Performance Evaluation of Fuzzy-Logic Controller Applied to a Transmission System with STATCOM

A. ABDERRAHMANI, A. CHAKER and A. LAOUFI

ABSTRACT - This paper proposes and validates the models to accurately represent the STATCOM in voltage stability studies of power systems and the development of a fuzzy logic controller for damping oscillations in FACTS. The ability of fuzzy logic to handle rough and unpredictable real world data made it suitable for a wide variety of applications, especially, when the models or processes are too complex to be analyzed by classical methods. These models are first validated by means of MATLAB simulations on a test system, and then are implemented into two different methods used to study voltage in the system.

Keywords: FACTS, STATCOM, Modeling, Reactive compensation, Controls Method, Fuzzy-Logic controller.

1. INTRODUCTION

As power demand grows rapidly and expansion in transmission and generation is restricted by the limited availability of resources and the strict environmental constraints, power systems are today much more loaded than before. This causes the power systems to be operated near their stability limits. The development and use of FACTS controllers in power transmission systems has led to many applications of these controllers to improve the stability of power networks.

The STATic synchronous shunts COMpensators (STATCOM) is one of the most versatile flexible AC transmission system devices, which can be used to control the reactive power flows in a transmission line by injecting a variable reactive current. The STATCOM is a power electronics-based Synchronous Voltage Generator (SVG) that generates a three-phase voltage from a DC capacitor in synchronism with the transmission line voltage. The basic STATCOM model consists of a step-down transformer with leakage reactance, a three-phase GTO VSI, and a DC side capacitor shown in Figure 1. The AC voltage difference across this transformer leakage reactance produces reactive power exchange between the STATCOM and the power system at the point of interface. The voltage can be regulated to improve the voltage profile of the interconnected power system, which is the primary duty of the STATCOM. A secondary damping function can be added to the STATCOM for enhancing power system dynamic stability.

The STATCOM main function is to regulate key bus voltage magnitude by dynamically absorbing or generating reactive power to the AC grid network, like a thyristor static compensator. This reactive power transfer is done through the leakage reactance of the coupling transformer by using a secondary transformer voltage in phase with the primary voltage (network side). This voltage is provided by a voltage-source PWM inverter and is always in quadrature to the STATCOM current [01]. The operation and control fundamentals of the STATCOM have been extensively discussed in [1], [5] and [12].

The control system is based on a decoupled strategy or d-q transformation that makes it possible to control the reactive current flow between the STATCOM and the transmission system. Until now, the most frequently used strategy has been the conventional property and integrates (PI). Proposed a fuzzy-logic controller as the substitution of the traditional controller. The results reveal that the fuzzy-logic controller proposed in this paper is very effective.

The operation of the full STATCOM model is fully studied in both capacitive and inductive modes in a power transmission system and load excursion.

Fig. 1. STATCOM configuration.

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2. STATCOM MODELS

Due to the nature of the inverter switching, the dynamic models of FACTS devices are nonlinear and non-constant. In addition, the dynamics of the inverter switches are much faster than the power system dynamics of interest. Therefore, it is desirable to develop a set of simplified state-based models for the FACTS devices that are sufficiently detailed to provide accurate representation of the real hardware system, yet simple enough for implementation in a power system simulation [13].

By injecting a current of variable magnitude in quadrature with the line voltage, the STATCOM can inject reactive power into the power system. The STATCOM does not employ a capacitor or reactor banks to produce reactive power as does the SVC, but instead uses a capacitor to maintain a constant voltage for the inverter operation. An equivalent circuit for the STATCOM is shown in Figure 2.

![Fig. 2. 2 Equivalent circuit of the STATCOM.](image)

\[
\begin{align*}
\frac{d}{dt} [I_{ab,d}] &= \begin{bmatrix}
\frac{R_{ab}}{L_{ab}} & 0 & 0 \\
0 & \frac{R_{ab}}{L_{ab}} & 0 \\
0 & 0 & -\frac{R_{ab}}{L_{ab}}
\end{bmatrix} [I_{ab,d}] + \begin{bmatrix}
\frac{1}{L_{ab}} \\
\frac{1}{L_{ab}} \\
\frac{1}{L_{ab}}
\end{bmatrix} (V_{1,d} - V_{a,b}) \\
\frac{d}{dt} [I_{ab,q}] &= \begin{bmatrix}
\frac{R_{ab}}{L_{ab}} & 0 & 0 \\
0 & \frac{R_{ab}}{L_{ab}} & 0 \\
0 & 0 & -\frac{R_{ab}}{L_{ab}}
\end{bmatrix} [I_{ab,q}] + \begin{bmatrix}
\frac{1}{L_{ab}} \\
\frac{1}{L_{ab}} \\
\frac{1}{L_{ab}}
\end{bmatrix} (V_{1,q} - V_{a,b})
\end{align*}
\]

Where:
- \(R_{ab}\) and \(L_{ab}\) represent the STATCOM transformer losses;
- \(V_{ab}\) and \(V_{a,b}\) are the inverter ac side phase voltages;
- \(V_{1,abc}\) are the System side three phase voltages.

The output of the STATCOM is given by:

\[E_s = k V_{DC} \cos(\alpha t + \phi)\]

Where:
- \(V_{DC}\) is the voltage across the capacitor;
- \(\alpha\) is the injected voltage phase angle;
- \(k\) is the PWM modulation gain.

The control objectives for the STATCOM are to provide independent reactive power support and to maintain constant the capacitor voltage. This is best accomplished by regulating the PWM switching commands to alter the modulation index and phase angle in equation 2.

3. DECOUPLED CONTROL METHOD

The new decoupled control system is based on a full \(dq\) decoupled current control strategy using both direct and quadrature current components of the STATCOM AC current [01].

It can be shown that with line resistance included, the mathematical model for the response of a Voltage Sourced Converter to an. applied voltage \(V=V_d\) into a synchronously rotating orthogonal system can be given as

\[
\frac{d}{dt} [I_{ab,d}] = \begin{bmatrix}
\frac{R_{ab}}{L_{ab}} & 0 & 0 \\
0 & \frac{R_{ab}}{L_{ab}} & 0 \\
0 & 0 & -\frac{R_{ab}}{L_{ab}}
\end{bmatrix} [I_{ab,d}] + \begin{bmatrix}
\frac{1}{L_{ab}} \\
\frac{1}{L_{ab}} \\
\frac{1}{L_{ab}}
\end{bmatrix} (V_{1,d} - V_{a,b})
\]

For the purposes of further derivation of the new control system, the classical decoupled watt-var algorithm was studied. By interdicting two new variables \(X_1\) and \(X_2\):

\[
\begin{align*}
X_1 &= \frac{1}{L_{ab}} (V_{1,d} - V_{a,b}) \\
X_2 &= \frac{1}{L_{ab}} (V_{1,q} - V_{a,b})
\end{align*}
\]

Thus we see that if we have \(U_1 = \alpha I_{ab,q} + X_1\) and \(U_2 = -\alpha I_{ab,q} + X_2\) as control variables.

Thus it is seen from equation (06) that by controlling \(U_1\) and \(U_2\) one can independently regulate \(I_{ab,d}\) and \(I_{ab,q}\) thereby controlling the real \((P_{ab})\) and the reactive power flow \((Q_{ab})\).

By controlling \(U_1\) the real power flow \((P_{ab})\) and hence the DC link capacitor voltage \((V_{DC})\) can be regulated. By controlling \(U_2\) the reactive power flow \((Q_{ab})\) can be regulated [01]. To close the feedback loop, the auxiliary variables \(U_1\) and \(U_2\) are controlled by proportional-integral (PI) controllers as given below in equation 7. The D-axis current \(I_{ab,d}\) is controlled by \(u_1\) and the Q-axis current \(I_{ab,q}\) is controlled by \(u_2\).

\[
\begin{align*}
I_{sh,d,ref} &= (K_{ph} + K_{ph}^d) (V_{CD,ref} - V_{CD}) \\
I_{sh,q,ref} &= (K_{ph} + K_{ph}^q) (V_{m,ref} - V_m)
\end{align*}
\]

The decoupled control system is implemented as shown in Figure 3. A phase locked loop (PLL) synchronizes on the positive sequence component of the three-phase terminal voltage at interface Bus 2. The output of the PLL is the angle \((\theta)\) that’s used to measure the direct axis and quadrature axis component of the AC
three-phase voltage and current. The outer regulation loop comprising the AC voltage regulator provides the reference current (Ishq_ref) for the current regulator that is always in quadrature with the terminal voltage to control the reactive power [01].

4. FUZZY LOGIC CONTROLLER (FLC) DESIGN METHODOLOGY

Shunt The disadvantage of PI controller is its inability to react to abrupt changes in the error signal, e, because it is only capable of determining the instantaneous value of the error signal without considering the change of the rise and fall of the error, which in mathematical terms is the derivative of the error signal, denoted as Δe. To solve this problem, Fuzzy logic control as it is shown in Fig. 5 is proposed.

Each of the two linguistic variables is defined over a universe of discourse namely U_e and U_Δe respectively. Let the universe of discourse for each of the input linguistic variable be divided into 5 fuzzy sets namely, Positive Big (PB), Positive Medium (PM), Zero (ZE), Negative Medium (NM), and Negative Big (NB). Each of the fuzzy set has a definite support. Each fuzzy set can be triangular, or trapezoidal or sigmoid. In this case, triangular fuzzy sets are used. Let the universe of discourse for the error be [-0.02 0.02]. Let the universe of discourse for the rate of change of error be [-0.006 0.006].

The expert knowledge is generally given in the following format.

"IF (e set of conditions) THEN (u set of consequent can be inferred)".

These statements contain a set of conditions and a set of decisions to be inferred. The set of decisions could be fuzzy sets.

<table>
<thead>
<tr>
<th>e</th>
<th>NB</th>
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<tr>
<td>Δe</td>
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5. DIGITAL SIMULATION RESULTS

To verify the validity and effectiveness of the proposed strategy, we conducted a simulation research and then offered the simulation waveform. The STATCOM is designed to control the voltage at Bus 2, and thus regulate the load bus voltage at Bus 3. The STATCOM is rated at 100 Mvar with the coupling transformer ratio of 500/4kV/15kV.

In the process, Load variations are simulated on Bus 4 to depict the behavior of the reduced model in steady state, thus validating the proposed model for small voltage variations (less than 10%).

The following load excursion sequence is tested, to validate and test the limits of the proposed reduced model for large system disturbances.

The STATCOM is connected to the power system at t=0 Sec with only load 1 in the system. The DC voltage is 19.28 kV.

Step 1- at t=0.1 the capacitive load Qc=1pu is connected by switching CB1. Therefore, the DC voltage has increased to 20.79 kV, the voltage is suddenly decreased by 1.8% (0.982 pu of nominal voltage without STATCOM). The STATCOM reacts by generating reactive power (Q=+70 Mvar) to keep voltage at 1 pu. The 100% settling time is approximately 63 ms. At this point.

Step 2- at t=0.2 this time, both the capacitive is removed from Bus 4. Unexpected End of Formula

Step 3- at t=0.3 the inductive load QL=1 pu is connected by switching CB2. The DC capacitor voltage has been lowered to 17.87 kV. The capacitive load has a compensative effect so the STATCOM absorbs about 0.7 p.u. of reactive power into the AC system at bus 2. The regulated bus voltage is now about 1 pu (without STATCOM 1.017 pu +1.7%).

Step 4- Finally, at t=0.4 s the source voltage in set back to its nominal value and the STATCOM operating point comes back to zero Mvar.

The STATCOM responds to any changes in the AC system voltage within two control methods. Figures 7, 8 and 9. shows the simulation results in the case of a
capacitive and inductive mode using the sample power transmission system. The digital simulation is carried out for the two controllers (PI and fuzzy). Both novel controllers’ schemes are validated under this condition in order to show their capability in keeping the STATCOM stable for a power system.

The digital simulation for the study system shown in Fig. 6 is carried out again under the same load excursions but using the Fuzzy logic controller. This new controller shows the elevated level of the stability of the power transmission system and provides a smooth transition from the capacitive to full inductive compensation level. The digital simulation results of this comparison are depicted in Fig. 7, 8 and 9.

To check the effect of the power system strength on the STATCOM stability, the digital simulation is carried out again in the proposed system shown in Figure 2. In this case, the loads of this power system are replaced with new loads, which are Load1 (Qc=1.7pu) and load2 (QL=1.7pu). Both control schemes were validated in order to show the effects of the control methods based on PWM.

The comparative response curves controller pi and fuzzy logic controller both are shown in the Fig. 7, 8 9 and 10. The response measured and reference quadrature current is obtained with & without the fuzzy logic controller and is shown in the Figs. 11. It is clearly observed from the simulation results that with the fuzzy logic controller, the dynamic performance of the power system is quite improved with the incorporation of the fuzzy logic controller. It is also observed that with the controller, the oscillations are also damped out in a lesser time. The response characteristics take less time to settle & reach the final steady state value. Therefore, the power system strength greatly affects the response time and stability of the STATCOM. If the PI controller is set to provide a fast response for a strong system, it may lead to possible instability for a weak power system. But the fuzzy logic controller is set to provide a suitable response for power system.

![Graph](image1)

**Fig. 10.** Line reactive power (Qc=1pu, QL=1pu).

![Graph](image2)

**Fig. 11.** Capacitor DC voltage (Qc=1pu, QL=1pu).

![Graph](image3)

**Fig. 12.** Measured and reference quadrature current: (a): PI controller (b): Fuzzy logic controller.

![Graph](image4)

**Fig. 13.** Terminal voltage of STATCOM (Qc=1.7pu, QL=1.7pu).

![Graph](image5)

**Fig. 14.** Current of STATCOM (Qc=1.7pu, QL=1.7pu).
6. CONCLUSION

The system has been modeled and simulated by Simulink/Matlab software to analyze and compare the performance of the STATCOM with the two controllers. The simulation results show that the program has been successfully used at 'DECOUPLED CONTROL METHOD'. The developed control strategy decoupled is not only simple, reliable, and may be easy to implement in real time applications. The performance of the developed method in this paper thus demonstrates the damping of the power system oscillations using the effectiveness of fuzzy logic controller for different system load power.

It is shown that the STATCOM with fuzzy logic controller provides better performance in the enhancement of dynamic and transient stability.

REFERENCES


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