Model reference self-tuning fractional order PID control based on for a power system stabilizer

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ABSTRACT

This paper presents a novel approach of self-tuning for a Modified Fractional Order PID (MFOPID) depends on the Model Reference Adaptive System (MRAS). The proposed self-tuning controller is applied to Power System Stabilizer (PSS). Takaji-Sugeno (TS) fuzzy logic technique is used to construct the MFOPID controller. The objective of MRAS is to update the five parameters of Takaji-Sugeno Modified FOPID (TSMFOPID) controller online. For different operating points of PSS, MRAS is applied to investigate the effectiveness of proposed controllers. The harmony optimization technique used to obtain the optimal parameters of TSMFOPID controllers and MRAS parameters. For different operating points with different disturbance under parameters variations the simulation results are obtained. This is to show that Self-Tuning of TSMFOPID based on (MRAS) have better performance than the fixed parameters TSMOFOPID controller.

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1. INTRODUCTION

Generator excitation control systems contain Automatic Voltage Regulators (AVR) for voltage regulation and conventional Power System Stabilizers (CPSS) for damping mechanical mode oscillations. The changes in operating conditions of PSS is challenge to update the controller parameters [1]. Therefore, the new studies seek to design advanced control techniques, which controllers adapt with the continuous change in operating points [2-4]. The conventional PID controller is common use in several of engineering applications. Due to the structure simplicity and easy parameter tuning, it is suitable for a certain operating point. In addition, its performance is good for linear and simple systems [5, 6]. Still, the behavior of PID control is linear and cannot deal with the high disturbance and high nonlinearity in complicated systems [5, 7, 8]. The current research directed to use the Fractional Order PID (FOPID) control where it presents the nonlinear face of PID control [9-11]. In FOPID controller, two additional parameters (the fractional integral and derivative gains) will be supplementary to increase the flexibility and reliability of controller [12-14]. Therefore, the dynamic performance of FOPID controller is enhanced compared to the conventional PID controller [15-17].

At different operating points for a certain system, adaptation online was used self- tuning using for the system. In this case, the fuzzy logic calculations need a long time and addition efforts by try and error is performed to obtain normalizing gains selection [18]. So, this study resort to the MRAS to self-tuning the TSMFOPID online where it has simple structure, easy to implement and fast calculations [19, 20].

The model-reference adaptive system (MRAS) presents one of the best adaptive control techniques. It may be regarded as an adaptive servo system in which the desired performance is expressed in terms of a reference model, which gives the desired response to a command signal [20]. It forces the overall system to follow the behavior of preselected model reference. The preselected model can be first or second order system according to the point of view the designer and complicated degree of the system [19].

In this Study, Takaji- Sugeno Fuzzy Type 3 (TS-Fuzzy Type 3) is designed by 21 rule triangular memberships. In the TSMFOPID design, the power of S operator for FOPID is lied between zero < λ > 2 for integral fraction order and zero < μ > 2 for derivative. Let the FOPID operated via the Ninteger Toolbox with internally unknown five parameters (kp, ki, kd, λ and μ) be named as (TBFOPID). While, a modified FOPID which has externally unknown five parameters (kp, ki, kd, λ and μ) constructed designed by TS fuzzy is named as TSMFOPID [21]. The performance of the TSMFOPID based on model reference adaptive system controller can be improved using different types of optimization technique Harmony Search (HS) [22, 23]. This paper presents, a new combination between modified FOPID controller based on TS technique (TSMFOPID) and Model reference as a tuner to design a new adaptively output feedback controller for PSS.

2. POWER SYSTEM STABILIZER MODEL

A single machine-infinite bus system whose linearized incremental model containing the voltage regulator and exciter can be demonstrated by the block diagram as shown in Figure 1. The parameters of the system are given in Table 1 [1, 24]. A number of cases are done that cover different operating points (normal, heavy and light load conditions) and parameters variation in the presence of a severe disturbance. These cases are applied to the system with optimal FOPID and self-tuning by Model Reference control. The constants K = [K1, …, K6] in the normal, heavy and light loads are given in Table 2. The parameters of the system are given in Table 2 [2, 25].

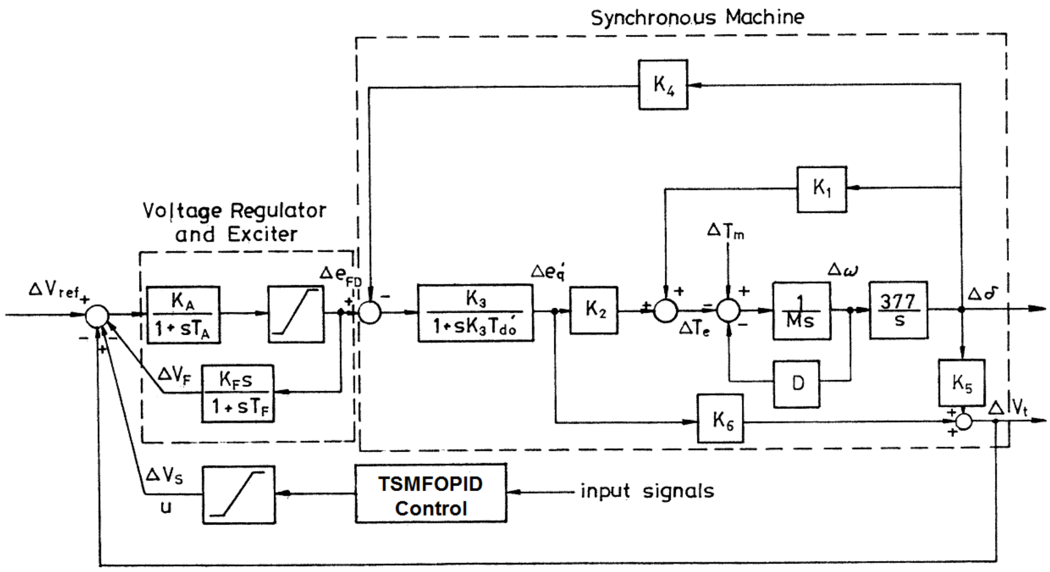


Figure. 1. Linearized incremental model of synchronous machine with an exciter and stabilizer.

Table 1. The parameters of the system

Parameter	Value	Parameter	Value
Ka	400	D	0
Ta	0.05	Efdmax	7.3
Tdo	5.9	Efdmin	-7.3
M	4.74	umax	0.12
Kf	0.025	umin	-0.12
Tf	1		0

Table 2. Operating conditions for K_1 to K_6

K	OP1=[1.0, 1.0] Normal load	OP2=[1.3, 0.9] Heavy load	OP3=[0.8, 1.2] Light load
K1	1.0753	0.6234	1.4076
K2	1.2581	1.2813	1.1984
K3	0.3071	0.3071	0.3071
K4	1.7131	1.7123	1.6461
K5	-0.0476	-0.2091	0.0742
K6	0.4972	0.4565	0.5488

3. CONTROL TECHNIQUES

This section shows the proposed control techniques. The first technique is the Modified FOPID controller based on Harmony search. The second technique is the self-tuning of modified FOPID controller based on optimal MRAS.

3.1. The FOPID Control

The Toolbox FOPID (TBFOPID) is usually used to simulate the FOPID control. It has five parameters internally selected by designer in one closed block as shown in Figure.2. To make adapt the FOPID control online a Takaji- Sugeno Fuzzy (type-3 fuzzy) technique is developed FOPID has external five terminals parameters as shown in Figure 3 [21, 26].

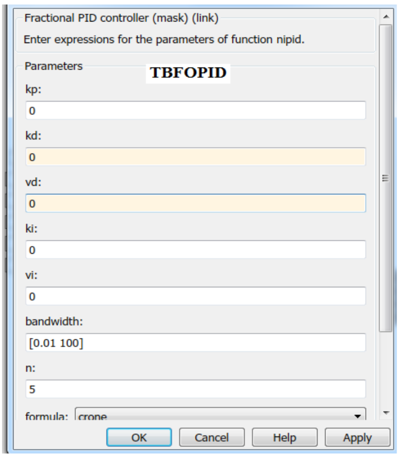


Figure 2. The block diagram with internal five unknown parameters kp, ki, kd, λ and μ

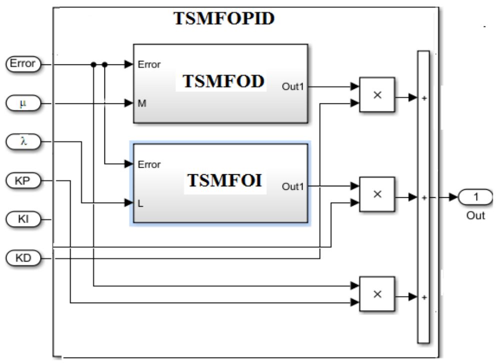


Figure 3. The block diagram with the external five parameters to be suitable for model reference self-tuning

The design steps of TSMFOI and TSMFOD can be summarized as follows [21]. The first step, let the input TS fuzzy membership functions for the fractional orders of the integral and derivative (λ and μ) values are select to be 21 triangular member ships functions. The universe of discourse values are equally distributed over the range [0, 2] and have their middle vertices placed at the points {0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2} .The membership selected by 21 triangular member ships as shown in Figure 4. The block of TSMFOD or TSMFOI and TSMFOPID 21 rules represents in Figure. 5.

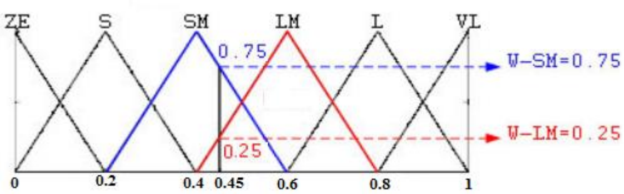


Figure 4. Input membership of the variables of λ and μ

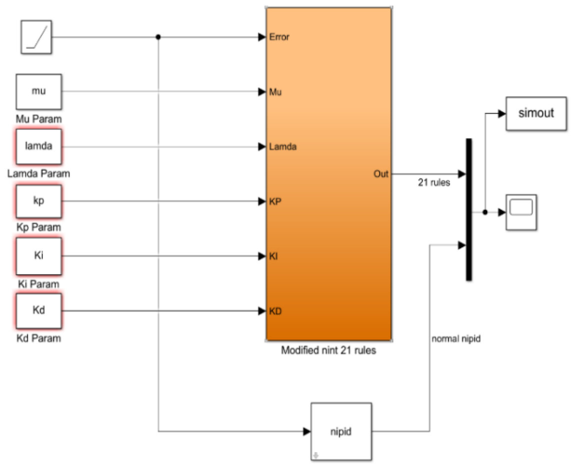


Figure 5. TSMFOPID controller with 21 memberships

The second step, recognize the TS-Fuzzy formula for the fractional orders of integral and derivative parameters (λ and μ) as shown in Figure. 6. If the input is λ the block diagram represents TSMFOI while if the input is μ the block diagram represents TSMFOD.

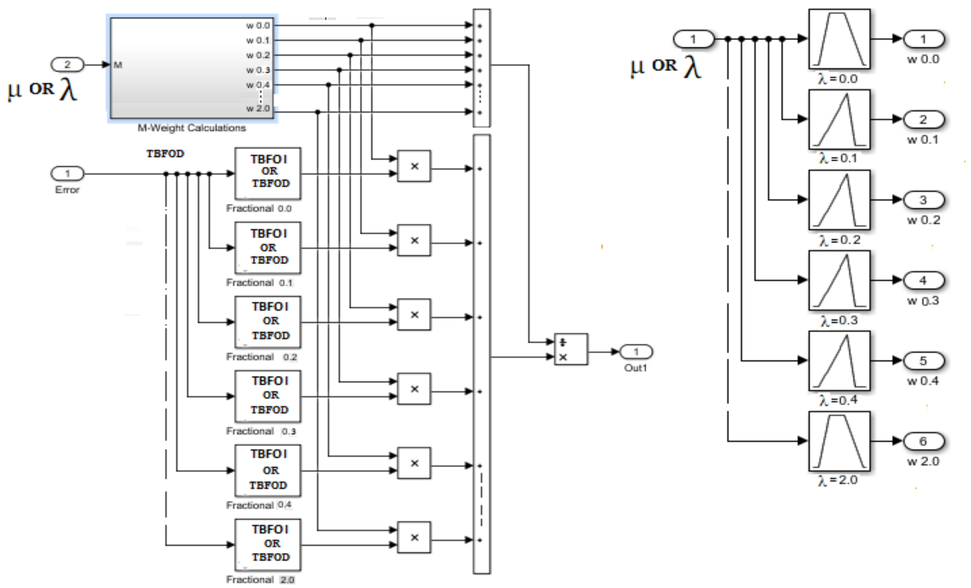


Figure 6. Block diagram the fractional orders of the integral and derivative.

The final outputs of the fuzzy systems that inferred for the TSMFOD or TSMFOI Implemented using Centroid for the defuzzification method [21]:

$$out_I = \frac{\Sigma_{\lambda_i} W_{\lambda_i} . F_{\lambda_i}}{\Sigma_{\lambda_i} W_{\lambda_i}} \; ; \; out_D = \frac{\Sigma_{\mu_i} W_{\mu_i} . F_{\mu_i}}{\Sigma_{\mu_i} W_{\mu_i}} \; ; \quad (1)$$

Where: λi ,μi ϵ {0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3,1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2}for 21 rules
Wλi is the weight of λi,
Wμi is the weight of μi,
Fλi is the output of TBFOPI whose λ value is λi
Fμi is the output of TBFOPD whose μ value is μi [12].

3.2. Harmony search optimization technique

The challenge point in the PID and FOPID controllers are selecting the appropriate parameters for a certain controlled plant. There are several methods to find the parameters of FOPID controller for example, try and error and Ziegler-Nichols method but, most of these techniques are rough roads. In this paper, the harmony search optimization technique will be used to obtain the optimal values of FOPID controller parameters according to the objective function as shown in (2) [22].

$$f = \frac{1}{(1-e^{-\beta})(M_p+e_{ss})+e^{-\beta}(t_s-t_r)} \tag{2}$$

Where e_{ss} is the steady state error, M_p is the overshoot of system response, t_s is the settling time and t_r is the rise time. Also, this objective function is able to compromise the designer requirements using 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 adjusting smaller than 0.7 the rise time and settling time will be reduced. Harmony search (HS) was suggested by Zong Woo Geem in 2001 [27]. It is well known that HS is a phenomenon-mimicking algorithm inspired by the improvisation process of musicians [28]. The initial population of Harmony Memory (HM) is chosen randomly. HM consists of Harmony Memory Solution (HMS) vectors. Table 3 shows the obtained parameters of TSMFOPID controller based on harmony search optimization technique.

Table 3. TSMFOPID parameters.

TSMFOPID parameters	Kp	Kd	vd	ki	vi
Parameters values	9.5603	5.3506	0.23714	2.5926	0.922

Both of conventional toolbox of FOPID and the Takaji-Sugeno (TS) modified FOPID (TSMFOPID) have the same response through the simulation results at different operating conditions. In addition, it is provided in [21].

$$H\,M = \begin{bmatrix} K_{p\,(1,1)} & K_{i\,(1,2)} & K_{d\,(1,3)} & vd_{\,(1,4)} & vi_{\,(1,5)} \\ K_{p\,(2,1)} & K_{i\,(22)} & K_{d\,(2,3)} & vd_{\,(2,4)} & vi_{\,(2,5)} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ K_{p\,(HMS,1)} & K_{i\,(HMS,2)} & K_{d\,(HMS,3)} & vd_{\,(HMS,4)} & vi_{\,(HMS,5)} \end{bmatrix} \tag{3}$$

3.3. The self-tuning TSMFOPID based on model reference technique

In this paper, the modified FOPID control parameters will be adjusted on-line using the model reference technique. The Model Reference Adaptive Control (MRAC) considers high-effectiveness adaptive controller [19]. It works as an adaptive servo system in which the wanted performance is described in form of a reference model. Figure. 7 demonstrates the main construction of self-tuning modified FOPID based on model reference technique. The details of Model Reference Adaptive System derivation are given in [29].

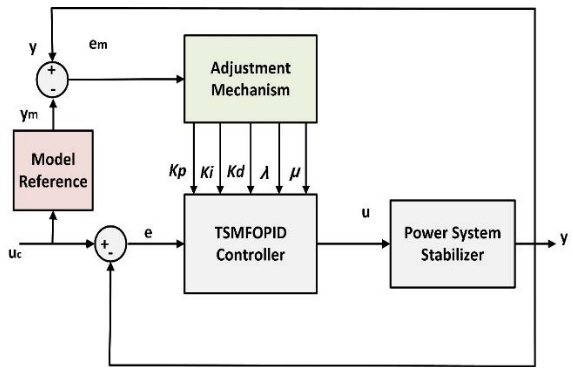


Figure 7. The overall system with self-tuning TSMFOPID based on model reference technique

The transfer function of FOPID control can be described as follows [29].

$$\frac{u(s)}{e(s)} = k_p + k_i \frac{1}{s^\lambda} + k_d s^\mu \tag{4}$$

$$e = u_c - y \tag{5}$$

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

$$\frac{y(s)}{u(s)} = \frac{k}{Ts+1} \tag{6}$$

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

$$\frac{y_m(s)}{u_c(s)} = \frac{k_m}{T_m s+1} \tag{7}$$

Where k_m and T_m are selected by designer.
From equations [4-6] can conclude that

$$y = \frac{k}{Ts+1}\left(k_p + k_i \frac{1}{s^\lambda} + k_d s^\mu\right)(u_c - y) \tag{8}$$

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

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

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

$$y = \frac{kk_p + kk_i.\frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1+kk_p + kk_i.\frac{1}{s^\lambda} + kk_d s^\mu} u_c \tag{9}$$

$$e_m = y - y_m \tag{10}$$

$$e_m = \left[\frac{kk_p + kk_i.\frac{1}{s^\lambda} + kk_d s^\mu}{Ts+1+kk_p + kk_i.\frac{1}{s^\lambda} + kk_d s^\mu} - \frac{k_m}{T_m s+1}\right] u_c \tag{11}$$

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

The (12) can be rewritten

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

$$\frac{\partial e_m}{\partial k_p} = \left[\frac{k(Ts+1)}{\left(Ts+kk_p+kk_i.\frac{1}{s^\lambda}+kk_d s^\mu+1\right)^2}\right] u_c \tag{14}$$

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

From (4) and (6)

$$\frac{\partial e_m}{\partial k_p} = \left[\frac{k^2 e}{\left(Ts+kk_p+kk_i.\frac{1}{s^\lambda}+kk_d s^\mu+1\right)}\right] \tag{16}$$

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

$$Ts + kk_p + kk_i.\frac{1}{s^\lambda} + kk_d s^\mu + 1 = T_m s + 1 \tag{17}$$

$$\frac{\partial e_m}{\partial k_p} = \frac{k^2 e}{T_m s+1} \quad (18)$$

From the MIT rule can obtain the following relationship

$$\frac{dk_p}{dt} = -\gamma.\, e_m.\frac{k^2 e}{T_m s+1} \quad (19)$$
$$\frac{dk_p}{dt} = -\gamma_1.\frac{e_m.e}{T_m s+1} \quad (21)$$
$$\gamma_1 = \gamma.\, k^2 \quad (21)$$
$$k_p)_{new} = \int \frac{dk_p}{dt}\, dt + k_p(0) \quad (22)$$

Where $k_p(0)$ is the initial value of proportional gain k_p, By the same steps.

$$k_i)_{new} = \int \frac{dk_i}{dt}\, dt + k_i(0) \quad (23)$$

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

$$k_d)_{new} = \int \frac{dk_d}{dt}\, dt + k_d(0) \quad (24)$$

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

$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda}\left[\frac{\left(kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu\right)}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)^2} - \frac{1}{(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1)}\right]u_c \quad (25)$$
$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda}\left[\frac{kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu-Ts-kk_p-kk_i\frac{1}{s^\lambda}-kk_d s^\mu-1}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)^2}\right]u_c \quad (26)$$
$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda}\left[\frac{-(Ts+1)}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)^2}\right]u_c \quad (27)$$
$$\frac{\partial e_m}{\partial \lambda} = \frac{kk_i \ln(s)}{s^\lambda}\left[\frac{-(Ts+1)}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)\left(kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu\right)}\right]y \quad (28)$$

Also, from (4) and (6)

$$\frac{\partial e_m}{\partial \lambda} = -\frac{k^2 k_i \ln(s)}{s^\lambda}\left[\frac{e}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)}\right] \quad (29)$$
$$\frac{\partial e_m}{\partial \lambda} = -\frac{k^2 k_i \ln(s)}{s^\lambda}.\frac{e}{T_m s+1} \quad (30)$$
$$\frac{d\lambda}{dt} = \gamma.\, e_m.\frac{k^2 k_i \ln(s)}{s^\lambda}.\frac{e}{T_m s+1} \quad (31)$$
$$\frac{d\lambda}{dt} = \gamma_4.\frac{e_m.e}{T_m s+1} \quad (32)$$
$$\gamma_4 = \gamma.\frac{k^2 k_i(0)\ln(s)}{s^{\lambda(0)}} = \gamma_2.\, k_i(0).\ln(s) \quad (33)$$
$$\lambda)_{new} = \int \frac{d\lambda}{dt}\, dt + \lambda(0) \quad (34)$$
$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d.s^\mu.\ln(s)}{Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1} - \frac{kk_d.s^\mu.\ln(s)\left(kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu\right)}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)^2}\right]u_c$$
$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d.s^\mu.\ln(s)\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1-kk_p-kk_i\frac{1}{s^\lambda}-kk_d s^\mu\right)}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)^2}\right]u_c \quad (35)$$
$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d.s^\mu.\ln(s)(Ts+1)}{\left(Ts+kk_p+kk_i\frac{1}{s^\lambda}+kk_d s^\mu+1\right)^2}\right]u_c \quad (36)$$

$$\frac{\partial e_m}{\partial \mu} = \left[\frac{kk_d.s^{\mu}.\ln(s)(Ts+1)}{\left(Ts+kk_p+kk_i\frac{1}{s^{\lambda}}+kk_d s^{\mu}+1\right)\left(kk_p+kk_i\frac{1}{s^{\lambda}}+kk_d s^{\mu}\right)}\right]y \quad (37)$$

Also, from (4) and (6)

$$\frac{\partial e_m}{\partial \mu} = \left[\frac{k^2 k_d.s^{\mu}.\ln(s).e}{\left(Ts+kk_p+kk_i\frac{1}{s^{\lambda}}+kk_d s^{\mu}+1\right)}\right] \quad (38)$$

$$\frac{\partial e_m}{\partial \mu} = \frac{k^2 k_d.s^{\mu}.\ln(s).e}{T_m s+1} \quad (39)$$

$$\frac{d\mu}{dt} = -\gamma.e_m.\frac{k^2 k_d.s^{\mu}.\ln(s).e}{T_m s+1} \quad (40)$$

$$\frac{d\mu}{dt} = -\gamma_5.\frac{e_m.e}{T_m s+1} \quad (41)$$

$$\gamma_5 = \gamma.k^2.k_d(0).s^{\mu(0)}.\ln(s) = \gamma_3.k_d(0).\ln(s) \quad (42)$$

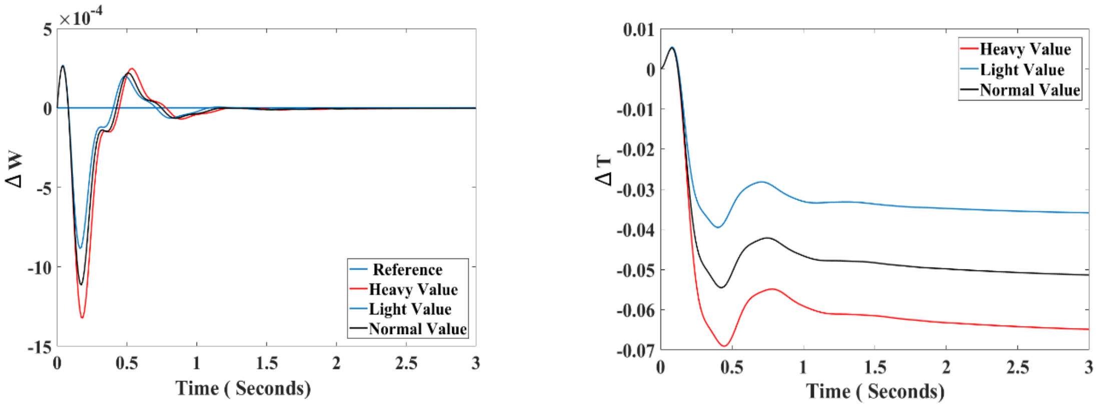
$$\mu)_{new} = \int \frac{d\mu}{dt}\,dt + \mu(0) \quad (43)$$

4. SIMULATION RESULTS

This section demonstrates the simulation results of fixed structure TSMFOPID and self-tuning TSMFOPID based on MRAS applied to PSS with different operating points (heavy and light parameters) through several types of disturbances.

Case 1: Fixed structure TSMFOPID performance at different operating condition.

The mechanical torque Tm and Vref increases suddenly with step value 5% in case heavy, light and normal parameters values. The results are demonstrated in Figure. 8. It is clear that fixed structure TSMFOPID response cannot adapt the changes in operating conditions. So, the self-tuning becomes essential to obtain high performance through several operating conditions and disturbances.

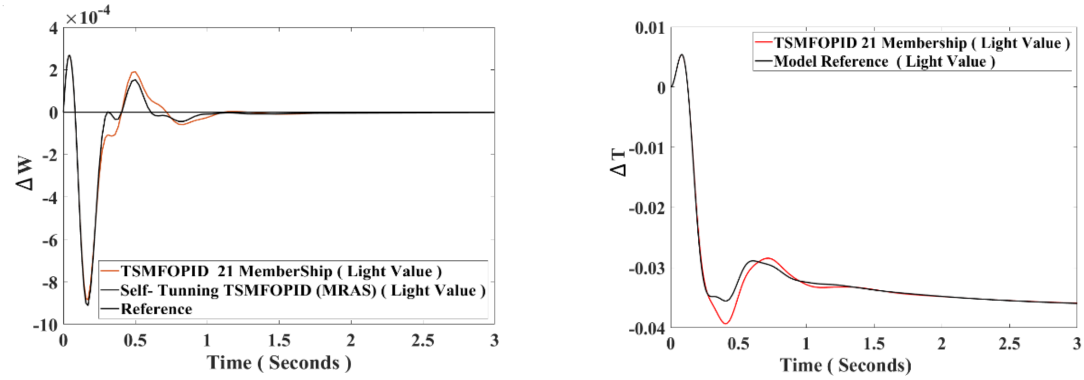


(a) (b)

Figure 8. The system dynamic response with step change 0.05

Case 2**:** Comparison between the fixed parameters TSMFOPID and self-tuning for TSMFOPID at light load condition.

In case of light parameters values, the mechanical torque Tm and Vref exposes to step change 5% high. The results are demonstrated in Figure. 9. It is noted that self-tuning TSMFOPID (MRAS) response has low fluctuations, small overshoot and it reach to reference point in small time.

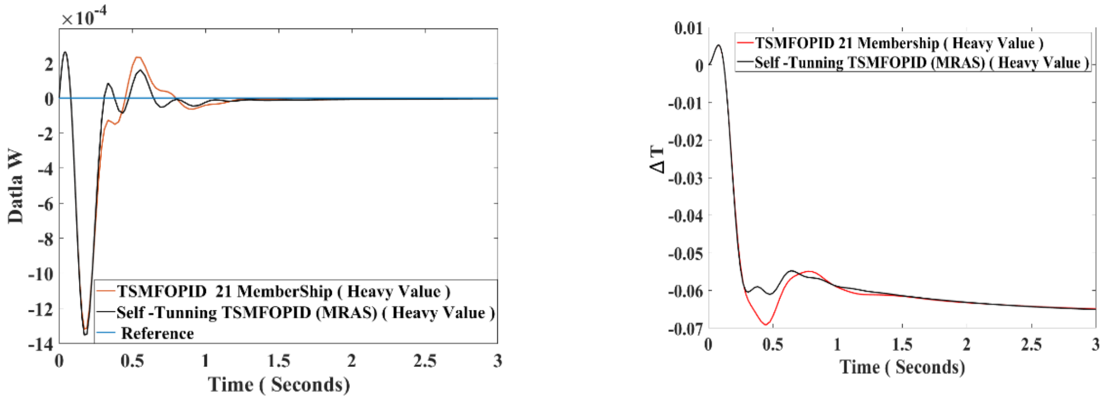


(a) (b)

Figure 9. The system dynamic responses at light condition

Case 3**:** Comparison between the fixed structure TSMFOPID and self-tuning TSMFOPID (MRAS) performance at heavy condition.

The proposed controllers were investigated by comparing the dynamic responses of the PSS at step disturbance 5% in the mechanical torque ΔTm and ΔVref. Figure. 10 illustrates the results of this case. It is obvious that the dynamic response of self-tuning TSMFOPID (MRAS) has a good performance compared to fixed parameters TSMFOPID controller where it has smaller overshoot and small settling time.



(a) (b)

Figure 10. System dynamic responses with reference tracking.

Case 4: The performance of the fixed structure TSMFOPID and self-tuning TSMFOPID during the parameters variations and heavy load condition.

To investigate the robustness of proposed controllers, the inertia coefficient increased to become M=1.5 of normal value and the disturbance for ΔTm and ΔVref represented by a 0.05 step change from zero to 2 seconds, then, decreased by 0.03 from 2 seconds to 4 seconds and finally decreased by 0.01 as shown in Figure. 11. Figure. 12 shows the system responses driven by self-tuning TSMFOPID (MRAS) and fixed parameters TSMFOPID controller when. It is clearly seen that the self-tuning TSMFOPID (MRAS) overcomes these variations and give good response with a small settling time, thus indicating the effectiveness of the self-tuning TSMFOPID (MRAS) over a wide range of parameter variation and change of operating conditions

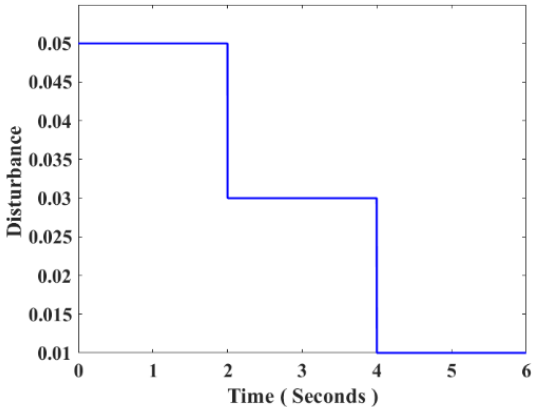
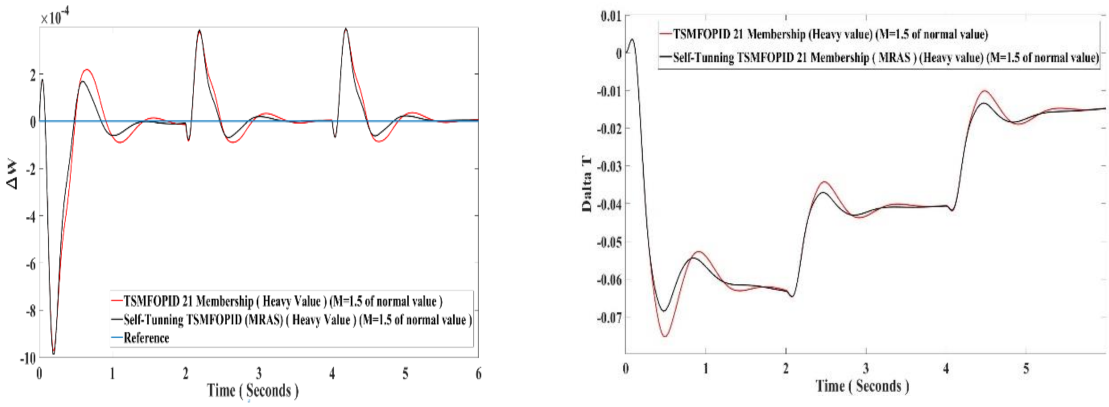


Figure 11. Variable disturbance for ΔTm and ΔVref



(a) (b)

Figure 12. System dynamic responses with reference tracking

5. CONCLUSION

A novel scheme of self-tuning Takaji-Sugeno Modified Fractional Order PID (TSMFOPID) baas on the Model Reference adaptive system (MRAS) applied on Power System Stabilizer (PSS). TS Fuzzy technique is used to construct a (TSMFOPID). The objective of Model Reference Adaptive System (MRAS) tunes the five parameters of Takaji-Sugeno Modified FOPID controller online. Different operating points for PSS were implemented to investigate the robustness of proposed controllers. The harmony optimization technique used to obtain the optimal parameters of proposed controllers. The simulation results provide that Self-Tuning TSMFOPID based on (MRAS) have better performance than the fixed parameters TSMOFOPID Controller.

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