Adaptive Neuro-Fuzzy Controller Based STATCOM for Reactive Power Compensator in Distribution Grid

Abstract. Compensation of reactive power is necessary for reduction the effects caused by the inductive load. To achieve these issues, the utilize power electronics devices are used to control the reactive power flow using static synchronous compensator STATCOM. It is a shunt connected FACTS compensator that provide/withdraw reactive power. This approach is implemented to enhance voltage drop in distribution grid. In this paper, an adaptive neuro-fuzzy logic controller based STATCOM is proposed to regulate the bus voltages of IEEE 9 bus 33kV distribution grid. Method of dq transformation is used for reactive power calculation due to its high accuracy and simple application. Adaptive controller designed based on Sugeno type fuzzy logic rules show that the compensator increases bus voltage about 19%, with damping oscillation during step change compared with the conventional PI controllers.

Introduction

Reactive power compensation is a critical issue in power system control. This type of power increases line losses and reduces the capability lines power transfer capability. Furthermore, reactive power should not be transmitted over a longer distance via the power line. Hence to address these issues, AC flexible systems that are adaptable static compensators STATCOM, unified power flow controllers UPFC, and static volt-ampere compensators SVC are used [1]. Shunt capacitive has long been used for reactive power compensation. This type of compensation increases power transfer capacity while also improving "transient stability.” The tool’s significant drawbacks are its limited range compensation capability and relaxed response. AC flexible system that is adaptable FACTS are new technology controllers developed by electric utilities to address the issues mentioned [2]. FACTS controllers can improve power system dynamic and steady-state performance by controlling network parameters like line impedance, terminal voltage, and burden angle [3]. FACTS gadgets offer variable equal remuneration, which is exceptionally compelling at controlling and further developing line security and power stream. By infusing controllable voltage (magnitude and angle) in corresponding with the distribution framework, the equal compensator in light of the static coordinated compensator STATCOM can give virtual compensation to the power line impedance [4]. Lately, new ways to deal with computerized mentality have been proposed to plan a STATCOM-based regulator. Particle swarm optimization PSO [5, 6], the genetic algorithm [7, 8], and the multiojective evolutionary algorithm [9] are among the new approaches. Since 1988, the artificial neural network ANN methodology has piqued the interest of many power engineering utilizations. Power system stabilizers, cost-effective load dispatching, and other applications fall into this category. These applications’ results demonstrated that ANN regulators have a high potential for further developing power framework disconnected and online applications [9]. For a parallel FACTS device, STATCOM, the neuro-fuzzy controller (an ANN controller based on fuzzy control) is used. In this paper, the authors will create a neuro-fuzzy controller-based STATCOM for power flow control and voltage dip enhancement in an IEEE 33kV nine-bus distribution grid.

Reactive power compensation

Figure 1 depicts a AC line circuit diagram and its boundaries, as well as its phasor graph, which portrays the connection among currents and voltages [10]. It is obvious that a relationship exists between the voltages at the sending and receiving ends, as well as the magnitude and phase difference variations. The load reactive component current, I_{L}, is responsible for the majority of the drop voltage in (V1= jI_{L}X_{L}). There are two types of control actions that can be used to keep the voltages close to the rated value:

1. load type compensation.
2. system type compensation.

In load type compensation this compensation is possible by adding a parallel capacitive load that compensate the reactive load current I_{L} in (I_{L}= -I_{x}). Doing so give the effective by increasing the combination power factor to become unity [11]. The absence of reactive load current mitigates or eliminates the drop voltage \Delta V_{1}, and this will be bringing receiving voltage V_{r} closer in its magnitude to sending voltage V_{s}, this condition is called load type compensation. As shown in Figure 2, the reactive power compensation regulates the desirable end voltage at the evaluated esteem, a power utility might introduce a responsive power compensator.
To repay the voltage distinction $\Delta V_2$, an extra of capacitive current, $\Delta I_c$, over $I_c$ that compensates for $I_x$, is drawn by the compensator. Whenever $\Delta I_c XL = \Delta V_2$, the not exactly helpful end voltage $V_r$, approaches the sending-end voltage $V_s$. Such compensators are used by power utilities to ensure the idea of supply to their clients [12]. This is the basic idea of the reactive compensation. In this paper, we use STATCOM, a high speed response power electronics switches based shunt reactive compensator.

**Voltage versus reactive power flow in the grid**

The voltage fluctuation in the grid mainly has two factors. First is the reactive power stream change in the framework. The second is the load change associated with the grid. Along these lines, the voltage framework is firmly connected with the reactive power stream [13]. Under any working load condition, the receptive force of the generation terminal must be in balance with the responsive power expected by the heap terminal. In terms of the supply system, which is a three-stage inverter, and the distribution network, which is an ideal source, the power conveyed by the line system is obtained:

\[
P = V_I \cos \phi = \frac{V_V r}{x} \sin \delta
\]

\[
Q = V_I \sin \phi = \frac{V_V r}{x} \cos \phi - \frac{v^2}{x}
\]

where: $V_v$, $V_l$ are the source and load voltages respectively, $I_l$ refers to the load current and the angles $\delta$ and $\phi$ are clarified in Figure 2.

When the grid system's load is fixed, the active power is predictable. At this operating point in simultaneous (1) and (2) where:

\[
Q = \sqrt{\left(\frac{V_V r}{x}\right)^2 - p^2} - \frac{v^2}{x}
\]

Voltage versus reactive power relation that required by the operating load is:

\[
Q = \frac{v^2}{x}
\]

If the power source reactive power output remains constant as the reactive load increases, this causes an unbalance between the power supply reactive power and the load terminal at the rated voltage, causing the system voltage to fall [14]. Otherwise, if the reactive power of the power supply exceeds the reactive load demand, the system will operate at a voltage higher than the rated voltage level.

**Reactive power flow controlled based on STATCOM**

STATCOM is one of the custom FACTS devices. Static VAR Compensator used at the Distribution grid. The VSC is the main component of the STATCOM as shown in Figure 1, that is based on high rating of power electronics devices technologies, that is a versatile device for injection or absorb reactive power from and to ac grid [15]. STATCOM is comparable to the customizable voltage source or current the source that can be obliged by its abundance and angle to change the responsive power passed on to the network.

The control of receptive power is accomplished through the guideline of a controlled voltage source behind the spillage impedance of a transformer, similarly to an ordinary coordinated compensator as displayed in Figure 3.
The two voltage phases should be congruent in the ideal case, according to Equation (6). The magnitude of V_{STATCOM} can be used to control the angle and amplitude of STATCOM current consumed or conveyed from/to the AC line [18]. When V_{STATCOM} is less than V the grid voltage, the current flow from the grid to the STATCOM device lags the grid voltage by 90°, which is emulated as inductance, and vice versa, which is emulated as capacitance and provides reactive power to the grid, where STATCOM in this case leads the grid voltage V by 90° [19]. The operation of STATCOM for provides inductive or capacitive reactive power support to the power grid shown in Figure 5.

Whenever the voltage network is decreased or raised to an ostensible worth, the STATCOM is restricted by the rating limit of the accessible its switching gadgets. Hence, the STATCOM current will stay unaltered. Because of the consistent case, the amplitude and angle change of V_{STATCOM} for reactive power compensation. For estimating reactive power, the dq hypothesis was utilized [20]. This hypothesis depends on time space, and it is valid for activity in consistent state or transient state, as well concerning conventional voltage and current power framework waveforms. The effortlessness of computations gives one more benefit normal for this hypothesis, which incorporates arithmetical estimation special case for the need of isolating the mean and rotated qualities for the determined power components. The d-q hypothesis plays out a change known as "park transformation" of a fixed directions reference framework abc to dq pivoting facilitates reference [22]. The transformation applied to time-domain for voltages and currents in the natural frames are as follows:

\[
\begin{bmatrix}
    v_d \\
    v_q 
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\
    -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\
\end{bmatrix} \begin{bmatrix}
    v_a \\
    v_b \\
    v_c 
\end{bmatrix}
\]

\[
\begin{bmatrix}
    i_d \\
    i_q 
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\
    -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c 
\end{bmatrix}
\]

Where \( \theta \) is the phase angle between the rotating and fixed coordinate system at each time and \( \theta \), the voltage phase shift. The reactive power compensated calculated from (7) and (8) is:

\[
q = v_di_d - v_qi_q
\]

STATCOM control scheme

The block chart of control system of STATCOM is shown in Figure 6. The line voltage and current are sensed and from that measurement the reactive power \( q \) is calculated by park transformations. The measured reactive power fills in as input for shut circle control. For generating error-signal Error\( q \), the ideal worth qref is compared to the measured q. This error signal is processed in the controller, which does the following:

\[
\text{Error}q = q_{\text{ref}} - q
\]

The angle of the embedded voltage can be changed by changing the indication of the sign to make the compensation in capacitive or inductive mode. Figure 6 shows the detailed neuro fuzzy logic controller based STATCOM for reactive power flow. The modulation index is controlled based on the error in reading of reactive power using ANFIS control system.

\[
\psi = \phi \pm \gamma
\]

In capacitive/inductive mode operations, the sign of the Error\( q \) in (10) \( \gamma \) can be adjusted.
Neuro-fuzzy control system

Modern control using fuzzy logic is suitable for uncertain systems, especially for systems difficult to derive its mathematical model. Fuzzy logic control (FLC) plays a crucial role in many factual applications [23]. There are many kinds of fuzzy surmising components, the Takagi-Sugeno (TS)-fuzzy is picked in this work. To tune the participation the artificial neural organization will be utilized with a TS-fuzzy like-PI regulator. TS-fuzzy regulator has an exceptionally non-straight with variable addition regulator. It creates wide varieties range gain of the regulator. Subjective choice regulator boundaries might prompt a satisfactory reaction or flimsiness framework. Better response may be achieved by using combined of ANN and fuzzy logic in neuro-fuzzy system for adapting the boundaries and rules of fluffy by utilizing ANN learning calculation. Such system can be trained without need to expert knowledge commonly required for the standard type of FCL, also the rules base can be reduced. Input boundaries and result participation MF’s are determined during the preparation stage [24]. The learning calculation objective is changing the information boundaries and result in MF’s so the best result matching is accomplished for the planned controller. A cross breed learning system “slope plunge GD and least-squares gauge LSE” is typically applied to for distinguishing the boundaries of the network [25]. In this study the input universe of discourse is split into 7-triangle MFs with overlapping of 50%, then for inputs $Q_{error}$ and $\Delta Q_{error}$ “two inputs”, with control rule of 49 consequents the linear functions need to be determined. To tune the rules of TS by using neuro-fuzzy, one set of data is need to be generated. Input data to the controller is a data vector of Errorq results as in equation 11, controller output are “modulation index” $m$ and phase angle $\psi$ respectively. To initialise the coefficients of the consequents, Mamdani fuzzy like PI controller described in Table 1 is used to start the training procedure, error and change of error relation.

Table 1. The parameters of the sensor

<table>
<thead>
<tr>
<th>Error/∆Error</th>
<th>HB</th>
<th>HM</th>
<th>HS</th>
<th>ZO</th>
<th>LS</th>
<th>LM</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB</td>
<td>HB</td>
<td>HB</td>
<td>HB</td>
<td>HM</td>
<td>HM</td>
<td>HS</td>
<td>ZO</td>
</tr>
<tr>
<td>HM</td>
<td>HB</td>
<td>HB</td>
<td>HM</td>
<td>HM</td>
<td>HS</td>
<td>ZO</td>
<td>ZO</td>
</tr>
<tr>
<td>HS</td>
<td>HB</td>
<td>HM</td>
<td>HS</td>
<td>HS</td>
<td>ZO</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>ZO</td>
<td>HM</td>
<td>HM</td>
<td>HS</td>
<td>ZO</td>
<td>LS</td>
<td>LM</td>
<td>LM</td>
</tr>
<tr>
<td>LS</td>
<td>HM</td>
<td>HS</td>
<td>ZO</td>
<td>LS</td>
<td>LS</td>
<td>LM</td>
<td>LB</td>
</tr>
<tr>
<td>LM</td>
<td>ZO</td>
<td>ZO</td>
<td>LS</td>
<td>LS</td>
<td>LM</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td>LB</td>
<td>ZO</td>
<td>ZO</td>
<td>LS</td>
<td>LS</td>
<td>LM</td>
<td>LB</td>
<td>LB</td>
</tr>
</tbody>
</table>

Simulation and results

A power framework comprising of nine buses, three generators is displayed in Figure 8. STATCOM installed at weak bus (Bus-6) for controlling the flow of reactive power and enhancing its associated voltage.

Fig.7. ANFIS validation surface

Fig.8. IEEE 33 kV 9-bus system with MATLAB/Simulink

As shown in Figure 8, simulation based on discrete phasor mode 50Hz takes a sample time of 50 microseconds. A DC voltage source is provided to a compensator which helps in absorbing or feeding the reactive power. At steady state condition, bus voltages are shown in Figure 9. It’s clear that bus-6 is the weakest bus with voltage of 0.8 pu. Test starts by step changing the injected voltage of STATCOM. compensation process by injected the controllable voltage $V_{STATCOM}$ that feeding the reactive power to compensate the voltage at bus-6. Figure 10 shows the action of STATCOM at t=0.5 sec.

Fig.9. Bus voltages before compensation in pu

In this case, $V_{STATCOM}$ greater than the line voltage, and the compensator acts as a capacitive, the voltage increased to about 0.99 pu with an increase ratio of about 19%. Figure
11 shows the STATCOM current in pu during compensation. A steady state current is about 0.43 pu, for 100 MVA base power, is required to compensate a large voltage dip (about 20%). Figures 12 and 13 show the active and reactive power injected to the grid. The injected reactive power is about 0.7 pu while no change in active power at steady state.

To validate the designed controller, a conventional PI was used to compare the response against step change in the load. Figure 15 shows the comparison between two types of controllers; it’s clear that ANFIS (neuro fuzzy controller) has less overshoot and faster in reach the steady state condition.

**Conclusion**

A reactive power flow control and voltage are adjacent for IEEE 9-bus 33 kV distribution network using neuro fuzzy logic controller based STATCOM. A circuit has been modelled and simulated using MATLAB/Simulink 50Hz discrete phasor mode. STATCOM modifies the controllable voltage’s amplitude and phase angle. It injects a controllable voltage to dominate the power in the alternating current line and boost the bus voltage. A neuro fuzzy logic controller was intended for the STATCOM control circuit. Simulation results show that the significant management of reactive power in bus-6 which increased the voltage about 19% also the STATCOM increase the knee point in power-voltage characteristic this will delay the voltage collapse. In other hand, neuro fuzzy controller enhances the response of STATCOM during compensation instant and modify the stability of the system.

**Authors:** dr Mahmood T. Alkhayyat. Mosul, Iraq, Northern Technical University, E-mail: m.t.alkhayyat@ntu.edu.iq, dr Mohammed Y. Suliman. Mosul, Iraq, Northern Technical University, E-mail: mohammed.yahya@ntu.edu.iq

**REFERENCES**


