DESIGN AND ANALYSIS OF OPTIMAL BASED CONTROL STRATEGY FOR D-STATCOM, GAZA LOW VOLTAGE NETWORK – CASE STUDY

Mahir Sabra¹, Ahmed A. Alamaren²

1: Assistant Professor, Electrical Eng. Dept., IUG, Palestine, msabra@uou.edu.ps
2: Master Student, Electrical Eng. Dept., IUG, Palestine, amreen.12@hotmail.com

ABSTRACT

This paper focuses on the Distribution Static Compensator (D-STATCOM) device, which is widely used to overcome the power quality problems. The paper proposes a control strategy for D-STATCOM based on optimal control methods; $H_2$ and $H_\infty$ methods, in order to utilize the benefits of the optimal control methods to reach optimum solutions for power quality problems. The proposed control strategy depends on $Dq$ transformation, Phase-Locked Loop (PLL) synchronization and constant DC link voltage. An optimal based control strategy is designed, then performance simulation is done using MATLAB environment, and analyzed on the demand of one of the low voltage (400V) networks of Gaza city as a case study to verify its effectiveness. The D-STATCOM device using the proposed optimal based control strategy provides fully voltage recovery (1 pu), fully Total Harmonic Distortion (THD) elimination (0.54% THD), maximum $p.f$ (0.99) and faster response (0.02 sec), which making it an effective solution for power quality problems.

KEYWORDS: Power quality, Sag, Swell, D-STATCOM, Optimal, $H_2$, $H_\infty$.

I. INTRODUCTION

The term *Power Quality* has become one of the most prolific buzzword in the power industry since the late 1980s. The issue in power quality problems is concerned on quality and continuity of supply, or power quality and supply quality. Both electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power [1].

A power quality problem is defined as any power problem manifested in voltage, current, or frequency deviations that result in power failure or disoperation of customer equipment from the perspective of customers [1].

Actually the power quality is the quality of the voltage that is being addressed in most cases. Technically, the power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw. Therefore, it is very useful to study the problems of the voltage quantity as power quality problems [1]. The most power quality problems that always occur at the distribution systems are voltage sag, voltage swell and harmonics. This paper will address these power problems.
**Voltage Sag/ Swell:** Voltage sag and voltage swell are characterized by their magnitude (pu value) and duration according to IEEE Standard 1159-1995 [2] as mentioned in Table 1.

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Voltage (pu)</th>
<th>Duration (cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Sag</td>
<td>0.1 – 0.9</td>
<td>0.5 – 30</td>
</tr>
<tr>
<td>Voltage Swell</td>
<td>1.1 – 1.8</td>
<td>0.5 – 30</td>
</tr>
</tbody>
</table>

A very common quantity to define the voltage sag is "percentage of sag"; \( \text{sag\%} \), which can be calculated using equation (1):

\[
\text{sag\%} = \frac{V_{\text{pre\_sag}} - V_{\text{sag}}}{V_{\text{pre\_sag}}} \times 100
\]  

(1)

Swells are less common than voltage sags, but also usually associated with system fault conditions. "Percentage of swell" term; \( \text{swell\%} \), is a quantity to define the voltage swell, which can be calculated using equation (2):

\[
\text{swell\%} = \frac{V_{\text{swell}} - V_{\text{pre\_swell}}}{V_{\text{pre\_swell}}} \times 100
\]  

(2)

Voltage sags and voltage swells cause devices/process down time, effect on product quality, failure/malfunction of customer equipments and associated production, maintenance and repair costs [3,4].

**Harmonics:** Harmonics are voltages or currents at frequencies that are integer multiples of the fundamental 50 Hz frequency (100 Hz, 150 Hz, 200 Hz, etc.) which combine with the fundamental voltage or current and produce a distorted waveform. Harmonic distortion exists due to the nonlinear characteristics of devices and loads so that does not draw sinusoidal current when a sinusoidal voltage is applied [5]. The current distortion, for each device, changes due to the consumption of active power, background voltage distortion and changes in the source impedance [6].

**Total Harmonic Distortion (THD)** is the percentage measurement of the distortion resulted in voltage or current waveforms due to harmonics, and it is defined as a ratio of all signal components of the multiple frequencies except the fundamental frequency, to the first signal component of the fundamental frequency:

\[
\text{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}}{V_1}
\]  

(3)
IEEE Standard 519-1992 [7] lists the limits of the THD which should be used as system design values for the "worst case" for normal operation. Table 2 shows the IEEE standard values of THD.

Table 2: Voltage Distortion Limits According to IEEE Std. 519-1992

<table>
<thead>
<tr>
<th>Bus Voltage (kV)</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69 and below</td>
<td>5.0</td>
</tr>
<tr>
<td>69 through 161</td>
<td>2.5</td>
</tr>
<tr>
<td>161 and above</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Custom Power Devices:** Custom power devices play a major role to overcome the power quality related problems occurring in the transmission and distribution network system. The concept of custom power devices is to use solid state power electronic components or static controllers aiming to supply reliable and high quality power to sensitive users. Among Custom power devices controllers, the shunt controllers have shown feasibility in term of cost-effectiveness and size reduction in a wide range of problem-solving from transmission to distribution levels. In this regard, Static Synchronous Compensator (STATCOM) is an effective solution of power quality problems. The STATCOM installed in distribution systems or near the loads to improve power factor and voltage regulation is called D-STATCOM [8-10].

Figure 1: Basic configuration of D-STATCOM device
**System Case Study:** Gaza electrical utility suffer from several power quality problems, and therefore it is a good case study to verify the optimal based control strategy. One of Gaza low voltage (400V) networks is chosen as a case study to apply and test the D-STATCOM device and analyze its behavior for power quality improvements. The choice was on Southern Al-Zaitoon Neighborhood low voltage network. The load of this network is rated at 410 KVA with 0.92 p.f. [11].

**II. MODELING OF D-STATCOM SYSTEM**

The D-STATCOM system can be represented as shown in Figure 2. This configuration may be represented per phase basis as shown in the Figure.

![Figure 2: D-STATCOM system with LC-filter](image)

where,

- $V_s$ supply voltage
- $R_s$ supply resistance
- $L_s$ supply inductance
- $i_s$ supply current
- $V_c$ voltage at load point
- $i_L$ load current
- $R_L$ Load resistance
- $i_{fc}$ current in C-branch of filter
- PCC Point of Common Coupling (Load)
- $R_c$ filter resistance (includes coupling transformer losses)
- $L_L$ Load inductance
- $i_f$ current in L-branch of filter
- $L_s$ supply inductance
- $i_s$ supply current
- $V_c$ voltage at load point
- $i_L$ load current
- $R_L$ Load resistance
- $L_L$ Load inductance
- $i_f$ current in L-branch of filter
- $V_{dc}$ DC voltage of the storage device
- $L_s$ filter inductance (includes leakage inductance of coupling transformer)
- $C$ shunt filter capacitor

System dynamics can be represented as:
\[
\frac{di_s}{dt} = \frac{V_s}{L_s} - \frac{i_s}{L_s} R_s - \frac{V_s}{L_s}
\]
\[
\frac{di_f}{dt} = \frac{V_{dc}}{L_c} - \frac{i_f}{L_c} R_c - \frac{V_c}{L_c}
\]
\[
\frac{di_L}{dt} = \frac{V_c}{L_L} - \frac{i_L}{L_L} R_L
\]
\[
\frac{dV_c}{dt} = \frac{i_s + i_f - i_L}{C}
\]

\(V_s\) will be considered as the system input \(u\), while \(V_c\) will be considered as the system output \(y\). \(V_{dc}\) is a constant term. The states will be chosen as: source current \(i_s\), compensated current \(i_f\), load current \(i_L\) and the PCC voltage \(V_c\). Thus, \(x_1 = i_s\), \(x_2 = i_f\), \(x_3 = i_L\), \(x_4 = V_c\) and \(y = x_4\).

Therefore, the differential equations (3)-(6) can be expressed by linear continuous time system, or state-space model as:

\[
\begin{bmatrix}
\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}
\end{bmatrix}
= 
\begin{bmatrix}
\frac{-R_s/L_s}{1} & 0 & 0 & -1/L_s \\
0 & \frac{-R_c/L_c}{1} & 0 & -1/L_c \\
0 & 0 & \frac{-R_L/L_L}{1} & 1/L_L \\
\frac{1/C}{1} & \frac{1/C}{1} & -1/C & 0
\end{bmatrix}
\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}
+ 
\begin{bmatrix} 1/L_s \\ 0 \\ 0 \\ 0 \end{bmatrix} u
\]

\[
y = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}
\]

III. ALGORITHM THE OPTIMAL BASED CONTROL STRATEGY FOR D-STATCOM

An optimal based control strategy of D-STATCOM with constant DC link is presented below and showed in Figure 3.

- The AC three phase voltages at the PCC point is measured and transformed into Dq reference frame.
- The \(V_d\) and \(V_q\) components are processed by separated, but similar two controllers to derive the compensating \(dq\) components. \(V_d\) component is compared with the 1.0 pu reference value and the \(V_q\) component is compared with the 0.0 pu reference value, to maintain the non disturbance voltage signal.
- The resultant \(V_d\) and \(V_q\) controlled components are combined with the \(V_0\) component (of 0' value) and then retransformed to the original three-phase abc stationary coordinate system using virtual Phase-Locked Loop (PLL) fixed at 50 Hz frequency and 0' phase shift, which result with ideal synchronized voltage signal with the main network voltage.
The resultant $V_{dc}$ voltage signal is fed to the Sinusoidal Pulse Width Modulation (SPWM) pattern to produce a switching pulses of the IGBT's gates of the D-STATCOM inverter.

The two separated controllers for the $V_d$ and $V_q$ components will be: optimal controllers; $H_2$ and $H_\infty$.

To attenuate harmonics, harmonic filters are placed at the point of the load, which are a combination of RLC circuit elements that tuned to eliminate the most harmonic orders causes distortion on the signal.

![Figure 3: MATLAB model of D-STATCOM control strategy](image)

**IV. Design of Optimal Controllers:**

Optimal control methods provides the best possible performance and reach the system which is supposed to be the best possible system of a particular type [12]. Hence, it is interesting that the optimal control of D-STATCOM be demonstrated for power quality improvement.

**$H_2$ Optimal Control:** The $H_2$ controller is an optimal controller that utilizes partial state information and noisy information. The $H_2$ controller estimates the system state,
which then used in the LQR. Hence, the $H_2$ controller is basically a regulator, and the $H_2$ controller is designed to reject white-noise disturbance inputs [12].

Consider a standard feedback system of Figure 4, which can be described as (8).

![Figure 4: Standard feedback control system](image)

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + B_v v(t) + B_u u(t) \\
z(t) &= C_1 x(t) + D_{12} u(t) \\
y(t) &= C_2 x(t) + D_{21} v(t)
\end{align*}
\] (8)

where $v$ is a vector of uncorrelated white-noise disturbances with unit intensity, $u$ is the control input vector, $z$ is the performance vector, and $y$ is the measurement vector. The task is to find a state space controller $K$, such that the feedback interconnection of $G$ and $K$ is well-posed, defines a stable state space model $F(G,K)$, and minimizes the $H_2$ norm of $F(G,K)$. The stable state space model $F(G,K)$ is:

\[
\begin{align*}
\dot{x}_c(t) &= A_c x(t) + B_c u(t) \\
y_c(t) &= C_c x(t)
\end{align*}
\] (9)

The solution of $H_2$ control problem is implemented by applying the control gain into the estimation of the states; $u(t) = K y(t)$. In the $H_2$ optimal estimation problem, the problem is to construct an estimator, such that its $H_2$-cost is minimized [13].

Designing the $H_2$ controller in MATLAB environment requires a set of models (in the form of transfer functions) that have different values parameters to be added to the original system, and then to be augmented in order to provide good performance of $H_2$ controller for the system with greater robustness. In the proposed control strategy of D-TATCOM system, the number of models is three, and these models will be represented by its transfer functions as weighting functions; $W_1$, $W_2$ and $W_3$. The three weighting functions were modified by trial and error manner until reaching the best response with:
These transfer functions are then augmented with the system transfer function in order to provide good performance of $H_2$ controller for the system with greater robustness.

**$H_\infty$ Optimal Control:** The 2-norm optimization problem can also be posed using the system $\infty$-norm as a cost function. The $\infty$-norm is the worst-case gain of the system and therefore provides a good match to engineering specifications, which are typically given in terms of bounds on errors and controls.

The standard task of $H_\infty$ optimal problem is to find a state space controller $K$, such that the feedback interconnection of $G$ and $K$ is well-posed, defines a stable state space model $F(G,K)$, and minimizes the $H_\infty$-norm of $F(G,K)$ [14].

Similar to $H_2$ control problem, the problem of finding a controller $u(t) = K y(t)$ such that the cost $J_\infty$ is minimized, can be solved in two stages: the first is solving a problem with complete state information, and the second stage consists of an associated worst-case estimation problem. A combination of the two stages provides the solution of the original $H_\infty$ control problem.

In MATLAB environment and similar to $H_2$ controller, designing the $H_\infty$ controller requires a set of models (transfer functions) to be added to the original system, and then to be augmented, and its number is three also. The models were modified by trial and error manner until reaching the best response with:

$$ W_1 = \frac{0.03s^2 + 0.05s}{0.05s^2 + 15s + 10} $$
$$ W_2 = \frac{5s + 10}{10s + 10} $$
$$ W_3 = 1 $$
V. SIMULATION RESULTS

Table 3 show all system parameters of the case study system and its D-STATCOM control system.

<table>
<thead>
<tr>
<th>Quantities</th>
<th>value</th>
<th>Quantities</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Voltage</td>
<td>400 V</td>
<td>C</td>
<td>60 µF</td>
</tr>
<tr>
<td>System frequency</td>
<td>50 Hz</td>
<td>DC storage device</td>
<td>700 V</td>
</tr>
<tr>
<td>Rs</td>
<td>0.254 Ω</td>
<td>Voltage sag</td>
<td>22.5%</td>
</tr>
<tr>
<td>Ls</td>
<td>0.808 mH</td>
<td>Sag time</td>
<td>0.2 sec to 0.4 sec</td>
</tr>
<tr>
<td>Rl</td>
<td>0.357 Ω</td>
<td>Voltage swell</td>
<td>15.0%</td>
</tr>
<tr>
<td>Ll</td>
<td>0.484 mH</td>
<td>Swell time</td>
<td>0.6 sec to 0.8 sec</td>
</tr>
<tr>
<td>Rc</td>
<td>0.010 Ω</td>
<td>Lc</td>
<td>2.5 mH</td>
</tr>
</tbody>
</table>

The simulation will be tested for sag and swell compensation, and for harmonic distortion mitigation as the main power quality problems. Sag and Swell conditions will be applied during three–phase fault and added three–phase capacitive load, respectively.

The simulation will be implemented for the D-STATCOM system under same problems with applying the proposed control strategy using traditional PI controller first for comparison purpose, and then using $H_2$ and $H_\infty$ controllers.

**System without Control:** The simulation results of the studied system under sag/swell conditions without D-STATCOM control is showed in Figure 5. The resultant Total harmonic distortion (THD) of the voltage signal is computed as 8.83% which exceed the IEEE standard (Table 2). THD is computed using Fast Fourier Transform tool (FFT) of MATLAB for up to 60th harmonic order.

**PI Controller:** As showed in Figure 6, the sag is mitigated to 0.93 pu voltage value (only 7.0% sag) and the swell problem was compensated to 1.0 pu value with an oscillation, while THD was mitigated to 1.05%, and p.f was mitigated to 0.975 value. These results are an acceptable results within IEEE standards.

**$H_2$ and $H_\infty$ Controllers:** $H_2$ and $H_\infty$ controllers guarantee the system robustness by good selection of the weighting functions. Same results can be obtained for $H_2$ and $H_\infty$. 

Copyright © 2012 IUG.
controllers as showed in Figure 7. Voltage sag and swell was fully recovered to 1.0 pu value, THD was mitigated to 0.55% and 0.54% for $H_2$ and $H_\infty$ controllers respectively, and $p.f$ was mitigated to 0.991 value. The voltage signal shape is very smooth and well mitigated, and that reflects the effectiveness of $H_2$ and $H_\infty$ controllers.

Figure 5: Simulation of the studied system without control
Figure 6: Simulation results of D-STATCOM system with PI controller

Figure 7: Simulation results of D-STATCOM system with $H_2$ and $H_{\infty}$ controllers
Summery of Results:

<table>
<thead>
<tr>
<th>Performance</th>
<th>No control</th>
<th>PI</th>
<th>$H_2$</th>
<th>$H_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage during Sag (pu)</td>
<td>0.775</td>
<td>0.93</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Voltage during Swell (pu)</td>
<td>1.156</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>THD (%)</td>
<td>8.83</td>
<td>1.05</td>
<td>0.55</td>
<td>0.54</td>
</tr>
<tr>
<td>$p.f$</td>
<td>0.92</td>
<td>0.975</td>
<td>0.991</td>
<td>0.992</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This paper mainly focused on the optimal control for the D-STATCOM; $H_2$ and $H_\infty$ controllers, which were not yet fully employed in the past, and that have made this research area very attractive. Optimal control knowledge is a very suitable base for D-STATCOM control and power quality solutions due to its role to provide the best possible performance with respect to given measure of performance (cost function) and to give the best possible system for voltage sag/swell compensation and THD elimination, in addition to disturbance and noise rejection.

As shown in the simulation results, the proposed control strategy for D-STATCOM gave good performance for the three controllers; PI, $H_2$ and $H_\infty$, and the controller response time is very fast (less than 50 ms as the worst case).

Applying $H_2$ and $H_\infty$ as an optimal controllers for D-STATCOM provided perfect and optimum results; fully recovered voltage level (1.0 pu, no oscillation), lowest THD values (0.54%), max. $p.f$ (0.992), fastest response (0.02 sec) and smoothest voltage wave form. The active and reactive power consumption in the case of $H_2$ and $H_\infty$ controllers has sustained values during various power problems and its compensations, which provide fixed system power factor.

In addition to its role to compensate the sag, swell voltages and THD, D-STATCOM has very good behavior in order to improve the power factor ($p.f$) for excellent levels. The proposed control strategy is proved to be able to compensate the power quality problems at 400V networks of Gaza utility. Therefore, it can be concluded that the D-STATCOM with the optimal based control strategy is a practical and realistic solution for power quality problems of Gaza power utility, and it can replace the manual tap changer used in the transformers to overcome the voltage variations during faults and load variations.
VII. REFERENCES


