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# Rough Fuzzy Control of SVC for Power System Stability Enhancement

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**Abstract** – This paper presents a new approach to the design of a rough fuzzy controller for the control loop of the SVC (static VAR system) in a two area power system for stability enhancement with particular emphasis on providing effective damping for oscillatory instabilities. The performances of the rough fuzzy and the conventional fuzzy controller are compared with that of the conventional PI controller for a variety of transient disturbances, highlighting the effectiveness of the rough fuzzy controller in damping the inter-area oscillations. The effect of the rough fuzzy controller in improving the CCT (critical clearing time) of the two area system is elaborated in this paper as well.

**Keywords:** Fuzzy controller, Fuzzy set, Rough fuzzy controller, Rough set, SVC

## 1. Introduction

With the deregulation and privatization of electricity supply, power systems are operating much closer to their stability limits than ever before. The implementation of Flexible AC Transmission Systems (FACTS) devices to enhance the power system stability has been widely recognized in the past [1, 2]. In particular, the Static Var Compensators (SVCs) have long been noted for the dynamic voltage support and reactive power compensation for improving the performance of electric power systems [3] and hence have been applied in various power systems across the world.

The primary application of SVCs is to provide reactive power support to maintain the bus bar voltage. In addition to voltage stability enhancement, SVCs can also be used to provide damping on power system oscillations and hence to improve the oscillatory stability [4-6]. Further more, SVCs can improve transient stability by dynamically supporting the voltage at strategic points. For any static VAR controller scheme, the firing angle control of the thyristor banks of the TCRFC type SVC determines the equivalent shunt admittance presented to the power system. Once the sizing and location of each compensator has been selected, the problem still remains of adopting feasible and implementable feedback control strategies for the SVCs. The SVC is equipped with a voltage regulator that provides primarily synchronizing torque. For additional damping, auxiliary control function is necessary.

The control of the SVC can be used to damp inter-area modes and this complements the PSS used at generating stations. The presence of a voltage regulator in the SVC, located at the midpoint of a line, helps to overcome the deleterious effect of the length of the line on system stability. The flexible modular approach was proposed by incorporating SVCs with auxiliary controllers in the power systems in [7, 8]. To prevent voltage instability, a nonlinear controller for the SVC is designed using a third-order nonlinear model and direct feedback linearizing technique in [3]. These designs assume the parameters of the controller to be known precisely, which can be problematic in practice. The exact values of certain parameters are very difficult to obtain due to practical limitations [9]. For instance, the impedance of the transmission line and the time constant of the regulator of the SVC may have some uncertainties and hence to overcome this, a robust nonlinear control technique is employed in [10]. However, with the increasing complexity and uncertainties in the system, it is necessary to investigate the implementation of intelligent controllers. With the advent of microprocessor-based controls, it is feasible to implement the adaptive control of SVCs with online system identification and automatic tuning. However, this requires a good understanding of the system model, with various aspects to be considered.

In many real processes, control relies heavily upon human experience. Numerous applications of the fuzzy controller to the control of various ill defined complex processes have been reported since Mamdani proposed the method [11]. The fuzzy logic based SVC control using the least number of rules for stabilization of a synchronous generator connected to a large power system is proposed in [12]. It uses the variable structure fuzzy controller concept for the auxiliary loop of the SVC. To further improve the robustness of the fuzzy control, an intelligent fuzzy control

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scheme is presented in [13]. The intelligent scheme recognizes the controlled object while controlling it. This control method in fact unifies the recognition of the fuzzy system and fuzzy control. The controller acknowledges and studies the controlled object repeatedly using such following methods as reversal propagation algorithm, pattern recognition algorithm, table enquiry algorithm, and orthorhombic least-square algorithm. To better handle uncertainties in the system, the authors in [14] presented a fuzzy logic controller combined with a PI controller for FACTS devices, mainly on SVC, to provide damping for a power system. The authors in [15] suggested a nonlinear variable gain fuzzy controller for FACTS devices. The fuzzy based controller is able to outperform a PI controller in system transient stability enhancement.

Although there have been advances in fuzzy based controllers for power system stability enhancement, the main disadvantage of fuzzy controllers are: the necessity of acquisition and preprocessing of the human operator's knowledge about the controlled process, sequential search through rule base, and the time consuming defuzzification process [16, 17]. This becomes obvious especially when dealing with power systems that require a large number of control variables. An alternative approach was presented by Pawlak as a rough set theory [18]. The difference between the membership functions of fuzzy sets and rough membership functions of rough sets is emphasized in [17]. The former are usually intuitively designed whereas the latter, being upper semi continuous functions, are computable in an algorithmic way. The theory of rough sets turned out to be applicable to many cases [17, 18]. Certain applications of rough set theory on power systems have been reported recently focusing on data mining applications [19, 20].

This paper presents the application of the rough fuzzy method in designing a controller for the control loop of the SVC to achieve better control efficiency. The input signal to the SVC controller is the deviation of bus bar voltage and its rate of change. To validate the effectiveness of this control strategy, computer simulation studies for the variety of transient disturbances of a two area power system are undertaken and compared with the conventional fuzzy and PI controllers.

This paper is organized as follows. Section II provides the overview of the SVC model. Section III discusses the implementation of fuzzy and rough-fuzzy techniques for the SVC control. It is followed by the case study and conclusions.

## 2. SVC Model

In this paper, SVC is used for application of the proposed rough fuzzy controller design. It is necessary to first give a brief description of the SVC models used for the controller design. The SVC is a shunt device of the FACTS family. It regulates voltage by generating or absorbing reactive power to or from the system. The SVC principle of operation is elaborately discussed in [1]. The model of a typical SVC is shown in Fig. 1

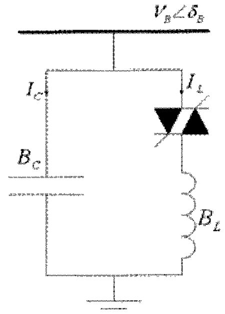

**Fig. 1.** A SVC model

The equivalent shunt admittance of an SVC, $B_{SVC}(\alpha)$, can be expressed as:

$$B_{SVC}(\alpha) = B_C - B_L(\alpha) \tag{1}$$

Where $B_C$ is the susceptance of the capacitor, the effective susceptance of the thyristor controlled rector (TCR), $B_L(\alpha)$, is controllable through adjusting the firing angle, α, of the thyristor. The steady state relationship is given as,

$$B_L(\alpha) = \frac{1}{\omega L}\frac{(2\pi + \sin 2\alpha - 2\alpha)}{\pi} \tag{2}$$

Since the firing angle control of the thyristor banks essentially controls the effective shunt admittance of the SVC presented to the network, the dynamic model can be expressed by (3),

$$\dot{B}_L(t) = \frac{1}{T_R(t)}(-B_L(t) + B_{L0} + k_B u_B(t)) \tag{3}$$

Where $T_R(t)$ is the parameter of the SVC regulator (in sec), $B_{L0}$ is the initial value of $B_L(t)$, and $k_B$ and $u_B(t)$ are gain and input of the SVC regulator. The dynamics from this SVC model will be considered together with inputs from the power system in the rough fuzzy controller design.

## 3. Design of Conventional Fuzzy and Rough-Fuzzy Controllers for SVC

This section deals with the design of the conventional fuzzy and rough fuzzy controller for the control loop of the SVC. The controller block for the SVC is shown in Fig. 2. The dynamics of the SVC are given in (3).

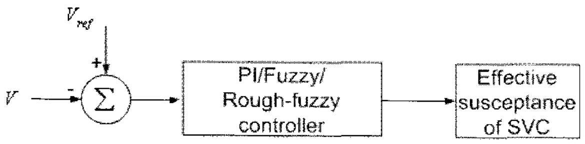

**Fig. 2.** SVC controller block

### 3.1 Fuzzy Rules

During the designing stage the linguistic variables are defined through their fuzzy membership functions and fuzzy sets. The error 'e' has three sets *ep* (error positive), *ez* (error zero), and *en* (error negative). Similarly, the rate (de/dt) has three sets *dep* (rate positive), *dez* (rate zero), and *den* (rate negative). Moreover, the fuzzy set control 'u' has three sets *op* (output positive), *oz* (output zero), and *on* (output negative) [12]. The fuzzy controller uses simple IF-THEN rules according to Table 1. The fuzzy rule table is taken from [21] which simulates the effect of the PI controller.

The membership functions for the error 'e' and its rate 'de/dt' are obtained, using trapezoidal and triangular membership characteristics (Fig. 3(a) and 3(b)). The membership values of the control outputs *on*, *oz*, and *op* for the output sets are presented in Fig. 3(c). The range of the membership functions is judiciously decided from various trials to obtain the best control performance.

**Table 1.** Fuzzy rule base for the control loop of the SVC

| e | de/dt | | |
|---|---|---|---|
| | *den* | *dez* | *dep* |
| *en* | *on* | *on* | *oz* |
| *ez* | *on* | *oz* | *op* |
| *ep* | *oz* | *op* | *op* |

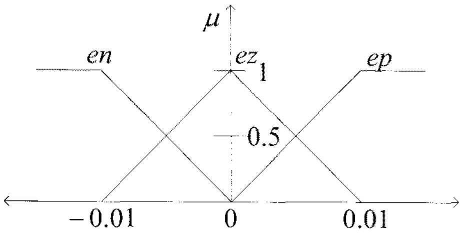

**Fig. 3 (a).** Membership function of error (e)

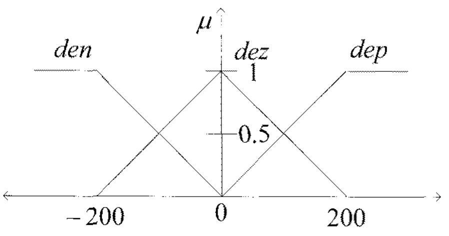

**Fig. 3. (b).** Membership function of error rate (de/dt)

The inference engine of the fuzzy-logic-based controller matches the preconditions of the rules in the fuzzy rule base with input state linguistic terms and performs implications. For example, for a given error and its rate, the firing strengths $\alpha_1$, $\alpha_2$,...$\alpha_9$ of rules 1 – 9 presented in Table-I are obtained as

$$\alpha_1 = \mu_{en}(e)^\wedge \mu_{den}(de/dt)$$

$$\alpha_2 = \mu_{ez}(e)^\wedge \mu_{den}(de/dt)$$

..........................................

$$\alpha_4 = \mu_{en}(e)^\wedge \mu_{dez}(de/dt)$$

..........................................

$$\alpha_9 = \mu_{ep}(e)^\wedge \mu_{dep}(de/dt)$$

where ^ stands for the fuzzy 'AND' operation and is the minimum operator. The control output of any rule is calculated by matching the strength of its precondition to its conclusion. Supposing rules 1, 2, and 4 have the same output set on, then Lukasiewicz OR is used to evaluate the output belongingness to 'on' class which is given by (5).

$$\beta_1 = \min(1, (\alpha_1 + \alpha_2 + \alpha_4)) \tag{5}$$

Using a centroid defuzzification technique, the incremental control output Δu is given by (6).

$$\Delta u = {\sum_i \beta_i u_i} \Big/ {\sum_i \beta_i} \tag{6}$$

where '$u_i$' corresponds to the center values of different output classes and $\beta_i$ is their firing strength. The linguistic fuzzy controller presented above is a nonlinear PI controller whose gains vary with the magnitude of the voltage error 'e' and its rate of change. Although this controller is expected to provide significant damping during transient disturbances of the power system, it may not be able to provide a robust control during significant changes in system operating conditions or parameters. Therefore, the concept of rough-fuzzy controller is introduced.

### 3.2 Rough Set Theory and Decision Table

Rough set theory, a new soft computing tool proposed by Pawlak, is concerned with the classificatory analysis of imprecise, uncertain, or incomplete information expressed in terms of data acquired from experience [17].

Let U be a finite set. The set U will be called a universe and elements of U will be referred to as states (situations or objects). Let R$\subseteq$U X U be an equivalence relation called an indiscernibility relation. We denote by U/R the family of all equivalence classes R, and $[x]_R$ denotes an equivalence class containing $x \subseteq$ U.

An ordered pair AR=<U, R> will be called an approximation space. With every $X \subseteq$ U we associate two sets defined as follows:

$$\underline{R}X = \{x \in U : [x]_R \subseteq X\}, \\ \overline{R}X = \{x \in U : [x]_R \cap X \neq \phi\} \tag{7}$$

called the R-lower and R-upper approximations of X in A$_R$, respectively. A set Bn$_R$($X$) = $\overline{R}\,X \setminus \underline{R}\,X$ will be called the R-boundary of $X$ in A$_R$. If $\overline{R}\,X = \underline{R}\,X$, we say that $X \subseteq$ U is R-exactly approximated in A. As we can see, in this case we have Bn$_R$($X$) = 0. If $\overline{R}\,X \neq \underline{R}\,X$, we say that $X \subseteq$U is R-roughly approximated in A$_R$. In this case we have Bn$_R$($X$) $\neq$ 0. In order to express numerically how a set can be approximated using all equivalence classes of R, we will use the accuracy of approximation of $X$ in A$_R$ (accuracy measure)

$$\alpha_R(X) = \frac{card\underline{R}X}{card\overline{R}X} \tag{8}$$

where, '*card*' refers to the cardinality of the rough sets. And if $X$ is R-exactly approximated in A$_R$ then $\alpha_R(X) = 1$. If X is R-roughly approximated in A$_R$, then $0 < \alpha_R(X) < 1$. Another measure derived from $\alpha_R(X)$ defined as Q$_R$($X$) = 1 - $\alpha_R(X)$ and is referred to as R-roughness of $X$. Roughness, as opposed to accuracy, represents the degree of inexact approximation of $X$ in A$_R$. Additional numerical characteristics of imprecision can be expressed by ( 9-11).

The rough R-membership function of the set $X$, is expressed as,

$$\mu_X^R(x) = \frac{card([x]_R \cap X)}{card([x]_R)} \tag{9}$$

With respect to the possessed knowledge, the coefficient characterizing the uncertainty of the membership of the element to the set can be written as

$$\mu_X(x) = \frac{card([x]_R \cap X)}{card(U)} \tag{10}$$

And the quality of approximation of the family $F = \{X_1, X_2, ......., X_n\}, X_i \subset U$ and $X_i \cap X_j \neq \phi$,

$$\gamma_R(F) = \frac{\sum_{i=1}^{n} card(\underline{R}X_i)}{card(U)} \tag{11}$$

These measures can be used to express the roughness factor and are presented in [17] in detail. The above-mentioned measures may be used in rough fuzzy controller synthesis.

The decision table is an effective tool in rough set methodology when performing data analysis. It can be viewed as a two dimensional table where each row describes an object with condition attributes and decision attributes.

In such a decision table an indiscernibility relation with respect to both condition and decision attributes can be determined. Two arbitrary rows in the decision table are indiscernible if and only if their condition and decision attributes have the same values. As it is seen, the indiscernibility relation divides all rows of the decision table into equivalence classes. The family of equivalence classes is denoted by C* when the condition attributes are considered. D* denotes the family of equivalence classes while decision attributes are considered. It should be emphasized here that one of the main implicational aspects of rough sets is to approximate elements of D* with elements of C*.

The corresponding knowledge base for a rough fuzzy controller for SVC is created in the following way. At the beginning, a decision table is made, where condition attributes C = {e, de} corresponds to a decision attribute D = {u} as presented in Table 2.

**Table 2.** Decision table in a rough set theory

| S. No | e | de | u | Decision rules implied |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | e=0, de=0 ⇒ u=0 |
| 2 | 1 | 0 | 0 | e=1, de=0 ⇒ u=0 |
| 3 | 2 | 0 | 1 | e=1, de=0 ⇒ u=1 |
| 4 | 0 | 1 | 0 | e=1, de=0 ⇒ u=0 |
| 5 | 1 | 1 | 1 | e=1, de=0 ⇒ u=1 |
| 6 | 2 | 1 | 2 | e=1, de=0 ⇒ u=2 |
| 7 | 0 | 2 | 1 | e=1, de=0 ⇒ u=1 |
| 8 | 1 | 2 | 2 | e=1, de=0 ⇒ u=2 |
| 9 | 2 | 2 | 2 | e=2, de=2 ⇒ u=2 |

For the condition attributes the following domain was assumed: e = de = {0, 1, 2} as shown in Fig.4 (a) and 4(b) and the domain u = {0, 1, 2} was assumed for the decision attribute as depicted in Fig. 4(c). The rules are identical to fuzzy rules in Table I. The range of the rough membership function is taken as half of the range of the fuzzy membership function. The respective non deterministic decision table contained 9 decision rules. Division of the universum U with respect to the indiscernibility relation for decisions gives D* = {X0, X1, X2}.

The accuracy measure and roughness factor for the elements of D* are as below:

$$\alpha_R(X_0) = 1/3, \quad \rho_R(X_0) = 2/3,$$
$$\alpha_R(X_1) = 1/3, \quad \rho_R(X_1) = 2/3,$$
$$\alpha_R(X_2) = 1/3, \quad \rho_R(X_2) = 2/3,$$

where $X_0$, $X_1$ and $X_2$ represent the output domain $u = \{0, 1, 2\}$.

Using the rough membership functions, the value of 1 is obtained for the certain regions and 0 for all uncertain regions of condition attributes and decision attributes as well.

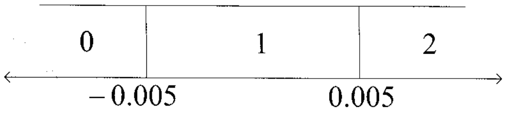

**Fig. 4(a).** Rough membership function of rough set 'e'

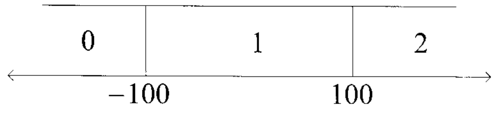

**Fig. 4(b).** Rough membership function of rough set 'de'

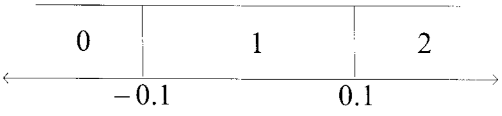

**Fig. 4(c).** Rough membership function of rough set 'u'

The difference between the membership functions of fuzzy sets and rough membership functions of rough sets should be emphasized. The former are usually intuitively designed whereas the latter, being upper semi continuous functions, are computable in an algorithmic way.

The number of rules fired in the case of the rough-fuzzy controller is far less than that of the fuzzy controller. For instance, for a particular value of 'e' and 'de', four rules are fired in the fuzzy controller whereas only one rule is fired in the case of the rough controller. However, from a computational point of view we may consider the rough membership functions of the rough sets as the step-function approximation of the membership functions of fuzzy sets, which are restricted to be either 1 or 0. While controlling the system it can be observed that using a fuzzy logic controller we get a smooth control value as a function of time; applying a rough fuzzy controller we get a sharp function of time for the control value. Nevertheless, the quality of control does not differ much for both controllers.

## 4. Case Study

The proposed controllers are tested on the two machine three bus power system shown in Fig 5. A system resembles a simplified two area model.

In the test power system, a 1000 MW hydraulic generation plant (M1) is connected to a load center through a long 500 kV, 700 km transmission line. A 5000 MW resistive load models the load center. This load is fed both by the remote 1000 MVA plant and by a local generator of 5000 MVA (plant M2).

The Static Var Compensator (Phasor Type) block of the FACTS library of MATLAB/SIMULINK is a simplified model that can simulate any SVC topology and is used in this paper to investigate the effect of the proposed controllers. It is interfaced with the phasor simulation option of the Powergui block (in the MATLAB) for studying the dynamic performance and transient stability of power systems. Therefore, Fig. 5 is simulated and a load flow has been performed on the system with plant M1 generating 950 MW and M2 4056 MW. Under this condition the line carries 944 MW, which is close to its surge impedance loading (SIL = 977 MW). To maintain system stability after faults, the transmission line is shunt compensated at its center by a 200MVAR static VAR compensator (SVC). The SVC does not have a power oscillation-damping (POD) unit. The two machines are equipped with a Hydraulic Turbine and Governor (HTG), and an Excitation system. To start the simulation in steady state, the machines and the regulators have been previously initialized by means of the Load Flow and Machine Initialization of the Powergui block. Load flow has been performed with machine M1 defined as a PV generation bus ($V$=13.8 KV, $P$=950 MW) and machine M2 defined as a swing bus ($V$=13.8 KV $\angle 0$ degrees). After the load flow has been solved, the reference mechanical powers and reference voltages for the two machines have been automatically updated in the two constant blocks connected at the HTG and excitation system inputs. The typical

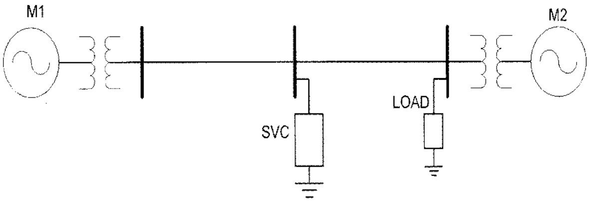

**Fig. 5.** A two machine system with SVC

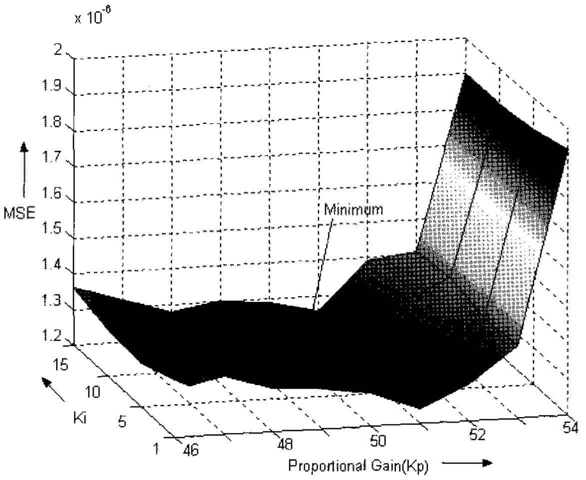

**Fig. 6.** MSE variation with different values of $K_p$ and $K_i$

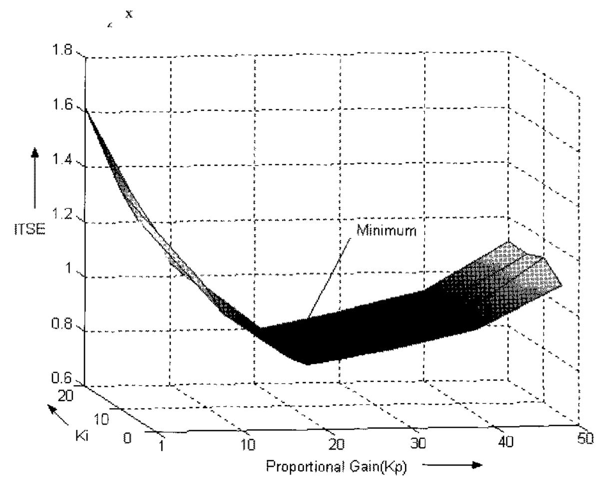

**Fig. 7.** ITSE variation with different values of $K_p$ and $K_i$

values are as follows: $P_{ref1}$=0.95 p.u. (950 MW), $V_{ref1}$=1.0 p.u.; $P_{ref2}$=0.8091 p.u. (4046 MW), and $V_{ref2}$=1.0 p.u. The error is $e(k)=V_{ref}-V(k)$, where $V_{ref}$ is the reference voltage in the SVC.

The conventional PI controller is optimized under the two criterions of Mean square error (MSE) and Integral time square error (ITSE) for the most commonly occurring disturbance i.e. a single phase to ground fault near generator 1. It is depicted in Fig. 6 and Fig. 7, respectively.

The inter-area oscillation of the system for the same fault is depicted in Fig. 8 for both schemes.

It is observed that with ITSE criterion the transient response is slightly better then the MSE method. Moreover, the ITSE scheme results to lower the values of gain hence it is easy to realize. So the values of the PI controller optimized under the ITSE criterion are chosen and the values of $K_P$ and $K_i$ are 20 and 10, respectively.

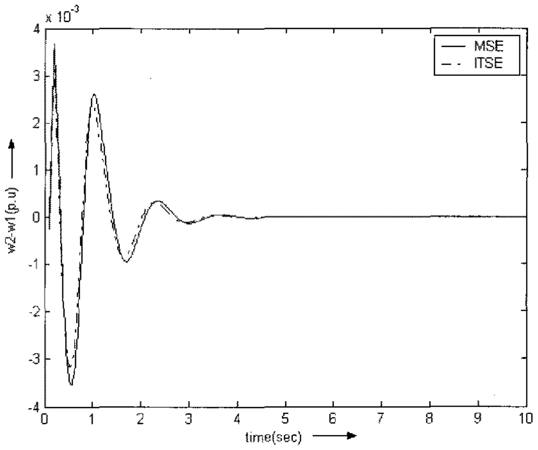

**Fig. 8.** Performance of the PI controller to damp out the inter area oscillations under the two optimizing scheme criterions

A single line to ground fault is initiated near the first generator at 0.1 sec after the simulation is started and the fault is removed without opening of the transmission lines. The response of different control schemes at two different operating conditions are shown in Fig. 9 and Fig. 10.

As the PI, fuzzy and rough fuzzy controllers are optimized for the single line to ground fault so that the response of the system under single LG fault is almost identical for all types of controllers as in Fig. 9. However, under the load change, the performance of the rough-fuzzy controller is much better than the other two controllers as depicted in Fig. 10. When the fault is removed by the opening of the transmission line under single LG fault, the response is as provided in Fig. 11. Here too, rough-fuzzy and fuzzy controllers perform better than the conventional PI controller. It shows that the rough fuzzy controller gives superior performance under changed system operating conditions.

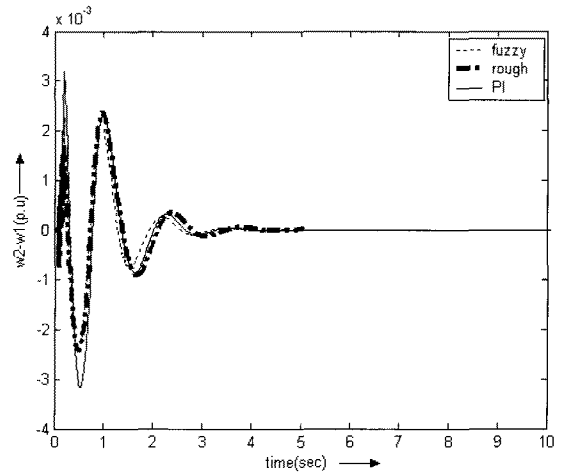

**Fig. 9.** Inter area oscillations of the system under LG fault and the load of 000 MW with different controllers

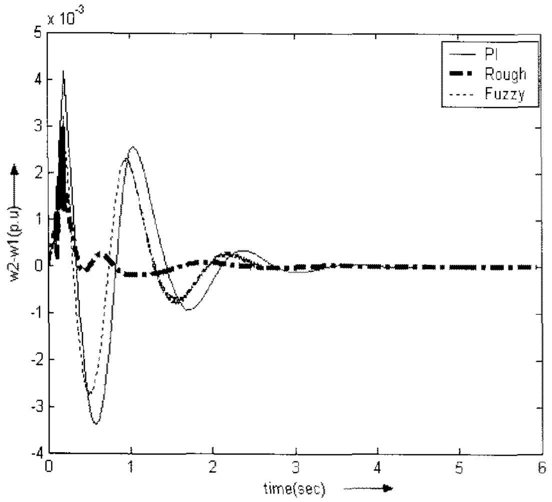

Fig 10. Inter area oscillations of the system under LG fault and load of 5500MW with different controllers

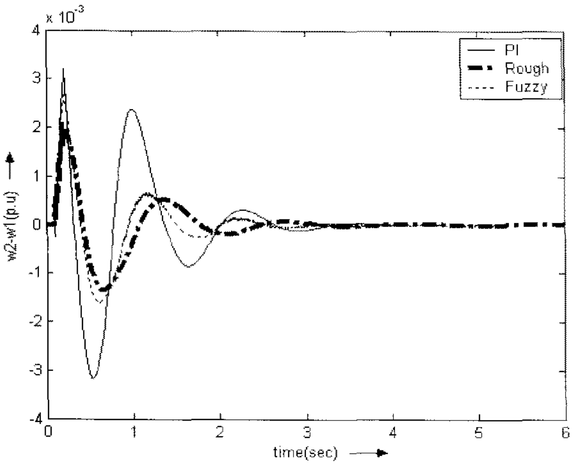

Fig. 11. Inter area oscillations of the system under LG fault and load of 5000MW with different controllers when fault is removed by opening of transmission line

The system is then subjected to a 3 Phase fault near the first generator at 0.1 sec after the simulation is started and the fault is removed from the system after 6 cycles (for 60 Hz. system frequency) without opening the transmission lines. The responses are presented in Fig. 12 and Fig. 13 under different loading conditions. The efficacy of the rough fuzzy controller over the other two controllers is again clear.

On the other hand, CCT for the same 3 phase fault is calculated and presented in Table 3. When the PI controller is used, the CCT is 8.304 cycles (60 Hz. System) and it is increased to 8.99 cycles with the implementation of the fuzzy controller. This is further improved with the help of the rough-fuzzy controller at which time the CCT of the system becomes 9.051 cycles. This is an improvement of 8% and 9% respectively, compared with the original PI controller alone. From a power system stability viewpoint, such improvement can be very useful especially during emergency situations when even seconds to allow emergency control to take effect could mean avoidance of cascading failure.

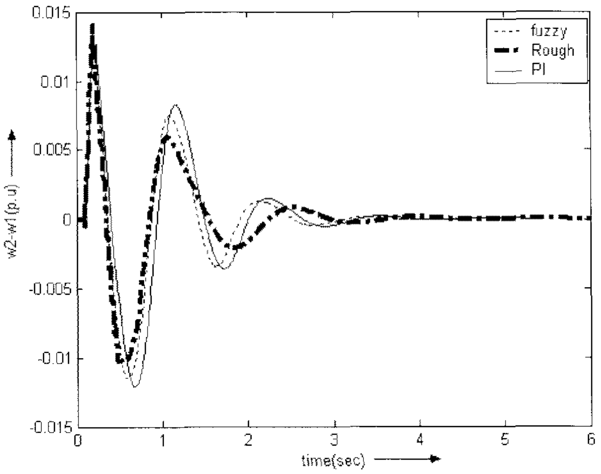

Fig. 12. Inter area oscillations of the system under 3 phase fault and load of 5000MW with different controllers.

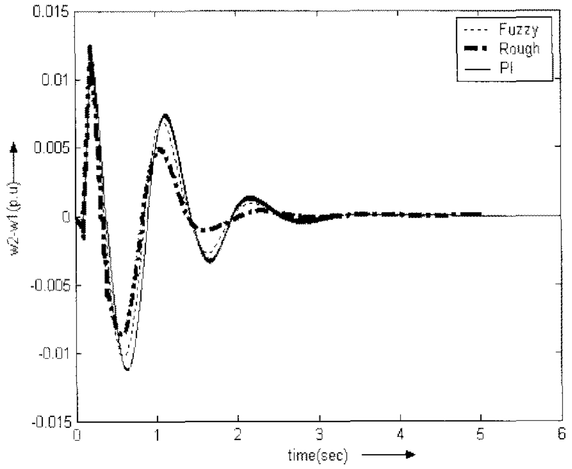

Fig. 13. Inter area oscillations of the system under 3 phase fault and load of 4500MW with different controllers

Table 3. Improvement in CCT with the application of different types of SVC controllers

| CCT with controllers (in cycles) | | |
|---|---|---|
| PI | Fuzzy | Rough-fuzzy |
| 8.304 | 8.99 | 9.051 |

## 5. Conclusion

A rough fuzzy based SVC controller is proposed in this paper to enhance power system oscillatory and transient stability. Although rough set theory had been proposed a long time ago as a data mining tool, the applications of a rough set theory in designing a rough fuzzy based control scheme to the stabilizing loop of a static VAR compensator for improving system damping during transient disturbances is still a novel development. Fuzzy controller approach has been used quite widely for various applications, however, how to extend fuzzy controller to plants where the number of fuzzy sets are too much to remain feasible is an outstanding question. Rough set theory provides a very useful solution to fuzzy controller design. It requires fewer rules to be fired with the rough fuzzy controller compared with the fuzzy only controller; and therefore it allows faster control. Based on this property, the rough fuzzy controller can be more useful for large scale power systems where large numbers of rules are required for the satisfactory performance of the controller. From a data mining point of view, although there has been increasing attention and application of the data mining method in power system security assessment, application of rough set theory is yet to be explored. The performance of the proposed rough fuzzy SVC controller, although not firing as much rules as the fuzzy controller, is compared with that of fuzzy alone and PI controllers. The rough fuzzy controller is found to be more effective than the conventional fuzzy and PI controller. Also, the CCT of the system is increased on the application of the rough fuzzy controller.

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