International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization on TPE (IOTPE)

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2011 Issue 9 Volume 3 Number 4 Pages 52-58

TRANSIENT STABILITY IMPROVEMENT WITH NEURO-FUZZY CONTROL OF STATCOM IN SMIB

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Abstract- In this paper, the goal is the improvement of transient condition in a single machine system with designing of the nonlinear controllers for static Synchronous Compensator (STATCOM). By obtaining the Lyapunov function in presence of compensator in the system, some controllers are designed for it which by satisfying the Lyapunov stability criteria will increase the margin of transient stability and decrease the oscillation in the single machine system. For single machine with infinite bus (SMIB), three control methods of energy function controller (EFC), Fuzzy controller (FC) and Neuro-Fuzzy controller (NFC) presented and considered the effect of each of the above mentioned control methods of power system stability enhancement. The results of the simulations confirm the Neuro-Fuzzy controller ability in the improvement of the system transient conditions after occurrence of the fault.

Keywords: Transient Stability, STATCOM, Energy Function Controller, Fuzzy Controller, Neuro-Fuzzy Controller.

I. INTRODUCTION

The increasing demand of electrical energy and power systems reconstruction have caused that these systems work near to their stability limits. One of the issues that must be considered during the design and utilization of power system is that system stability against great signal turbulences. Regarding the importance of transient stability in power systems, we will seek a method which leads to system stability improvement. In the past decades, sudden progresses of semi-conductor industry and using them in power applications raised the concept of Flexible AC Transmission Systems (FACTS) [15]. Among the components of FACTS, static synchronous compensator (STATCOM) plays an effective role to solve extensive problems from transmission to distribution levels. Neural networks are able to provide a non-linear map between input and output which is based on a series of educational data. This property can be used to design a non-linear controller for STATCOM.

There are various methods to implement neural networks, so it could be designed different controllers with different neural networks for a compensator. Then we consider some specially designed controllers by this method for STATCOM. Chandrakar and Kothari in [1] used neural network as a plant indicator. Feedback linearizing type neural network of a nonlinear controller shall be learnt to substitute complex mathematical equations. We use a radial base function (RBF) type neural network which serves as a non-linear plant indicator. Malik et al in [2] proposed an adaptive linear element neuron (ADLEN) type neural network. We here offer an adaptive neural controller for a single machine infinite bus system that proposed controller of uses an ADLEN type neural network to introduce the system's dynamic equations and a pole shift (PS) controller.

A fuzzy controller consisting two control cycle offered in the reference [3] to improve static synchronous compensator efficiency. The first cycle which is named the main cycle attenuates AC bus voltage in steady state conditions and the system fluctuations in transient conditions. The second controller cycle which is named complementary controller, regulates DC capacitor voltage of the controller, moreover, decreased output voltage through the harmonic SPAWN technique.

In [10], it is considered controlling UPFC by Neuro network based on Lyapunov in order to improve power system transient stability. In [11], SSSC, STATCAM, and UPFC have been controlled by RBFN controller, and their function has been compared in transient stability improvement. By considering the various methods of Neuro-Fuzzy controlling, its function has been developed on the various subjects of power. ANFIS is one of the Neuro-Fuzzy methods, which has been described in a paper for the first time in 1993 [12]. Though ANFIS is an efficient controllable method and has so many advantages, it has not been used in power systems sufficiently. ANFIS samples applied in controlling Facts devices have been studied in [13].

The most important characteristics of Neuro networks include the capability of training and generalizing these networks based on the observations, the capability of data parallel processing, and the possibility and capability of function estimating. On the other hand, fuzzy systems have a favorable function in encountering the inconclusiveness, and are considered as a tool for using the knowledge of scientists and specialists it the form of membership function [14]. By combining these two models with Neuro-Fuzzy models, it can be developed a powerful tool for modeling, simulating and predicting. Therefore, we have used this method in this controllable method. In this paper because of using energy function the results are clearly better then the paper [16, 17] which have used of parallel levels method because this method is an approximate one for studying transient stability improvement.

II. SINGLE MACHINE SYSTEM MODELING

Figure 1 shows the system's equivalent. X_1 shows reactance between the generator's internal bus and the m bus (STATCOM location bus) and X_2 shows the equivalent reactance between the middle bus and the infinite bus considering system data in Appendix.

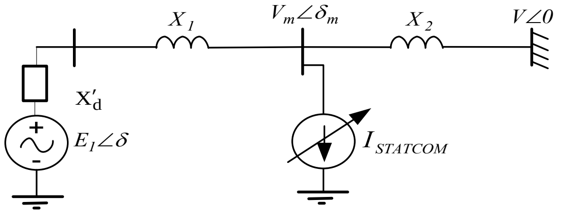

Figure 1. A single machine infinite bus system in presence of STATCOM

III. MODELING OF SYSTEM

Static synchronous compensator is the first parallel controller which is based on power converter. This component has not the limitations of natural commutation in SVC and works as forced commutation and could be modeled as a reactive flow resources regarding STATCOM performance which could inject lead or lag current to the power system. The cause of modeling in this stage is that STATCOM has the capability of producing any sinusoidal current in very short time and of suitable preciseness and almost independent of its terminal voltage (V_m).

In other words, fast dynamic response of STATCOM following a reference current allows us to model it as an ideal sinusoidal current independently of the terminal voltage. We prefer and use some control methods which are responsible for single machine infinite bus system improvement. Such a system receives information such as STATCOM terminal voltage, the rotor angle of Synchronous machine and the instantaneous angular speed of Synchronous machine.

Figure 1 shows a STATCOM as a parallel reactive current source ($I_s = \left|I_s\right| e^{j\delta k \pm 90^\circ}$) [4]. Where internal voltage of the machine and infinite bus voltage denote as $E'\angle\delta$ an $V_m\angle\delta_m$, respectively. Voltage amplitude and m bus angle are calculated as follows [4]:

$$V_m = \frac{E'X_2\cos(\delta-\delta_m)+VX_1\cos\delta_m+X_1X_2I_{STATCOM}}{X_1+X_2} \tag{1}$$

$$\delta_m = \tan^{-1}\left(\frac{E'X_2\sin\delta}{VX_1+E'X_2\cos\delta}\right) \tag{2}$$

The above equations show that the angle δ_m is independent of I_s. The output power P_e is correspondingly obtained:

$$P_c = \frac{E'V_m}{X_1}\sin(\delta-\delta_m) \tag{3}$$

Using Equations (1) and (2), we calculate P_e:

$$P_e = P_{\max}\sin\delta + cI_s\sin(\delta-\delta_m) \tag{4}$$

where, $P_{\max} = \frac{E'V}{X_1+X_2}$, $C = \frac{E'X_2}{X_1+X_2}$.

where the first right hand term of the Equation (4) shows the output power of the machine without STATCOM. Influence of STATCOM shows in P_e has been showed by the second term remember that the above equations have resulted for the capacitance made of STATCOM performance. In the inductor mode, I_s in the Equations (1) and (2) replaces by $-I_s$. The dynamic behavior of the machine in classic model holds by differential equations:

$$\frac{d\delta}{dt} = \omega \tag{5}$$

$$\frac{d\omega}{dt} = \frac{1}{M}\left(P_m - P_e - D\omega\right) \tag{6}$$

where δ, ω, M, D, P_m, P_e are angle, speed, inertia moment, attenuation coefficient, input mechanical power and output electrical power of the machine, respectively note that P_e depends on STATCOM current and we improve attenuation by controlling the current Is.

IV. ENERGY FUNCTION CONTROLLER (EFC)

If we choose the current STATCOM inject to the network so that it satisfies Lyapunov stability function [5] and the rate of transient energy loss maximizes, system will tend toward stability. Energy function of the system, V, for the classic model of power system is as follows [6]:

$$V = \frac{1}{2}M\omega^2 + \left[-P_m\left(\delta-\delta_s\right) - P_{\max}\left(\cos\delta-\cos\delta_s\right)\right] \tag{7}$$

where δ_s is the angle of post fault stable equilibrium point. The first right hand term of the Equation (7) is the kinetic energy (V_{KE}) and the second one is the potential energy (V_{pe}).

The Equation (7) shows that the Lyapunov function value is zero in the stable equilibrium point. In order to improve system stability, we need a controller in which the energy function value tends to zero as soon as possible, since the Lyapunov function value tending to zero indicates the equilibrium state of the system. To this end, the controller must act so that the slope of the energy functions in negative of time and the function value decreases continuously and tends to zero. To fulfill such a controller, we first derive the function $V(\delta, w)$ with respect to time As follows:

$$\dot{V}(\delta,\omega)=\frac{dV}{dt}=\frac{dV_{KE}}{dt}+\frac{dV_{PE}}{dt}=\frac{\partial V_{KE}}{\partial \omega}.\frac{\partial \omega}{\partial t}+\frac{\partial V_{PE}}{\partial \delta}.\frac{\partial \delta}{\partial t} \quad (8)$$

Using (5) and $\dot{V}(\delta,\omega)$ we have:

$$\dot{V}(\delta,\omega)=\text{-}D\omega\text{-}cI_s\omega\sin(\delta\text{-}\delta_m) \quad (9)$$

To satisfying Lyapunov function criteria, it entails that the right hand of the Equation (9) is negative semi-definite and so I_s shall be selected by the following rule:

$$I_s=k\omega\sin(\delta\text{-}\delta_m)\ ,\ I_s^{\min}\le I_s\le I_s^{\max} \quad (10)$$

where k is a positive constant and depends on the nominal power of STATCOM. It is worthy of note that δ_m is in the interval $(0,\delta)$ where $-\pi\le\delta\le\pi$ and the sign of $\sin(\delta\text{-}\delta_m)$ is similar to that of $\sin(\delta)$. Thus, the stability criteria change or $\text{sign}(V)$, with STATCOM current is as follows:

$$\dot{V}=k\omega\sin\left(\delta\right) \quad (11)$$

The Equation (10) shows that the current I_s depends on the generator angle and the machine speed. For the single machine system in Figure 1, the speed and angle of the machine could be estimated by some local measurement. [7]. The additional attenuation which is introduced by STATCOM using the equation (9) and $\dot{V}$ in the equation (11) could be written as follows:

$$\dot{V}=\left[D+CK\sin^2(\delta\text{-}\delta_m)\right]\omega^2 \quad (12)$$

When both the attenuation coefficient (D) and the STATCOM current (K) are zero, $\dot{V}$ will be zero regarding the Equation (12). In this case, the Equation (8) could be rewritten as follows:

$$\frac{dV_{KE}}{dt}=-\frac{dV_{PE}}{dt} \quad (13)$$

This equation expresses the fluctuations of kinetic and potential energies and their conversion to each other we show this in the next section by simulation. Here, it is necessary to note that the energy function method limits modeling seriously and it cannot be used in complex modeling of the machines with advanced controllers. If there is no attenuation in the system, the generator angle fluctuations will be non attenuating sinusoidal one provided that being stable. We can enhance the system stability through increasing attenuation and controlling STATCOM suitably.

Figure 2 shows the system transient energy of a single machine infinite bus system with a controller (for STATCOM) which is designed by the energy function method (EFC). The Equation (13) implies that if the error correction period is shorter than the critical time of error correction and no compensator inject current to the system and is also not in the system, the system energy after occurring error will fluctuate as the Figure 3. On the other words, there is a map between K_e and P_e with the ratio 1:1. So, the transient energy after occurring error remains constant and causes the machine angle being non attenuated.

A factor showing increase in the system stability is the critical time of error correction in the system. The designed controller via energy function can increase the critical time. Figure 4 shows the effect of energy function compensator on increasing critical time of error correction. As you see, in a given time, if the compensator does not connect to the network, the system will not be able to hold its stability fluctuation and the generator's internal angle will be continuously increased. Thus, this system is totally unstable while it can be remained stable in the first fluctuation with the existence of the designed controller and tends to its stable value after some cycles but it is evident that it attenuates slowly in the flowing, we design a controller that improves the first fluctuation stability and can be attenuated fast. If there is no compensator in the system and the system can't keep its stability in the first fluctuation, the system energy after occurring error increases continuously and tends to infinite.

Figure 5 shows the characteristic curve of kinetic energy, potential energy and total energy of the system after occurring the three-phase short circuit fault which leads to instability of the single machine network. It is obvious that the system kinetic energy tends to infinite meaning that the generator rotor rotates with high speed and causes that the generator exits from the system.

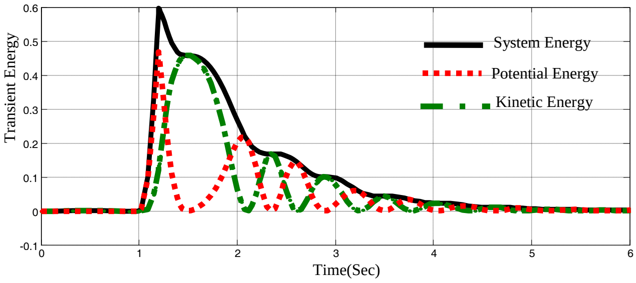

Figure 2. The effect of EFC controller for STATCOM on decreasing system's transient energy after occurring fault

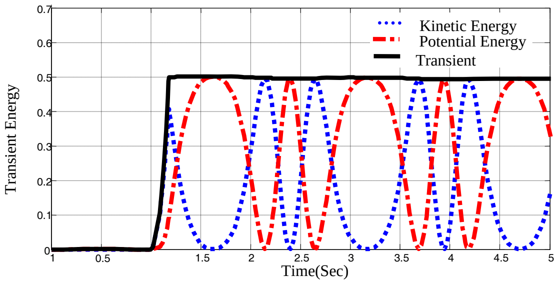

Figure 3. The system energy after occurring three phase short circuit fault without STATCOM

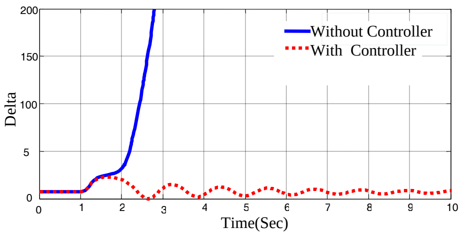

Figure 4. The effect of STATCOM on the system transient stability

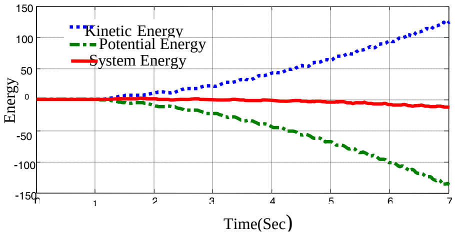

Figure 5. Energy curve for the system instability

V. FUZZY CONTROLLER (FC)

The EFC controller, if the error time is close to the critical time of error correction, however can preserve the system stability, but it cannot attenuate the system transient fluctuations so, regarding fuzzy systems are based on rule and the transient fluctuations can be attenuated by fuzzy rules faster. Determining fuzzy controller input is done according to the system variables which are visible, estimable and measurable. Controller input can be chosen among STATCOM bus voltage, electrical power, generator speed, and internal angle. We used the generator's internal angle and the generator speed as inputs. Here the generator's internal angle and the generator speed differences are considered as error and error derivation respectively for fuzzy controller input.

A. Membership Functions

The proposed fuzzy controller is based on Mamdani control which uses "if and then" rules for inference engine. We consider a fuzzy variable for each control input and these inputs become fuzzy ones via suitable memberships and we also define suitable membership functions for output variables. We consider the generator's internal angle and its speed as input variables.

Figures 6 and 7 Show the corresponding membership functions. Where in Figure 6, VS: Very small, S: Small, M: Middle, B: Big, VB: Very Big and in Figure 7, NVB: Negative very big, NB: Negative Big, Z: Zero, PB: positive Big, PVB: Positive Very Big. The number and domain of each membership function can be determined according to designer's experiences and the system configuration. As can be noted see in the figures, selection of a specific shape for generator angle and frequency membership functions is based on the machine frequency behavior, so that after big turbulences, it helps transient stability improvement and otherwise, it attenuates transient fluctuations.

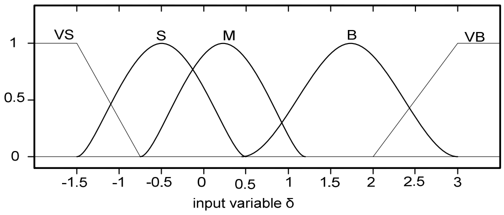

Figure 6.The generator angle membership function for fuzzy controller input

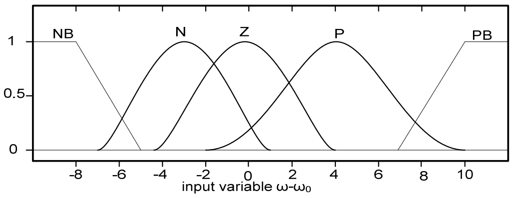

Figure 7. Speed differences membership function for fuzzy controller input

Setting these functions is done using trial and error method and simulation results, the determination of the Null membership function domain (Z) for the generator speed differences and the mean membership function (M) for the generator internal angle is of specific importance because the power system is always subjected to various turbulences and STATCOM shall not react to the fluctuation which do not lead to stability problems. Setting membership function is done with regard to the fact that the worst conditions in the transient stability problem occurs when a short circuit error occurs on the generator buses of the network or in one end of transmission lines.

We can determine the membership functions regarding the designed controller (EFC) inputs. Figure 8 shows the output membership functions which are used to introduce defuzzification output. Defuzzification maker which is applied, uses the centroid method [8-9], where, IB: Inductor Big, I: Inductor, Z: Zero, C: Capacitor, CB: Capacitor Big.

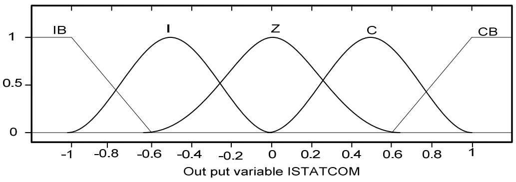

Figure 8. The membership functions of STATCOM reactive current for fuzzy controller output

B. Rules Base

Table 1 shows the rules of the proposed controller. STATCOM current as an output variable is determined according to the input variables (ω, δ). For example, we can refer to the following cases:

- If δ is very big and ω is positive and big, then STATCOM current shall be capacitance and big.
- If δ is very small and ω is negative and big, the STATCOM current shall be inductance and big.

Table 1. Rule Base of Fuzzy controller

δ / ω	VS	S	M	B	VB
NB	IB	IB	I	I	I
N	IB	IB	I	I	I
Z	I	I	Z	C	C
P	C	C	C	CB	CB
PB	C	C	C	CB	CB

In order to study the controller behavior in various conditions The rationale governing these rules is justified as follows, when the system frequency is higher than the nominal one and the rotor angle is increasing, it can be resulted that the generator input mechanical power is higher than its output electrical power, so STATCOM must act in the capacitance mode and inject reactive power to the network, so the capacity of the transmission line which connected to a bus STATCOM located on it, increases and the transient stability improves. Other cases are justified similarly.

VI. NEURO-FUZZY CONTROLLER (NFC)

In order to improve the designed controller performance for work point changes, fuzzy inference method seems suitable but we seek an effective method to determine fuzzy controller rules. In the previous section, we used the system energy function extracted rules to achieve fuzzy rules. But we can use a hybrid method to achieve these rules by a self-regulative method.

If we add the adaptation properties and being regulated, to the fuzzy system, we will obtain Neuro-Fuzzy system. In these systems all parameters belonging to fuzzy rule could be regulated using the learning property of neural networks. And we do not further concern about how to form the rules and membership functions domain and also output coefficients that are, these parameters regulate instantaneously and achieve their optimal value. The proposed method utilizes the system input-output pairs to generate rules and membership functions. Here, the single machine infinite bus system controller is learned using ANFIS. We need a set of educational data to learn controller the required educational data serve as input and output vectors of fuzzy and energy function controllers. The input signal of this controller is the generator internal angle and speed differences and the output signal is the static synchronous compensator injected current which is proportional to both input vectors.

In order to achieve neural networks educational patterns, NFC controller is used in the following work conditions:

- Short circuit fault occurs in various locations of the system.
- STATCOM capacity: 0.2 to 1.2 times of the nominal capacity is inserted to the system.
- Error period: 150ms to the critical time of error.
- Various combinations of the above three cases.

We can achieve 50 pairs of input-output patterns regarding the above various work conditions. These 50 patterns satisfied the Lyapunov criteria as well so that each output is a function of two input vector. The neural network using input and output signals which are 2×50 and 1×50 matrices respectively, learn the system so that it leads to obtain membership functions' rules and intervals and finally to the better controller response.

VII. SIMULATION RESULTS

At first, in this paper, the fuzzy control mode is implemented and considers its effect on critical time of error correction and on attenuation of power fluctuations. In this section; it is used of the generator internal angle and its speed as the controller inputs. Then, this paper has compared the performance of fuzzy controller vs. energy function controller. Then by the neural network, we implement this controller for a single machine system and its simulation is compared with EFC controller. At last, we compare the properties of the designed controllers' altogether. The software MATLAB/SIMULINK has been used to implement dynamic equations of the system.

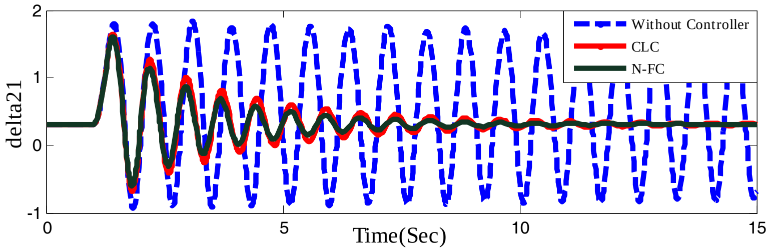

Figure 9. The generator's internal angle after occurring fault with the presence of energy function and Neuro-Fuzzy controllers

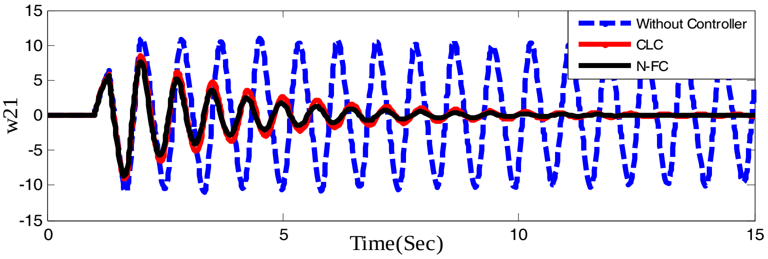

Figure 10. The generator's speed differences after occurring fault with the presence of energy function and Neuro-Fuzzy controllers

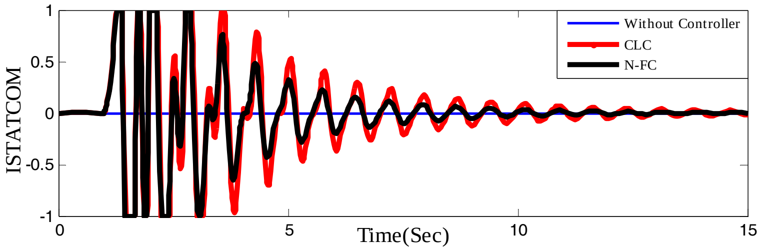

Figure 11. STATCOM current with the presence of energy function and Neuro-Fuzzy controllers

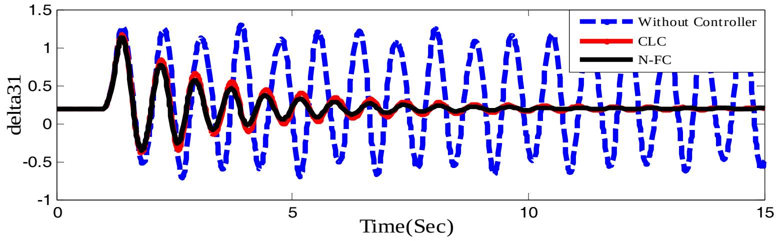

Figure 12. The generator internal angle after accruing fault with the presence of energy function, Neuro-Fuzzy controllers

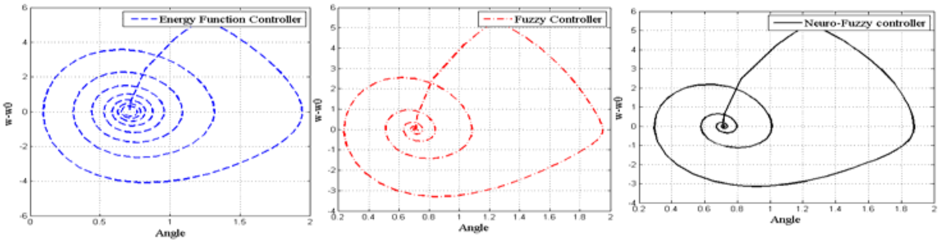

Figure 13. Phase plane curve with the presence of energy function, Fuzzy and Neuro-Fuzzy controllers

VIII. CONCLUSIONS

Calculating the critical time of error by three designed controller shows that Neuro-Fuzzy controller increases the critical time of error correction more than the other two controllers. Table 2 represents the critical time of error correction with the presence of the designed controllers. Figures 9-13 show that the Neuro-Fuzzy controller can increase the system's fluctuation attenuation and the critical time of error correction more than the other two controllers and it, in general, improves the system transient stability and is the most suitable single-machine system controller.

Table 2. Simulation result

Controller	Without controller	EFC	FC	NFC
critical time(s)	0.195	0.223	0.204	0.226

APPENDIX

SMIB Data

H=3.8 sec, f=60 Hz, X_d=0.38 pu, X_1=0.5 pu, X_2=0.12 pu, V=0.994 pu

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BIOGRAPHIES

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