Effect of DC Capacitor Size on D-STATCOM Voltage Regulation
Performance Evaluation

Abstract. This paper describes the modelling and simulation of distribution static compensator (D-STATCOM) focused with effect of DC capacitor size and voltage regulation. Different capacitor values have been investigated to reduce the load ripple voltage during the charging and discharging of the capacitor. The optimum capacitor value has been determined to obtain the lowest ripple voltage within the rage of 8%. Capacitive and inductive mode of D-STATCOM operation have been also investigated and obtained results proved that the capability of the D-STATCOM in regulating the system voltage is near to the rated value of 1.0 p.u.

Streszczenie. W artykule przedstawiono sposób budowy modelu i symulacje kompensatora pasywnego D-STATCOM, ze naciskiem na analizę wpływu pojemności kondensatorów oraz regulacji napięcia na jego działanie. Badania wykonano dla różnych pojemności i wyznaczono optymalną, zapewniającą najmniejsze wahania napięcia (w zakresie 8%). Analizę poddano działanie kompensatora przy charakterze pojemnościowym i indukcyjnym. (Badanie wpływu pojemności kondensatora DC na skuteczność regulacji napięcia kompensatora pasywnego D-STATCOM)

Keywords: D-STATCOM, DC capacitor, power quality, voltage ripple, voltage regulation.
Stoła klucze: D-STATCOM, kondensator DC, jakość energii, wahania napięcia, regulacji napięcia.

Introduction

D-STATCOM is a kind of custom power device which is used to regulate the system voltage and thereby protect the distribution system from power quality disturbances such as voltage sags, swells, voltage flicker and voltage unbalance [1, 2]. The main components of the D-STATCOM are the inverter using either GTO or IGBT, dc capacitor, coupling transformer and control system. It can be regarded as an active energy-exchanging device because it utilizes the passive energy storage component to realize the energy storing and exchanging and the switches to control the reactive power flow between different phases of a distribution system [3, 4]. The reactive power provided by the D-STATCOM is either capacitive or inductive depending on whether the magnitude of the D-STATCOM output voltage is larger or smaller than the magnitude of the system voltage [5, 6].

In recent years, D-STATCOM has been extensively studied in which many papers in the literature have discussed its theory, modelling, control and applications [3-9]. Design and performance evaluation of a D-STATCOM requires extensive analysis of the interaction between the D-STATCOM and the associated distribution system. Such an analysis is usually done by using time-domain simulation tools.

In the operation of D-STATCOM, the problem of power quality problems like voltage regulation, ripple voltage, harmonics generated by the device have been addressed in [3, 10]. Methods for reducing ripple voltage, harmonics produced by D-STATCOM are by means of capacitance effects and the PWM switching technique and filters. Studies on the use of D-STATCOM in improving voltage regulations have been investigated by many researchers [11-14]. The D-STATCOM is simulated on a test distribution system for improving voltage regulation to critical loads by acting as a dc source to provide reactive power to the load. An optimum size of dc capacitor can be determined by considering its physical size, cost and the possibility of resonance for a given coupling reactance. If the frequency of the resulting harmonic component coincides with the resonance frequency of the dc capacitor and the coupling reactance then the resulting harmonic distortion at the ac side can be very high. The dc capacitor resonance may lead to excessive magnifications of some harmonic components and increasing harmonic distortion of the D-STATCOM current. In the simulation, the coupling reactance is not considered so the possibility of harmonic resonance to occur will be reduced. But consideration of harmonic resonance is given because loads are inductive and this may have some effect on the dc capacitance.

To determine the dc capacitor size, Cdc, firstly consider the energy loss of the capacitor in one period as [19],

\[ \Delta E_c(t) = \frac{C_{dc}}{2} \left( V_{C_{max}}^2 - V_{dc}^2 \right) \]

where, \( V_{C_{max}} \) is the pre-set upper limit of the voltage across the capacitor, \( V_{dc} \) is voltage across the capacitor and \( C_{dc} \) is dc capacitor.

But the energy loss is also supplied by the utility voltage source, \( V_S \) and the peak value of the charging current, \( I_{sc} \), in which the energy loss can be written as,

\[ \Delta E_c(t) = \int_0^t V_S \sin\omega t \cdot I_{sc} \sin\omega t \, dt \]

Simplifying equation (2),
ΔE₂(t) = VscIsc \int_{0}^{T} \sin^2 \omega t \, dt = \frac{1}{2} V_{sc} I_{sc} T

where, V_s is peak phase voltage of the D-STATCOM and T is the period of one cycle.

Equating equations (1) and (3), gives,

\[ \frac{C_{dc}}{2} \left( V_{c,\text{max}}^2 - V_{dc}^2 \right) = \frac{1}{2} V_{sc} I_{sc} T \tag{4} \]

While the load current is reduced, the charging current \( I_{dc} \) will be equal to the change in load current \( \Delta I \). Hence, an extra utility source current \( \Delta I \) will charge the energy storage capacitor. Substituting \( \Delta I \) for \( I_{dc} \), equation (4) becomes,

\[ \frac{C_{dc}}{2} \left( V_{c,\text{max}}^2 - V_{dc}^2 \right) = \frac{1}{2} V_{s} \Delta I T \tag{5} \]

where, \( \Delta I \) is the step drop of load current which can be determined by the difference between the load current before and during faults.

Therefore, using equation (5) the dc capacitance value for a three phase system can be derived as,

\[ C_{dc} = 3 \frac{V_{s} \Delta I T}{V_{c,\text{max}}^2 - V_{dc}^2} \tag{6} \]

where, \( V_{dc} \) is the peak phase voltage of the D-STATCOM and the derivations of \( V_{dc} \) and equation (6) can be found in [20, 21], respectively.

Thus, to calculate the dc capacitance value, the load currents profile at the distribution system without the D-STATCOM are considered and written as [19],

\[ P_s = \frac{V_s V_m}{X_L} \sin \delta \tag{7} \]

\[ Q_s = \frac{V_s}{X_L} (V_s - V_m) \cos \delta \tag{8} \]

where \( V_s \) is the system voltage, \( V_m \) is the D-STATCOM voltage, \( X_L \) is the line reactance and \( \delta \) is the phase angle displacement between \( V_s \) and \( V_m \).

From equation (8), it can be implied that reactive power exchange between the D-STATCOM and the ac system is controlled by varying the amplitude of the D-STATCOM output voltage. If the ac system voltage is greater than the D-STATCOM output voltage, that is, \( V_s > V_m \), current will flow from the ac system into the inverter, resulting in the device acting as an inductor which absorbs reactive power. By controlling the D-STATCOM output voltage, the capacitor voltage can be decreased or increased so as to control the reactive power output of the device. The operating modes of the D-STATCOM showing leading and lagging conditions are illustrated in Fig. 2.

Fig. 2. Operation modes of D-STATCOM

The real power exchange between the D-STATCOM and the ac system can be controlled by adjusting the phase shift between the D-STATCOM output voltage and ac system voltage. The D-STATCOM can supply real power into the ac system if the D-STATCOM output voltage is leading the system voltage, that is, \( \delta > 0 \). On the other hand it absorbs real power from the ac system if its voltage lags behind the system voltage, that is, \( \delta < 0 \).

The capacitor in the D-STATCOM is used to maintain dc voltage to the inverter. The amplitude of the inverter voltage \( V_{in} \) is proportional to the dc voltage of the capacitor, which is proportional to the amount of energy stored in the capacitor. If there is a small lagging or leading phase shift, active power flows through the inverter, charging or discharging the capacitor. The charging or discharging of the capacitor affects the dc voltage level and consequently, alters the amplitude of the inverter ac voltage.

**D-STATCOM in a Distribution System**

A simplified distribution system model has been chosen as a test system for investigating the performance of the D-STATCOM. The system considers several static and induction motor (IM) loads, which are connected to a common load bus. The D-STATCOM is connected in shunt between the loads and the 22 kV substation. The detailed load characteristics of various ratings are given in Table 1. The D-STATCOM in the test distribution system has been implemented in PSCAD/EMTDC.

Table 1 | Loads in the test distribution system |
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Load</td>
<td>Type</td>
<td>Rating</td>
<td>Parameters</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Load 1</td>
<td>RL</td>
<td>1.2 MVA, 0.90 P.F.</td>
<td>363.33</td>
</tr>
<tr>
<td>Load 2</td>
<td>RL</td>
<td>0.5 MVA, 0.95 P.F.</td>
<td>871.21</td>
</tr>
<tr>
<td>Load 3</td>
<td>IM</td>
<td>1600 H P, 50 Hz</td>
<td>---</td>
</tr>
<tr>
<td>Load 4</td>
<td>IM</td>
<td>1600 H P, 50 Hz</td>
<td>---</td>
</tr>
<tr>
<td>Load 5</td>
<td>RL</td>
<td>1.2 MVA, 0.90 P.F.</td>
<td>363.33</td>
</tr>
</tbody>
</table>
Results and Discussion

To evaluate the performance of the D-STATCOM, it is simulated using the PSCAD/EMTDC transient simulation program. There are twelve single-phase transformers with each rated at 5 MVA, 22/4.16 kV and a leakage reactance of 0.01 p.u. Simulations were carried out to illustrate the effect of dc capacitor size, D-STATCOM as voltage regulator. Prior to simulations, sizing of dc capacitance value, D-STATCOM mode of operation were investigated.

Effect of DC Capacitor Sizing: As mentioned earlier, the size of DC capacitor is chosen by considering its physical size, cost and performance of the D-STATCOM. To investigate the effect of the capacitance on the performance of the D-STATCOM, the capacitance values are varied using the values of 1500 μF, 1800 μF, 2000 μF. However, an optimum capacitance value of 2430 μF is calculated using equation (6). To illustrate the effect of the capacitance, simulations were carried on the D-STATCOM by creating a three phase fault at time t=1.5 s for a duration of 0.75 s. During the fault condition, a voltage sag condition is created and the D-STATCOM performs its voltage sag mitigation capability. In this simulation, the load voltage responses are recorded for different capacitance values as shown in Fig. 3.

![Fig. 3. Load voltage response for capacitance values of a) 1500 b) 1800 c) 2000 d) 2430 μF.](attachment:image)

Table 2  Effect of DC capacitance on ripple voltage

<table>
<thead>
<tr>
<th>DC Capacitance value in μF</th>
<th>Max Ripple Voltage in p.u</th>
<th>Min Ripple Voltage in p.u</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>1.29</td>
<td>0.82</td>
</tr>
<tr>
<td>1800</td>
<td>1.23</td>
<td>0.86</td>
</tr>
<tr>
<td>2000</td>
<td>1.17</td>
<td>0.89</td>
</tr>
<tr>
<td>2430</td>
<td>1.08</td>
<td>0.94</td>
</tr>
</tbody>
</table>

The load ripple voltages which are due to the charging and discharging of the capacitor can be seen in the figure and are recorded as shown in Table 2. Results shown in Table 2 indicate that by increasing the capacitance values, the range between the per unit maximum and minimum ripple voltages decreases. Using the optimum capacitance value of 2430 μF, the lowest ripple voltage can be obtained to within the range of 8% considering an ideal voltage of 1.0 per unit.

D-STATCOM as a Voltage Regulator: To show the effectiveness of the D-STATCOM in providing continuous voltage regulation, simulations were carried under two load conditions, that is, considering either a capacitive load or an inductive load in which both are rated at 1.2 MVA. Simulations were first carried out by considering a purely capacitive load and the results are shown in Fig. 4 (a) in which it indicates that without the D-STATCOM connected in the distribution system, the effect of the capacitive load results in a high load voltage of 1.10 p.u. With the D-STATCOM connected and switched at time t = 0.45 s, the load voltage returns to near its rated voltage of 0.996 per unit as shown in Fig. 4 (b). Figure 5.8 shows the D-STATCOM current lagging behind the load voltage by 90 degrees so as to illustrate the operation of the D-STATCOM as an inductive compensator.

![Fig. 4. Capacitive load voltage a) without b) with D-STATCOM](attachment:image)

![Fig. 5. Reactive power of the system and dc capacitor voltage](attachment:image)

![Fig. 6. Inductive load voltage a) without and b) with D-STATCOM](attachment:image)
To simulate a relatively low voltage condition, the system is connected to a purely inductive load. Fig. 6 (a) shows the system voltage response under an inductive load condition in which the voltage reaches a low steady-state value of 0.85 p.u. without the D-STATCOM connected in the distribution system. By connecting the D-STATCOM to the system, the system returns to its rated voltage of 0.999 p.u. within a very short time as shown in Fig. 6 (b).

Fig. 7 shows that the reactive power is generated and the dc voltage is increased, so as to increase the load voltage from 0.85 p.u. to 0.999 p.u. as shown in Fig. 7 (b). These results thus prove the capability of the D-STATCOM in regulating the system voltage to near its rated value of 1.0 p.u.

![Fig. 7. Reactive power of the system and dc capacitor voltage](image)

**Conclusion**

The simulation of D-STATCOM model focused on effect of capacitance towards ripple voltage and regulation in a test distribution system were developed using the PSCAD/EMTDC electromagnetic transient program. In this study, the effect of the capacitance values of 1500 μF, 1800 μF, 2000 μF and 2430 μF have been investigated on the performance of the D-STATCOM. However, an optimum capacitance value of 2430 μF provides the lowest ripple voltage within the range of 8% considering an ideal voltage of 1.0 per unit. Capacitive and inductive load have been considered to show the effectiveness of the D-STATCOM in providing continuous voltage regulation. In both cases, the D-STATCOM provides near its rated voltage to the distribution system. By connecting the D-STATCOM to the system in which the voltage reaches a low steady-state value of 0.85 p.u. without the D-STATCOM connected, the reactive power is generated and the dc voltage is increased, so as to increase the load voltage from 0.85 p.u. to 0.999 p.u. as shown in Fig. 7 (b). These results thus prove the capability of the D-STATCOM in regulating the system voltage to near its rated value of 1.0 p.u.

![Fig. 7. Reactive power of the system and dc capacitor voltage](image)

**REFERENCES**


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