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OPTIMAL DESIGN OF FRACTIONAL ORDER ANFIS-PSS BASED ON NSGA-II AIMED AT MITIGATION OF DG-CONNECTION TRANSIENT IMPACTS

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Abstract. Connection of Distributed Generation (DG) in the power system can create undesirable impacts on the stability characteristics. The subsequent transient instability, thereupon, severe oscillations in rotor of synchronous machines have led to trip of affected generation. Application of power system stabilizer (PSS) is regarded as an effective solution in order to suppress these oscillations; as well its innovative version can stabilize the power system much faster. Hence, Fractional Order (FO) controller has been here consolidated with Adaptive Neuro-Fuzzy Inference System (ANFIS) for constructing an effective PSS to improve both the system voltage profile and rotor angle stability. FO controller with consideration of its supplemental parameters has provided an appropriate tool to reinforce the performance of ANFIS. So-called FOANFIS-PSS has been thoroughly evaluated during connection of DG units to the 12-bus 3-area power system. Furthermore, Non-dominated Sorting Genetic Algorithms-II (NSGA-II) which is a common and prominent non-domination based genetic algorithm to unravel the multi objective optimization problems, it has been used to solve the aforementioned problem related to DG-connection. To validate the transient performance of suggested stabilizer, it has been thoroughly compared with ANFIS-PSS and Conventional PSS (CPSS). Finally, the simulation results have transparently approved the stabilization capability of FOANFIS-PSS as compared with ANFIS-PSS and CPSS to enhance of both the voltage profile stability and rotor angle stability.

Key words: DG-Connection, FOANFIS-PSS, ANFIS-PSS, CPSS, NAGA-II, Power System Stability.

1. INTRODUCTION

With enlargement of interconnected multi-area power systems around the word, the stability issue has become more and more critical in recent years. In the main, the power systems have often undergone by many different perturbations which may cause low frequency oscillations. Connection of Distributed Generation (DG) into the transmission and sub-transmission lines and stations can result in increasing the fault levels, and accordingly raising the stress on power system components [1–3]. The transient stability during the connection of DG units is recognized as one of the challenging issues related to these generators that oblige the electrical company to accurately select installation location and avoid the risk of instability.

That is why numerous innovative controllers have been proposed by scholars as Power System Stabilizer (PSS) to obliterate the oscillations and keep the system stable. PSS provides an auxiliary stabilizing signal for excitation system of synchronous generators which increases the system damping torque. Rotor speed deviation or bus frequency deviation can be selected as PSS's inputs [4]. Due to the complexity and non-linearity of interconnected power systems, as critical challenge facing the control experts, several effective control techniques such as fuzzy, sliding mode controller, fractional order controller and suchlike have been applied to more vanquish the inefficiency of traditional classic control techniques [5–7]. Proportional-Integral (PI) and Proportional-Derivative (PD) based fuzzy controllers have been applied as PSS to abate low frequency oscillations [8]. A new self-tuning fuzzy based PSS strategy is proposed where its parameters have been optimally adjusted using Pattern Search Algorithm (PSA) [9]. A Mamdani fuzzy logic controller has been engaged to design PSS based on optimal rule base toward reducing the power system oscillations [10]. Likewise, a fuzzy logic PSS based on optimal Crowding Genetic Algorithm (CGA) is suggested to abate the inter-area and local-area modes of oscillations, and the controller's efficiency has been evaluated to minimize the root-mean-square deviation of the machine rotor speed [11]. An optimal fuzzy-logic PSS based on adaptive evolutionary algorithm is proposed whereas diminution of the absolute rotor speed deviation is considered as transient stability criterion [12]. Numerous controllers based on fuzzy logic controller have been yet proposed and applied in many different nonlinear systems whose behaviours are extremely intricate to model [13–15]. Considering benefits of both FLC and Artificial Neural Network (ANN), the best strategy for creating a powerful processing tool is incorporating them together whereby the Adaptive Neuro Fuzzy Inference System (ANFIS) has been revealed. In fact, ANFIS combines the self-learning sufficiency of ANN with the linguistic expression function of fuzzy inference [16]. Following that, ANFIS controller is applied to construct an effective and drastic PSS in order to mitigate the frequency oscillations caused by DG connection. Furthermore, the performance of ANFIS-PSS can be more upgraded using fractional calculus, which is one category of mathematic sciences that analyzes the study of derivatives and integrals of non-integer orders. So, it turned out that so-called FOANFIS-PSS is introduced.

Majority of papers have only focused one kind of stability benchmark; either rotor angle stability or voltage profile stability. But then, both of them have been here formulated as a separate objective functions to provide suitable result. Note that, there are two different strategies to construct the optimization problems: First strategy is based on a scalar objective function that a single objective problem would consequently be made, whereas, the results cannot be precisely and confidently cited [17]. Second strategy is based on a Pareto optimal solution set that enables the user to make a trade-off between crucial objective functions [18]. Due to multi-objective nature of design problem, it would have to be taken a multi objective optimization technique. In this regard, Non-dominated Sorting Genetic Algorithms-II (NSGA-II), a common and prominent non-domination based on GA, has been employed to solve the optimization problem.

This paper has appropriately dealt with the subsequent impacts of DG connection into a 12-bus 3-generator power system i.e. rotor angle stability and voltage profile stability. Therefore, the suggested FOANFIS-PSS represent an appropriate damping signal for the excitation system based on an error signal measured from rotor speed deviation. Meanwhile, the parameters of understudy controllers have been subsequently tuned by means of NSGA-II technique. The transient performance of FOANFIS-PSS have been verified and compered with ANFIS-PSS and CPSS pres. Finally, the simulation results have transparently approved the stabilization capability of FOANFIS-PSS as compared with ANFIS-PSS and CPSS to enhance of both the voltage profile stability and rotor angle stability.

2. MULTI AREA POWER SYSTEM WITH PRESENCE OF DG UNITS

2.1. 12-BUS 3-AREA POWER SYSTEM

To evaluate the stabilization capability of FOANFIS-PSS during connection of DG units to the power systems, 12-bus multi-machine power system [19] has been simulated in MATLAB SIMULINK which is shown in Fig. 1. This system has been constructed by 12 buses, 4 generators and 3 areas. Generator G1 is stated as infinite bus. DGs are generally classified into two distinct groups with respect to the interfacing of DG i.e. asynchronous/synchronous machine based DG and inverter based DG. In this paper, Diesel Engine (DE) which is one kinds of Synchronous Machine (SM) based DG has been engaged to deal with the stability problem. Rate of each DE is 25MW, 22 kV which is tied to the respective buses through step-up transformers (22 kV/230 kV) as shown in Fig. 1. Three DG units are deployed to this system in area 3 that high-load area is located at 12-bus system. One of the DG units is connected to bus 13 and remaining two DGs are connected to bus 14. Bus 13 and bus 14 are the two auxiliary buses added to the original 12-bus system to connect the DG units. Buses 13 and 14 are connected to buses 4 and 3, respectively, through 22 kV / 230 kV step-up transformers. All the relevant parameters of the original 12-bus system are given in [19].

2.2. MODELING OF DIESEL ENGINE & GOVERNOR SYSTEM

Schematic of a DE is presented in Fig. 2a. Each DE has a primary controller, actuator and speed regulator, that speed adaption is regarded as its prominent duty. This structure is investigated in [20]. In this block, SM speed and mechanical power are considered as input and output, respectively. The structure maintains the speed of DG to its nominal speed. DE has been constructed using a gain, regulator, throttle actuator, and engine time delay. The DE output torque boundary is between 0 and 1.1 pu. The values of regulator gain and time constants *i.e.* K, T_1 and T_2 are 40, 0.01 and 0.02, respectively. The actuator time constants *i.e.* T_3, T_4 and T_5 are 0.25, 0.009 and 0.0384, respectively. Meantime, the engine time delay is 24 ms. The inertia constant (H) of DE+SM is 1.75 s. The second-order modeling of DE-Governor (DEG) compound is presented in Fig. 3a. Likewise, an IEEE type 1 Voltage Regulator-Exciter (VRE) presented in Fig. 2b provides the required reactive power at terminal of SM. The value of regulator gain and time constants *i.e.* K_a, T_a are 200 and 0.02, respectively, and also, gains of exciter and damping filter *i.e.* K_e K_f are 1 and 0.001, respectively.

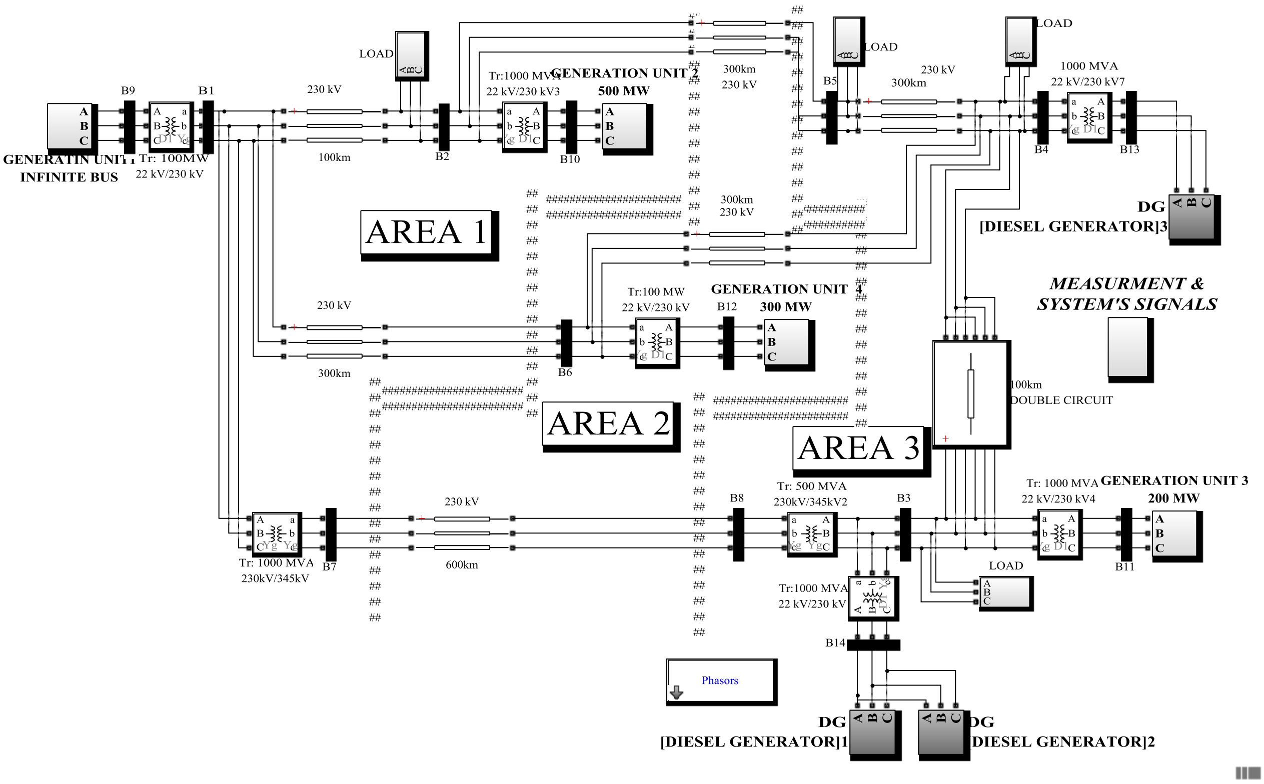

Fig. 1 – 12-bus test system with presence of DG units.

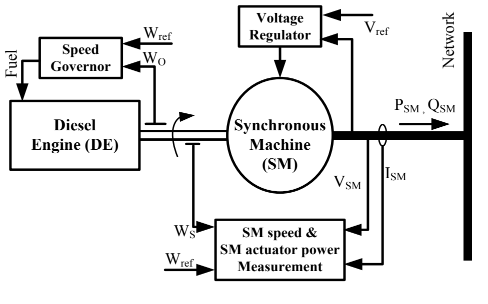

Fig. 2 – Schematic of diesel engine along with its controller.

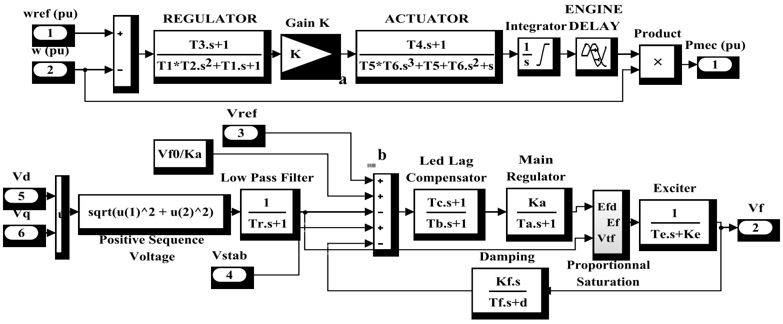

Fig. 3 – Structure of: a) governor b) voltage regulator and exciter.

3. DESIGN OF PSS BY ANFIS-TYPE FUZZY ALONG WITH CONVENTIONAL PSS

3.1. ANFIS CONTROL STRATEGY AND STRUCTURE

ANFIS is a category of adaptive multi-layer feed-forward networks which is functionally similar to Fuzzy Inference System (FIS). In fact, ANFIS acts same as an adaptive network simulator of Takagi–Sugeno type FIS. ANFIS synthesizes the self-learning capability of Neural Network (NN) with the fuzzy's linguistic expression function [21, 22]. The feed-forward multilayer NN has been frequently scheduled to solve the control problems. The back propagation method is extensively engaged to train the feed-forward multilayer NN. ANFIS has automatically adapted all the parameters using back propagation gradient descent algorithm and the least squares estimation for non-linear and linear parameters, respectively [23–25]. Fuzzy reasoning is explained in Fig. 4a, and the relevant equivalent ANFIS construction is presented in Fig. 4b. The ANFIS structure consists of five layers.

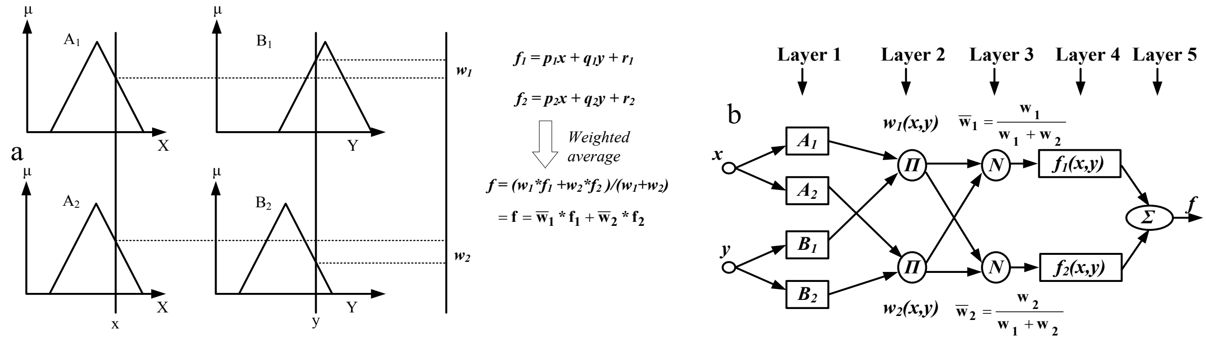

Fig. 4 – a) Multi-layer perception fuzzy reasoning; b) equivalent ANFIS structure.

Layer 1. Each node *'i'* in this layer indicated by a square node with a node function Eq. 1:

$$O_i^1 = \mu_{A_i}(x) \tag{1}$$

O_i^1 is the membership function of A_i and it defines the degree to which the presented x satisfies A_i. ANFIS suggests several types of membership functions including: trapezoidal, triangular, generalized bell, Gaussian curve, Gaussian combination. $\mu_{Ai}(x)$ is commonly selected to be triangle-shape::

$$\mu_{A_i}(x) = \begin{Bmatrix} 0 & x \le a_i \\ \frac{x-a_i}{b_i-a_i} & a_i \le x \le b_i \\ \frac{c_i-x}{c_i-b_i} & b_i \le x \le c_i \\ 0 & c_i \le x \end{Bmatrix} \tag{2}$$

which can be contracted by:

$$\mu_{A_i}(x) = \max\left(\min\left(\frac{x-a_i}{b_i-a_i}, \frac{c_i-x}{c_i-b_i}\right), 0\right) \tag{3}$$

and a_i, b_i, c_i are the parameters set. During changing the values of these parameters, the triangle-shaped functions change consequently, thus represent different forms of membership functions on linguistic label A_i.

Layer 2. Each node in this layer is indicated by circle node with Π label multiple input/output signals:

$$O_i^2 = w_i = \mu_{A_i}(x) * \mu_{B_i}(y). \tag{4}$$

Layer 3. Each node in this layer is indicated by circle node with *N* label calculates the ratio of the *ith* rules' firing strength to the sum of all rules' firing strengths:

$$O_i^3 = \overline{w}_i = \frac{w_i}{w_1 + w_2}. \tag{5}$$

Layer 4. Each node in this layer is indicated by square node calculates the contribution of the *ith* rule:

$$O_i^4 = \overline{w}_i f_i = \overline{w}_i (p_i x + q_i x + r_i). \tag{6}$$

Where, w_i is the output of layer 3 and p_i, q_i, r_i are the parameters set.

Layer 5. Single node is indicated by circle node calculates the final output:

$$O_i^5 = \text{overal output} = \sum \overline{w}_i f_i = \frac{\sum_i \overline{w}_i f_i}{\sum_i \overline{w}_i}. \tag{7}$$

The overall output i.e. *f* can be represented by a linear merger of the consequent parameters:

$$f = \frac{w_1}{w_1+w_2} f_1 + \frac{w_2}{w_1+w_2} f_2 = \overline{w}_1 f_1 + \overline{w}_2 f_2 = (\overline{w}_1 x)p_1 + (\overline{w}_1 y)q_1 + (\overline{w}_1)r_1 + (\overline{w}_2 x)p_2 + (\overline{w}_2 y)q_2 + (\overline{w}_2)r_2 \tag{8}$$

3.2. ANFIS-PSS MODEL

Schematic of ANFIS-PSS is given in Fig. 5a, which has been constructed by a sensor time constants, a limiter blocks, a compensator block and ANFIS structure. In this study, 15 ms is taken for value of sensor time constant. In viewpoint of damping the low frequency oscillations, number of zeroes must be more than poles [26, 27]. ANFIS-PSS prepares an appropriate phase and gain according to perturbation states to feed the AVR input in order to mitigate the power system oscillations. The parameters of ANFIS-PSS which should be identified by NSGA-II techniques are: K_c, T_c, K_e, K_{de} and K_u.

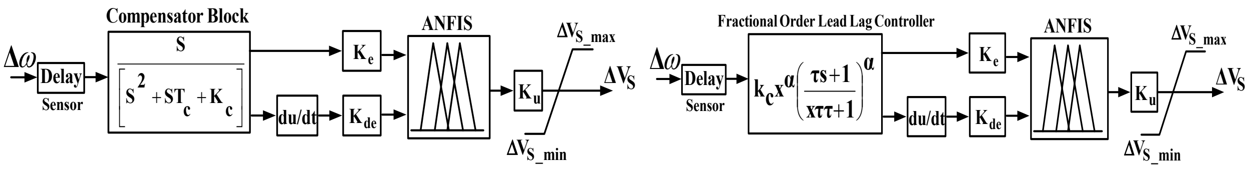

Fig. 5 – a) Structure of the ANFIS-PSS; b) structure of the FOANFIS-PSS.

3.3. FRACTIONAL ORDER LEAD LAG CONTROLLER

Fractional order is the general ordinary calculus utilizing the capability provided by non-integer order of Laplace variable s. FO calculus with respect to its advantages has begun to get appreciated in numerous fields [28–30]. In this study, the following equation related to fractional lead lag controller is initially presented as follows:

$$C(s) = k_c \left(\frac{s + 1/\tau}{s + 1/x\tau} \right)^{\alpha} = k_c x^{\alpha} \left(\frac{\tau s + 1}{x\tau s + 1} \right)^{\alpha}, \qquad 0 < x < 1. \tag{9}$$

Schematic of FOANFIS-PSS is given in Fig. 5b. $1/\tau$ is zero frequency, and also $1/x\tau$ is pole frequency for $\alpha > 0$. It is clear that, this controller reveals a fractional lead controller by $\alpha > 0$ and $0 < x < 1$, and also a fractional lag controller by $\alpha < 0$ and $0 < x < 1$, considering $0 < x < 1$ for both cases.

Aforementioned analytical approach has been consolidated with ANFIS-PSS to ameliorate its dynamic performance. According to Fig. 6, considering the integer lead lag controller, ω_m is the geometric mean of the corner ω_{zero} and ω_{pole}, which is expressed by:

$$\omega_m = 1/\tau\sqrt{x}\,. \tag{10}$$

In this frequency, the controller characteristic is:

$$\left| \frac{C(s)}{k_c x^{\alpha}} \right|_{\omega=\omega_m} = \left| C'(s) \right|_{\omega=\omega_m} = \left(\sqrt{\frac{(\tau\omega_m)^2 + 1}{x(\tau\omega_m)^2 + 1}} \right)^{\alpha} = \left(\frac{1}{\sqrt{x}} \right)^{\alpha} \tag{11}$$

$$\arg\left(C'(s)\right)_{\omega=\omega_m} = \phi_m = \alpha \sin^{-1}\left(\frac{1 - x}{1 + x} \right) \tag{12}$$

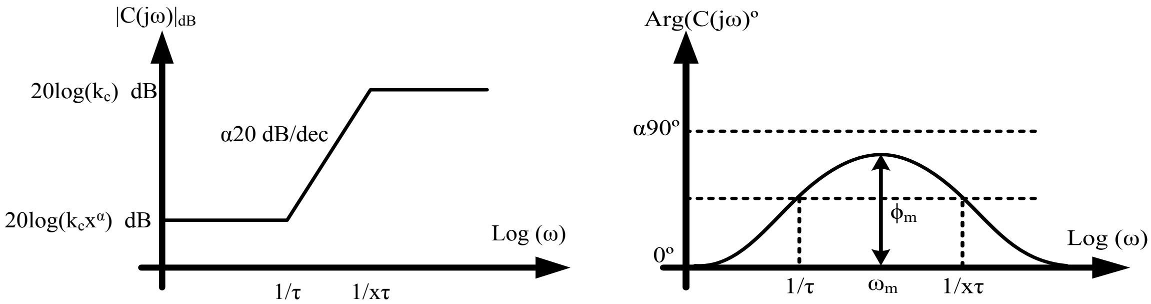

Fig. 6 – Bode diagram of transmittance C(s) with $\alpha > 0$.

4. NON-DOMINATED SORTING GENETIC ALGORITHM-II

4.1. BASIC CONCEPTS OF MULTI OBJECTIVE FUNCTIONS

All the Pareto optimal solutions in the objective space are known as so-called Pareto optimal set which was firstly suggested by Goldberg [31]. The problem's solution can be mathematically:

Find X which optimizes:

$$f(X)=[f_1(X), f_2(X),..., f_k(X)]. \tag{13}$$

Subject to:

$$g_i(x)\le 0\,; i=1,\,2,...,n \tag{14}$$

$$h_i(x)=0\,; i=1,2,...,p \tag{15}$$

where $X=[X_1, X_2,..., X_n]^{\mathrm{T}}$, which is the decision variables' vector, f_i, $i=1,2,...,k$ are the objective functions and g_i, h_j, $i=1,2,...,m$, $j=1,2,...,p$ are the problem's constraint functions.

4.2. GENETIC OPERATORS

Simulated binary crossover method is engaged to simulate binary crossover that is presented as follows

$$c_{1,k}=\frac{1}{2}\left[(1-\beta_k)p_{1,k}+(1+\beta_k)p_{2,k}\right] \tag{16}$$

$$c_{2,k}=\frac{1}{2}\left[(1+\beta_k)p_{1,k}+(1-\beta_k)p_{2,k}\right], \tag{17}$$

where, $c_{i,k}$ is the *ith* child with *kth* part, $p_{i,k}$ is the chosen parent and β_k (≥0) is randomly created

$$p(\beta)=\frac{1}{2}(\eta_c+1)\beta^{\eta_c}\,,\ \text{if}\ \ 0\le\beta\le 1 \tag{18}$$

$$p(\beta)=\frac{1}{2}(\eta_c+1)\ {}^{1}\!\!\diagup_{\beta^{\eta_c+2}}\,,\ \text{if}\ \ 1<\beta\,. \tag{19}$$

The distribution index (η_c) can be acquired using a uniform sampled random number u between (0, 1).

$$\beta(u)=(2u)^{1/(\eta+1)} \tag{20}$$

$$\beta(u)=\frac{1}{\left[2(1-u)\right]^{1/(\eta+1)}}\,. \tag{21}$$

The polynomial mutation is used which is identified as follows:

$$c_k=p_k+\left(p_k^u-p_k^l\right)\delta_k \tag{22}$$

where, c_k and p_k are child and parent, respectively, as well as P_k^l and P_k^u are the lower and upper bounds on the parent components, respectively. δ_k is the small deviation defined as follows:

$$\delta_k=(2r_k)^{1/(\eta_m+1)}-1,\ \text{if}\ \ r_k<0.5 \tag{23}$$

$$\delta_k=1-\left[2(1-r_k)\right]^{1/(\eta_m+1)}\ ,\ \text{if}\ \ r_k\ge 0.5, \tag{24}$$

where, $r_k$is randomly chosen between (0, 1) and η_m is mutation distribution index.

5. SIMULATION RESULTS

5.1. OBJECTIVE FUNCTION

To analyze the system controllability, a number of strategies such as: ITAE, IAE, ISE, and ITSE have been employed for relevant studies. In this paper, ITAE criterion is considered for both the objective functions i.e. J_ω and J_V to improve the rotor angle stability and voltage profile stability:

$$J_{\omega} = \int_{t=0}^{t=t_{sim}} \left(\sum |\Delta\omega_2| + |\Delta\omega_3| + |\Delta\omega_4| \right) t\,\mathrm{d}t \tag{25}$$

$$J_V = \int_{t=0}^{t=t_{sim}} \left(\sum |\Delta V_{10}| + |\Delta V_{11}| + |\Delta V_{12}| \right) t\,\mathrm{d}t. \tag{26}$$

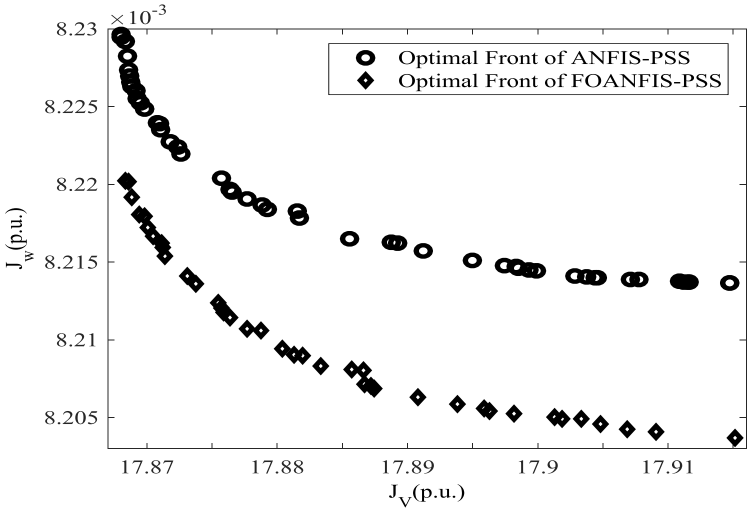

Fig. 7 – Optimal Pareto front.

5.2. CONNECTING DG UNITS INTO THE POWER SYSTEM

To assess, compare and validate the performance of suggested FOANFIS-PSS, the power system has been affected by connection of two DG units to the bus 14 at $t = 5$ s, then, another remaining unit will be connected to bus 13 at $t = 10$ s, and subsequently, all of them will be exited at $t = 15$ s. It is worth mentioning that the designed plan will precisely and perfectly test the performance of FOANFIS-PSS during the entry and exit of DG units. The performance suggested stabilizer has been compared with ANFIS-PSS and CPSS. Meantime, the optimal Pareto front is presented in Fig. 7. The simulation results under DG connection conditions are presented in Figs. 8–10. As can be seen, ANFIS-PSS has presented a significant response as compared with CPSS. Following that, fractional version of this controller *i.e.*, FOANFIS-PSS has more enhanced both the voltage profile stability and rotor angle stability.

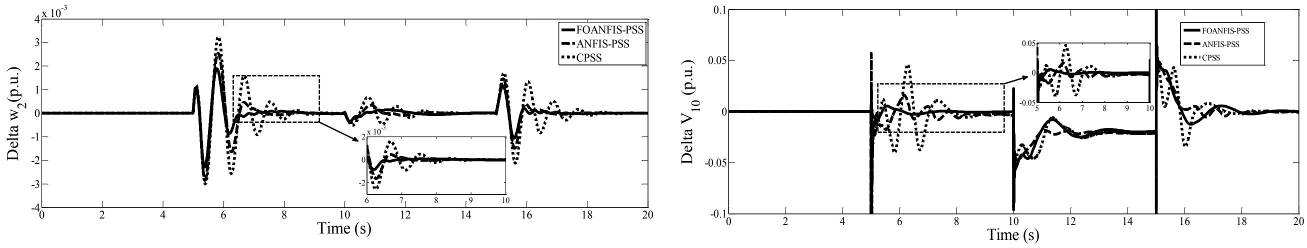

Fig. 8 – Speed deviation and terminal voltage deviation of generator 2 under entry and exit of DG units.

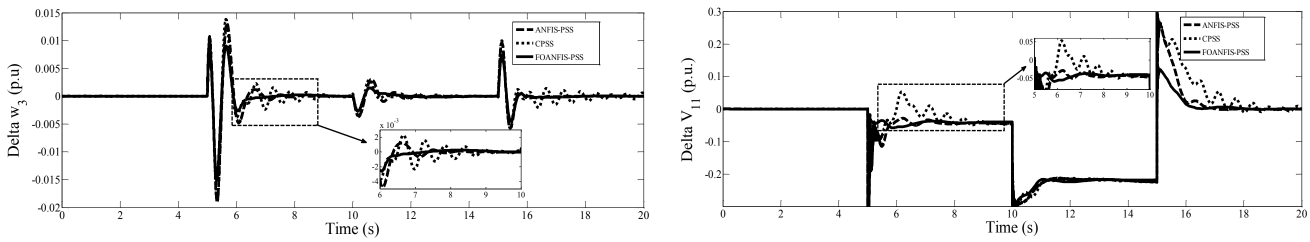

Fig. 9 – Speed deviation and terminal voltage deviation of generator 3 under entry and exit of DG units.

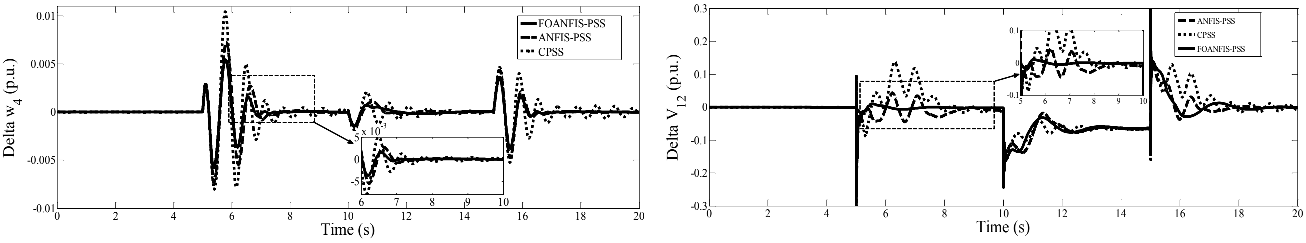

Fig. 10 – Speed deviation and terminal voltage deviation of generator 4 under entry and exit of DG units.

6. CONCLUSION

In this paper, an innovative power system stabilizer based on fractional order and adaptive neuro-fuzzy *i.e.* FOANFIS-PSS is introduced to quickly retrieve the affected power system caused by entry and exit of DG units into the stable status. Considering this, enhancement of both the important stability issues i.e., the voltage profile stability and rotor angle stability have been formulated as a multi objective optimization problem. Due to the convergence and exploratory performance of NSGA-II, the optimization scheme has been formulated based on this algorithm to accurately tune the parameters of stabilizers. A 12-bus 3-area power system has been taken into account to provide an appropriate bed in order to appraise and validate the transient performance of FOANFIS-PSS for enhancement of both the voltage profile stability and rotor angle stability. Furthermore, ANFIS-PSS and CPSS have been tested along with the suggested stabilizer to more clarify its transient efficiency. In a word, the simulations results drawn out from the multi-area power system have transparently corroborated the stabilization capability of FOANFIS-PSS as compared with ANFIS-PSS and CPSS aimed at enhancement of both the voltage profile stability and rotor angle stability.

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