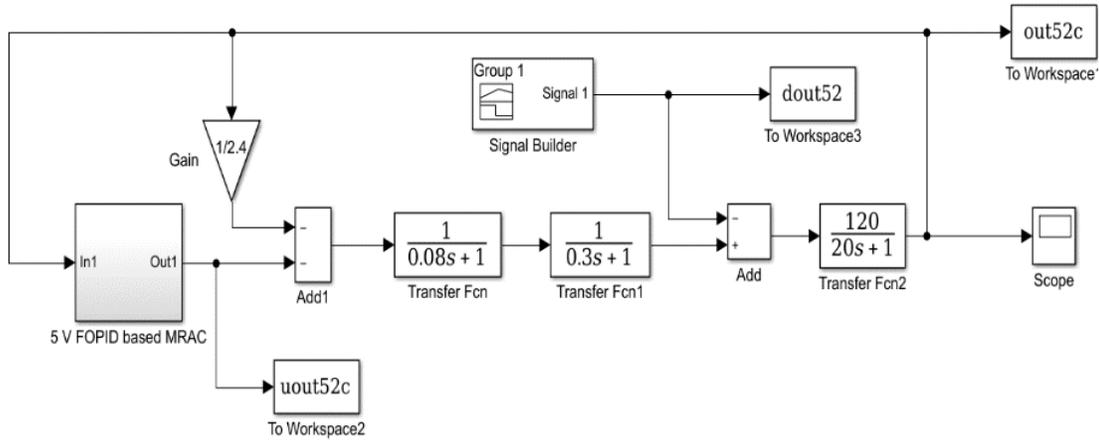


Figure 3. The simulink diagram of the overall system with self-tuning FOPID based on optimal model reference technique

The results are divided into two cases. The normal case where applied two types of the disturbers. These disturbers namely $\Delta Pd1$ as shown in Figure 4 and $\Delta Pd2$ as illustrated in Figure 5. The parametric uncertainty case where to change the operating point to test the powerful of the proposed method against their counterparts

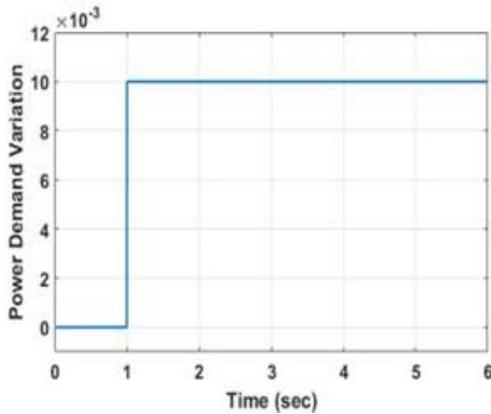


Figure 4. Power demand variation ($\Delta Pd1$)

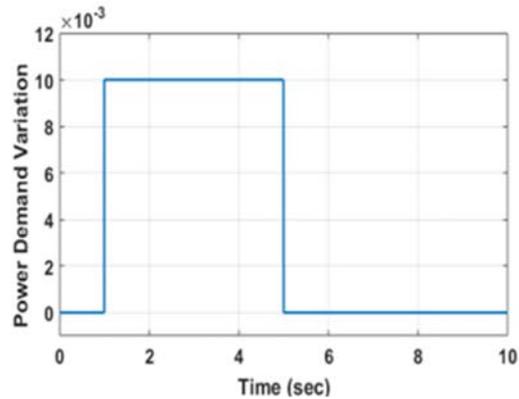


Figure 5. Power demand variation ($\Delta Pd2$)

4.1. Normal case

Two experiments were done at normal operating condition. The dynamic response of the system frequency ΔF with the system driven by each type of the proposed controllers. In experiment number one where $\Delta Pd1$ is applied to the system. Figure 6 shows the time response of the system. Also, the output signal of each controller is shown in Figure 7. In experiment number two, Figure 8 demonstrates the time response of the system when $\Delta Pd2$ is applied to the system. Figure 9 presents the controller’s outputs signals.

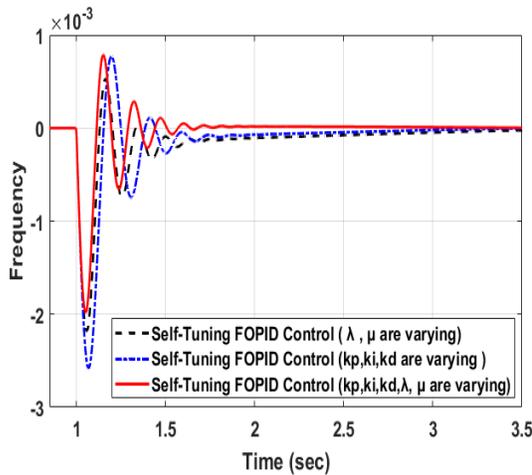


Figure 6. System dynamic responses at $\Delta Pd1$

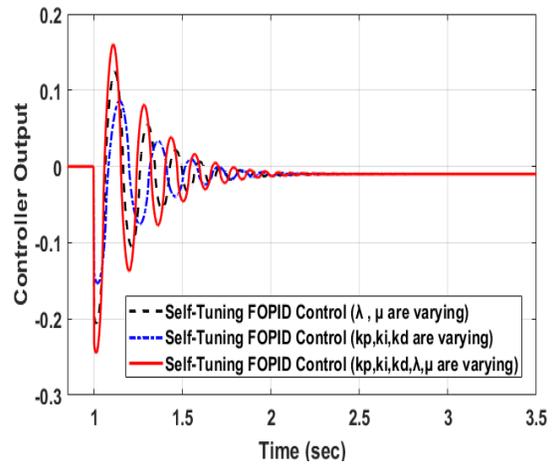


Figure 7. The controller's output signals at $\Delta Pd1$

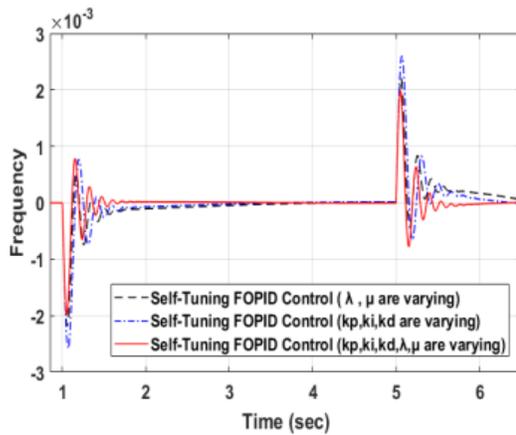


Figure 8. System dynamic responses at $\Delta Pd2$

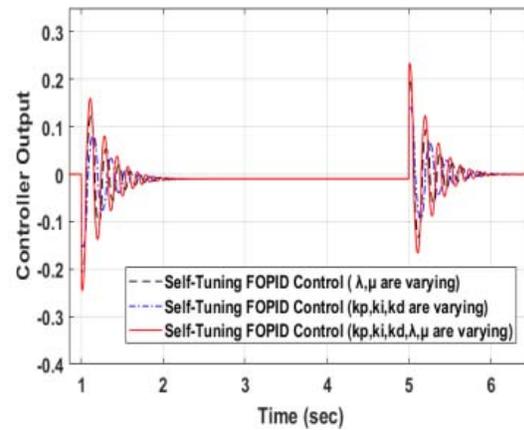


Figure 9. The controller's output signals at $\Delta Pd2$

It is clearly shown that The proposed third method of self-tuning FOPID controller gives battery performance with a smaller settling time and acceptable undershoot but with a relatively higher effort as shown in the response of its control output response u . also, the proposed third type of self-tuning FOPID controller recover to zero steady state error after a smaller time delay from the application of the two disturbance types.

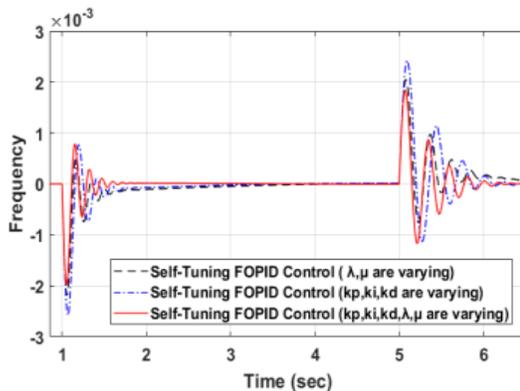
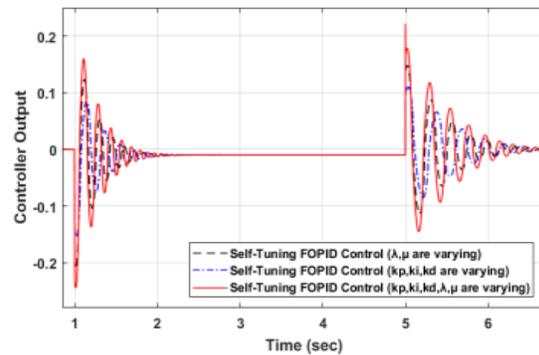
4.2. Parametric uncertainty case

In this subsection, the parametric uncertainties of the power system have to be considered. According to load variation and power system configuration, the operation points of the system will be changed randomly during a daily cycle. The system parametric uncertainties are obtained by changing parameters by 50% from their normal values according to Table 3 and under the power demand variation $\Delta Pd2$. In this experiment, the power system responses at $\Delta Pd2$, including the effect of the parametric uncertainties is presented in Figure 10 and the controllers outputs are shown in Figure 11.

According to these results, it is clear that the proposed third method of self-tuning FOPID control shows the best response compared to other controllers. Also, the results approve the effectiveness and the ability of the proposed controller against the parametric uncertainties. Moreover, the undershoot at 1 second and overshoot at 5 second of third method of self-tuning FOPID control are significant small compared to other methods of self-tuning FOPID control.

Table 3. Parametric Uncertainties

Parameters	Down (0-1) sec	Normal (1-5) sec	Up (5-7) sec
k_p	60	120	180
T_p	10	20	30
R	1.2	2.4	3.6
T_T	0.15	0.3	0.45
T_G	0.04	0.08	0.12

Figure 10. System dynamic responses at ΔP_d and parametric uncertaintiesFigure 11. The controller's output signals at ΔP_d and parametric uncertainties

5. CONCLUSION

A novel technique has been developed to tune the fractional order PID (FOPID) control online based on optimal Model Reference Adaptive Control (MRAC) for power system load frequency control as a case study. This work investigates the robustness of the proposed technique by applied different types of disturbances and parametric uncertainty. There are three methods of self-tuning FOPID control have been implemented. The first method, the three integer parameters (proportional, integral and derivative gains) are constant while the fractional integral and derivative gains are variable. The second method, the fractional integral and derivative gains are constant while the three integer parameters (proportional, integral and derivative gains) are variable. The third method, the all five parameters are variable and change continuously online. The simulation results demonstrate that the third method of self-tuning FOPID control can absorb the sudden disturbance faster than other techniques. Also, it can suppress the system uncertainty in a small time compared to other control techniques.

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