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Multilevel STATCOM of Cascaded Two-Level Inverter for High-Power Applications

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Abstract: **-- A simple static VAR compensating scheme using a cascaded two-level inverter-based multilevel inverter is proposed. The topology consists of two standard two-level inverters connected in cascade through open-end windings of a three-phase transformer. The dc-link voltages of the inverters are regulated at different levels to obtain four-level operation. the performance of the proposed scheme under balanced and unbalanced supply-voltage conditions. Further, stability behavior of the topology is investigated. The dynamic model is developed and transfer functions are derived. The system behavior is analyzed for VARious operating conditions**

Index Terms**— DC-link voltage balance, active power oscillation damping, flicker attenuation, multilevel inverter, power quality, static compensator (STATCOM).**

I. INTRODUCTION

The application of flexible ac transmission systems controllers such as static compensator and static synchronous series compensator is increasing in power systems. This is due to their ability to stabilize the transmission systems and to improve the power quality in distribution systems. STATCOM is popularly accepted as a reliable reactive power controller replacing conventional VAR compensators, such as the thyristor switched capacitor and thyristor controlled reactor.

Generally in high power applications of VAR compensation is achieved using multilevel inverters. These inverters consist of a large number of dc sources which are usually realized by capacitors. Hence, the converters draw a small amount of active power to maintain dc voltage of capacitors and to compensate the losses in the converter. However, due to mismatch in conduction and switching losses of the switching devices, the capacitors voltages are unbalanced.

Cascade H-bridge is the most popular for static VAR compensation. The control of individual dclink voltage of the capacitors is difficult. Static VAR compensation by cascading conventional multilevel two level inverters is an attractive solution for high-power applications. One of the advantages of this topology is that by maintaining asymmetric voltages at the dc links of the inverters the number of levels in the output voltage waveform can be increased.

The overall control is simple compared to conventional multilevel inverters. A three-level inverter and two level inverter are connected on either side of the transformer low voltage winding. In three-level operation is obtained by using standard two-level inverters. The dc-link voltage balance between the inverters is affected by the reactive power supplied to the grid. The topology uses standard two-level inverters to achieve multilevel operation. The dc-link voltages of the inverters are regulated at asymmetrical levels to obtain four-level operation. To verify the efficacy of the proposed control strategy, the simulation study is carried out for balanced and unbalanced supply-voltage conditions.

II. CASCADED TWO-LEVEL INVERTER BASED MULTILEVEL STATCOM

A cascaded two-level inverter-based multilevel STATCOM using standard two level inverters. The inverters are connected on the low voltage side of the transformer and the high voltage side is connected to the grid. The dc-link voltages of the inverters are maintained constant and modulation indices are controlled to achieve the required objective. The proposed control scheme is derived from the ac side of the equivalent circuit which is shown in Fig. 3.

$$\begin{bmatrix} \frac{di_a'}{dt} \\ \frac{di_b'}{dt} \\ \frac{di_c'}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 \\ 0 & \frac{-r}{L} & 0 \\ 0 & 0 & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i_a' \\ i_b' \\ i_c' \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_a' - (e_{a1} - e_{a2}) \\ v_b' - (e_{b1} - e_{b2}) \\ v_c' - (e_{c1} - e_{c2}) \end{bmatrix} \quad (1)$$

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Equation (1) represents the mathematical model of multilevel STATCOM in the stationary reference frame. This model is transformed to the synchronously rotating reference frame [14]. The d □ q axes reference voltage components of the converter

converter e_d^* and e_q^* are controlled as

$$e_d^* = -x_1 + \omega L i_q' + v_d' \quad (2)$$

$$e_q^* = -x_2 - \omega L i_d' + v_q' \quad (3)$$

The synchronously rotating frame is aligned with source voltage vector so that the q -component of the source voltage 'q v is made zero. The control parameters 1 x and 2 x are controlled as follows.

$$x_1 = \left(k_{p1} + \frac{k_{i1}}{s}\right)\left(i_d^* - i_d'\right) \quad (4)$$

$$x_2 = \left(k_{p2} + \frac{k_{i2}}{s}\right)\left(i_q^* - i_q'\right) \quad (5)$$

The d -axis reference current * d i is obtained as

$$i_d^* = \left(k_{p3} + \frac{k_{i3}}{s}\right)\left[\left(v_{dc1}^* + v_{dc2}^*\right) - \left(v_{dc1} + v_{dc2}\right)\right] \quad (6)$$

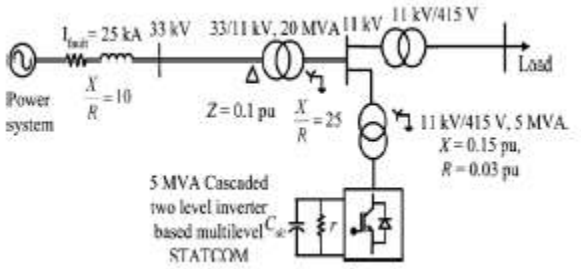

Fig. 1. Power system and the STATCOM model

A. Control Strategy

The control block diagram is shown in Fig. 4. The unit signals cos□t and sin□t are generated from the phase-locked loop (PLL) using three-phase supply voltages [14]. The converter currents are transformed to the synchronous rotating reference frame using the unit signals. The switching frequency ripple in the converter current components is eliminated using a low-pass filter (LPF). From

$\left(v_{dc1}^* + v_{dc2}^*\right)$ and i_q^* loops the controller

For the cascaded inverter. With these reference voltages, the inverter supplies the desired reactive current and draws required active current to regulate

$$v_{dc1}^* + v_{dc2}^*$$

total dc-link voltage

However, this will not ensure that individual dc-link voltages are controlled at their respective reference values. Hence, additional control is required to regulate individual dc-link voltages of the inverters.

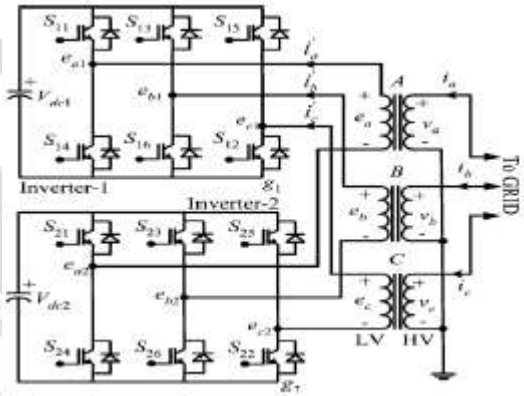

Fig. 2. Cascaded two-level inverter-based multilevel STATCOM

B. DC-Link Balance Controller

The resulting voltage of the cascaded converter can

The resulting voltage of the cascaded converter can be given as $e_1 \angle \delta$ where $e_1 = \sqrt{e_d^2 + e_q^2}$ and $\delta = \tan^{-1}\left(\left(e_q\right)/\left(e_d\right)\right)$ The active power transfer between the source and inverter depends on δ and is usually small in the inverters supplying var to the

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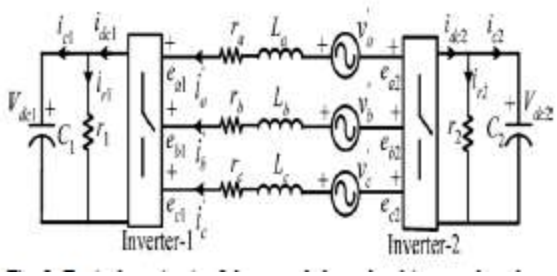
grid [1]. Hence, δ can be assumed to be proportional to e_q. Therefore the $q-$axis reference voltage component of inverter-2 e^*_{q2} is derived to control the dc-link voltage of inverter-2 as

$$e^*_{q2} = \left(k_{p4} + \frac{k_{i4}}{s}\right)\left(v^*_{dc2} - v_{dc2}\right) \quad (7)$$



The $q-$ axis reference voltage component of inverter-1 e^*_{q1} is obtained as

$$e^*_{q1} = e^*_q - e^*_{q2} \quad (8)$$

The dc-link voltage of inverter-2 v_{dc2} is controlled at 0.366 times the dc-link voltage of inverter-1 v_{dc1} [9]. It results in four-level operation in the output voltage and improves the harmonic spectrum. Expressing dc-link voltages of inverter-1 and inverter-2 in terms of total dc-link voltage v_{dc} as

$$v_{dc1} = 0.732 v_{dc} \quad (9)$$

$$v_{dc2} = 0.268 v_{dc} \quad (10)$$

Since the dc-link voltages of the two inverters are regulated the reference d □ axis voltage component e is divided in between the two inverters in proportion to their respective dc-link voltage as

$$e_{d1} = 0.732 e^*_d \quad (11)$$

$$e_{d2} = 0.268 e^*_d \quad (12)$$

C. Unbalanced Conditions

Network voltages are unbalanced due to asymmetric faults or unbalanced loads [16]. As a result, negative sequence voltage appears in the supply voltage. This causes a double supply frequency component in the dc-link voltage of the inverter. This double frequency component injects the third harmonic component in the ac side [17]. Moreover, due to negative-sequence voltage, large negative sequence current flows through the inverter which may cause the STATCOM to trip [16]. Therefore, during unbalance, the inverter voltages are controlled in such a way that either negative-sequence current flowing into the inverter is eliminated or reduces the unbalance in the grid voltage. In the latter case, STATCOM needs to supply large currents since the interfacing impedance is small. This may lead to tripping of the converter.

The negative-sequence reference voltage components of the inverter e^*_{dn} and e^*_{qn} are controlled similar to positive-sequence components in the negative synchronous rotating frame as [18]

$$e^*_{dn} = -x_3 + (-\omega L) i'_{qn} + v'_{dn} \quad (13)$$

$$e^*_{qn} = -x_4 - (-\omega L) i'_{dn} + v'_{qn} \quad (14)$$

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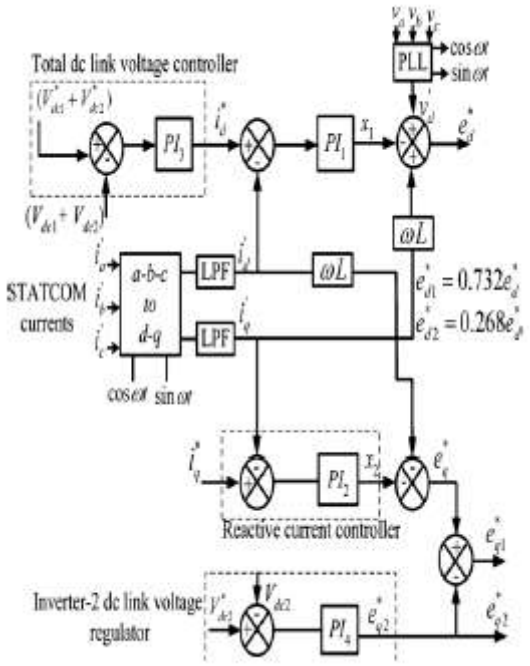

Fig. 4. Control block diagram.

where v_{dn}, v_{qn} are $d-q$ axes negative-sequence voltage components of the supply i^*_{qn} and i^*_{dn} are $d-q$ axes negative-sequence current components of the inverter, respectively. The control parameters x_3 and x_4 are controlled as follows

$$x_3 = \left(k_{p5} + \frac{k_{i5}}{s}\right)\left(i^*_{dn} - i'_{dn}\right) \qquad (15)$$

$$x_4 = \left(k_{p6} + \frac{k_{i6}}{s}\right)\left(i^*_{qn} - i'_{qn}\right) \qquad (16)$$

III. STABILITY ANALYSIS

Considering the dc side of the two inverters in Fig. 3, the complete dynamics of the system are derived in the Appendix. The transfer function $\Delta\tilde{v}_{dc1}(s)/\Delta\tilde{v}\delta_1(s)$ is as follows and the transfer function

$\Delta\tilde{v}_{dc2}(s)/\Delta\tilde{\delta}_2(s)$ is

$$\frac{\Delta\tilde{v}_{dc1}(s)}{\Delta\tilde{\delta}_1(s)} = \frac{num_1(s)}{den(s)} \qquad (17)$$

$$\frac{\Delta\tilde{v}_{dc2}(s)}{\Delta\tilde{\delta}_2(s)} = \frac{num_2(s)}{den(s)} \qquad (18)$$

The transfer function $\Delta\tilde{v}_{dc1}(s)/\Delta\tilde{v}\delta_1(s)$ for $i_{qo} = 1.02$ p.u., (capacitive mode) is given in From (17), it can be observed that all poles as well as all zeros lie on the left half of the s-plane for this operating condition. Fig.5. shows the frequency response of the transfer function $\Delta\tilde{v}_{dc1}(s)/\Delta\tilde{v}\delta_1(s)$ for the same operating condition. From the figure, it can be observed that the system has sufficient gain and phase margins for this operating condition. Fig. 6 shows an enlarged root locus of the transfer function $\Delta\tilde{v}_{dc1}(s)/\Delta\tilde{v}\delta_1(s)$ when STATCOM is in inductive mode of operation. The reactive component

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qo i is set at 0.75 p.u. and proportional gain *p k* is VARied from 0 to 10. It can be seen that all poles lie on the left half of the s-plane for this case as well. However, one zero shift to the right half and three zeros lie on the left half of the plane. Moreover it can be seen that closed-loop poles of the system shift to the right half of the s-plane for high controller gains.

IV. SIMULATION RESULTS

The system configuration shown in Fig. 1 is considered for simulation. The simulation study is carried out using MATLAB/SIMULINK. The system parameters are given in Table I.

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A. *Reactive Power Control*

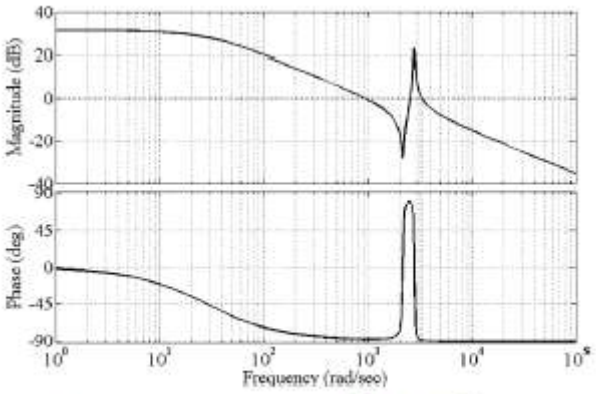

Fig. 5. Frequency response $\Delta\hat{v}_{dc1}(s)/\Delta\hat{v}\delta_1(s)$

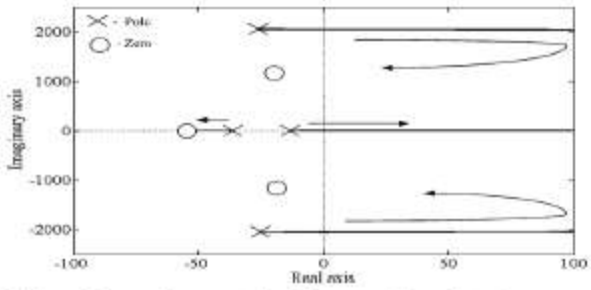

Fig.6. Root locus of the transfer function $\Delta\hat{v}_{dc1}(s)/\Delta\hat{v}\delta_1(s)$

In this case reactive power is directly injected into the grid by setting the reference reactive current component i_q^* at a particular value. Initially, i_q^* is set at 0.5 p.u. At $t = 2.0$ s, i_q^* is changed to -0.5 p.u. Fig.7(a) shows the source voltage and converter current of the A-phase. Fig.7(b)

TABLE I
SIMULATION SYSTEM PARAMETERS

Rated power	5MVA
Transformer voltage rating	11KV/400
AC Supply frequence f	50Hz
Inverter-1 DC link voltage v_{dc1}	659 V
Inverter-2 DC link voltage v_{dc2}	241 V
Transformer leakage resistance x_1	15%
Transformer resistance R	3%
DC link capacitances $c_1 \cdot c_2$	50 Mf
Switching frequence	1200Hz

Shows the dc-link voltages of two inverters. From the figure, it can be seen that the dc-link voltages of the inverters are regulated at their respective reference values when the STATCOM mode is changed from capacitive to inductive.

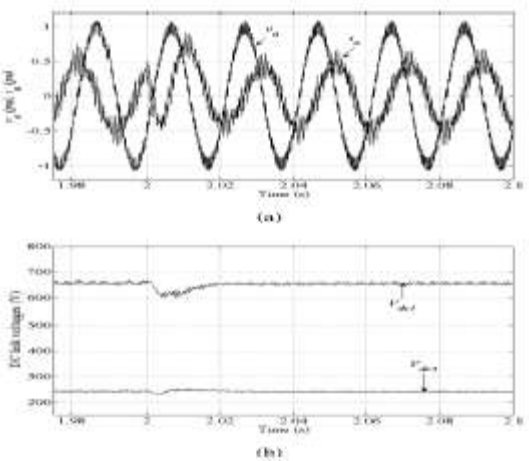

Fig. 7. Reactive power control. (a) Source voltage and inverter current. (b) DC-link voltages of two inverters.

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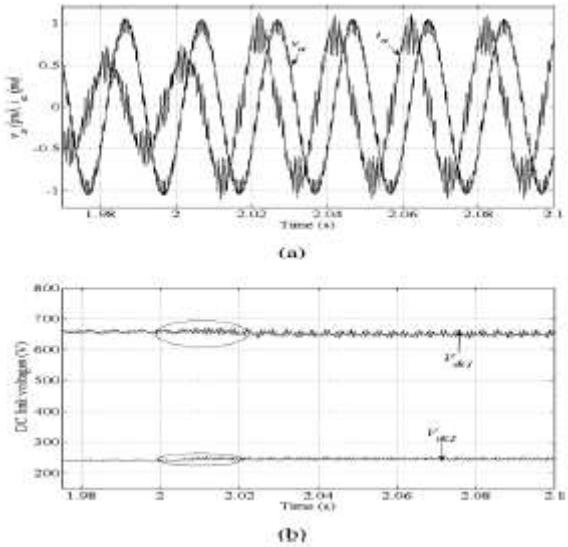

Fig. 8. Load compensation. (a) Source voltage and inverter current. (b) DC-link voltages of two inverters.

B. Load Compensation

In this case, the STATCOM compensates the reactive power of the load. Initially, STATCOM is supplying a current of 0.5 p.u. At t = 2.0 s, the load current is increased so that STATCOM supplies its rated current of 1 p.u. Fig. 8(a) shows source voltage and converter current while Fig. 8(b) shows the dc-link voltages of two inverters. The dc-link voltages are maintained at their respective reference values when the operating conditions are changed.

C. Operation During the Fault Condition

In this case, a single-phase-to-ground fault is created at t = 1.2 s, on the A-phase of the HV side of the 33/11-kV transformer. The fault is cleared after 200 ms. Fig. 9(a) shows voltages across the LV side of the 33/11-kV transformer. Fig. 9(b) and (c) shows the d – q axes components of negative-sequence current of the converter. These currents are regulated at zero during the fault condition.

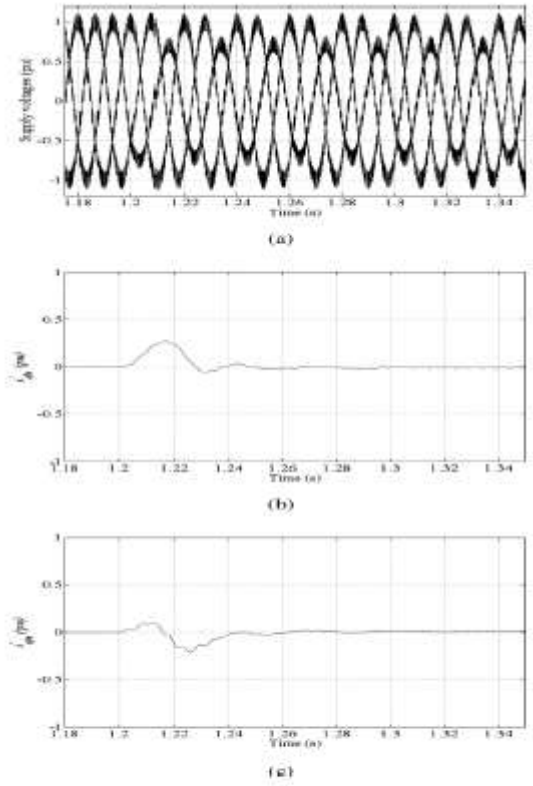

Fig. 9. Operation during fault. (a) Grid voltages on the LV side of the transformer. (b) $d-$ axis negative-sequence current component i'_{dn} (c) $q-$ axis negative- sequence current component i'_{qn} .

VI. CONCLUSION

DC-link voltage balance is one of the major issues in cascaded inverter-based STATCOMs. In this paper, a simple VAR compensating scheme is proposed for a cascaded two-level inverter- based multilevel inverter. The scheme ensures regulation of dc-link voltages of inverters at asymmetrical levels and reactive power compensation. The performance of the scheme is validated by simulation and experimentations under balanced and unbalanced voltage conditions. Further, the cause for instability when there is a change in reference current is investigated. The dynamic model is developed and transfer functions are derived. System behavior is analyzed for various operating conditions. From the analysis, it is inferred that the system is a non-minimum phase type, that is, poles of the transfer

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function always lie on the left half of the -plane. However, zeros shift to the right half of the -plane for certain operating conditions. For such a system, oscillatory instability for high controller gains exists.

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