Research on Three-phase Four-wire Inverter

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Abstract: The concept of Voltage Source Converter (VSC) based hybrid AC and DC distribution system architecture is proposed, which can solve the traditional AC distribution power quality problems and respond to the request of DC distribution development. At first, a novel VSC system structure combining the four-leg based three-phase four-wire with LC filter is adopted, using the overall coordination control scheme of the AC current tracking compensation based grid-interfaced VSC. In the end, the 75 kW simulation experimental system is designed and tested to verify the performance of the proposed VSC under DC distribution, distributed DC sources conditions, as well as power quality management of AC distribution.

1. Introduction

Under the pressure of relentless energy situation and human ecological environment, countries all over the world are doing their utmost to develop and utilize sustainable clean energy as a future energy development strategy. In the meanwhile, more and more attention has been paid to the DG (Distributed Generation), such as solar energy, wind energy, fuel cell and so on [1-2]. However, when the AC power distribution network is used to realize the access of DG and supply power to the DC load, a large number of converters and multilevel power converters are needed, which are not in conformity with the characteristics of the small DC load [3-6]. Compared to AC power distribution, DC distribution is more powerful, reliable and efficient. Not only the frequency stability, reactive power balance and other questions of connecting to AC network can be avoided, but the quantity of the converter and the transformation series of the electrical energy can be reduced if the DC load and DG are connected to the DC distribution network for its outstanding energy saving advantages. It can be seen clearly from research [7] that the low voltage DC power supply model can be applied to the majority of low-voltage AC load, which can reduce the power loss, enhance the reliability of power supply and improve the power quality. Therefore, with the wide access of DG in distribution network and an increasing development of DC load, the AC/DC mixed distribution network will be the tremendous tendency under the AC distribution network.

The voltage source converter (VSC) in three-phase four-wire system is used in this paper. Not only...
has the function of traditional power converter which contains DG DC grid-connected, AC grid reactive power and harmonic compensation, but can also balance the three-phase AC load transformer, three-phase current symmetrical and unity power factor. And what’s more, VSC can avoid the impact caused by the low utilization of DG grid-connected devices and the frequently switching on the stability of local power grid, which can realize one machine with multiple functions, simplify the system structure, and save equipment investment[8-9].

2. The System Structure of VSC
The VSC which consists of LC filter and four arms can manage to govern the power quality issue in distribution network. Figure 1 shows the considered topology.

![Figure 1. VSC overall system architecture.](image)

Since the VSC was applied to three-phase four-wire low-voltage distribution networks, four arms with three-phase four-wire structure was utilized in this paper[10-12]. For controlling the VSC as a whole, the first three arms are served to compensate the positive sequence and negative sequence harmonic current in AC power distribution network and the fourth arm was used to regulate the zero sequence current of the distribution network. In addition, the LC filter is used to filter the high frequency components of the grid-connected current of VSC, and reduce the influence of the electromagnetic interference on the sensitive load. In order to meet the requirements of DC load as well as DG voltage level, and make the DC voltage level match the existing AC load, VSC DC side voltage \( V_d \) should be stable at \((760\, \text{V}, \pm 5\%)\). In figure 1, \( i_s, i_u, i_l \) represent transformer current of the AC grid, the grid-connected current of UPC and the AC load current separately; \( L_f, R_f \) represent the filter inductance and resistance of the first three arms; \( L_n, R_n \) represent the filter inductance and resistance of the fourth arm; \( C \) is the filter capacitor.

3. The Overall Coordination Control Research of the VSC

3.1. The Fundamental Compensation Principle of the VSC
In analyzing the operating principle of the VSC, the VSC is shunted in the grid in order to simplify its operation. The simplified schematic diagram was shown as figure 2.
According to the rule of power balance, the reactive power and the harmonic power which the load needed should be absolutely provided by VSC to make the front-end power frequency transformer of AC distribution network only provides the fundamental balanced three-phase active power. Supposed that $i_l$ is the nonlinear dissymmetry current in AC distribution network, $i_s$ is the outlet current of the transformer and $i_u$ is the grid-connected current of VSC. The formula can be gotten by the figure 2.

$$i_s = i_l - i_u$$

(1)

The nonlinear load current $i_l$ consists of the fundamental active current component $i_p$ and the harmonic current component $i_h$,

$$i_l = i_p + i_q + i_h$$

(2)

if $i_s=i_u+i_h$, is is equal to $i_p$. That's to say, the AC network only provides active current and is not affected by the harmonic and reactive current in the load current. The three-phase current balance of the distribution transformer cannot be guaranteed, especially when the active power of each phase is different, the amplitude of the three-phase current will be significantly different. In order to solve the above problems, the power supplied by the DG in the DC network should be deducted from the total load power in the mixed distribution network. The residual power is divided equally in the three-phase of the transformer. So,

$$P_{sa} = P_{sb} = P_{sc} = \frac{1}{3}(P_{avg} + P_u - P_d)$$

(3)

The three-phase active current amplitude of the transformer can be equal by formula (3) when taking the three-phase voltage distortion and unbalance of the distribution out of consideration. Further, if you can keep the phase current and voltage phase synchronization, the output of the three-phase current will be symmetrical and power factor will be close to 1 when the transformer three-phase unbalanced load can be achieved. In addition, the transformer three-phase symmetric active current can be transformed and distributed again by the VSC according to the power requirement of each phase load. Finally, the reactive power of each phase load can be provided entirely.

### 3.2. The online instruction current algorithm of the VSC

Since the current compensation algorithm based on the instantaneous power theory involves multiple $\alpha\beta$ or dq transform, the calculation is complex and cannot balance the three-phase asymmetrical load current. Therefore, in this paper, time domain compensation current algorithm based on energy balance is used to simplify the calculation and the three-phase current of the transformer would be symmetric. The block diagram is shown as figure 3. When grid voltage distorted seriously, the three-phase positive sequence fundamental voltage components should be kept separate from three-phase asymmetry voltage adopting instantaneous symmetrical component method before calculating the reference value of the VSC compensation current in order to gain content result.
Active power calculation

1/3
PLL
lai
lbi
lci
lavgP
lapi
lbpi
lcpi
pav pbv ...

Zero sequence current separation
un
i
-1
drefV

Figure 3. Block diagram of VSC grid-connected reference current algorithm.

Considering the DG grid-connected, AC load power is supplied by the transformer and DG together. Suppose that the total active power of three-phase ac load is \( P_{\text{avg}} \), the total power consumption of DC distribution network and the total power of DG are \( P_u \) and \( P_d \), respectively. Transformer current reference value is \( * \) and the reference value of VSC grid current is \( * \). Their calculations are

\[
\begin{align*}
    i_u^* &= i_u - i_u^* = i_u - \frac{v_p}{\Delta_i} (P_{\text{avg}} + P_u - P_d) \\
    i_b^* &= i_b - i_b^* = i_b - \frac{v_p}{\Delta_i} (P_{\text{avg}} + P_u - P_d) \\
    i_c^* &= i_c - i_c^* = i_c - \frac{v_p}{\Delta_i} (P_{\text{avg}} + P_u - P_d) \\
    i_u &= -(i_u^* + i_b^* + i_c^*) = -(i_u + i_b + i_c)
\end{align*}
\]

(4)

Where \( v_p, v_p^*, v_p^* \) are the fundamental positive sequence component of the three-phase voltage at PCC point. In this paper, the three-phase voltage of the AC distribution network is approximately symmetry and only contains the fundamental positive sequence voltage component. Supposed that \( \theta_a, \theta_b, \theta_c \) is the phase of \( V_p, V_{ph}, V_{pc} \). Then the type (4) can be simplified into

\[
\begin{align*}
    i_u^* &= i_u - \frac{1}{v_p} (P_{\text{avg}} + P_u - P_d)\theta_a \\
    i_b^* &= i_b - \frac{1}{v_p} (P_{\text{avg}} + P_u - P_d)\theta_b \\
    i_c^* &= i_c - \frac{1}{v_p} (P_{\text{avg}} + P_u - P_d)\theta_c \\
    i_u &= -(i_u^* + i_b^* + i_c^*) = -(i_u + i_b + i_c)
\end{align*}
\]

(5)

Distribution transformers share the remaining active load after deducting the DG power in the whole system. The calculation for the type of \( P_{\text{avg}} \) is

\[
P_{\text{avg}} = \frac{1}{T} \int_{t_1}^{t_2} (v_{p_1} i_u + v_{ph} i_b + v_{pc} i_c) dt
\]

(6)

\( V_d \) is influenced by the difference of \( P_u \) and \( P_b \). When \( P_u - P_d > 0 \), the capacitor in the DC side is in the discharging state and the \( V_d \) will reduce; when \( P_u - P_d < 0 \), the capacitor in the DC side is in the charging.
state and the $V_d$ will increase. When $P_u$-$P_d$=0, both the energy of the capacitor and the $V_d$ will keep constant. In order to ensure the normal power supply of the DC distribution network, $V_d$ should be controlled through the VSC to maintain the set value $V_{dref}$, so that the VSC reference current contains the corresponding capacitor charging and discharging current component to regulate the capacitor voltage. To this end, proportional integral (PI) controller is used to control $V_d$. When the $D_d$< $V_{dref}$, the control of VSC grid-connected current contains a set of three-phase symmetrical pure active current obtained from the AC network side to charge the capacitor; When the $D_d$> $V_{dref}$, the excess energy in the DC side is poured into the AC network, which is controlled by the VSC combines with the transformers and the AC load. The calculation formula between $P_u$ and $P_d$ is

$$P_u - P_d = K_p \Delta V_d + K_i \int \Delta V_d dt$$

$$\Delta V_d = V_{dref} - V_d$$

(7)

Where, $K_p$ and $K_i$ represent the proportional gain and integral gain of the PI controller in external voltage loop.

### 3.3. The Control System Design of VSC

In two-phase synchronous rotating reference frame (d-q), the active power $P$ of the VSC and the reactive power $Q$ of the VSC have the linear proportional relation to $i_q$ on the axis $q$ and the $i_d$ on the axis $d$ separately. That's to say, the active and reactive power of the VSC can be adjusted by the $i_q$ and $i_d$. So P and Q can be decoupled controlled. In this paper, the first three arms of VSC is a whole to realize the decoupling control of PQ in the dq coordinates. VSC adopts the double loop control mode of current inner loop and voltage outer loop. The grid-connected current is traced swiftly, which is realized by the inner current loop. The total voltage $V_d$ keeps around the value of the $V_{dref}$, which was realized by the outer voltage loop. Both of the two loops are controlled by the PI controller. Because of the little value of the filter capacitor $C$, the influence of VSC which was generated by the filter capacitor can be neglected and the LC can be equivalent to L for simplified analysis when the states of the VSC were analyzed[13]. The first three arms equations based on synchronous rotating coordinate of dq are shown as follows.

$$v_{ad} = (K_{ip} + \frac{K_d}{s}) (i_{ad} - i_{ad}) + v_{pd} - \omega L_s i_{up}$$

$$v_{aq} = (K_{ip} + \frac{K_d}{s}) (i_{aq} - i_{aq}) + v_{pq} + \omega L_s i_{up}$$

(8)

Where, $v_{pd}$, $v_{qd}$ represent the axis $d$ and $q$ of the voltage $v_p$, $v_{q}$; $i_{ad}$, $i_{aq}$ represent the axis $d$ and $q$ of the output voltage $v_o$. $i_{ad}$, $i_{aq}$ represent the axis $d$ and $q$ of the grid-connected current $i_u$ of VSC. $K_d$, $K_{ip}$ represent the proportional control gain and the integral control gain in the inner current loop[14]. Compared to the first three bridge arms, it is easier to control the fourth bridge of VSC arm to produce the corresponding compensation current. Figure 4 is the VSC control block diagram using PWM control. This does not reflect the voltage outer loop because the $i_u^*$ algorithm has been included in the external voltage loop. $i_u^*$ contains the current component that regulates $V_d$ to remain on the $V_{ref}$. 

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4. Experimental simulation analysis

In order to verify the feasibility of VSC running in grid-connected mode, a simulation system with rated power of 75 kW is built on the PSIM. The simulation parameters are shown in Table 1. The AC harmonic current source in each phase of AC distribution network is used to simulate the nonlinear load. Presume that the three-phase voltage is symmetrical and the distribution network only contained the fundamental positive sequence component.

| Simulation Parameters | Value |
|-----------------------|-------|
| VSC Parameters        |       |
| $R_{fa}=R_{fb}=R_{fc}=5$ mΩ |
| $L_{fa}=L_{fb}=L_{fc}=400$ μH |
| $L_{n}=800$ μH | $C=10$ μF | $V_{ef}=760$ V |
| Three-phase AC Load    |       |
| $Z_a=3+j3.14$ Ω |
| $Z_b=5+j3.77$ Ω |
| $Z_c=3+j4.71$ Ω |
| AC harmonic current source |     |
| $I_{a3}=5$ A | $I_{b3}=3$ A |
| $I_{a5}=2$ A | $I_{b5}=2$ A | $I_{b7}=1$ A |
| $I_{a11}=5$ A | $I_{a7}=1$ A | $I_{a11}=0.5$ A |
| AC load disturbance power | $P_a'=9.68$ kW | $P_b'=0$ kW | $P_c'=9.68$ kW |
| Switching frequency    | 25 kHz |

Figure 5 shows the three-phase current and neutral line current waveform of transformer in AC power distribution network when VSC is not connected to the grid to compensate. Figure 6 shows another conditions when VSC has connected to the grid. The current effective value (ARMS), current unbalance degree (CUD), current harmonic ratio (THD), power factor (PF) and other parameters are shown in Table 2 (a) and Table 2 (b).
Table 2 (a) and Table 2 (b) show that VSC can effectively reduce the unbalanced degree of the transformer three-phase current. The reactive power in the AC network will be compensated and the harmonic current will be suppressed, too. So the transformer can obtain the unity power factor.

Figure 7 shows the current waveform of the four bridge arms when the VSC connected to the grid. The VSC fourth bridge arm provides a channel for the zero sequence current of the AC load and prevents it from flowing into the transformer.

Table 2. Transformer operating parameters before and after the VSC interconnection.

(a) Operating Parameters of Transformer before VSC Grid-connection Compensation.

| Parameters | \(i_{sa}\) (A) | \(i_{sb}\) (A) | \(i_{sc}\) (A) | \(i_{sn}\) (A) |
|------------|----------------|----------------|----------------|----------------|
| \(A_{RMS}\) | 50.8100        | 35.3900        | 39.5400        | 27.6400        |
| CUD/\%     | 21.2400        | 15.5600        | 5.6500         |                |
| THD/\%     | 8.1400         | 12.2000        | 9.2000         | -              |
| PF         | 0.6889         | 0.7929         | 0.5235         | -              |

(b) Transformer Operating Parameters after VSC Grid-connected Compensation.

| Parameters | \(i_{sa}\) (A) | \(i_{sb}\) (A) | \(i_{sc}\) (A) | \(i_{sn}\) (A) |
|------------|----------------|----------------|----------------|----------------|
| \(A_{RMS}\) | 62.8200        | 62.4000        | 62.6500        | 0.6400         |
| CUD/\%     | 3.1900         | 3.5100         | 0.4800         | -              |
| THD/\%     | 2.1300         | 2.1000         | 2.1200         | -              |
| PF         | 0.99983        | 0.99982        | 0.99987        | -              |
Figure 7. VSC compensation current waveform.

Figure 8 shows the waveform of the total DC side voltage $V_d$.

![Current Waveform](image1.png)

**Figure 7.** VSC compensation current waveform.

**Figure 8.** DC voltage waveform after VSC interconnection.

In order to verify the dynamic performance of VSC under load disturbance, increase the DC load at $t=0.2s$, and further increase AC load at $t=0.24s$. Therefore, the simulation is shown as Fig.9. The parameters CUD, THD, PE are shown in Table 3 when the load is increased. It shows that the system voltage and current can be adjusted efficiently by the VSC and then the system will be in a steady state operation when the load was disturbing. The three-phase current of the transformer is basically symmetrical and the power factor is approximately 1. The maximum steady state deviation of $V_{dc}$ is no more than 1.6%, which can meet the requirement of power quality.

![Current Waveform](image2.png)

**Figure 9.** Simulation results with load change

**Table 3.** Transformer operating parameters after load changing

| Parameters | $i_{sa}$ | $i_{sb}$ | $i_{sc}$ | $i_{sn}$ |
|------------|----------|----------|----------|----------|

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A\textsubscript{RMS} & 113.5100 & 115.2300 & 119.1700 & 0.6100 \\
CUD\%/ & 2.1200 & 0.6400 & 2.7600 & - \\
THD\%/ & 3.6800 & 3.5000 & 3.5100 & - \\
PF & 0.9991 & 0.9984 & 0.9993 & - \\

5. **Conclusion**

In this paper, the VSC structure can be used to realize the comprehensive control of harmonics, reactive power and unbalanced three-phase load in AC distribution network. The simulations results show that in the case of load unbalance, load disturbance and DG disturbance in hybrid distribution network, VSC can effectively control the AC power quality and control the DC voltage balance. Not only can the three-phase current of the transformer in three-phase four wire low-voltage AC distribution network will be symmetrical but the unity power factor can be obtained. By the way, the reliable DC supply and the DC grid-connection of the DG will be realized.

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