Reactive Power Control using STATCOM for Power System Voltage Improvement

Sabah Abdulkareem Yousif
sabah.enp26@student.uomosul.edu.iq

Saad Enad Mohammed
saadmohamed@uomosul.edu.iq

Electrical Engineering Department, Collage of Engineering, University of Mosul

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ABSTRACT
Stability of power system is the ability of the system, with a certain initial operation conditions, to restore the operating balance conditions after exposure to disturbance such as faults or sudden load changes. More attention is required to address voltage instability problems to keep voltage profile under control during abnormal conditions. This paper proposes a Static Synchronous Compensator (STATCOM) using (MATLAB / Simulink Program) The STATCOM includes proportional-integral (PI) control model is used to control the voltage during abnormal conditions by absorbing or injecting reactive power into the power system. Simple and reliable PI controller has been used and designed to be stable under various operating conditions. Three phase Two level PWM strategy technic used in STATCOM controller to decrease the harmonics injected after adding STATCOM to the power system (THD = 2.21%). The simulation study has been done by using 9 buses IEEE system after making a disturbance such as sudden load change. Then the voltage profile during this interval is being studied with and without using STATCOM. The simulation results show that adding STATCOM to this system led to improve the voltage profile during disturbance interval and made the system more stable and reliable by preventing the disturbance effects from reaching the generation side (Vbus 5 = 0.8980 pu, during disturbance before adding STATCOM, Vbus 5 = 1.0003 pu, during disturbance after adding STATCOM). The fast response of the STATCOM controller gives the ability of injecting or absorbing reactive power during disturbances and keeping the system voltages within the IEEE standards limits (0.95 pu < V < 1.05 pu).

Keywords:

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1. INTRODUCTION
Power system is a complex grid which consists of generators, transformers, transmission lines and different loads. Increased in power demand led to increase the load on the transmission lines and this will cause the power system to run at its thermal limits [1]. Increased in voltage stability and control in some power systems of operating and planning have become a limiting factor. Adding a new transmission line is very complex and depends on too many factors so the new researches focused on inserting new devices to the transmission lines to increase the capability of the transmitted power and make the transmission line more flexible instead of installing a new transmission line. Flexible Alternating Current Transmission System (FACTS) is a power system supported with new devices to make the system more flexible by controlling all variables of the system such as voltage, current, impedance and phase angle [2].

STATCOM is one of the FACTS devices and is connected in parallel with the power system via leakage reactance. The ability of fast response in absorbing or injecting reactive power into the system during disturbances made the STATCOM is the most suitable device to control the reactive power in power system. The working principle of the STATCOM is that the voltage source inverter produces controlled AC voltage in primary side of
transformer-leakage reactance. The potential difference between two sides of the reactor, works to exchange active and reactive power between the STATCOM and the power system. Several, STATCOM dynamic experiments, were implemented to arrive at an appropriate design in enhancing voltage to improve the voltage profile of power system [3].

2. STATCOM
2.1. Principle of Operations
The principle of operation of the STATCOM is generating a three-phase voltage close to the sinusoidal waveform. The AC voltage generated in STATCIM depends on the DC side regulated by DC capacitor or energy source which controlled by a suitable control strategy to maintain a fast response and decrease the injected harmonics into the power system. Inserted FACTS devices into power system lead to inject harmonics in that system and to decrease the injected harmonics many control strategies have been studied and implemented to keep these harmonics within the permission limits [4]. Figure 1 shows some of those strategies to reduce the total harmonic distortion after adding FACTS devices [5].

2.2. Modes of Operation
There are three modes of operation in STATCOM:
Mode (I): if \( V_1 < V_2 \) the STATCOM works as a capacitor.
Mode (II): if \( V_1 > V_2 \) the STATCOM works as an inductor.
Mode (III): if \( V_1 = V_2 \) the STATCOM is floating in this mode because no reactive power exchanged between the two nodes. Figure 2 explain the modes of operation of STATCOM [7].

\[
P = \frac{V_1 V_2}{X} \sin \delta \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 1
\]
\[
Q = \frac{V_1 V_2}{X} \cos \delta - \frac{V_1^2}{X} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots 2
\]

3. STATCOM MODEL
3.1. System Configuration
The equivalent circuit of adding STATCOM to AC power system is shown in figure 3. where:
\( v_a, v_b, v_c \) represent the three phase voltages at system side.
\( e_a, e_b, e_c \) represent the three phase output voltages at Inverter side.
\( i_a, i_b, i_c \) are the three phase Inverter output currents.
\( L \) is the transformer leakage inductance.
\( R \) is the series resistance with the voltage source converter (VSC) and it is representing the summation of the inverter losses and the transformer winding resistance losses.
\( R_s \) is the parallel resistance with the capacitor and it is representing the summation of the power losses in the capacitor and the switching losses of the inverter [9].
Fig. 3 The equivalent circuit of adding STATCOM to AC power system

3.2. Dynamic Equations of the STATCOM

From figure 3 and by taking KVL equation it can be obtained.

\[ v_a - e_a = R_i + L_i \frac{di_a}{dt} \]  
\[ v_b - e_b = R_i + L_i \frac{di_b}{dt} \]  
\[ v_c - e_c = R_i + L_i \frac{di_c}{dt} \]

The equations above can be written in matrix form as follows:

\[
\begin{bmatrix}
  -R & 0 & 0 \\
  0 & -R & 0 \\
  0 & 0 & -R
\end{bmatrix} \begin{bmatrix}
  i_d \\
  i_q \\
  i_c
\end{bmatrix} = \begin{bmatrix}
  v_a - e_a \\
  v_b - e_b \\
  v_c - e_c
\end{bmatrix}
\]  

Where \( p = \frac{d}{dt} \) operator

Converting equation 4 from abc axis to dq axis using park transformation (equation 5).

\[
\begin{bmatrix}
  e_d \\
  e_q
\end{bmatrix} = \begin{bmatrix}
  \cos \phi & \cos \left( \phi - \frac{2\pi}{3} \right) & \cos \left( \phi + \frac{2\pi}{3} \right) \\
  -\sin \phi & -\sin \left( \phi - \frac{2\pi}{3} \right) & -\sin \left( \phi + \frac{2\pi}{3} \right) \\
  \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
  i_d \\
  i_q \\
  i_c
\end{bmatrix}
\]

Where the angle \( \phi \) is the angle between (d-axis) and the phase a-axis of the abc coordinate.

After using the equation 5, it can be converting abc-axis to dq-axis. The relation between two axes is defined as follow [10]:

\[
\begin{bmatrix}
  e_d \\
  e_q
\end{bmatrix} = \begin{bmatrix}
  \frac{3}{2} [c]^T & \begin{bmatrix}
  i_d \\
  i_q \\
  0
\end{bmatrix}
\end{bmatrix} [c]
\]

Converting equation 4 from abc axes to dq axes by park transformation equation (equation 5).

\[
p \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} = \begin{bmatrix}
  -R & w \\
  -L & -R
\end{bmatrix} \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} + \frac{w}{L} \begin{bmatrix}
  V_d - e_d \\
  V_q - e_q
\end{bmatrix}
\]

Where \( w = \frac{d\phi}{dt} \)

Inverter DC side equation can be written as:

\[
pV_{dc} = \frac{1}{C} (i_s - i_{dc})
\]

\[
= \frac{1}{R_s \cdot C} (V_s - V_{dc}) - \frac{1}{C} i_{dc}
\]

Instantaneous power on the AC side of the inverter is calculated by:

\[
P_{ac} = e_a i_a + e_b i_b + e_c i_c
\]

The relationship between the direct abc - axes and dq - axes is shown in figure 4. From this figure and after transforming the abc frame to dq frame can be obtained:

\[
P_{ac} = \frac{3}{2} (e_d i_d + e_q i_q)
\]
Fig. 4 Vector diagram of phase and dq voltages

Active power on the DC side of the inverter is calculated by:

\[ P_{dc} = V_{dc}i_{dc} \]

Assume instantaneous power exchange between AC and DC side of the inverter is equal after neglecting the losses inside the inverter, equation 11 must hold:

\[ V_{ac}i_{ac} = 2\left(e_{d}i_{d} + e_{q}i_{q}\right) \]

So,

\[ i_{dc} = \frac{3}{2}\left(\frac{e_{d}i_{d} + e_{q}i_{q}}{V_{dc}}\right) \]

Assuming d-axis coincides with the voltage vector, that is means, \( V_{d} = |v| \), and \( V_{q} \) becomes zero. Neglecting the voltage harmonics produced by the inverter, one can write the pair of equations for \( e_{d} \) and \( e_{q} \).

When the STATCOM inverter operates in SPWM mode, then the inverter output voltage of must satisfy the following equations

\[ e_{d} = KV_{dc} \cos \alpha \]
\[ e_{q} = KV_{dc} \sin \alpha \]

M and \( \alpha \) in equation (13) represent the modulation index and the firing angle of the sinusoidal reference wave referring to the system voltage vector, while K is a factor which relates the DC side Voltage to the peak of the phase to neutral voltage at AC side of the inverter and depends on number of pulses used in converter.

Combining eqn. 7 with eqn. 6 and substituting them by eqn. 12 and eqn. 13, a dynamic model of the STATCOM can set up as:

\[
p \begin{bmatrix} i_{d} \\
V_{dc} \end{bmatrix} = \begin{bmatrix} [A] & [B] \end{bmatrix} \begin{bmatrix} \Delta i_{d} \\
\Delta V_{dc} \end{bmatrix}
\]

Where \( [A] = \begin{bmatrix} -\frac{R}{L} & \frac{1}{L} & 0 \\
-\frac{\omega_{0}}{L} & -\frac{R}{L} & 0 \\
0 & 0 & -\frac{1}{R_{s}C} \end{bmatrix} \)

Converting eqn. 14 to a linear system form as shown in equation 15.

\[
p \begin{bmatrix} \Delta i_{d} \\
\Delta i_{q} \\
\Delta V_{dc} \end{bmatrix} = \begin{bmatrix} [A] & [B] \end{bmatrix} \begin{bmatrix} \Delta M \\
\Delta \alpha \end{bmatrix}
\]

Where

\[
\begin{bmatrix} \Delta i_{d} \\
\Delta i_{q} \\
\Delta V_{dc} \end{bmatrix} = \begin{bmatrix} i_{d} - i_{do} \\
i_{q} - i_{qo} \\
V_{dc} - V_{dco} \end{bmatrix}, \quad [\Delta M \Delta \alpha] = [M - M_{0}] [\alpha - \alpha_{0}]
\]

And

\[
[A] = \begin{bmatrix} -\frac{R}{L} & \frac{1}{L} & 0 \\
-\frac{\omega_{0}}{L} & -\frac{R}{L} & 0 \\
\frac{3M_{0}}{4C} & \frac{3M_{0}}{4C} & -\frac{1}{R_{s}C} \end{bmatrix}
\]

\[
[B] = \begin{bmatrix} \frac{V_{dco} \cos \alpha_{0}}{2L} & \frac{V_{dco} \sin \alpha_{0}}{2L} \\
\frac{V_{dco} \cos \alpha_{0}}{2L} & \frac{V_{dco} \sin \alpha_{0}}{2L} \\
\frac{3(V_{dco} \cos \alpha_{0} + \frac{L}{R_{s}C} \sin \alpha_{0})}{4C} & \frac{3(V_{dco} \cos \alpha_{0} - \frac{L}{R_{s}C} \sin \alpha_{0})}{4C} \end{bmatrix}
\]

Where \( [\Delta i_{d} \Delta i_{q} \Delta V_{dc}]^{T} \) are state space variables vectors, and \( [\Delta M \Delta \alpha]^{T} \) are the control variables.

The conventional control strategy can be specific, based on the equation (15) and the block diagram of STATCOM controller is shown in figure 5. The phase locked loop (PLL) coincides with the three-phase positive sequence component of the initial component of the phase voltage. [10].

Fig. 5 STATCOM Controller

4. RESULTS AND DISCUSSION
Sudden load change and repeated faults in the network led to instability in the power system, as well as decreasing the voltage at system buses. MATLAB/Simulink program used to simulate the system then find out the weak bus in the system and modify it using STATCOM to enhance the voltage profile and improve the system stability. In this work a sudden load change introduced to IEEE 9-buses system near Bus 5. The system studied under two cases, without and with STATCOM.

Case A: IEEE 9-busbars system without STATCOM.
Case B: IEEE 9-busbars system with STATCOM.

**Case A: IEEE 9-Busbars System without STATCOM.**

A sudden load change added to the system near bus 5 as shown in Figure 6. The voltage at system buses during the interval of disturbance is shown in Table 1 and Figure 7. Adding this disturbance to the system led to decrease the voltage at system buses especially bus 5, it is clear from the results that bus 5 is the weakest bus in the system, with a voltage of 0.8980 p.u., this value of the bus voltage is not accepted depends upon IEEE standard limits (0.95 <V <1.05) p.u.

**Table 1: Load flow results of IEEE 9-bus system without STATCOM**

<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage (p.u)</th>
<th>PLOAD (MW)</th>
<th>QLOAD (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.9736</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 5</td>
<td>0.8980</td>
<td>125</td>
<td>50</td>
</tr>
<tr>
<td>Bus 6</td>
<td>0.9581</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>Bus 7</td>
<td>0.9556</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 8</td>
<td>0.9513</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>Bus 9</td>
<td>0.9747</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Fig. 6 Simulink model of IEEE 9-bus system**

In this case, STATCOM added to the standard power system after adding sudden load change near bus 5 as shown in Figure 8, where the results of the system buses voltages are shown in Table 2 and Figure 9. Adding STATCOM to the system enhanced the system voltage profile during the interval of disturbance. The fast response of STATCOM with suitable control strategy made the system more stable during abnormal conditions.

**Case B: IEEE 9-Bus System with STATCOM.**

**Table 2: Load flow of IEEE 9-bus System with STATCOM**

<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage (p.u)</th>
<th>PLOAD (MW)</th>
<th>QLOAD (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>1.0248</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 5</td>
<td>1.0003</td>
<td>125</td>
<td>50</td>
</tr>
<tr>
<td>Bus 6</td>
<td>1.0100</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>Bus 7</td>
<td>1.0171</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 8</td>
<td>1.0082</td>
<td>100</td>
<td>35</td>
</tr>
</tbody>
</table>

**Fig. 8 Simulink model of IEEE 9-bus System with STATCOM**
It is easier to see the difference between the two cases by combination the results of the two cases in one figure such as shown in figure 10.

The STATCOM active and reactive power during the disturbance is shown in Fig. 11. The STATCOM added to the system at t = 2Sec where the sudden load change added during the interval (5-9) Sec. The fast response of the STATCOM to inject instantaneous reactive power into the system during the disturbance led to compensate the voltage drop at system buses instantaneously and enhanced the voltage profile of the power system. The STATCOM DC-side is supported with capacitor so no active power exchange between the system and STATCOM.

The modulation index during the disturbance period is shown in Figure 12. The modulation index increased from (0.71) to (0.73) during the period (5-9) seconds, which represents the period of adding disturbance. The static synchronous compensator senses the drop in voltage at the point of common connection (pcc) and gives a signal to the STATCOM controller, which increase the modulation index and inject reactive power into the system to compensate the drop of the voltage.

5. CONCLUSION
In this article STATCOM has been proposed to improve the voltage profile of power system. The main feature of the STATCOM is the compensation of reactive power, so it can simultaneously compensate for the sag and its amplification by injecting or absorbing the reactive current through the transformer connected between the system and the STATCOM. The simulation is performed using (MATLAB / Simulink). Reactive power is inversely proportional to the magnitude of bus voltage. Increase in load reactive power on a bus stresses the particular bus and increase the voltage drop at bus, if this drop continues the
particular bus will collapse. Adding sudden load to the system led to decrease the voltage at all system buses especially bus 5 (0.8980 p. u). this value of voltage is not accepted depends on IEEE standards limits (0.95 - 1.05) pu. Adding STATCOM to that system under same conditions led to enhance the voltage stability of the system where the voltage at bus 5 became 1.0003 pu. The fast response of STATCOM controller and capability of instantaneous reactive power compensation make the power system more stable and reliable during abnormal conditions. Harmonics injected into the power system has been decreased using PWM technique in STATCOM controller (THD = 2.21%). Converter losses has been neglected in this work by assuming that the switch device is an ideal switch.

REFERENCES

التحكم في القدرة المتفاعلة باستخدام المعوض المتزامن الساكن لتحسين فولتية نظام القدرة

صباح عبد الكريم يوسف

saadmohamed@uomosul.edu.iq
sabah.enp26@student.uomosul.edu.iq

جامعة الموصل - كلية الهندسة - قسم الهندسة الكهربائية

المؤلف:

تعتبر استقرارية نظام القدرة الكهربائية على أنها قابلية النظام، عند تعريضه إلى اضطرابات معينة مثل الاعطال أو التغييرات المفاجئة في الحمل. أصبح من الضروري زيادة الاهتمام بمعالجة مشاكل عدم استقرار النظام في أنظمة القدرة الكهربائية للحفاظ على مستوى إنتاجية القدرة. تهدف هذه الدراسة إلى تحليل الاستقرار من ناحية النظام، حيث تعتبر المعوض المتزامن الساكن دوائر السيطرة (PI controller) للتحكم في فولتية النظام خلال فترة الاضطراب. تحتوي المقالة على دراسة نموذج نظام القدرة الكهربائي، حيث تم استخدام برنامج MATLAB/Simulink، مع تضمين أساليب التحكم المتميزة، لإظهار فعالية المعوض المتزامن الساكن في تحسين استقرار النظام وضمان إنتاجية القدرة.

المؤلف:

تدور الدراسة على استقرار نظام القدرة الكهربائي، حيث تتم استخدام معوض متزامن ساكن، لإظهار فعاليته في تحسين استقرار النظام وضمان إنتاجية القدرة.

العنوان:

التحكم في القدرة المتفاعلة باستخدام المعوض المتزامن الساكن لتحسين فولتية نظام القدرة

الملخص:

يعتبر نظام القدرة الكهربائي من الأنظمة ذات القدرة الكبيرة، حيث تتم الانتباه لاستقراره وضمان إنتاجية القدرة في حالة حدوث اضطرابات مفاجئة. تستخدم المعوض المتزامن الساكن دوراً في تحسين استقرار النظام، حيث يمكنه التحكم في فولتية النظام خلال فترة الاضطراب. يتم استخدام برنامج MATLAB/Simulink في هذا البحث، حيث يتم استخدام المعوض المتزامن الساكن كدوائر السيطرة (PI controller) لتحسين استقرار النظام.

الكلمات الدالة:

النقل التيار المتناوب المرن، المعوض المتزامن الساكن، استقرارية نظام القدرة، معوضة القدرة المتفاعلة.