Chapter 3

3. Selection of Passive elements for STATCOM

3.1 Introduction

Apart from the power electronic control of the STATCOM, optimum selection of passive elements viz. coupling inductor and dc capacitor is of subtle importance as it controls the performance, cost, size of STATCOM. Selection methodology of passive elements of 3ph. STATCOM is discussed in [C1-C4]. In this chapter, selection methodology for two passive elements, i.e. coupling inductor $L_{ac}$, dc capacitor $C_{dc}$ of SHE PWM controlled single phase STATCOM is discussed. Selection of $L_{ac}$ is constrained by the rated current of the STATCOM and the distortion in the STATCOM ac side current. Increase in the value of coupling inductance reduces ripple in the STATCOM current but at the same time requires higher dc bus voltage for the required current. Increased dc bus voltage increases voltage stress across the VSI switches. A smaller coupling inductor brings down the dc bus voltage requirements but increases distortion in the STATCOM current. Selection of $C_{dc}$ is mainly constrained by allowable dc bus voltage ripple. A large dc capacitor increases cost and causes sluggish response of the dc voltage control loop. The peculiarity single phase STATCOM is that there exists second harmonic ripple in the dc bus voltage. The value of the dc capacitor has to be chosen in such a manner as to minimize the second harmonic ripple in $V_{dc}$. A shunt ripple filter is required to be connected at the input of STATCOM to filter the
unwanted switching frequency harmonics in the STATCOM current and sometimes to supply fundamental capacitive reactive power. Design of shunt ripple discussed at the end.

### 3.2 Selection of coupling inductor

Consider the fundamental frequency equivalent circuit of the SHE PWM controlled STATCOM as shown in Fig. 3.1. It is presumed that the switching elements, coupling inductor are ideal. From Fig. 3.1, applying Kirchoff’s voltage law,

\[ V_{al} = V_s + j I_{cl} \omega L_{ac} \]  \hspace{1cm} (3.1)

where, \( V_{al} \) is the fundamental component of the VSI output. \( V_{al} \) can expressed as,

\[ V_{al} = \frac{4V_{dc}}{\pi} \sum_{j=1}^{N} (-1)^j \cos(\alpha_j) \]  \hspace{1cm} (3.2)

where \( N \) is the number of chops per quarter cycle to eliminate \((N-1)\) harmonics and \( \alpha_j \) are the switching angles as shown in Fig. 2.13 of Chapter 2.

Expressing in p.u. values with base values as, \( V_{base} = V_s \), rated supply voltage and \( I_{base} = I_{cl} \), rated fundamental current supplied by STATCOM the equation (3.1) becomes,

\[ 1 + X_{ac} = \frac{4V_{dc}}{\pi} \sum_{j=1}^{N} (-1)^j \cos(\alpha_j) \]  \hspace{1cm} (3.3)

This equation gives minimum value of \( X_{ac} \). From equivalent circuit for harmonics as shown in Fig. 3.2,

\[ V_{ak} = j k X_{cl} I_{ak} \]  \hspace{1cm} (3.4)

The total demand distortion (TDD) is defined as,

\[ TDD_i = \frac{100}{I_{cl}} \left\{ \sum_{k=2}^{\infty} \left( \frac{V_{ak}}{k X_{ac}} \right)^2 \right\}^{\frac{1}{2}} \]  \hspace{1cm} (3.5)

where,
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\[ V_{dc} = \frac{4V_{dc}}{k\pi} \sum_{j=1}^{N} (-1)^{j+1} \cos(k\alpha_j) \]  \hspace{1cm} (3.6)

and \( I_{c1} \) is the rated fundamental current of the STATCOM.

Figure 3-1: Equivalent circuit of STATCOM at fundamental frequency

\[ \begin{align*}
  j\omega L_{ac} & \quad j\omega L_{ac} \\
  V_s & \quad V_0 \\
  j\omega L_{ac} & \quad V_{0k}
\end{align*} \]

Figure 3-2: Equivalent circuit of STATCOM at harmonics

Substituting (3.6) in (3.5),

\[ TDD_i = \frac{100}{I_{c1} X_{ac}} \left\{ \sum_{k=2}^{\infty} \left( \frac{4V_{dc}}{k\pi} \sum_{j=1}^{N} (-1)^{j+1} \cos(k\alpha_j) \right)^2 \right\}^{\frac{1}{2}} \]  \hspace{1cm} (3.7)

Considering \( I_{c1} \) as 1 p.u., \( X_{ac} \) can be calculated as,

\[ X_{ac} = \frac{100}{TDD} \left\{ \sum_{k=2}^{\infty} \left( \frac{4V_{dc}}{k\pi} \sum_{j=1}^{N} (-1)^{j+1} \cos(k\alpha_j) \right)^2 \right\}^{\frac{1}{2}} \]  \hspace{1cm} (3.8)

The equations to be solved are (3.3) and (3.8) to get the optimum value of \( L_{ac} \).

### 3.3 Selection of DC Capacitor

DC capacitor plays an important role in STATCOM performance and its overall cost as well. Proper sizing of dc capacitor is essential to lower the system cost and optimize performance. An expression is derived for dc capacitor voltage, \( V_{dc} \). The optimum value of \( C_{dc} \) is selected to meet the minimum (5%) ripple dc bus voltage constraint. The equivalent circuit of H-bridge VSI is shown in Fig. 3.3. The dc side current, \( i_{dc} \) and the injected current, \( I_c \) be related by following equation [C2],

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\[ i_{dc}(t) = sw(t)i_a(t) \]  \hspace{1cm} (3.9)

The switching function, \( sw(t) \) is defined as, \( sw(t) = \frac{V_o(t)}{V_{dc}} \)

![Schematic diagram of H-Bridge VSI](image)

Figure 3-3: Schematic diagram of H-Bridge VSI

Considering fundamental component of injected current,

\[ i_c(t) = I_m \sin(\omega t \pm \phi) \]  \hspace{1cm} (3.10)

Substituting in (3.9),

\[ i_{dc}(t) = \frac{V_o(t)}{V_{dc}} I_m \sin(\omega t \pm \phi) \]  \hspace{1cm} (3.11)

where,

\[ V_o(t) = \sum_{k=1}^{\infty} V_{ak} \sin(k\omega t) \]  \hspace{1cm} (3.12)

Substituting (3.12) in (3.11),

\[ i_{dc}(t) = \frac{1}{V_{dc}} \sum_{k=1}^{\infty} V_{ak} \sin(k\omega t) \]  \hspace{1cm} (3.13)

Considering only fundamental component of \( V_o(t) \),

\[ i_{dc}(t) \approx \frac{V_o1}{V_{dc}} I_m \sin(\omega t \pm \phi) \]  \hspace{1cm} (3.14)

\[ C_{dc} \frac{dV_{dc}}{dt} = \frac{V_o1}{V_{dc}} I_m \sin(\omega t) \sin(\omega t \pm \phi) \]  \hspace{1cm} (3.15)

Simplifying further,

\[ \frac{dV_{dc}}{dt} = \frac{V_o1}{2C_{dc}V_{dc}} I_m \left[ \cos(\phi) - \cos(2\omega t \pm \phi) \right] \]  \hspace{1cm} (3.16)
and

$$V_{dc}(t) = V_{dc}(0) - \frac{V_{ol} I_m}{4 C_{dc} V_{dc}} \sin(2\omega t \pm \phi) \quad (3.17)$$

where $V_{dc}(0)$ is the steady value of the dc bus voltage.

Peak-to-peak ripple voltage across $C_{dc}$,

$$\Delta V_{dc} = \frac{V_{ol} I_{am}}{2\omega C_{dc} V_{dc}} \quad (3.18)$$

By specifying $\Delta V_{dc}$ optimum value of $C_{dc}$ can be calculated as,

$$C_{dc} = \frac{m I_{am}}{2\omega \Delta V_{dc}} \quad (3.20)$$

### 3.4 Design of ripple filter

As shown in[B3], the significant harmonics in the VSI output, after elimination of $N-1$ harmonics are, $2N+1$, $2N+3$, $2N+5$ and $2N+7$. In the present application, $N=12$, which implies that the dominant harmonics present in the VSI output will be $25^{th}$, $27^{th}$, $29^{th}$ and $31^{st}$ order. Because of the harmonic components, the THD of the VSI current will be high and cross the IEEE-519 limits. In order to suppress the dominant harmonic components in the VSI current, appropriate filter is necessary. Various ripple filter topologies are shown in Fig. 3.4.

![Figure 3-4: SRF topologies used in the custom power devices](image)

For the present application, high-pass LCR filter is appropriate considering the number of harmonics to be suppressed. The high-pass LCR type filter illustrated in Fig. 3.4(d) exhibits a tuned filter characteristic if the series resonant frequency of $C_F$ and $L_F$ in its structure is tuned to dominant harmonic component, presently $2N+1$ order harmonic. Moreover, it exhibits high-
pass filter characteristics due to resistor $R_d$ in its structure. $R_d$ also provides damping for resonances. The harmonic equivalent circuit of the high-pass LCR type filter is shown in Fig. 3.5. The transfer function of the filter $T(s)$ is defined as ratio of the line current $I_{HS}$ to the harmonic current source $I_H$ given as follows.

$$T(s) = \frac{s^2L_F C_F R_d + sL_F + R_d}{S^2L_S L_F C_F + s^2(L_F + L_s)C_F R_d + sL_F + R_d}$$  \hspace{1cm} (3.21)

Figure 3-5 Equivalent circuit of the VSI, high-pass LCR filter and supply at harmonic frequencies

For tuned filter characteristics, the impedance of $L_F$ should be smaller than $R_d$ at the resonant frequency. As the $R_d$ value increases, the filter impedance characteristic resembles the impedance characteristics of tuned filter and
loses its high-pass characteristics. Therefore, its impedance characteristic exhibits tuned filter characteristics to filter out the most dominant harmonic with high $R_d$ values. The typical frequency response of the transfer function shown in Fig. 3.6 is drawn for various values of $R_d$ for fixed values of $C_F$ and $L_F$. Effect of increasing value of $R_d$ on the performance of the filter can be seen in the characteristics. The selection of the $L_F$, $C_F$ values is based on the chosen value of the reactive power compensated by the filter and the chosen resonant frequency of the branch. The selection of $L_F$, $C_F$ can be performed as follows,

Let the capacitive reactive power at fundamental frequency supplied by the filter be,

\[ Q_f = dQ_1 \]
\[ Q_f = -B_1 V_s^2 \] (3.21)

where, $B_1$ is the susceptance of the filter branch at fundamental frequency. For an $LC$ branch having high quality factor, resistance in the branch can be neglected and the branch susceptance can be expressed as,

\[ B_1 = \text{Im} \left\{ \frac{1}{j\omega L_F + \frac{1}{j\omega C_F}} \right\} = \frac{\omega C_F}{1 - \omega^2 L_F C_F} \] (3.22)

If the branch is tuned to the harmonic frequency $n\omega$ in order to provide low impedance path for a harmonic of order $n$, then,

\[ L_F C_F = \frac{1}{n^2 \omega^2} \] (3.23)

Therefore the reactive power provided by the $LC$ branch can be expressed as,

\[ Q_f = \frac{\omega C_F}{1 - \omega^2 L_F C_F} V_s^2 \] (3.24)

From (3.24),

\[ Q_f = \frac{\omega C_F}{1 - \frac{1}{n^2}} V_s^2 \] (3.25)

The required value of the $C_F$ can be calculated as,
\[
C_F = \frac{Q_F \left(1 - \frac{1}{n^2}\right)}{\omega V_s^2}
\]

(3.26)

Similarly the value of \( L_F \) can be calculated as,

\[
L_F = \frac{V_s^2}{Q_F \omega (n^2 - 1)}
\]

(3.27)

Based on the value of impedance of the \( L_F \) at harmonic frequency, value of \( R_d \) can be chosen to get high-pass response. The dominant harmonic in the VSI current is 25\(^{th}\) i.e. 1250Hz. The high pass filter’s LC elements are tuned to 1250 Hz and selection \( C_F \) is as per the required fundamental capacitive reactive power. The value of \( R_d \) is chosen to be 0.8\( \Omega \). The simulated response of the current without filter is shown in Fig. 3.7. The harmonic spectrum of the current is shown in Fig. 3.8. The THD of the VSI current without filter is 10.1\%. The VSI current with LCR high pass filter in Fig. 3.9 and its harmonic spectrum is shown in Fig. 3.10. The THD of the VSI current with LCR high-pass filter is dropped down to 6.1\%
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Figure 3-8: Harmonic spectrum of VSI current without LCR high-pass filter

Figure 3-9: VSI current with LCR high-pass harmonic filter

Figure 3-10: Harmonic spectrum of VSI current with LCR high-pass filter
3.5 Summary

The procedure for selecting optimum values of coupling inductor, $L_{ac}$ and dc capacitor $C_{dc}$ for SHE PWM STATCOM is presented. The selection of $L_{ac}$ is mainly constrained by the limits on the distortion in the STATCOM current. The value of $C_{dc}$ is decided so as to minimize second harmonic ripple in the dc bus voltage. The design of high pass type filter is also proposed for minimizing ripple in the STATCOM current. The validation is performed by performing computer simulations and presented in the next chapter.