Designing Neuro-Fuzzy Controller for GUPFC to Improve Transient Stability based on Lyapunov Energy Function

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Abstract

In recent years, because of the regeneration and development of power systems many of their technical and economical characteristics have been changed in different sections of generation, transmission, distribution and consumption. This issue has great impact on transmission systems because of the increased demand and limitation in creation of new lines. System stability against disturbances of big signal is one of the important issues that have been under threat as a result of this issue. In such circumstances, FACTS devices have great impact on increase of control ability and power system stability. One of the most effective FACTS devices is generalized unified power flow controller (GUPFC). It can combine the capabilities of SSSC, STATCOM and TCPAR by control of different parameters of network and can be used as a multipurpose tool. In this essay, designing a neuro-fuzzy controller for GUPFC to improve transient stability has been investigated. For this purposed, a controllable compensator has been designed to increase transient stability margin and damp transient oscillation in such systems by use of lyapunov stability criterion. Since transient energy function of system is a suitable tool for investigating of stability issue, optimization of GUPFC energy function has been noticed in order to reach the highest margin of transient stability. This idea is the basis of producing required teaching information in ANFIS network and can be used as a GUPFC controller. In this essay, the impact of GUPFC on single machine system, infinite bus (SMIB) and 9-bus system (Anderson and Fouad, 1977) by use of supposed method has been studied. Moreover by simulation of other FACTS devices such as UPFC and IPFC, the priority of GUPFC has been shown and the comparison of its result has been proved.

Keywords:

Generalized unified power flow controller (GUPFC), transient stability, lyapunov energy function, critical cleaning time (CCT), neuro-fuzzy control.

1. Introduction

With improvement of energy consumption, systems of energy transmission are confronted with power transmission limitation crisis. These limitations are created to sustain stability and provide permissible level of voltage. So capacity of practical exploitation of transmission line is less than real capacity of lines. This will lead to lack of optimized exploitation from the systems of energy transmission. One way to increase the capacity of power transmission is to create new lines. This isn't so easy and has many problems. With improvement of half-conductive industry and its use in power system, the concept of flexible energy transmission systems is introduced so that we can use real capacity of transmission system without establishing of new lines. One of the most important characteristics of these elements is to increase transmission level of these lines up to their thermal limit without decreasing security and reliability of network, and the other characteristics of these devices are that we can remove old control system with the help of power electronic and build systems that are cheaper, more reliable and smaller. These devices are used to strengthen control and improve transmission capacity of network.

GUPFC consists of a static synchronous compensator (SSSC) and n number static series compensators which are connected to each other through DC connector. This device was introduced for the first time by Fardanesh and his colleagues in 2000. This article introduces new concept about SVC (source voltage connector) involving several connectors (three or more than three) based on FACTS devices as a control of DC subnet. Control sub-network can be considered as a multi-terminal DC transmission system by use of some series and shunt convertor which are connected to each other.

The power of these convertors is AC and they are used for the final control in AC power system [1]. One year after that, zhang and his colleagues in [2] modeled GUPFC in the studies of optimized power flow. In this essay, one of the new concepts of GUPFC controller or multi-line UPFC is investigated. GUPFC can control bus voltage and power flow with more than one line and even can control a sub-net. GUPFC can be better than UPFC, although a few essays have studied these devices. Three years after the introducing GUPFC, San and his colleagues

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published an essay about the application of GUPFC in a Chinese Sichuan network. This essay investigates the application of GUPFC in a real power system for power flow and voltage control. By use of GUPFC with four-convertor in a Chinese Sichuan power system, the distribution of power flow of this system has been more reasonable and the level of transient stability of the system has been increased. Moreover, a new controller was suggested for four-convertor GUPFC and with complete simulation for showing its efficiency was modeled [3]. There are other investigated topics about GUPFC such as: designing the compensation controller [4], the role of compensator in power oscillation damping [5], the role of compensator in increase of available power transmission capability (ATC) and GUPFC locating to remove power transmission limitations [6], optimizing power flow [7], power flow controller [8] and further studies about power flow[9]. In [9] comparison of IPFC with GUPFC for management of transmission line limitation was studied. The results of IPFC and GUPFC with constant impedance, constant current and constant power load have been compared with the results of all buses with constant power load (P&Q).

IPFC and GUPFC with and without load zero inflation poisson (ZIP) exist in [10], use of UPFC and GUPFC controllers for maximizing useful transmission capability exists in [12], and also in essay [13] exists the basis of suggested controller (GUPFC) for maximizing time derivative of potential part of energy function for as power system. The results show that the amounts of series voltage injection of GUPFC and the amounts of shunt current should be set for the maximum amounts. In this way, the angle of series voltage injection changes to some extant of 180 angle. The results show that a GUPFC can be used as an efficient tool for improving transient stability and damping of oscillation. So, suitable control is essential for this issue. The comparison of UPFC with GUPFC for improving the quality of power was shown in [14] and the impact of GUPFC on stability of small signal of power systems was shown in [15]. The designing of ANFIS controller for calculating of lyapunov energy function for the purpose of improving transient stability and reaching the highest margin of transient stability was done in [16].

This work was done by optimizing of IPFC energy function and control of IPFC parameters. The designing of neuro-fuzzy controller based on transient energy function for improving transient stability was shown in [17]. Essay [18] evaluated transient stability. The analysis of non-linear transient stability after the dynamic fault is one of the challenging parts for evaluating of dynamical security. This essay suggests a new approach for evaluating of transient stability. The new approach has generalized the idea of energy function and spread the concept of energy function to lyapunov function family. Unlike available energy function and its variables, lyapunov function decrease in a point near the balanced point [19]. Intelligent systems in control of FACTS devices and its other applications have been noticed in this essay, like the use of UPFC Fuzzy control for improving transient stability. In reference [20], UPFC intelligent control by designing two fuzzy controllers was shown. One of the controllers was used for calculating of necessary power for improving transient stability and the other one was used for control of UPFC parameters to produce calculated power. In some essays, the application of neural networks in control of FACTS devices such as UPFC was shown [21].

In [22], control of UPFC by neural network based on lyapunov theory to improve transient stability of power system was considered. In reference [23], SSSC, STATCOM and UPFC which are controlled by RBFN controller and also their functions in improving transient stability were compared. With development of different methods of neuro-fuzzy control, it was used in different sections of power system. One of the methods neuro-fuzzy is ANFIS which was proposed and completely explained for the first time in 1993[24]. In spite of the advantages of this control method, it was not used very much in power system. The function of ANFIS in UPFC control was noticed in reference [2] to damp the oscillations of low frequency. In this reference, Hybrid method was used for teaching ANFIS controller. In such situations, linear model of Hefron –Philips power system with UPFC was used. The function of ANFIS in different situations for damping of oscillation was investigated and priority of ANFIS controller to controller with constant gain was proved. The other methods of neuro-fuzzy methods were investigated in some references like [26]. In this essay presenting of different models and formula were investigated. The basic principles of function along with local structure and capabilities of GUPFC control were shown. Then the mathematical model and relations that are the basis of problem solving as well as extracted energy function for GUPFC were discussed. Then control strategy including the way of using neuro-fuzzy method and how to improve transient stability were explained. At last, with presenting tables and graphs, transient stability through compensating of system with controlled GUPFC with ANFIS controller was proved.

2. The model of system

2.1 generalized unified power flow controller (GUPFC)

In traditional concepts of power transmission, GUPFC is able to control simultaneously all parameters that affect power distribution in line transmission (voltage, impedance and phase angle) and this is the concept of unified in GUPFC. Moreover, GUPFC can control independently the power flow of two active and reactive powers in control line. In all previous controller, the changes of active power is similar to changes of reactive power, in other words, the increase of power flow in active power load to increase of power flow in reactive power[2]. The simplest type of this compensator is a three-convertor controller that contains one shunt convertor and two series convertor for two transmission lines. Reference [1] shows the capability of GUPFC in control of voltage and power in comparison to IPFC and UPFC and also shows its capability in control of bus voltage independent of capability of control in active and reactive power in two transmission lines which is installed on them. In this way, this combination can control simultaneously five quantities such as bus voltage, active and reactive power in two transmission lines.

GUPFC is a completed synchronous voltage source (SVS [1]). It was shown by voltage phasor $(0 \leq V_T \leq V_{Tmax})V_T$ and angles of φ_{T1} and $\varphi_{T2}(0 \leq \varphi_T \leq 2\pi)$ in frequency of main elements (power system) and is placed series-shunt with transmission lines.

In recent practical project, GUPFC consists of three voltage source convertors as shown in figure2. In figure 2, convertor 1 is parallel with convertor 2 and 3. They use one common DC connector which is supplied by a DC capacitor. As pointed previously, this structure works as an AC-AC power convertor and active power can easily flow between AC terminals in convertor. Moreover, each convertor can generate or absorb independently active power in its AC output terminal.

Convertor 2 and convertor 3 play the main role in GUPFC by injection of V_T containing controllable V_T and phase angles φ_{T1} and φ_{T2} . This injection voltage is as a synchronous AC voltage source. The current of transmission line by flowing from the voltage source leads to interchange of active and reactive power between the convertor and AC system. The exchanged reactive power in AC terminal (i.e, in series adjoint transformer) was generated inner by connector. The exchanged active power in AC terminal which was appeared in AC connector as a negative or positive active power is converted to DC power.

By use of phase diagram, the main function of control of flow by GUPFC is shown in figure 3. The voltage setting through injection voltage with in-phase and out of phase continues changes for the improvement of voltage was shown as $\left(V_T = \pm\Delta V(\varphi_{Tw} = 0)\right)$ in figure 3-a.

[1] synchronous voltage source

Series reactive compensation was shown in figure 3-b. In this figure $(V_T = V_C)$ with angles of 90 toward current I was injected. This function is similar to compensation of series capacitive and inductive line that is obtained for SSSC. The voltage of series injection compensation can be kept fixed independent of changes of line current or it can change according to line current to do line compensation by series or reactive capacitor.

The setting of phase angle was shown in figure 3-c. In this figure, the voltage $V_T = V_\sigma$ containing angular proportion with Vs was injected so that transferring of desirable phase σ without any change in quantity is obtained. So GUPFC can work as a complete phase angle regulator (PAR) and supply reactive power related to transmission angle control through local production of reactive power.

The control of power flow with some functions was shown in figure 3-d. In this figure the setting of terminal voltage, series-capacitive compensation of line and transferring of phase can be done simultaneously. According to this figure, we have this formula:$V_T = \Delta V + V_C + V_\sigma$. This capability is only related to GUPFC. No apparatus has this capability. The range of transferred power control that is independent of transmission angle δ , not only shows high capability of GUPFC in functions of power flow but also shows its ability for improving of transient stability and damping of power oscillation [1,2].

In a lossless system, GUPFC can be shown by series voltage source with reactance X_s that is related to its transformer along with a current source with shunt connection. This diagram is shown in figure 4. In this diagram, GUPFC is placed between two buses i and j. The phase of current I_T is similar to the phase of V_i and shows exchanged active power between the series and shunt branches. This is the same power that is injected to power network by series branch. Iq shows shunt reactive branch that is independent of voltage Vi:

2.2 The injection model of GUPFC

Controllable parameters of GUPFC are: the magnitude of voltage of series branch (V_T), the voltage angles of series branch $(\varphi_{T1} and\ \varphi_{T2})$ toward bus voltage (Vi) and reactive current of shunt branch (Iq). Active current I_T depends on active power that series branch will inject to network. In other word, its amount as it will be shown later will be determined in a way that the balance of active power will be kept between series and shunt branch.

Series and shunt branch phasor diagram of GUPFC in the form of magnitude-angle of series branch voltage $(\varphi_{T1}, \varphi_{T2}, V_T)$ and current of shunt branch (I_q, I_T) along with voltage vectors and network current are shown in figure 5. In figure 6, the injection power of series branch is shown. This model is similar to injection model of SSSC and relations of GUPFC can be extracted with adding of shunt branch.

$$P_{si} = \frac{V_i V_T}{X_S} sin(\varphi_T) + V_i \cdot I_T \qquad (1)$$

$$P_{sj} = -\frac{V_j V_T}{X_S} sin(\theta_{ij} + \varphi_T) \qquad (2)$$

$$Q_{si} = \frac{V_i \cdot V_T}{X_S} cos(\varphi_T) + V_i \cdot I_q \qquad (3)$$

$$Q_{sj} = -\frac{V_j \cdot V_T}{X_S} cos(\theta_{ij} + \varphi_T) \qquad (4)$$

In it $(\theta_{ij} = \theta_i - \theta_j)$ according to figure 5 and 6.

3. Energy function

In reference [27] and [28] are shown when GUPFC has the maximum magnitude of V_T and I_q, the maximum margin of transient stability will be obtained. So when V_T and I_q set at the maximum of their limits and φ_T is constant, lyapunov energy function of GUPFC is definable for the first oscillation. It is clear that the use of GUPFC with constant parameters do not have any effect in improving of transient stability, but reference[27] has proved if the parameters of GUPFC are controlled in the form of sectional constant [2], the definition of energy function is true.

For extracting of function energy with GUPFC [29], SPEF model is used. As explained before, the classic model for generator was considered. It is modeled repeatedly as a constant admittance. Energy function of the entire system including n bus and m generator is written as below:

$$V(\tilde{\omega}, \tilde{\phi}, V) = V_k(\tilde{\omega}) + V_{p1}(\tilde{\phi}, V) + V_{p2}(\tilde{\phi}) + K \quad (5)$$

$$\textit{In it: } \tilde{\phi} = \left[\tilde{\delta}^T, \tilde{\theta}^T\right]^T \qquad (6)$$

δ : vector consisting of rotor angles of m generator

θ: vector consisting of voltage angles at n bus

ω: vector consisting of rotor speed of m generator

V: vector consisting of voltage magnitude of n bus.

The symbol (~) over the variables has been written to present the variables toward the COA [3] frame. K is an optional constant which is usually set so that it sets the equation source on Zero. V_K is a kinetic energy and the remaining sentences are potential energy of system (7). V_{p2} as potential energy of system loads and V_{p1} are as below:

$$V_{p1}(\tilde{\phi}, V) = -\sum_{i=1}^{m} P_{mi}\, \tilde{\phi}_i + \sum_{i=m+1}^{m+N} \int \frac{Q(V_i)}{V_i} dV_i - \frac{1}{2}\sum_{i=1}^{m+N}\sum_{j=1}^{m+N} B_{ij} V_i V_j \cos\tilde{\phi}_{ij} \qquad (7)$$

P_{mi} is a mechanical energy input of machine i, $Q(V_i)$ is dependent reactive to bus voltage i and B_{ij} is susceptance in increased admittance matrix. If injection active power of GUPFC, i.e: P_{si} and P_{sj} are multiplied in $\dot{\theta}_i$ *and* $\dot{\theta}_j$ and their results are added, the following formula is obtained.

$$P_{si}\dot{\theta}_{ij} = \frac{V_i V_T}{X_S} sin(\theta_{ij} + \varphi_T)\dot{\theta}_{ij} \qquad (8)$$

Now the relation (3) is multiplied in $\dot{V}_i$ and divided in V_i and the relation (4) is multiplies in $\dot{V}_j$ and divided in V_j

$$\frac{Q_{si}}{V_i}\dot{V}_i = \frac{\dot{V}_i V_T}{X_S} cos(\varphi_T) + \dot{V}_i \cdot I_q \qquad (9)$$

$$\frac{Q_{sj}}{V_j}\dot{V}_j = -\frac{\dot{V}_j V_T}{X_S} cos(\theta_{ij} + \varphi_T) \qquad (10)$$

From the sum of (8) and (9), the following result is obtained:

$$\frac{V_{Tw}}{X_{Sw}} \cdot \left[V_j\, sin(\theta_{ijw} + \varphi_{Tw})\dot{\theta}_{ijw} + \dot{V}_i\, cos(\varphi_{Tw}) - \dot{V}_j\, cos(\theta_{ijw} + \varphi_{Tw})\right] + \dot{V}_i \cdot I_q \qquad (11)$$

Now the integral of this relation is calculated. But there is not a fixed process for calculating of such integrals. With respect to controllable strategy, there is a method for solving devices of FACTS. If V_T and I_q are set at maximum of magnitude and φ_T is considered as a sectional constant, we can write the relation (11) as below:

$$\frac{d}{dt}\left[\frac{V_{Tw}}{X_{Sw}}\left(V_i\, cos(\varphi_{Tw}) - V_j\, cos(\theta_{ijw} + \varphi_{Tw})\right) + V_i \cdot I_q\right] \qquad (12)$$

Now Lyapunov energy function of GUPFC can be obtained as a function with form of $V_{GUPFC} = f(\mathbf{V}_i, \mathbf{V}_j)$ by

[2] sectional constant

[3] Center of Angle

integrating of relation (12). So potential energy of GUPFC is obtained as following:

$$V_{GUPFC} = \sum_{w=1}^{n}\left[\frac{V_{Tw}}{X_{TRSw}}\left(V_i.\cos(\varphi_{Tw}) - \mathrm{V}_{jw}.\cos(\theta_{ijw}+\varphi_{Tw})\right)\right] + I_q.V_i \quad (13)$$

According to figure 6 this function is the result of adding reactive functions Qsi and Qsj and shows entire reactive injection power to system by GUPFC. With comparison of energy function of GUPFC with other devices of FACTS, we understand energy function of all devices of FACTS is related to reactive power. When FACTS devices do not work as voltage or current source such as SVC, CSC and phase exchanger transformers, energy function is equal to the half of adding of reactive power.

$$V_{(SVC,CSC,PST)} = \frac{Q_i+Q_j}{2} \quad (14)$$

About UPFC, SSSC and GUPFC energy function is the sum of reactive powers [27]:

$$V_{(GUPFC,SSSC,UPFC)} = Q_i + Q_j \quad (15)$$

According to two above relations, extraction of energy function from sum of reactive powers cannot be used equally for all devices of FACTS. With extraction of GUPFC energy function, we can add it to the entire energy function of network, i.e: relation [5], so:

$$V(\tilde{\omega},\tilde{\phi},V) = V_k(\tilde{\omega}) + V_{p1}(\tilde{\phi},V) + V_{p2}(\tilde{\phi}) + V_{GUPFC}(\tilde{\phi}) + K \quad (16)$$

If there has been more than one GUPFC in network, we define energy function for each of them and add it to the entire network.

4. Control Method

As pointed before, when the improvement of transient stability is the final goal, two controllable parameters such as V_T and I_q should be set at its maximum magnitude in proportion with selected nominal value. In other word, after the selection of power and nominal voltage of GUPFC, 2 parameters among 4 controllable parameters will be determined. So parameters φ_{T1} *and* φ_{T2} will be remained. Moreover, the more GUPFC injects energy to network the more margin of transient stability security will be. So we can use GUPFC energy function for optimized control of GUPFC for the purpose of transient stability. φ_{T1} *and* φ_{T2} should be selected in a way so that GUPFC in energy function in relation (13) will be maximized. In this way, GUPFC injects the most amount of energy to network and at last the most margin of transient stability security will be obtained.

This approach is the basis of producing necessary information for ANFIS network, and the different values of δ, Vi obtained from the performance of simulated system in different situations of place and time of different faults is replaced in GUPFC energy function of relation (13) and the value of φ_{T1} *and* φ_{T2} should be determined in a way so that V_{GUPFC} will be maximized. This way generates necessary teaching information. The number of teaching data is about 3000 and the number of test data is about 50 which are obtained from 50 different patterns. ANFIS network is taught by this information and put in a network. When a fault takes place, immediately after fault removal, GUPFC enters the network and the values of δ and V_i are measured and entered ANFIS controller. Its output will be φ_{T1} *and* φ_{T2} based on adjusted and trained network and they are generated to improve transient stability. The value of I_T is generated with respect to the balance of active power and it is determined as a result of all parameters of GUPFC. The structure of ANFIS network is shown in figure 7. Figure 8 shows functions of membership for voltage and voltage angle. Then the value of φ_{T2} can be calculated by the values of θ_i , u_i and φ_{T1}

5. Simulation

5.1 Single machine system

Single machine system with GUPFC is shown in figure 11. The investigation of transient stability is done during the first oscillation and during this time, critical clearing time (CCT[4]) is evaluated. The purpose of critical clearing time is the last occasion for clearing disturbance in available system.

It is obvious if the fault keeps on after this time, the system will be unstable. For finding critical clearing time, stage 2 is used. So fault time is gradually increased until the system will be unstable. Three phase fault that is the worst and the most common fault in practical power systems is considered for all simulations. The place of fault is considered in the middle of line L2. By this method, critical clearing time for system SMIB without any compensation is 216ms.

[4] critical clearing time

Now this method is repeated again for calculating of critical clearing time, but GUPFC is placed in network. If GUPFC with the highest nominal value, i.e the magnitude of series voltage 0.4p.u and the magnitude of shunt current 0.1p.u, is placed in network, the critical clearing time will be 244ms and leads to 13% increase in CCT.

Figure (12) shows one system with three phase fault while GUPFC has not done compensation. The result is obtained when the fault time is about 240ms. After the extraction of result the moment of happening of fault is transferred to zero so that the repetition of figures will be prevented in steady state before the fault.

Figure (12) show the system without GUPFC and Figure (13) show the system with GUPFC. These figures prove the impact of GUPFC on stability of system. The analysis of phase surface is a graphical method for the study of second-degree system. Because of its graphical characteristic, this method provides suitable tool for observing the behavior of system in figure (14) the phase surface diagram of the system with and without compensation is shown. Horizontal axis shows machine angle and vertical axis shows its speed. These figures prove clearly the ability of GUPFC in stability of unstable system. The output is shown immediately after the moment of fault removal. In part (a) of the figure, the convergence of the system to the initial operating point is observable from some oscillations. This occurs when the system is instable in part (b).

5.2 Simulation of multi-machine system

Selected multi-machine system is IEEE 9-bus system which is shown in figure 15. For simplification, classic model of generators, constant admittance for loads and constant input powers are used. For study of system, at first calculating of power flow is done. Moreover, the admittance matrix of network should be calculated in three states:

- Before disturbance
- During disturbance
- After disturbance

It is easier to describe transient stability of system by use of rotor angles of generating according to inertia center of all generators. Since generator1 is the biggest generator of network, we can estimate δ_{COA} with $\delta_1$more accurately. So genarator1 is selected as a reference generator and the variables of δ and ω are evaluated toward it.

5.2.1The system performance if disturbance would be occurred

Similar to single machine state with use of three phase fault to system as shown its place in figure 15, critical clearing time is calculated with gradual increasing of fault time. For system without compensation, the fault time is 117ms. The system variables by applying fault at the length of 110ms is shown in figure (16). Here fault removal is followed by disconnecting of line from network, so both oscillations after the fault and admittance matrix after the fault is different from before the fault.

When the system is compensated by use of GUPFC to improve transient stability, its effect should be modeled. Therefore 2 changes occur on main system, the first one is fault occurrence and the second is entrance of GUPFC into network. The first case as explained before is modeled by change of matrix admittance and its calculation in three spans of time and changes of power. For study of GUPFC in network, its effect on powers of network is directly considered. So injection active power by GUPFC affects electrical powers of generators and at last improvement of performance is obtained. By considering the value 0.2p.u for magnitude of voltage of series branches and current 0.1p.u for shunt branches of GUPFC, the critical clearing time is 149ms and this results in about 27% increase in CCT. For comparison of system confronting with fault at the length of 149ms in two states with and without compensation, the system variables are shown in figure 17. Here we suppose that similar to single machine state, the system has been steady state and then fault is occurred. But in showing the result the moment of fault occurrence is transferred to zero in order to prevent from the repetition of steady state.

Figure (18) also clearly shows the stability of system with compensation toward without compensation. In figure (19) the phase surface diagram in two states with compensation and without compensation is shown. The horizontal axis is machine angle and vertical axis is its speed. These figures clearly prove the ability of GUPFC in stability of unstable system. Here the output is shown from the moment after fault removal. In part (a) the convergence of the system to the initial operating point after some oscillation is observable. In this situation part (b) of the system is unstable. If the magnitude of voltage of series branch increases, CCT will increase more and the result is summarized in table 1. In all states, the current of shunt branch is considered 0.1p.u.

The control method of GUPFC for multi machine system is exactly considered similar to single machine system so that its efficiency for multi machine system will be proved. The method is not repeated since it is same for all. The output of controller that is the voltage angle of GUPFC series branches is shown in figure (20). According to considerable important of critical fault time in multi-machine system, the efficiency of suggested method is proved. At last with comparison of GUPFC with other devices of FACTS in multi machine system, its efficiency is proved. By applying I_q=0 or in other word by omitting of shunt branch, the performance of GUPFC will be similar to IPFC. In this state, critical clearing time for multi machine system is 139ms. Now if V_{T1} = 0 and V_{T2} = 0, in other word by omitting series branches, GUPFC work like STATCOM. In this state, critical clearing time is 124ms. The result of this discussion along with the setting of values of GUPFC series and shunt branch in three states are summarized in table 2. The control method of all FACTS devices is neuro-fuzzy method.

6. Conclusion

In this essay, improvement of transient stability by use of GUPFC with ANFIS controller is investigated. In comparison with othe6. r FACTS devices, GUPFC has great impact on transient stability of system because it involves two series branches and one shunt branch. In single machine system, when GUPFC is used, CCT will be improved about 13%. The use of suggested method on 9-bus network shows if GUPFC with the highest power enters the network, critical clearing time will be increased about 56% and this a wonderful effect. The improvement of transient stability is done by the use of GUPFC with neuro-fuzzy controller and with emphasis on energy function method.

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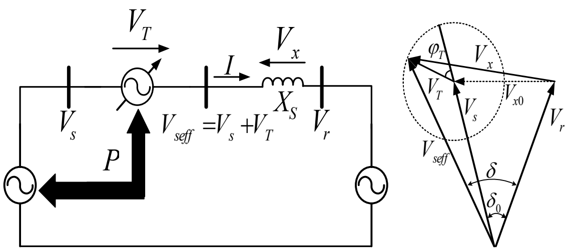


Figure1: Conceptual diagram of GUPFC in power system with two machines [2]

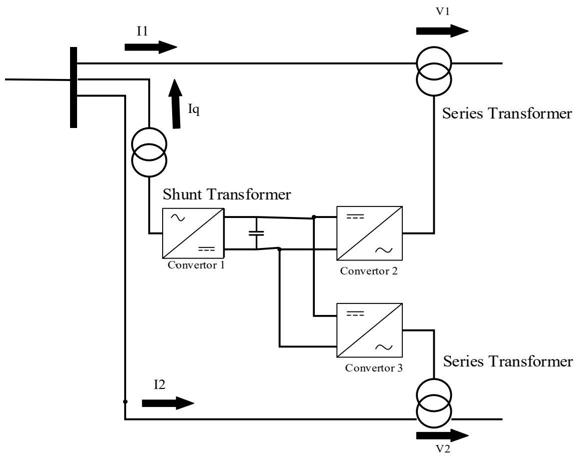


Figure 2: the simple structure of GUPFC by three voltage source convertors consisting of two series convertors and one shunt convertor [2].

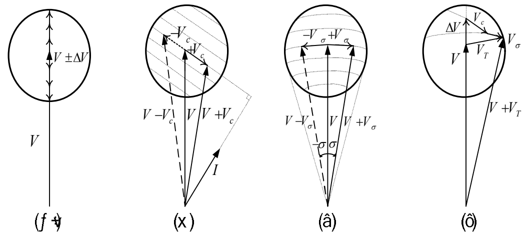


Figure 3: phasor diagrams showing the capabilities of current transmission control by GUPFC [1].

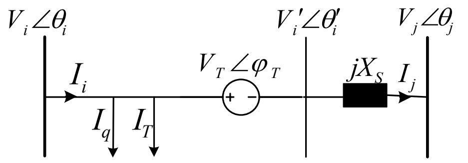


Figure 4: Basic model of GUPFC [17]

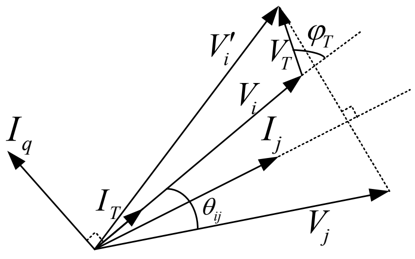


Figure 5: phasor diagram

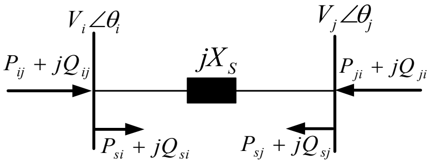


Figure 6: The model of injection powers of GUPFC [17]

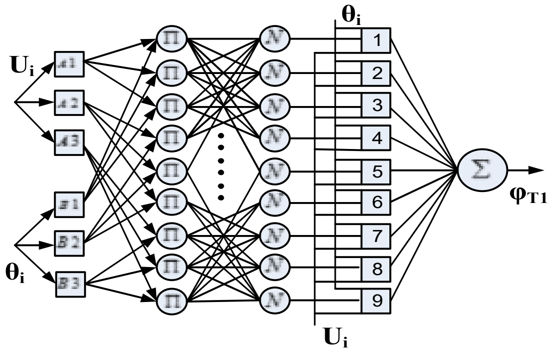
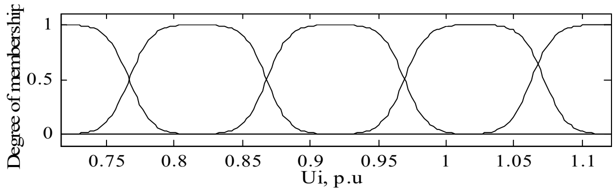
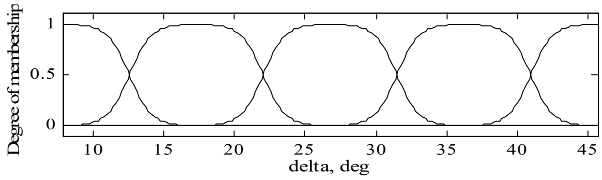


Figure 7: the structure of ANFIS network for calculating of φ_{T1}



(a)



(b)

Figure 8: the function of membership a) voltage and b) the voltage angle for calculating of φ_{T1}

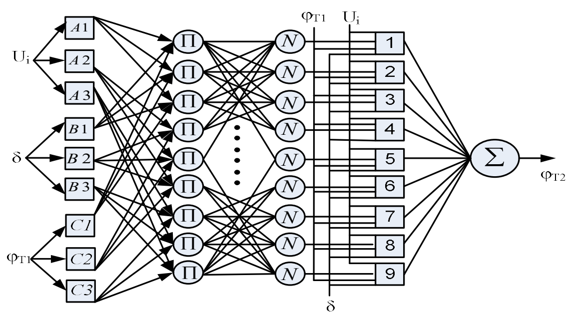
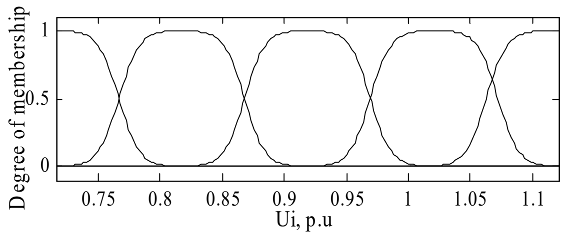
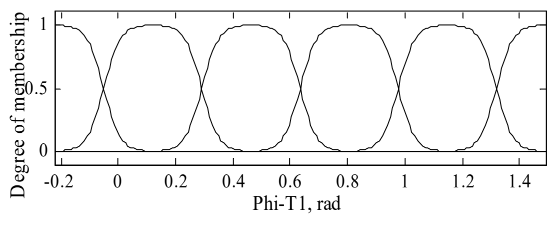


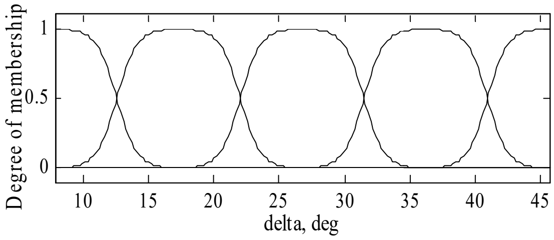
Figure 9: The structure of ANFIS network for calculating of φ_{T2}



(a)



(b)



(c)

Figure 10: Functions of membership. a)voltage b)the voltage angle and c)φ_{T2} for calculating of φ_{T2}

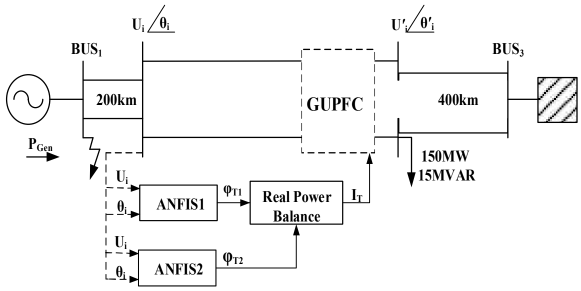


Figure 11: Single machine system with GUPFC

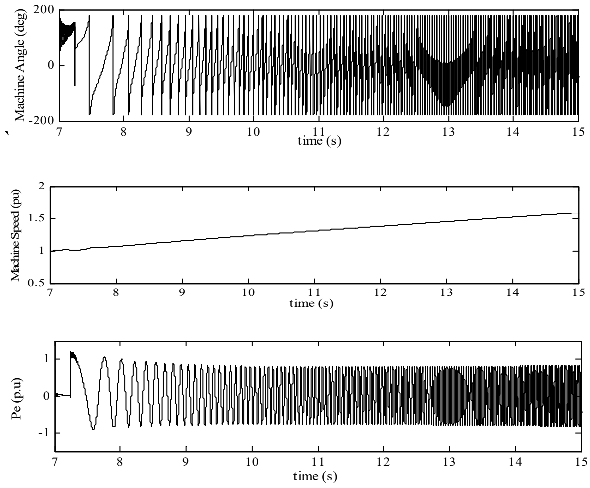


Figure 12: system variables if a short circuit would be made at the length of 240ms without compensation

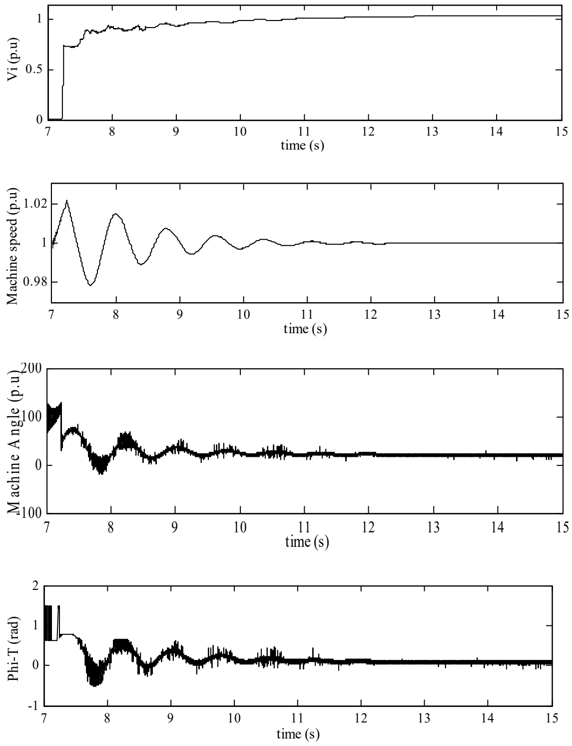
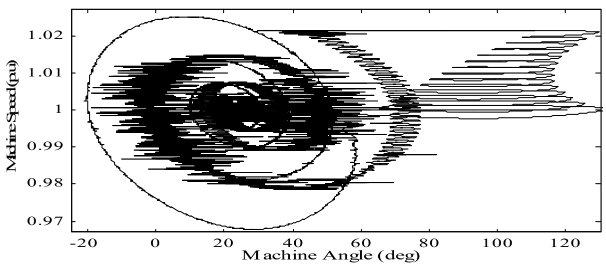
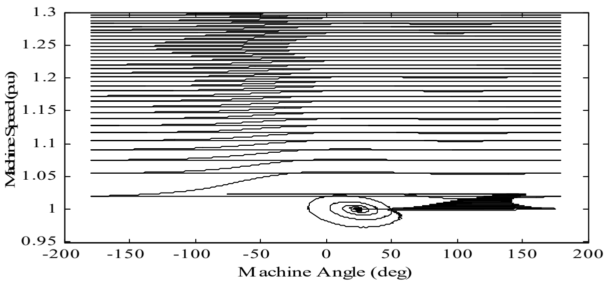


Figure 13: system variables if a short circuit would be made at the length of 240ms with GUPFC compensation



(a)



(b)

Figure 14: the phase diagram of the system if a short circuit would be made at the length of 240ms in two states (a) with GUPFC (b) without GUPFC

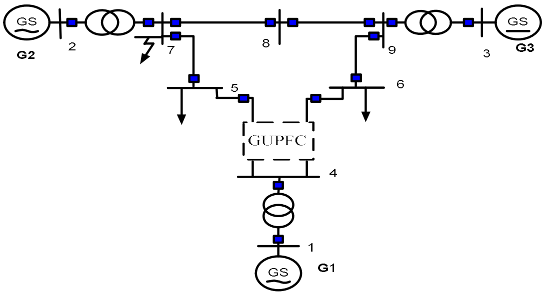


Figure 15: IEEE 9-bus diagram

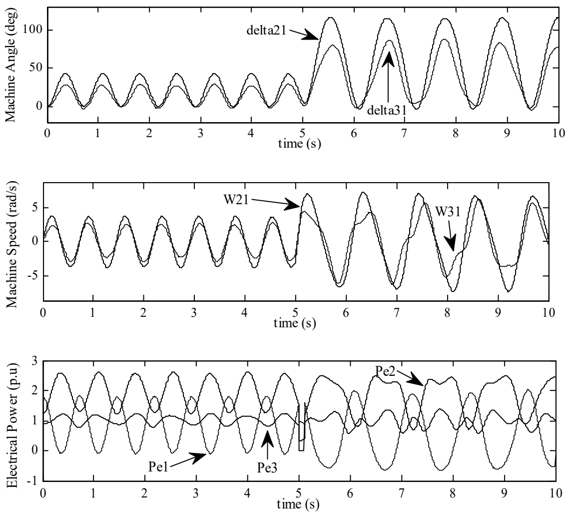
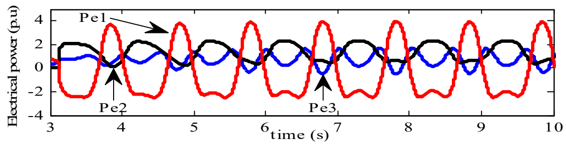
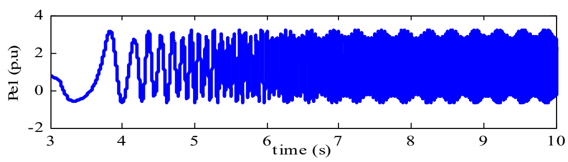


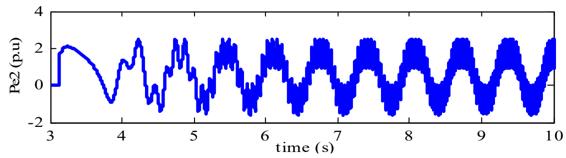
Figure 16: system variables if a short circuit would be made at the length of 110ms without compensation



(a)



(b)



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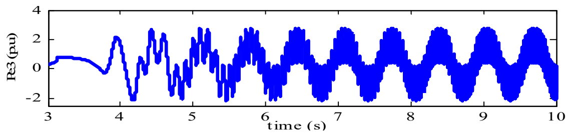


(d)

Figure 17: the comparison of system variables if a short circuit would be made at the length of 149ms in to states with compensation and without compensation (a) the power of generators with GUPFC (b),(c).(d) the power of generators without GUPFC

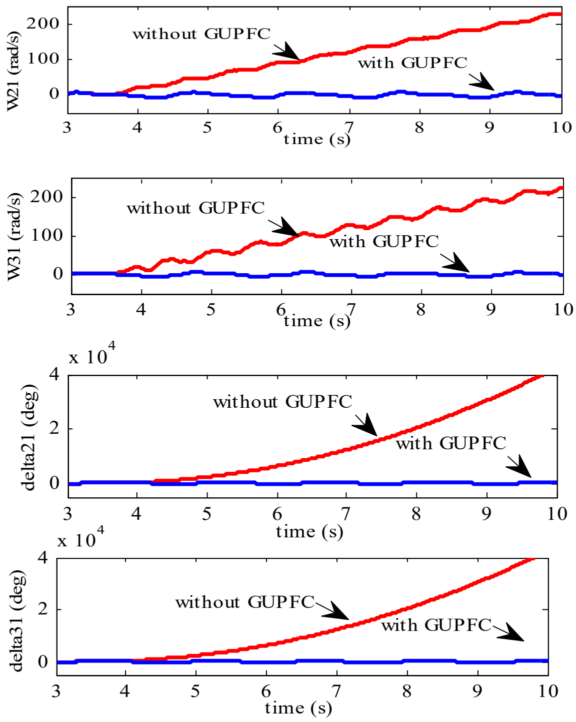
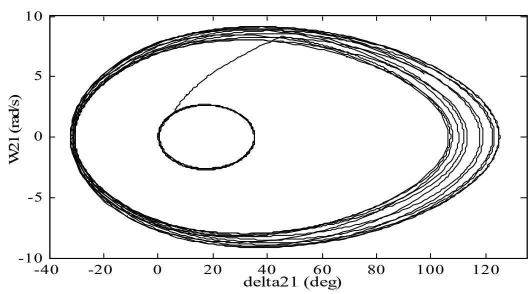
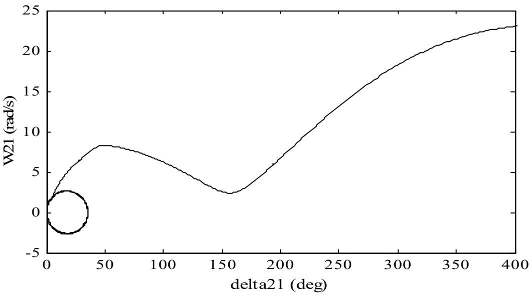


Figure 18: the comparison of system variables if a short circuit would be made at the length of 149ms in to states with compensation and without compensation



(a)



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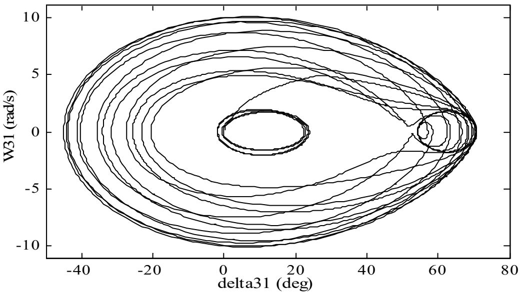
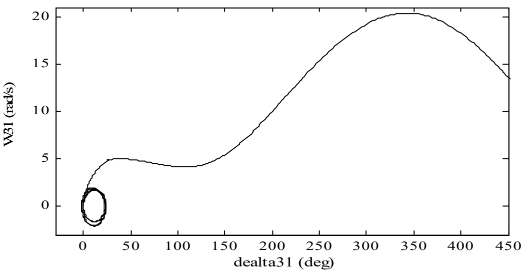


(c)



(d)

Figure 19: phase surface diagram: a and c with GUPFC compensation, b and d without compensation

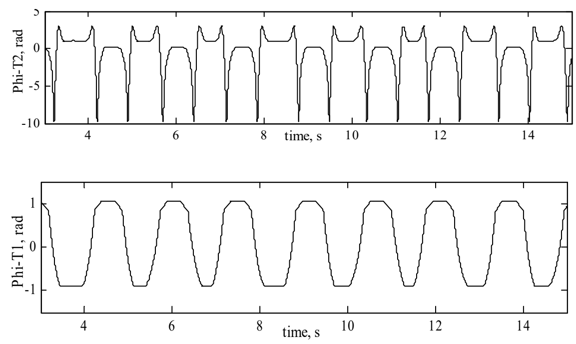


Figure 20: voltage angle of series branch

Table 1: the comparison of critical clearing time in different states for the system

V_{T1} (p.u) And V_{T2} (p.u)	CCT(ms)	The level of increase (%)
0.2	149	27.3
0.3	164	41
0.4	183	56

Table 2: comparison of critical clearing time in different states

	V_{T1} (p.u)	V_{T2} (p.u)	I_q (p.u)	CCT(ms)
Without compensation	0	0	0	117
With GUPFC	0.2	0.2	0.1	149
	0.3	0.3	0.1	164
	0.4	0.4	0.1	183
With IPFC	0.4	0	0.1	139
With UPFC	0.4	0.4	0	131
With STATCOM	0	0	0.1	124