Virtual Flux Direct Power Control of Diode Clamped 3-Level VSI based DSTATCOM

This paper presents the performance evaluation and comparisons of voltage oriented control (VOC) and virtual flux direct power control (VF-DPC) strategies for diode clamped 3-Level voltage source inverter (VSI) based DSTATCOM. The theoretical background is described and the merits and demerits of each scheme are studied through simulations. Simulation studies are carried using MATLAB/Simulink. Performance parameters such as Algorithm complexity, steady state and dynamic performances, total harmonic distortion (THD), etc. are compared with both control strategies. Effect of unbalanced power source voltages and distorted voltages are also studied and compared through simulations. The simulation results show that virtual flux direct power control is a viable alternative to voltage oriented control (VOC) technique which is based on d-q theory for VSI based DSTATCOM.

Keywords: VF estimator, Voltage oriented control, direct power control, Virtual flux DPC, Three-Level VSI, DSTATCOM.

1. INTRODUCTION

The widespread use of solid state converters is a cause of concern due to its impact on power system in general and power quality in distribution systems in specific. VSI based DSTATCOM is a viable solution to improve power quality of a distribution network. DSTATCOM is a custom power device which is connected in shunt with the distribution network. DSTATCOM injects a compensating current of variable magnitude, phase and frequency components at point of common coupling (PCC).

A number of techniques have been proposed in the recent past to control VSI based DSTATCOM. Most popular conventional method which is still in use is voltage oriented control (VOC) technique where the direct axis lies along with voltage vector [1]. This technique requires coordinate transformation and decoupling is required between active and reactive components.

Direct power control technique has gained much attention in the last decade by the researchers. Estimation of converter active and reactive powers is based on converter switching states and dc link voltage [2]. AC voltage sensors can be avoided in this technique which improves the reliability, cost effective and increases the speed of response.

Virtual flux direct power control method is an improvement of DPC [3]. Estimation of active and reactive powers of the converter is based on the virtual flux. Thanks to the natural low pass filter behavior of an integrator used in this approach. Line side inductance along with PCC voltages can be treated as virtual motor and integration of voltages leads to
virtual flux. The proposed control strategy is tested for distorted voltage sources, unbalanced power source voltages and non linear loads from the view point of steady state and dynamic performance, harmonic distortion in the currents, etc. Figure.1 shows a diode clamped 3-Level VSI based DSTATCOM which connected to distribution network.

![Figure 1: Diode clamped 3L-VSI connected to distribution network](image)

2. PRINCIPLE OF DIODE CLAMPED 3-LEVEL PWM CONVERTER

The main circuit of diode clamped 3-Level converter is shown in Figure.1. Diode clamped 3L VSI is connected to PCC through tie reactance. Any control strategy that is applied to inverter should aim to maintain the dc link voltage constant and force the source current to be approximately sinusoidal and in phase with the source voltage, therefore this is called unity power factor (UPF) condition. The switches (Sa1, Sa2'), (Sb1, Sb2'), (Sc1, Sc2') are operating as main switches for PWM, and (Sa2, Sa1'), (Sb2, Sb1') and (Sc2, Sc1') are auxiliary switches to clamp the output terminal potentials to the neutral point potential, together with (D11 – D32). Although the structure of three level inverters is more complicated than two level inverters, the operation is straight forward and well known [4]. The topology of three level diode clamped inverter is given in table I. In summary each phase node (a, b, c) can be connected to any node in the capacitor bank (1, ½, and 0). Connection of phase a to junctions 1 and 0 can be accomplished by switching Sa1 and Sa2 both OFF and both ON respectively. Connection to junction ½ (middle) is accomplished by gating Sa1 OFF and Sa2 ON. In this representation, the labels Sx1 and Sx2 are used to identify the switches as well as logic (1=ON, 0=OFF).

Since the switches in each leg of three level inverter are always switched in pairs, the complement switches are labeled Sx1’ and Sx2’ accordingly. According to this description, the inverter phase relationships for the phase a are presented in table I.
**TABLE I** Switching logic of three level inverters

<table>
<thead>
<tr>
<th>Da</th>
<th>Sa1</th>
<th>Sa2</th>
<th>Sa1’</th>
<th>Sa2’</th>
<th>V_{ag}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(\frac{1}{2})</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>v_{c1}</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>v_{c1}+v_{c2}</td>
</tr>
</tbody>
</table>

### 3. POWER CONTROL STRATEGIES

#### 3.1 Voltage Oriented Control (VOC): Voltage oriented control is a classical control scheme for PWM converter based DSTATCOM and widely used in 2-Level topology. A characteristic feature for this current controller is the processing of signals in two coordinate systems which is shown in Figure 2. The first is the stationary \(\alpha - \beta\) coordinate system and the second is the synchronously rotating \(d - q\) coordinate system.

Three phase measured values are converted to equivalent two-phase system \(\alpha - \beta\) and then are transformed to the rotating coordinate system in a block \(\alpha - \beta / d - q\).

\[
\begin{bmatrix}
    k_d \\
    k_q
\end{bmatrix} =
\begin{bmatrix}
    \cos \chi_{vl} & \sin \chi_{vl} \\
    -\sin \chi_{vl} & \cos \chi_{vl}
\end{bmatrix}
\begin{bmatrix}
    k_{\alpha} \\
    k_{\beta}
\end{bmatrix}
\]

(1)

Thanks to this type of transformation as the control values are dc signals. An inverse transformation \(d - q / \alpha - \beta\) is achieved on the output of the control system, and it gives the converter reference signals in stationary coordinates [1].

\[
\begin{bmatrix}
    k_{\alpha} \\
    k_{\beta}
\end{bmatrix} =
\begin{bmatrix}
    \cos \chi_{vl} & -\sin \chi_{vl} \\
    \sin \chi_{vl} & \cos \chi_{vl}
\end{bmatrix}
\begin{bmatrix}
    k_d \\
    k_q
\end{bmatrix}
\]

(2)

For both coordinate transformations the angle of the voltage vector \(\chi_{vl}\) is defined as

\[
\sin \chi_{vl} = \frac{v_{L\beta}}{\sqrt{v_{La}^2 + v_{L\beta}^2}}
\]

\[
\cos \chi_{vl} = \frac{v_{La}}{\sqrt{v_{La}^2 + v_{L\beta}^2}}
\]

In voltage oriented d-q coordinates, the converter ac line current vector \(i\) is split into two rectangular components \(i = [i_d, i_q]\). The component \(i_q\) determines reactive power, where as \(i_d\) determines active power flow. Thus the reactive and active power can be controlled independently. The UPF condition is met when the line current vector, \(i\) is aligned with the line voltage vector, \(v\). By placing the d-axis of the rotating coordinates on the line voltage vector a simplified dynamic model can be obtained. Switching signals for PWM converter are generated by a SVM/SPWM modulator block that is shown in Figure 2.
3.2 Virtual Flux Direct Power Control (VFDPC)

The main idea of DPC is similar to the well known direct torque control (DTC) for induction motors. Instead of torque and stator flux the instantaneous active and reactive powers are controlled. Transformation into rotating coordinates is not required and the equations are easily implemented. In this configuration, the dc-bus voltage is regulated by controlling the active power, and the unity power factor operation is achieved by controlling the reactive power to be zero. This method uses the estimated virtual flux (VF) vector instead of the line voltage vector in the control [5]. Consequently AC voltage-sensorless line power estimation is much less noisy, thanks to the natural low-pass behavior of the integrator used in the calculation algorithm. The Concept of virtual flux is based on assumption that the voltages imposed by the line power in combination with the AC side inductors can be quantities related to a virtual AC motor. $R$ and $L$ represent the stator resistance and leakage inductance of the virtual motor. Phase-to-phase line voltages: $v_{ab}, v_{bc}, v_{ca}$ can be considered as induced by a virtual flux. In other words, the integration of the voltages leads to a virtual flux vector in stationary $\alpha - \beta$ coordinates as follows.
A virtual flux equation can be presented as,

\[ \bar{\psi}_L = \psi_s + \psi_I \]

(3)

Where \( \bar{\psi}_L \) -- Estimated line flux

\( \psi_s \) -- Converter flux

\( \psi_I \) -- Inductor flux

Based on the measured dc link voltage \( V_{dc} \) and the converter switching states \( D_a, D_b, D_c \) the converter voltages are estimated as follows

\[ v_{s\alpha} = \frac{2}{3} V_{dc} \left( D_a - \frac{1}{2} (D_b + D_c) \right) \]

(4)

\[ v_{s\beta} = \frac{1}{\sqrt{2}} V_{dc} (D_b - D_q) \]

(5)
Voltages must be integrated in order to get virtual flux components

\[
\psi_{s\alpha} = \int v_{s\alpha} \, dt
\]

\[
\psi_{s\beta} = \int v_{s\beta} \, dt
\]

\[
\psi_{L\alpha} = \int \left( v_{s\alpha} - L \frac{di_{L\alpha}}{dt} \right) \]

\[
\psi_{L\beta} = \int \left( v_{s\beta} - L \frac{di_{L\beta}}{dt} \right)
\]
The measured converter currents \( i_{L\alpha}, i_{L\beta} \) and the estimated virtual flux components are used for the power estimation.

The voltage equation can be written as:

\[
\frac{dv_L}{dt} = \frac{d}{dt} \psi_S - R \frac{di_L}{dt} - L \frac{d}{dt} i_L
\]  

(8)

In practice, \( R \) can be neglected, giving

\[
\frac{dv_L}{dt} = \frac{d}{dt} (\psi_S) - L \frac{d}{dt} i_L = v_S - L \frac{d}{dt} i_L
\]  

(9)

Using complex notation, the instantaneous power can be calculated as

\[
p = \text{Re}(v_L \cdot i_L^*)
\]

\[
q = \text{Im}(v_L \cdot i_L^*)
\]  

(10)

Where * denotes the conjugate line current vector. The line voltage can be expressed by the virtual flux as:

\[
v_L = \frac{d}{dt} \psi_L = \frac{d}{dt} (\psi_L e^{j\omega t}) = \frac{d}{dt} \psi_L e^{j\omega t} + j \omega \psi_L e^{j\omega t}
\]

\[= \frac{d}{dt} \psi_L e^{j\omega t} + j \omega \psi_L\]

(11)

Where \( \psi_L \) denotes the space vector and \( \psi_L \) its amplitude.

\[
\frac{dv_L}{dt} = \frac{d}{dt} (|\psi_{L\alpha}| + j |\psi_{L\beta}|) = \frac{d}{dt} (\psi_{L\alpha} + j \psi_{L\beta})
\]  

(12)

\[
\frac{dv_L}{dt} i_L^* = \left\{ \frac{d}{dt} (|\psi_{L\alpha}| + j |\psi_{L\beta}|) \right\} (i_{L\alpha} - ji_{L\beta})
\]  

(13)

That gives

\[
p = \left\{ \frac{d}{dt} (|\psi_{L\alpha}| i_{L\alpha} + |\psi_{L\beta}| i_{L\beta}) + \omega (\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha}) \right\}
\]  

(14)

and

\[
q = \left\{ -\frac{d}{dt} (|\psi_{L\alpha}| i_{L\beta} + |\psi_{L\beta}| i_{L\alpha}) + \omega (\psi_{L\alpha} i_{L\alpha} + \psi_{L\beta} i_{L\beta}) \right\}
\]  

(15)

For sinusoidal and balanced line voltage the derivatives of the flux amplitudes are zero [5].

The instantaneous active and reactive powers can be computed as

\[
p = \left\{ \omega (\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha}) \right\}
\]

\[
q = \left\{ \omega (\psi_{L\alpha} i_{L\alpha} + \psi_{L\beta} i_{L\beta}) \right\}
\]  

(15)

Block scheme of p-q estimator part is shown in Figure.
After estimating the instantaneous active and reactive powers of the converter, they are compared with the desired values (reactive power reference is set to zero for unity power factor condition and active power reference is obtained from dc link voltage control loop). Errors are generated from the estimated and reference values, this error is processed through their respective PI controllers to minimize the errors. Outputs of these controllers along with virtual flux vector are used to generate switching signals by the modulator, they are given by the equation (16).

\[
\begin{bmatrix}
    v_{s\alpha} \\
    v_{s\beta}
\end{bmatrix} =
\begin{bmatrix}
    - \sin \gamma \varphi L & - \cos \gamma \varphi L \\
    \cos \gamma \varphi L & - \sin \gamma \varphi L
\end{bmatrix}
\begin{bmatrix}
    v_{v\alpha} \\
    v_{v\beta}
\end{bmatrix}
\]

(16)

where

\[
\sin \gamma \varphi L = \frac{\psi_{L\beta}}{\sqrt{\psi_{L\alpha}^2 + \psi_{L\beta}^2}}
\]

\[
\cos \gamma \varphi L = \frac{\psi_{L\alpha}}{\sqrt{\psi_{L\alpha}^2 + \psi_{L\beta}^2}}
\]
4. SIMULATION STUDIES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Link Voltage</td>
<td>1000V</td>
</tr>
<tr>
<td>Utility Line Voltage</td>
<td>415V</td>
</tr>
<tr>
<td>Utility Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Average switching frequency</td>
<td>2kHz</td>
</tr>
<tr>
<td>Inverter loss resistance R</td>
<td>2kOhms</td>
</tr>
<tr>
<td>Line inductance</td>
<td>0.3mH</td>
</tr>
<tr>
<td>Regulation capacitor</td>
<td>12000uF</td>
</tr>
</tbody>
</table>

Simulations have been carried out in MATLAB/Simulink environment with the specifications given in the table II to evaluate the performance in terms of complexity of control algorithm, steady state and dynamic performance and THD in currents and voltages.
A. **Complexity of control algorithm**: No coordinate transformation is required in case of Virtual flux DPC as there are no AC voltage sensors used in it. Obviously the time consumption of an algorithm flow in VOC is more. As there are no AC voltage sensors used in VFDPC, the reliability also improved.

B. **Steady state performance**: It is observed in the simulation that, Source current is in phase with the source voltage when DSTATCOM is brought into operation. Another observation is that the dc link voltage is maintained constant indicating that the switching and conduction losses of the converter are supplied by the source to maintain so. THD in Source current, inverter current and voltage are given for VOC strategy in Figure 8 (a-d), and Figure. 9 (a-c) for VFDPC strategy. It is observed that VFDPC has less THD compared to VOC.
Figure 8 d) THD in inverter current with VOC

Figure 9 a) THD in source current with VFDPC

Figure 9 b) THD in inverter L-L voltage

Figure 9 c) THD in inverter current with VFDPC
C. **Dynamic performance:** DC link voltage, id, iq for VOC are given in Figure. 10 (a-b), and DC link voltage, estimated p and q for VFDPC are given in Figure. 11 (a-b). In voltage oriented control id and iq are reaching steady state in 0.3S and dc link voltage is stable from 0.2S. But in VFDPC approach it can be observed that p and q are settling at 0.1S which indicates fast dynamic response when compared to VOC.
D. Distorted source: For harmonic source simulation, a voltage source with 5th and 7th harmonics is applied to each line of the distribution network under VFDPC strategy.

\[ v_a = V_m \sin(\omega t) + 0.2 \times [V_m \sin(5\omega t) + V_m \sin(7\omega t)] \]  

\[ v_b = V_m \sin\left[ \omega t - \frac{2\pi}{3} \right] + 0.2 \times \left[ V_m \sin\left( 5\omega t + \frac{2\pi}{3} \right) + V_m \sin\left( 7\omega t - \frac{2\pi}{3} \right) \right] \]  

\[ v_c = V_m \sin\left( \omega t + \frac{2\pi}{3} \right) + 0.2 \times \left[ V_m \sin\left( 5\omega t - \frac{2\pi}{3} \right) + V_m \sin\left( 7\omega t + \frac{2\pi}{3} \right) \right] \]  

In the above equations, \( V_m \) is the source voltage amplitude. The amplitudes of 5th and 7th harmonics are assumed 20% each of the fundamental source voltage amplitude. Figure 12 (a-c) shows the distorted source phase voltages, distorted source currents and source current when DSTATCOM is connected to distribution network with VFDPC approach. Figure 12-d shows source currents in all three phases with voltage oriented control. It can be observed that source current is sinusoidal when DSTATCOM is connected to the network in both VFDPC and VOC strategies, but THD in source currents is less in VFDPC when compared to VOC. Figure 12-e shows the virtual flux and alpha beta components of modulating signals. Figure 12-f shows the dc link voltage which is stable during distortion in the source side with both the control strategies.

![Figure 12 a) Distorted source currents in all three phases](image1)

![Figure 12 b) Distorted source voltages in all three phases](image2)
5. CONCLUSIONS:

Diode clamped 3-Level PWM converter is most widely used topology for high power applications. In this paper two typical control strategies for these converters are described and evaluated. Simulation results highlight the differences among these control schemes.
The advantages and disadvantages of these control schemes are summarized thoroughly and tabulated in table.....Better dynamic performance and less harmonic distortion could be observed in VFDPC and similar steady state performance obtained both with conventional VOC as well as VFDPC strategies. Hence it can be concluded that VFDPC is a viable alternative to VOC for VSI based DSTATCOM applications in view of better dynamic performance and harmonic distortions.

REFERENCES:


