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 inconstancy, 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](image)

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 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.

The Equation (7) shows that the Lyapunov function value is zero in the stable equilibrium point. The first right hand term of the Equation (1) 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:

\[
\frac{d\delta}{dt} = \omega
\]

\[
\frac{d\omega}{dt} = \frac{1}{M} \left( P_m - P_e - D\omega \right)
\]

where $\delta$, $\omega$, $M$, $D$, $P_m$, $P_e$ 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 $I_s$.

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, $V_e$ for the classic model of power system is as follows [6]:

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

\[
The above equations show that the angle $\delta_m$ is independent of $I_s$. The output power $P_e$ is correspondingly obtained:

\[
P_e = \frac{E'V_m \sin(\delta - \delta_m)}{X_1}
\]

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

\[
P_e = P_{max} \sin \delta + cI_s \sin(\delta - \delta_m)
\]

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

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
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\[
\frac{d\omega}{dt} = \frac{1}{M} \left( P_m - P_e - D\omega \right)
\]
\[
\dot{V}(\delta, \omega) = \frac{dV}{dt} = \frac{dV_{KE}}{dt} + \frac{dV_{PE}}{dt} = \frac{\partial V_{KE}}{\partial \delta} \dot{\delta} + \frac{\partial V_{PE}}{\partial \delta} \dot{\delta}
\]  

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

\[
\dot{V}(\delta, \omega) = -D \omega - C I \omega \sin(\delta - \delta_m)
\]

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:

\[
I_s = k \omega \sin(\delta - \delta_m), \quad I_s^{\min} \leq I_s \leq I_s^{\max}
\]

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

\[
\dot{V} = k \omega \sin(\delta)
\]

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:

\[
\dot{V} = [D + C K \sin^2(\delta - \delta_m)] \omega^2
\]

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:

\[
\frac{dV_{KE}}{dt} = -\frac{dV_{PE}}{dt}
\]

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 \( K_s \) 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.
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, N: Negative, 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.

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>
<thead>
<tr>
<th>ω</th>
<th>VS</th>
<th>S</th>
<th>M</th>
<th>B</th>
<th>VB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>IB</td>
<td>IB</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>N</td>
<td>IB</td>
<td>IB</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Z</td>
<td>I</td>
<td>I</td>
<td>Z</td>
<td>C</td>
<td>C</td>
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<tr>
<td>P</td>
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<td>C</td>
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<td>CB</td>
<td>CB</td>
</tr>
<tr>
<td>PB</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>CB</td>
<td>CB</td>
</tr>
</tbody>
</table>

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 method which is applied, uses the centroid method [8-9], where, IB: Inductor Big, I: Inductor, Z: Zero, C: Capacitor, CB: Capacitor Big.
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](image1.png)  
Figure 9. The generator's internal angle after occurring fault with the presence of energy function and Neuro-Fuzzy controllers

![Figure 10](image2.png)  
Figure 10. The generator's speed differences after occurring fault with the presence of energy function and Neuro-Fuzzy controllers
VIII. CONCLUSIONS

Calculating the critical time of error by three designed controllers 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

<table>
<thead>
<tr>
<th>Controller</th>
<th>Without controller</th>
<th>EFC</th>
<th>FC</th>
<th>NFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>critical time(s)</td>
<td>0.195</td>
<td>0.223</td>
<td>0.204</td>
<td>0.226</td>
</tr>
</tbody>
</table>

APPENDIX

SMIB Data

\[ H=3.8 \text{ sec}, f=60 \text{ Hz}, X_{p}=0.38 \text{ pu}, X_{s}=0.5 \text{ pu}, X_{r}=0.12 \text{ pu}, V=0.994 \text{ pu} \]

REFERENCES


**BIOGRAPHIES**

**Hassan Barati** was born in Dezful, Iran, in 1973. He received his B.Sc. degree in Electronic Engineering from Isfahan University of Technology, Isfahan, Iran, in 1994. He received his M.Sc. degree in Electrical Engineering from University of Tabriz, Tabriz, Iran, in 1997. He obtained the Ph.D. degree in Electrical Engineering from the Islamic Azad University, Science and Research Branch, Tehran, Iran, in 2007. His research interests are power system analysis, restructured power system, and FACTS devices.

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