Damping of Power System Disturbances using UPFC Based on Fuzzy Logic

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Abstract: This paper presents a new control method based on Fuzzy Logic technique to control a Unified Power Flow Controller (UPFC) installed in a single-machine infinite-bus power system. The objective of the Fuzzy Logic based UPFC controller is to damp power system oscillations. The Fuzzy Logic based UPFC controller is designed by selecting appropriate Controller parameters based on the knowledge of the power system performance. Simple Fuzzy Logic controller using MAMDANI-type inference system is used. The effectiveness of the new controller is demonstrated through time-domain simulation studies. The results of these studies show that the designed controller has an excellent capability in damping power system oscillations.

Keywords: Power System Disturbances; FACTS; Fuzzy Logic; Unified Power Flow Controller (UPFC).

I. INTRODUCTION

Power systems are also often subject to low frequency electro-mechanical oscillations resulting from electrical disturbances and consequence of the development of interconnection of large power system. The growth of the demand for electrical energy leads to loading the transmission system near their limits. Thus, the occurrence of the LFO has increased. FACTS Controllers has capability to control network conditions quickly and this feature of FACTS can be used to improve power system stability. The UPFC is a FACTS device that can be used to the LFO. The primarily use of UPFC is to control the power flow in power systems. The UPFC also used for enhancement of transient stability, mitigation of system oscillations and voltage regulation. It is used to control the power flow in the transmission systems by controlling the impedance, voltage magnitude and phase angle. This device can allow the path of power as we desire. UPFC is actually a combination of two FACTS device which are STATCOM (Static Synchronous Compensator) and SSSC (Static Series Synchronous Compensator). Generally, power system stabilizers (PSS) are applied on selected generators to damp local oscillation modes effectively. The fast progress in the field of power electronics has widened the option for power industry to improve power system stability via utilization of the controllable flexible alternating current transmission system (FACTS).

According to IEEE, FACTS device is “a power-electronic based system and other static equipment that provide control of one or more ac-transmission system parameters to enhance controllability and increase power-transfer capability”. As Power System Stabilizer been applied to damp local oscillation modes, Static VAR Compensator (SVC) which is one of the FACTS devices, has been used as a supplementary controller to improve transient stability and power oscillation damping of the system. However, conventional controller cannot provide satisfactory Performance over a wide range of operation points and under large disturbances since power system is a non-linear system. Now a days, fuzzy logic controller (FLC) provides an effective control theory in enhancing power system stability due to its easiness in design also capability of tolerating uncertainty and imprecision in system parameters and condition changes. Fuzzy-coordination controller is presented in this paper for the coordinated of traditional FACTS controllers. The fuzzy logic controllers are rule-based controllers in which a set of rules represents a control decision mechanism to adjust the effect of certain cases coming from power system. Furthermore, fuzzy logic controllers do not require a mathematical model of the system. They can cover a wider range of operating conditions and they are robust. This paper focuses on the optimization of conventional power oscillation damping (POD) controllers and fuzzy logic coordination of them. By using fuzzy-coordination controller, the coordination objectives of the FACTS devices are quite well achieved.

II. PROPOSED WORK

This paper presents a new control method based on Fuzzy Logic technique to control a Unified Power Flow Controller (UPFC) installed in a single-machine infinite-bus power system. The objective of the Fuzzy Logic based UPFC controller is to damp power system oscillations. Single-machine power system equipped with a UPFC is used to model the system. The Fuzzy Logic based UPFC controller is designed by selecting appropriate controller parameters based on the knowledge of the power system performance. The UPFC is a generalized synchronous voltage source (SVS), represented at the fundamental frequency by voltage Phasor with controllable magnitude and angle in series with the
transmission line UPFC consists of two voltage source converters. In the parallel branch of UPFC the active power is controlled by the phase angle of the converter output voltage. In the series branch of UPFC the active and reactive power flows in the transmission line are influenced by the amplitude as well as the phase angle of the series injected voltage. Therefore, the active power controller can significantly affects the reactive power flow and vice versa.

**Fig 1. UPFC installed in a single-machine infinite-bus power system.**

**A. Model of the Power System Including UPFC**

UPFC is one of the famous FACTs devices that is used to improve power system stability. Fig.1 shows a single machine-infinite-bus (SMIB) system with UPFC. It is assumed that the UPFC performance is based on pulse width Modulation (PWM) converters.

\[
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E' \\
\Delta E_\beta \\
\Delta v_{dc}
\end{bmatrix}
= 
\begin{bmatrix}
0 & \omega_b & 0 & 0 & 0 \\
-\frac{k_1}{M} & -\frac{D}{M} & \frac{k_2}{M} & 0 & -\frac{k_\beta}{M} \\
\frac{k_1}{T_{dE}} & 0 & \frac{1}{T_{dE}} & 0 & -\frac{k_\beta}{T_{dE}} \\
-\frac{k_1}{T_{dE}} & 0 & \frac{1}{T_{dE}} & 0 & -\frac{k_\beta}{T_{dE}} \\
\frac{k_1}{T_{dE}} & 0 & \frac{1}{T_{dE}} & 0 & -\frac{k_\beta}{T_{dE}}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E' \\
\Delta E_\beta \\
\Delta v_{dc}
\end{bmatrix}
\]

In figure 1 me, mb and \(\delta E, \delta B\) are the amplitude modulation ratio and phase angle of the reference voltage of each voltage source converter respectively. These values are the input control signals of the UPFC (fig 2). As it mentioned previously, a linearized model of the power system is used in dynamic studies of power system. In order to consider the effect of UPFC in damping of LFO, the dynamic model of the UPFC is employed; In this model the resistance and transient of the transformers of the UPFC can be ignored. Where \(\Delta m_E, \Delta m_B, \Delta \delta E\) and \(\Delta \delta B\) are the deviation of input control signals of the UPFC.

**Fig2. Unified Power Flow Controller (Phasor Type).**

**B. STATCOM**

In 1999 the first SVC with Voltage source converter called STATCOM (Static compensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyrstors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage. The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC. This means, that even during most severe contingencies, the STATCOM keeps its full capability.

In the distributed energy sector the usage of voltage source converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power. STATCOMs are based on Voltage Sourced Converter (VSC) topology and utilize either Gate-Turn-off Thyristors (GTO) or isolated Gate Bipolar Transistors (IGBT) devices. The STATCOM is a very fast acting, electronic equivalent of a synchronous condenser. If the STATCOM voltage, \(V_s\), (which is proportional to the dc bus voltage \(V_c\)) is larger than bus voltage, \(E_s\), then leading or capacitive VARS are produced (fig 3). If \(V_s\) is smaller than \(E_s\) then lagging or inductive VARS are produced.
C. The Control Mechanism of Series Converter

The main function of UPFC is actualized by the series converter. It controls the magnitude and the angle of the voltage injected in series with the line. This voltage injection is always intended to influence the power flow the line.

Fig. 4: Fuzzy controller based control mechanism.

The magnitude and the phase angle of series-injected voltage $V_{\text{inj}}$ is calculated by control mechanism to provide the desired real and reactive power flow in the transmission line. In the process of doing this, the series inverter will exchange real and reactive power with the line. The reactive power is electronically provided by the series inverter and the real power is transmitted to the dc terminals. The control mechanism of series converter is shown in Fig. 4.

III. FUZZY LOGIC

In this context, FL is a problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded micro-controllers to large, networked, multi-channel PC or workstation-based data acquisition and control systems. It can be implemented in hardware, software, or a combination of both. FL provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. FL's approach to control problems mimics how a person would make decisions, only much faster. Figure 5 shows the block diagram of fuzzy logic.

Fig. 5. FLC block diagram.

A. Fuzzy Logic Different From Conventional Control Methods

FL incorporates a simple, rule-based IF X AND Y THEN Z approach to a solving control problem rather than attempting to model a system mathematically. The FL model is empirically-based, relying on an operator's experience rather than their technical understanding of the system. For example, rather than dealing with temperature control in terms such as "SP = 500F", "T < 1000F", or "210C < TEMP < 220C", terms like "IF (process is too cool) AND (process is getting colder) THEN (add heat to the process)" or "IF (process is too hot) AND (process is heating rapidly) THEN (cool the process quickly)" are used. These terms are imprecise and yet very descriptive of what must actually happen. Consider what you do in the shower if the temperature is too cold: you will make the water comfortable very quickly with little trouble. FL is capable of mimicking this type of behavior but at very high rate.

B. FL Working Method

FL requires some numerical parameters in order to operate such as what is considered significant error and significant rate-of-change-of-error, but exact values of these numbers are usually not critical unless very responsive performance is required in which case empirical tuning would determine them. For example, a simple temperature control system could use a single temperature feedback sensor whose data is subtracted from the command signal to compute "error" and then time-differentiated to yield the error slope or rate-of-change-of-error, hereafter called "error-dot". Error might have units of degs F and a small error considered to be 2F while a large error is 5F. The "error-dot" might then have units of degs/min with a small error-dot considered to be 5F/min and a large one being 15F/min. These values don't have to be symmetrical and can be "tweaked" once the system is operating in order to optimize performance. Generally, FL is so forgiving that the system will probably work the first time without any tweaking. The section of FLC is divided in three subsections. These subsections are given as summarized in the following:

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1. Fuzzification

The fuzzification process is concerned with finding a fuzzy representation of non-fuzzy input values where it achieved through application of the MF associated with each fuzzy set in the rule input space. A fuzzy set is an extension of a classical set. If \( X \) is the universe of discourse and its elements are denoted by \( x \), then a fuzzy set \( A \) in \( X \) is defined as a set of ordered pairs. Thus, in mathematical equation:

\[
A = \{x, \mu_A(x) | x \in X\}
\]

(2)

Where \( \mu_A(x) \) is called the MF of \( x \) in \( A \). MF is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. There are several types of MFs such as triangular, trapezoid, Gaussian and polynomial. Triangular is the simplest and effective MF since it is formed using straight lines. For the F-SVC, the triangular type of MF is been used. The inputs are fuzzified using three fuzzy sets: positive (P), zero (Z) and negative (N), as shown in Fig. 4. The inputs to the fuzzy controller are error and derivative error \( (e(k), _{(k)}) \).

As mentioned before, Takagi-Sugeno has two types of output MF which are constant and linear. As for this controller, linear type of output MF is utilized. Both inputs and output of the FLC run at normalized universe \([-1 1]\).

2. Membership Functions

The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system. There are different memberships functions associated with each input and output response. Some features to note are:

\[
\text{SHAPE: Triangular is common, but bell, trapezoidal, haversine and, exponential have been used. More complex functions are possible but require greater computing overhead to implement. HEIGHT or magnitude (usually normalized to 1) WIDTH (of the base of function), SHOULDERING (locks height at maximum if an outer function. Shouldered functions evaluate as 1.0 past their center) CENTER points (center of the member function shape) OVERLAP (N&Z, Z&P, typically about 50% of width but can be less). Figure 6 illustrates the features of the triangular membership function which is used in this example because of its mathematical simplicity. Other shapes can be used but the triangular shape lends itself to this illustration. The degree of membership (DOM) is determined by plugging the selected input parameter (error or error-dot) into the horizontal axis and projecting vertically to the upper boundary of the membership function(s).}

3. Error & Error-Dot Function Membership

The degree of membership for an "error" of -1.0 projects up to the middle of the overlapping part of the "negative" and "zero" function so the result is "negative" membership = 0.5 and "zero" membership = 0.5. Only rules associated with "negative" & "zero" error will actually apply to the output response. This selects only the left and middle columns of the rule matrix. For an "error-dot" of +2.5, a "zero" and "positive" membership of 0.5 is indicated. This selects the middle and bottom rows of the rule matrix. By overlaying the two regions of the rule matrix, it can be seen that only the rules in the 2-by-2 square in the lower left corner (rules 4,5,7,8) of the rules matrix will generate non-zero output conclusions. The others have a zero weighting due to the logical AND in the rules.

4. Inference

The task of the inference process is to map the fuzzified inputs (as received from the fuzzification process) to the rule base, and to produce a fuzzified output for each rule. The relation between the inputs and output of FLC is defined by a set of rules. A typical rule in a Takagi- Sugeno fuzzy model has the form:

If Input 1 = \( x \) and Input 2 = \( y \), then

Output is:

\[
z = ax + by + c
\]

Fig:6: The features of a membership function.

Rule 1: If voltage error, \( e \) (k) is N AND change of error \( de(k) \) is Z, then the output (susceptance) is \( N \).

Rule 2: If voltage error, \( e \) (k) is Z AND change of error \( de(k) \) is Z, then the output (susceptance) is \( Z \).

The two inputs and single output of FLC will result in total of 9 rules. Table 1 shows the rule base of the FLC.
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TABLE I: Rule Base of the Fuzzy Controller

<table>
<thead>
<tr>
<th>ε[k]</th>
<th>ε[k]</th>
<th>u[k]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>N</td>
<td>Z</td>
</tr>
<tr>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Z</td>
<td>N</td>
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<tr>
<td>P</td>
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<tr>
<td>P</td>
<td>Z</td>
<td>P</td>
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</table>

5. Defuzzification

In the defuzzification process, the controller outputs represented as linguistic labels by a fuzzy set are converted to the real control (analog) signals. In the created fuzzy model, “Sugeno’s Weighted Average” method which is the special case of “Mamdani Model” is selected for the defuzzification process [21]. According to this model, the defuzzification is achieved by using following equations:

\[
y = \frac{\sum_{i=1}^{M} w_i y_i}{\sum_{i=1}^{M} w_i}
\]

\[
w_i = \prod_{k=1}^{n} M_{R_i}^{e_k}(x_k)
\]

Where \( w_i \) the overall truth value of the rule is \( \epsilon^{k}, y_i^{e_k}(x_k) \). The membership function described the meaning of the linguistic variable \( R_i \).

C. FL Defining Methods

1. Define the control objectives and criteria: What am I trying to control? What do I have to do to control the system? What kind of response do I need? What are the possible (probable) system failure modes?
2. Determine the input and output relationships and choose a minimum number of variables for input to the FL engine (typically error and rate-of-change-of-error).
3. Using the rule-based structure of FL, break the control problem down into a series of IF X AND Y THEN Z rules that defines the desired system output response for given system input conditions. The number and complexity of rules depends on the number of input parameters that are to be processed and the number fuzzy variables associated with each parameter. If possible, use at least one variable and its time derivative. Although it is possible to use a single, instantaneous error parameter without knowing its rate of change, this cripples the system’s ability to minimize overshoot for a step inputs.
4. Create FL membership functions that define the meaning (values) of Input/output terms used in the rules.
5. Create the necessary pre- and post-processing FL routines if implementing in S/W, otherwise program the rules into the FL H/W engine.
6. Test the system, evaluate the results, tune the rules and membership functions, and retest until satisfactory results are obtained.

1. Signal Processing

The control signals are produced from the output of FLC process. They are used in the generation of switching signals for converter by comparing with carrier signal.

IV. SIMULATION RESULTS

Firstly Simulation is done with the help of MATLAB software for the model of SMIB with UPFC as shown in the above section.

Fig7: Disturbances in Transmission lines.

Fig8: Output waveform of Rotor angle, Rotor Speed and Torque.
Taking step change in mechanical input power ($P_m = 0.01$ pu.) shown in Fig. 7. Consequently simulation results show that fuzzy controller successfully increases damping rate and decreases the amplitude of low frequency oscillations (fig 8 and 9).

V. CONCLUSION

In this paper, a complete state space model for a single machine infinite-bus power system equipped with a UPFC is presented to study power system oscillations. Two controllers based on fuzzy logic technique have been developed and investigated. Time simulations based on small system disturbances have shown the effectiveness of these controllers in damping power system oscillations. In future enhancement we can change the type of controller like Distributed Power Flow Controller for improving the stability and other system parameters.

VI. REFERENCES