A Method for Band Width Determination of Multiband Hysteresis Modulation, for any Given Switching Frequency Maximum of Inverter

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ABSTRACT

Now day, the inverters used in many electrical applications such as UPS, motors driver, compensators, and so on. One of the best topologies of inverters is the Cascaded H-bridge. In this paper the Cascaded H-bridge seven-level inverter topology and six-band hysteresis modulation for distribution static compensator (DSTATCOM) are briefly studied. Comparing with the Tsypkin's method, a Sliding-Mode controller for a DSTATCOM has been considered as a new method for bandwidth determination of a multiband hysteresis modulation, which has been used for desired maximum switching frequency of the inverter. Moreover, controlling of the dc-link voltage, a series of simulation results for a seven-level inverter used in DSTATCOM, has been shows the effectiveness of proposed method for system operation for unbalanced and variable loads.

Key words: Cascaded H-bridge inverter, Distribution static compensator (DSTATCOM), Multiband hysteresis modulation, Sliding-mode control, Tsypkin's method.

Introduction

The first multilevel inverters were introduced around 30 years ago. Regarding to lower switching losses, higher performance and also electromagnetic compatibility of mentioned inverters these can usedfor various high voltage systems via the optimal tuning of their performance. Recently, various multilevel topologies have been introduced and the most important are considered by diode clamping, flying capacitor and also the H-bridge cascaded multilevel inverters. However, due to modular implementation of the cascaded structure, this has more usage as the inverter. On the other hands, a well known modulation method used in the inverters called hysteresis modulation. In this method the parameters design is most important for band width determination which is relative to switching losses with the specified given limit. Now, in this paper, a new method for the bandwidth calculating of a multiband hysteresis modulation has been introduced. In this way, the inverter used in distribution static compensator (DSTATCOM) is considered as a voltage source inverter (VSI) which the desired voltage should be produced by the hysteresis modulation via the Sliding-Mode controller. In the second part, a seven-level cascaded inverter has been illustrated and the model of DSTATCOM with sliding mode controller has been illustrated in the third part. Moreover, a novel method for hysteresis bandwidth determination has been studied in forth. The fifth section describes the control method for the dc-link voltage of a seven-level inverter using PI controller and shows the simulated results of its operation in a DSTATCOM (Corzine, K.A. and M.W. Wielebski, 2004).

2- Seven-Level H-bridge Cascaded Inverter:

A seven-level cascaded inverter using DSTATCOM has been shown in fig. 1. As shown in Fig. 2 the inverter consists of three H-bridges and the output voltage is sum of the each. Regarding to fig. 3, each H-bridge can be switched in three levels which are \(-V_{dc}/3\), \(+V_{dc}/3\) and 0. In fig. 3 each switch can be considered with an IGBT switch using one anti-parallel diode. Considering of switches positions, the output voltage and current path have been shown for each H-Bridge in Table 1. The most advantages of seven-level cascaded inverter is the low voltage stress \((dv/dt)\) for each switch which is equal to \(V_{dc}/3\). It is clear that the switching losses are relative to switching frequency so, this is limited to maximum frequency of switching to avoid of exceeding.
Fig. 1: Using of Seven-Level Cascaded inverter in a DSTATCOM.

Fig. 2: Seven layer inverter H-bridge

Fig. 3: Structure of each of H-bridges.
Table I: Conduction of Switches and Diodes Based Upon Load Current.

<table>
<thead>
<tr>
<th>$V_d$</th>
<th>Conduction of Elements of Inverter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{V_{dc}}{3}$</td>
<td>$S_{11}$ and $S_{14}$</td>
<td>$I_{dh} &gt; 0$</td>
</tr>
<tr>
<td></td>
<td>$D_{11}$ and $D_{14}$</td>
<td>$I_{dh} &lt; 0$</td>
</tr>
<tr>
<td>$\frac{V_{dc}}{3}$</td>
<td>$D_{12}$ and $D_{13}$</td>
<td>$I_{dh} &gt; 0$</td>
</tr>
<tr>
<td></td>
<td>$S_{12}$ and $S_{13}$</td>
<td>$I_{dh} &lt; 0$</td>
</tr>
<tr>
<td>0</td>
<td>$S_{11}$ and $D_{12}$</td>
<td>$I_{dh} &gt; 0$</td>
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<td></td>
<td>$D_{11}$ and $S_{12}$</td>
<td>$I_{dh} &lt; 0$</td>
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<tr>
<td>0</td>
<td>$D_{13}$ and $S_{14}$</td>
<td>$I_{dh} &gt; 0$</td>
</tr>
<tr>
<td></td>
<td>$S_{13}$ and $D_{14}$</td>
<td>$I_{dh} &lt; 0$</td>
</tr>
</tbody>
</table>

3- SLIDING-MODE Control and DSTATCOM Model:

In this part, the sliding-mode controller for the load voltage control with DSTATCOM has been described. A distribution system controlled by DSTATCOM is shown in fig. 4. The load has been supplied by a voltage source $V_s$ via a feeder with $L_a$ and $R_f$ impedances. Moreover, another voltage source inverter (VSI) has been used in the DSTATCOM system which is connected to the load via a parallel connection. The capacitor filter $C_f$ is connected to the load, for THD voltage reduction. In fig. 4, a non-linear load has been considered to simulation of a rectifier. Also, $R_p$ and $L_p$ are considered as the total impedance of the relative shunt path. Moreover, $V_{dc}$ and $u$ are the dc-link voltage and controllable coefficient of output VSI output which must produced by sliding-mode controller and hysteresis modulation. In a seven-level inverter the discrete values of $u$ are $-1, -2/3, -1/3, 0, +1/3, +2/3$ and $+1$. Regarding to system operation, the current of branches are the source current ($i_{sh}$), load current ($i_l$), current of the filter capacitor ($i_{cf}$), inverter output current ($i_{in}$) and injected current by the shunt path which is ($i_{sh}$) (Gupta, R., 2010).

![Fig. 4: Model of compensated distribution system by DSTATCOM.](image)

In order to control law designing with independent parameters for load and distribution system, the state vector is defined as $z^T = [\dot{v}_t^T, v_t^T]$ where, $v_t$ is the terminal voltage just is the point-of-common-coupling (PCC), and $\dot{v}_t^T$ is its derivative which can obtain from $i_{cf}/C_f$. Considering the terminal voltage as the output of state space model, the bellow equation can be written:

\[
\begin{align*}
\dot{z} &= Fz + g_2u + g_3d \quad v_t = h_z z \\
F &= \begin{bmatrix} -R_f & -1 \\ L_f & 0 \end{bmatrix} \\
g_1 &= \frac{V_{dc}}{C_f L_f} \\
g_2 &= \begin{bmatrix} 1 \\ 0 \end{bmatrix} \\
h_z &= \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\
\end{align*}
\]

(1)

Where $d$ is the periodic voltage source which is related to the shunt current by below equation:

\[
d = \frac{1}{C_f} \begin{bmatrix} 0 \\ \frac{d i_{sh}}{dt} \end{bmatrix} \\
\]

(2)
State vector $z(t)$ must reach to reference vector $z_r^T = [\dot{v}_{tr}, v_{tr}]$ with desired precision. Now, the sliding-mode control law must be designed for sinusoidal terminal voltage tracking with 50 or 60 Hz frequency which can be written by following equation:

$$v_{tr}(t) = V_p \sin(\omega_0 t - \delta_p)$$

(3)

Where, $V_p$ is the amplitude of reference terminal voltage, $\delta_p$ is its phase with respect to the phase of voltage source ($v_t$) and $\omega_0$ is the angular frequency of distribution system (Gupta, R., 2010). Using the reference vector $z_r$ and the equation (3), state space reference model can be defined as follow:

$$\dot{z}_r = A_r z_r + B_r r$$

$$v_{tr} = C_r z_r$$

$$A_r = \begin{bmatrix} 0 & -\omega_0^2 \\ 1 & 0 \end{bmatrix}$$

$$B_r = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C_r = [0 \ 1]$$

$$r(t) = V_p \omega_0 \text{Dirac}(t - \delta_p)$$

(4)

Where $\delta$ is Dirac function and $r(t)$ is input of the reference state space model (Carpita, M. and M. Marchesoni, 1996). Moreover, sliding surface $S_e$ which is also called a switching function is defined as follows:

$$S_e = K z_e = k_1 (v_{tr} - v_r) + k_2 (v_{tr} - v_t)$$

$$z_e = \begin{bmatrix} \ddot{v}_{tr} - v_r \\ v_{tr} - v_t \end{bmatrix}$$

$$K = [k_1 \ k_2]$$

(5)

Where, $k_1$ and $k_2$ are positive feedback gains. In designing of sliding-mode controller there are two conditions for reaching and sliding phases which must satisfy by the following condition:

$$\ddot{V} = S_e. S_e < 0$$

(6)

Regarding to equation (6), the following control law for variable structure $u$ is achieved:

$$u = \begin{cases} u^+ & \text{when } S_e > 0 \\ u^- & \text{when } S_e < 0 \end{cases}$$

(7)

Where, $u^+$ and $u^-$ are maximum and minimum energy of control law, respectively. While the equation (6) be satisfied, the control law defined in (7) cussed to system operation on a given sliding surface i.e., $S_e = 0$. With obtaining of continuous control law $u$ defined in (7) considering $S_e = 0$ for $z_e$, it can be written by bellow:

$$z_e = G z_e ; \ G = \begin{bmatrix} -k_2 & 0 \\ k_1 & 0 \end{bmatrix}$$

(8)

For positive value of $k_2/k_1$, the Eigen values of $G$ be in left side of $s$-plane and dynamical error of states will be stable. Also, states of the system under sliding-mode control, will reach to the reference model defined by (4) independently and non-relative to load and the distribution system parameters. Considering ideal sliding-mode control operation, IGBT switches must operate with very high frequency which isn’t possible because switching frequency of IGBTs (or any practical switches) is limit. To solving of this problem the hysteresis modulation will describe in the next part (Gupta, R., 2010).

4- Six-band hysteresis modulation:

Fig. 5 shows six-band hysteresis modulation with similar bands for the seven-level cascaded inverter. In Fig. 5 $h$ and $\delta$ are total hysteresis bandwidth and dead zone used to prevent interference of operation respectively. In Fig. 5, $s^* = K \cdot z_e$, and $s = K \cdot z$ are linear combination of reference model states and linear combination of states of system (1), respectively. Using algorithm (9), the above modulation (Fig. 5) can be easily implemented, (which in Fig. 5, $u^* = -u^- = 1$).
Fig. 5: Six-band hysteresis modulation.

The switching method of each switch of the seven-level inverter is based on $u$, which is derived from hysteresis modulation. For example, if $u$ be $-1/3$ the H-bridge shown in Fig. 2 be activated, i.e., switches $(S_{a12}, S_{a13})$ are on and the two other H-bridges are inactive which means that their output voltage is $0$ volt. Using sliding-mode control and under steady state condition, the frequency of $S$ is lower than the switching frequency. So with instantaneous estimation of the inverter during one cycle of inverter fundamental frequency, operation of the inverter for each band of the multi-band hysteresis modulation regardless of dead zone $\delta$ as shown in figure 5, can be shown by Fig. 6.

Fig. 6: Estimation of $S^+$ and $S^-$ operation in the third band of six-band hysteresis modulation, as shown in Fig. 5, in short time of fundamental frequency of one cycle.
Fig. 7: Shifted hysteresis band correspondingly for different levels.

Regarding to Fig. 6, it can be written that:

\[
\frac{dS^+}{dt} - \frac{dS^+}{dt} t_1 = \frac{h}{3} \]
\[
\frac{dS^-}{dt} - \frac{dS^-}{dt} t_2 = -\frac{h}{3} \]
\[
t_1 + t_2 = T_{sw}; \quad f_{sw} = \frac{1}{T_{sw}}; \quad U^+ = 0, U^- = -\frac{1}{3}
\]  

In Fig.6,$f_{sw}, S^+$ and $S^-$ are the instantaneous switching frequency, linear combination of the system state for inputs $U^+$ and $U^-$, respectively. It is important that, the equation (10) will satisfied for each band of the multiband hysteresis modulation shown in Fig. 5. Now, from (10) and (11) can be written as:

\[
h = \frac{3}{f_{sw}} \left[ \frac{\left( \frac{dS^+}{dt} - \frac{dS^+}{dt} \right) \left( \frac{dS^+}{dt} - \frac{dS^-}{dt} \right)}{\left( \frac{dS^-}{dt} - \frac{dS^-}{dt} \right)} \right]
\]  

Replacing (1) into (12), we have:

\[
h = \frac{3}{f_{sw}} \left[ \frac{\left( \frac{dS^+}{dt} - p - K_{g1} U^\prime \right) \left( \frac{dS^+}{dt} - p - K_{g1} U^\prime \right)}{K_{g1} [u - u^\prime]} \right] \]

Where $p = K \cdot (F z + g z d)$

Now, to obtaining the desired hysteresis bandwidth($h$) for the given effective maximum switching frequency ($f_{sw_{max}}$), each band should be shifted to the relative origin as shown in Fig. 7. According to Fig. 7, it can be written that (Gupta, R., 2010):

\[
U^+ = \frac{1}{6} \quad U^- = -\frac{1}{6}
\]  

Replacing (14) in the (13):

\[
f_{sw} = \frac{K_{g1}}{4h} \left[ 1 - \left( \frac{6}{K_{g1}} \left( \frac{dS^+}{dt} - p \right) \right)^2 \right]
\]  

According to (15), the hysteresis band $h$ can obtained from the given effective maximum switching frequency $f_{sw_{max}}$ as follows:
In the next section, the implementation of seven-level cascaded inverter in the DSTATCOM for control of nonlinear load voltage will be presented.

5-Simulation Seven-Level Cascaded Inverter Used in the DSTATCOM:

Considering system data given in Table II. The nonlinear load is assumed as a nonlinear rectifier which its output dc voltage is supplied by a parallel dc capacitor \( C_{dc} \) that is used for resistive load \( R_{dc} \).

Table II: Parameters of three-phase system used for simulation (Gupta, R., 2010).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage source ( v_s )</td>
<td>3.3 kV ( \text{rms} ) ((L - L))</td>
</tr>
<tr>
<td>System frequency ( f_s )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>( L_s ) and ( R_s ) for each phase</td>
<td>6.9 mH, 0.363 ( \Omega )</td>
</tr>
<tr>
<td>( L_T ) and ( R_T )</td>
<td>2.3 mH, 0.628 ( \Omega )</td>
</tr>
<tr>
<td>Filter capacitor ( C_f )</td>
<td>125 ( \mu F )</td>
</tr>
<tr>
<td>Dc-link voltage</td>
<td>3 kV</td>
</tr>
<tr>
<td>Dc voltage of each H-bridge</td>
<td>1 kV</td>
</tr>
<tr>
<td>Load of each the phase</td>
<td>( Z_a = 15 + j15 , \Omega )</td>
</tr>
<tr>
<td></td>
<td>( Z_b = 18 + j15.7 , \Omega )</td>
</tr>
<tr>
<td></td>
<td>( Z_c = 16 + j16.3 , \Omega )</td>
</tr>
<tr>
<td>The characteristics of non-linear load</td>
<td>( R_{dc} = 18 , \Omega ) ( C_{dc} = 1000 , \mu F )</td>
</tr>
<tr>
<td>Feedback gains</td>
<td>( k_1 = 0.001 ) ( k_2 = 6 )</td>
</tr>
</tbody>
</table>

The hysteresis bandwidth \( h \) for \( f_{sw_{max}} = 3 \, \text{kHz} \) is obtained 869.5 volts by the listed parameters in Table II, using (16). In (Gupta, R., 2010), this value using the Tsypkin's method is obtained 869 volts. As some advantages of this work, it is notable that the Tsypkin's method presented in (Gupta, R., 2006) was graphical form that needs more time to calculate the bandwidth \( h \), however in the presented method the bandwidth \( h \) is obtained by simple replacement of the system data in (16). Also, the presented method in this paper with respect to presented Tsypkin's method in (Gupta, R., 2006) to for \( h \) calculating, has been obtained precise enough, as shown in Fig. 9. As shown in Fig. 9, error of \( h \) determination in the proposed method with respect to the Tsypkin's method presented in (Gupta, R., 2006) for different effective maximum frequency \( f_{sw_{max}} \) as shown in Fig. 9. It is clear that this error is decreased with increasing of effective maximum frequency. In the simulation, the dead zone \( \delta \) has been chosen 50 volts and amplitude of the voltage source has been considered to 2690 volts. Also, the reference phase \( \delta_p \) and a PI controller as shown in Fig. 8 have been used for voltage control of the dc-link (Mishra, M.K., 2003).

Fig. 8: Control block for the dc link voltage control via a PI controller.

In Fig. 8, \( V_{dc} \), \( V_{dcref} \), \( K_p \), \( P_{shref} \), \( P_{sh} \) and \( P_{sh} \) are the average voltage of all dc-link capacitors for the three phases, reference dc-link voltage, proportional gain, integral gain, reference mean power for compensating the dc-link voltage drop, instantaneous power of the shunt path, and mean power of the shunt path respectively. According to Fig. 8, difference between the average voltage of capacitors in dc-link and the reference dc-link voltage \( V_{dcref} \) is multiplied by positive gain \( K_p \) and it is assumed as the reference mean power \( P_{shref} \) and the PI controller is as follows (Mishra, M.K., 2003):

\[
\delta_p = K_p (P_{sh} - P_{shref}) + K_I \int (P_{sh} - P_{shref}) \, dt
\]  

(17)
The values of the gains in simulation have been selected via the better shown experimental results as bellow:

\[ K_{pr} = 1400 \quad K_p = 4 \times 10^{-6} \quad K_I = 6 \times 10^{-6} \quad (18) \]

For robust performance analyze of system performance and designed controller, a three-phase load change has been considered at 3 sec, as following:

\[ Z_a = 3.75 + j1.42 \Omega \]
\[ Z_b = 3.91 + j1.43 \Omega \]
\[ Z_c = 3.80 + j1.43 \Omega \quad (19) \]

The system performance which can shows the robust operation after load changing, capacitor voltages and also the terminal voltage have been shows in Fig. 10 and Fig.11. Regarding these figures, all parameters have been reached to their reference values after short time. Due to load impedance decreasing after 3 sec, transmitted active power from the source voltage \( v_x \) should increase. So, the power angle \( \delta_p \) has been changed properly by controller task. Regarding to above illustration, the power angle has been reached to more negative value to active power injection which is shown in Fig.12. As can be seen in Fig. 11, the voltage of each capacitor, has been reached to reference value with a good performance and short during time, after the load changing. It is key note that the swapping technique of switching algorithm for each H-bridge during each cycle for distribution of the same charge and discharge of each capacitors, is implemented in this study which is one of the advantages of this work. As a more illustration, the terminal voltage and its THD are shown in Fig. 10 and Fig. 13, respectively. In Fig. 14 the output of multiband hysteresis, i.e. input \( u \) to the inverter output for phase a have been shows. According to Fig. 13 it is clear that THD of terminal voltage decreases after DSTATCOM connecting, and the DSTATCOM operates as an active filter to sub harmonics decreasing.

![Fig. 9: The obtained Error for parameter in the proposed method with respect to the Tsypkin's method.](image)

![Fig. 10-a: Terminal voltage before connecting the DSTATCOM, b) Terminal voltage after connecting the DSTATCOM](image)
**Fig. 11:** Capacitors’ voltages for, a) Phase “a”, b) Phase “b”, c) Phase “c”.

**Fig. 12:** The output controller ($\delta_p$) for the dc-link voltage.

**Fig. 13:** THD of phase “a” terminal voltage, a) before connecting DSTATCOM, b) after connecting DSTATCOM (THD is calculated after the load change).

**Fig. 14:** Flow mode controller output with six-band modulation for phase “a”.

6. Conclusion:

In this paper, seven-level cascaded H-bridge inverter used in distribution system static was introduced, and a new method to calculate bandwidth in the multiband hysteresis modulation was proposed. Moreover, the robustness performance of the DSTATCOM under load change about 70% was analyzed. Finally, a series of simulation results shows effectiveness of proposed method and advantages of this work comparing to others for enhancement of THD terminal voltage with DSTATCOM.

References


