Advanced Research in Electrical and Electronic Engineering
Print ISSN: 2349-5804; Online ISSN: 2349-5812 Volume 2, Number 7 April-June (2015) pp. 74-78

http://www.krishisanskriti.org/areee.html

# Cascaded Two Level Inverter Based Multilevel STATCOM for Power Quality Improvement

**Trishala Bahubali Indi[1] and Arpitha Raju B[2]**

*[1,2]Dr. Ambedkar Institute of Technology, Bangalore, Karnataka, India*
*E-mail: [1]trishalaindi9@gmail.com, [2]rajuarpitha@gmail.com*

**Abstract—***Static Synchronous Compensator (STATCOM) which is a shunt connected voltage source converter (VSC) based FACTS controller has the main application in voltage control and reactive power compensation. Balancing DC link voltage of the inverter is the major research area. This paper presents a simple STATCOM scheme with simple control strategy for the voltage balance. The topology consists of two standard two-level inverters connected in cascade through open end windings of a three phase transformer. By adjusting asymmetric voltages at the dc links of the inverters the number of levels in output voltage can be varied. The dc link voltage of inverter-2 must be set at 0.366 times the dc-link voltage of inverter-1. Simulation study is carried out in MATLAB/SIMULINK to predict the performance of the scheme under different conditions. The system is simulated for reactive power compensation and load compensation. Proposed topology has better utilization of dc link voltage and it has low total harmonic distortion (THD). Stability analysis of the system is performed by developing the dynamic model and transfer functions.*

## 1. INTRODUCTION

Modern power systems are highly complex due to the increase in electrical energy demands with acceptable quality and cost. Due to this increased demand the restructuring of power utilities has increased the uncertainties in system operation. The demands for lower power losses, faster response to the system parameter changes and higher stability have stimulated the development of flexible ac transmission systems (FACTS) controllers. This allows the flexible operation of ac transmission system and can accommodate parameter changes easily without stressing the system. FACTS have become the technology of choice in voltage control, reactive/active power flow, transient and steady state stabilization. FACTS controllers such as static compensator (STATCOM) and static synchronous series compensator (SSSC), is increasing in power system. They improve the power quality in distribution systems and stabilize the transmission system. STATCOM is gaining fast publicity and popularly accepted as a reliable reactive power controller. The overload capability of STATCOM has made it more commonly used. STATCOM keeps its full capability during most severe contingencies also [1].

In high power applications, voltage source converter based var compensation is achieved using multilevel inverters. Multilevel inverters present a new set of features that are well suited for use in reactive power compensation. It is easier to produce a high power, high voltage inverter with multilevel structure. The multilevel converter especially cascaded H-bridge are used for STATCOM application [2]-[4]. These inverters consist of a large number of dc sources which are shown by capacitors. The voltage across the capacitors is unbalanced due to the mismatch in the conduction and switching losses. Hence controlling of individual dc-link voltage of the capacitors is difficult. Several topologies with different control schemes are presented in literature [5]-[6]. But these topologies require large number of dc capacitors and control of individual dc-link voltage of the capacitor is difficult. SVC by cascading conventional multilevel/two level inverters is a solution for high power application. The topology consists of two standard two-level inverter connected in cascade through open-end winding of a three phase transformer. These topologies are popular in high power drives also as in [7]. The power quality can be improved with the proposed scheme.The number of levels in output voltage can be increased by maintaining asymmetric voltages at the dc links of the inverter.Hence overall control scheme is simple compared to conventional multilevel inverters.

## 2. CASCADED TWO LEVEL INVERTER BASED MULTILEVEL STATCOM

The system considered in this paper is shown in Fig. 1. The proposed scheme of cascaded two level inverter based multilevel STATCOM using two standard two-level inverter is given in Fig. 2.The inverters are connected on the low-voltage (LV) side of the transformer and the high-voltage (HV) side is connected to the grid. The dc-link voltages are maintained asymmetrically at constant values and the modulation indices are controlled to achieve the required objective. From the ac side of the equivalent circuit shown in Fig. 3 the proposed control scheme is derived. In Fig. 3,$v_a'$, $v_b'$and $v_c'$are the source voltages referred to LV side of the transformer, $r_a$, $r_b$, and $r_c$ are the resistances which represents the losses in the transformer and two inverters, $L_a$, $L_b$ and $L_c$ are inductances of transformer windings, and $e_{a1}$, $e_{b1}$, $e_{c1}$ and $e_{a2}$, $e_{b2}$, $e_{c2}$ are the output voltages of inverter 1 and 2 respectively. $r_1$, $r_2$ are the leakage resistance of dc-link capacitors $C_1$ and $C_2$, respectively.

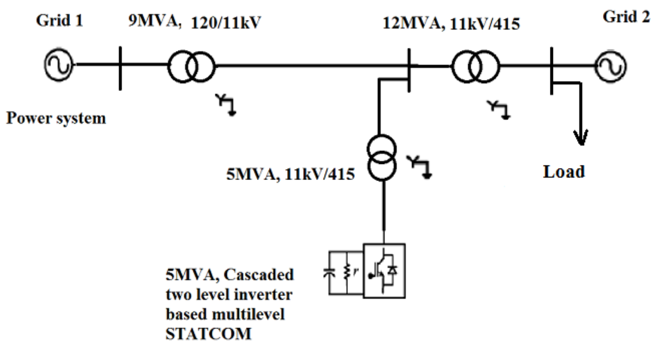


**Fig. 1: Power system and STATCOM considered**

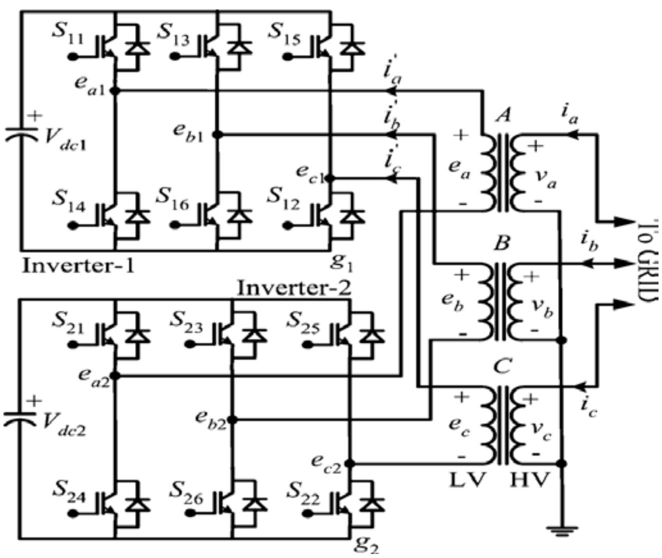


**Fig. 2: Cascaded two-level inverter based STATCOM**

Writing KVL for each phase and assuming $r_a = r_b = r_c = r$, $L_a = L_b = L_c = L$ then dynamic model can be derived as

$$-v_a' + r_a i_a' + L_a \frac{di_a'}{dt} + (e_{a1} - e_{a2}) = 0 \quad (1)$$

$$-v_b' + r_b i_b' + L_b \frac{di_b'}{dt} + (e_{b1} - e_{b2}) = 0 \quad (2)$$

$$-v_c' + r_c i_c' + L_c \frac{di_c'}{dt} + (e_{c1} - e_{c2}) = 0 \quad (3)$$

$$\begin{bmatrix} \frac{di'_a}{dt} \\ \frac{di'_b}{dt} \\ \frac{di'_c}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 \\ 0 & \frac{-r}{L} & 0 \\ 0 & 0 & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i'_a \\ i'_b \\ i'_c \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v'_a \\ v'_b \\ v'_c \end{bmatrix} \quad (4)$$

Equation (4) represents the mathematical model of the cascaded two-level inverter based multilevel STATCOM in reference frame. This is transformed to synchronously rotating reference frame. Due to this conversion both active and reactive currents are decoupled and can be controlled independently [8]. The system model in synchronously rotating frame is given by

$$\begin{bmatrix} \frac{di'_d}{dt} \\ \frac{di'_q}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 \\ 0 & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v'_d - e_d^* \\ -e_q^* \end{bmatrix} \quad (5)$$

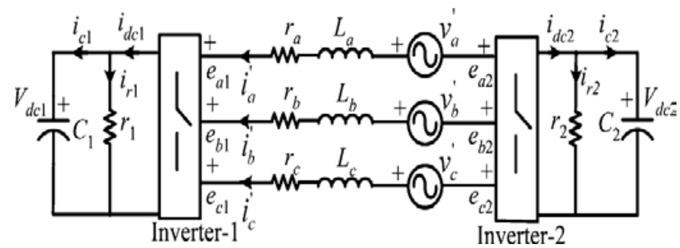


**Fig. 3: Equivalent circuit of the cascaded two-level inverter based multilevel STATCOM**

Where $e_d^*$ and $e_q^*$ are d-q axes reference voltage components of the converter. For controlling the active and reactive currents the STATCOM d-q voltage components are controlled. These are controlled as follows.

$$e_d^* = -x_1 + wLi_q' + v_d' \quad (6)$$

$$e_q^* = -x_2 + wLi_d' + v_q' \quad (7)$$

q component of the voltage source made 0, so that d component of the voltage source, $v_d$ is aligned with synchronously rotating frame.Where$v_d'$ is the d-axis voltage component of the ac source and $i_q'$ and $i_d'$ are d-q axes current components of the cascaded inverter, respectively. The synchronously rotating frame is aligned with source voltage vector so that the q-component of the source voltage $v_q'$is made zero. The control parameters $x_1$ and $x_2$are controlled as

$$x_1 = (k_{p1} + \frac{k_{i1}}{s})\,(i_d^* - i_d') \quad (8)$$

$$x_2 = (k_{p2} + \frac{k_{i2}}{s})\,(i_q^* - i_q') \quad (9)$$

The d-axis reference currents $i_d^*$ is obtained as

$$i_d{}^* = (k_{p3} + \frac{k_{i3}}{s})\,[(V^*_{dc1} + V^*_{dc2}) - (V_{dc1} + V_{dc2})] \quad (12)$$

where $V^*_{dc1}$, $V^*_{dc2}$ and $V_{dc1}$, $V_{dc2}$ are the reference and actual dc-link voltages of inverters 1 and 2, respectively. The q-axis reference current $i_q{}^*$ is obtained either from an outer voltage regulation loop when the converter is used in transmission-line voltage support or from the load in case of load compensation.

## 3. CONTROL SCHEME

The control block diagram considered is shown in Fig. 4. The phase locked loop (PLL) generates unit signals cos*wt* and sin*wt* using three-phase voltages ($v_a$, $v_b$, $v_c$). With the help of these unit signals the converters currents are transformed into synchronously rotating frame. A low-pass filter (LPF) helps in eliminating the switching frequency ripple in converter current component.

From ($V^*_{dc1}$ + $V^*_{dc2}$) and $i_q^*$ loops, the controller generates d-q axes reference voltages, $e_d^*$ and $e_q^*$ for the cascaded inverter. With these reference voltages, the inverter supplies the desired reactive current ($i_q^*$) and draws required active current ($i_d'$) to regulate total dc-link voltages $V^*_{dc1}$ + $V^*_{dc2}$. An additionalcontroller is required to ensure the individual dc-link voltages are controlled at their respective reference values.

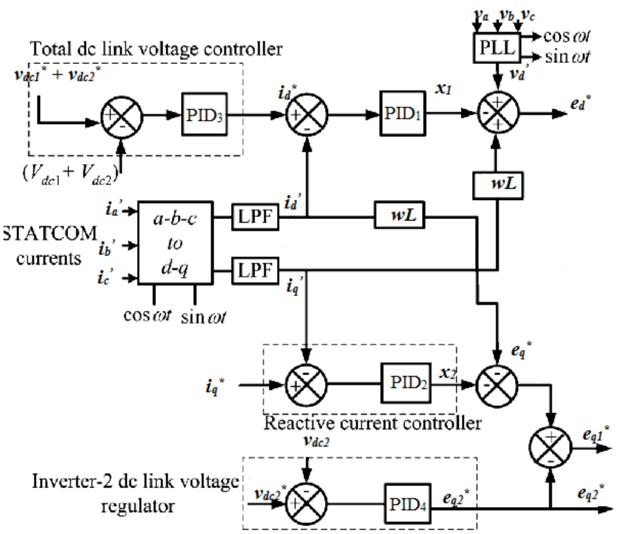


**Fig. 4: Control block diagram**

Balancing DC link voltage is the major research these days. The output voltage of the cascaded converter can be given by $e_I\hat{\delta}$ where $e_I = \sqrt{e_d^2 + e_q^2}$ and $\delta = \tan^{-1}\left(\frac{e_q}{e_d}\right)$. $\delta$ is the factor on which the flow of active power between source and the inverter depends. Ideally it should be zero if inverter is only supplying var to the grid. But in practical case it is usually a small value other than zero. Hence δ can be assumed to be proportional to $e_q$. To control the dc-link voltage of inverter-2 the q-axis reference voltage component of inverter-2 i.e. $e_{q2}^*$ is derived.

$$e_{q2}^* = (k_{p4} + \frac{k_{i4}}{s})\,(V^*_{dc2} - V_{dc2}) \tag{13}$$

From the control diagram q-axis reference voltage component of the inverter-1 is obtained as

$$e_{q1}^* = e_q^* - e_{q2}^* \tag{14}$$

This cascaded inverter uses 12-sided polygonal voltage space vector for reactive power compensation. To obtain 12-sided polygonal voltage space vectors, the dc-link voltage of the inverter-2 must be maintained at 0.366 times the dc-link voltage of the inverter-1[8]. 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

$$v_{dc1} = 0.732 v_{dc} \tag{15}$$

$$v_{dc2} = 0.268 v_{dc} \tag{16}$$

Since the dc-link dc voltages of the two inverters are regulated, the d-axis reference voltage component is dividingin proportion to their respective dc-link voltages as,

$$e_{d1}^* = 0.732\, e_d^* \tag{17}$$

$$e_{d2}^* = 0.268\, e_d^* \tag{18}$$

If the actual dc link voltage of the inverter-2 is less than reference dc-link voltage of the inverter the angle $\delta_2$ increases and $\delta_1$ decreases. Hence power transferred to inverter-2 increases and it decreases for inverter-1. The power transfer to inverter-2 is directly controlled and it is indirectly controlled for inverter-1. Hence during any disturbances like fault, load change the dc-link voltage of inverter-2 is restored directly and quickly compared to that of inverter-1. The reference voltages are generated in stationary frame for inverter-1 and inverter-2 using $e_{d1}^*$, $e_{q1}^*$ and $e_{d2}^*$, $e_{q2}^*$ respectively. The reference voltages generated for inverter-2 are in phase opposition to that of inverter-2. Sinusoidal pulse width modulation is used to generate the gate signals [9]. As the reference voltages of the two inverters' are in phase opposition, the predominant harmonics appears at double the switching frequency.

The control strategy works well for unbalanced system voltage condition. Due to asymmetric faults or unbalanced loads network voltages are unbalanced. This unbalance causes a double supply frequency component in the dc-link voltage of the converter. Due to this there will be third harmonic component in the ac side [10].

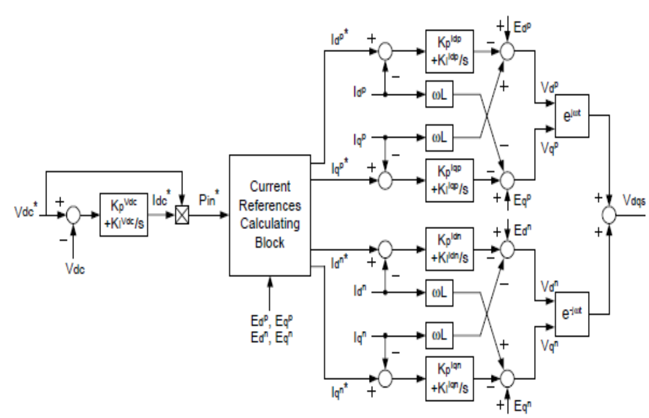


**Fig. 5 Detailed control block for unbalanced case**

The large negative sequence current flows through the inverter which causes the STATCOM to trip. Hence during the unbalance, inverter voltages are controlled in such a way that either negative-sequence current flowing into the inverter is eliminated or it reduces the unbalance in the grid voltage.Fig. 5 gives the detailed analysis controlling positive and negative sequence components separately. The negative sequence reference voltage components of the inverters are controlled as

$$e_{dn}^{*} = -x_3 + (-wL)i_{qn}^{'} + v_{dn}^{'} \quad (19)$$

$$e_{qn}^{*} = -x_4 + (-wL)i_{dn}^{'} + v_{qn}^{'} \quad (20)$$

The control parameters $x_3$and $x_4$ are controlled as

$$x_3 = (k_{p5} + \frac{k_{i5}}{s})\,(i_{dn}^{*} - i_{dn}^{'}) \quad (21)$$

$$x_4 = (k_{p5} + \frac{k_{i5}}{s})\,(i_{qn}^{*} - i_{qn}^{'}) \quad (22)$$

Since it is necessary to block the negative-sequence current flowing through the inverter the reference values of negative sequence current component must be set to zero.

## 4. STABILITY ANALYSIS

By considering the dc side of the equivalent circuit shown in Fig. 3, the dynamics of the system are derived in the Appendix. The transfer function $\Delta\widehat{v_{dc1}}$ (s) / $\Delta\widehat{\delta_1}$ is as follows.

$$\frac{\Delta\widehat{v_{dc1}}\,(s)}{\Delta\widehat{\delta_1}} = \frac{num_1(s)}{den\,(s)} \quad (23)$$

And the transfer function $\Delta\widehat{v_{dc2}(s)}$ / $\Delta\delta_2$ is

$$\frac{\Delta\widehat{v_{dc2}}}{\Delta\widehat{\delta_2}} = \frac{num_2(s)}{den\,(s)} \quad (24)$$

Where $num_1(s), den(s)$ and $num_2$ are given in the Appendix. From the transfer function (23) and (24), it can be observed that the denominator is a function of resistances (R, $R_1$, $R_2$), reactances ($X_1$, $X_{c1}$, $X_{c2}$) and modulation indices ($m_1$, $m_2$) and $\sin^2(\delta_{10} - \delta_{20})$. Although the denominator has the term $(\delta_{10} - \delta_{20})$, the product $\sin^2(\delta_{10} - \delta_{20})$ is always positive. Hence poles of the transfer functions always lie on the left half of s-plane. And the numerators of both the transfer functions are functions of operating conditions$i_{do}^{'}$,$i_{qo}^{'}$, $\delta_{10}$ and $\delta_{20}$. Mainly the positions of the zeros of the transfer functions depends on $i_{qo}^{'}$ , $\delta_1$ , $\delta_2$. As the mode of operation changes the sign of these changes. Hence the zeros shift to the right half of the s-plane for certain operating conditions. The system may exhibit oscillatory instability when there is a step change in reference for high current gains. Hence it is necessary to design the controller gain suitably to avoid the instability.

## 5. SIMULATION RESULTS

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

**Table I: Simulation Parameters.**

| | |
|---|---|
| Rated power | 12MVA |
| Transformer voltage rating | 11Kv/415 |
| AC supply frequency | 50Hz |
| Inverter-1 DC link voltage | 659V |
| Inverter-2 DC link voltage | 251V |
| Transformer leakage reactance | 8% |
| Transformer resistance | 2% |
| DC-link capacitance | 50MF |

## 6. OPERATION DURING FAULT CONDITION

In this case, a three-phase fault is created at t=0.4s, on the HV side of the 11kV/415V transformer. The fault is cleared after 100ms. Fig. 6 shows the d-q axes components of negative-sequence current of the converter. These currents are regulated at zero during the fault condition. The system is analyzed for different type of system faults

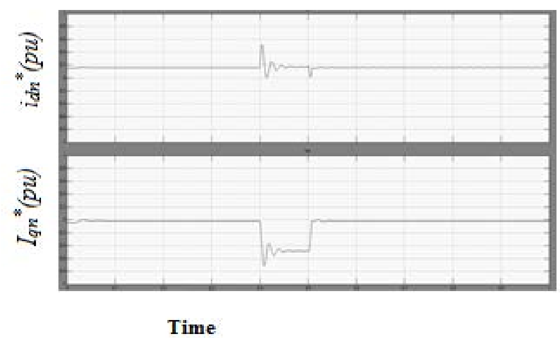


**Fig. 6: d and q axes negative sequence current component**

## 7. LOAD COMPENSATION

The STATCOM has the ability to compensate the reactive power of the load in case of sudden change in the load. Initially, the STATCOM is supplying a current of +0.5 p.u. At some point of time if the load current is increased so that STATCOM supplies its rated current of 1.p.u. Even though the operating conditions are changed dc-link voltages are maintained at their respective reference values. Dc link voltages of both the inverter is shown in Fig. 7.

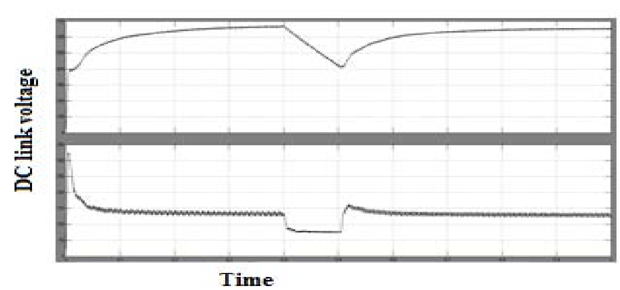


**Fig. 7: DC link voltages of both the inverter**

## 8. CONCLUSION

In cascaded inverter based STATCOM the DC-link voltage balance is the major issue. A simple cascaded two-level inverter based multilevel STATCOM is proposed. Asymmetric dc-link voltage balance ensures the reactive power compensation during fault and load changes. The performance of the scheme is validated by simulation under balanced and unbalanced voltage conditions. The simple control scheme ensures the dc link voltage balance. Dynamic model for the system is developed and thetransfer function is derived. From the analysis, it is clear that poles of the system always lie on the left half of the s-plane. But, zeros shift to the right half of the s-plane for certain operating condition.

## 9. APPENDIX

$$\mathrm{den}(s) = \{(s + \frac{wR}{X_l})^2 (s+ \frac{wX_{c1}}{R_1}) (s+\frac{wX_{c2}}{R_2}) + \frac{3}{2}(m_1 w)^2 \frac{X_{c1}}{X_l} (s+ \frac{wR}{X_l}) (s+\frac{wX_{c2}}{R_2}) + \frac{3}{2}(m_2 w)^2 (s + \frac{wR}{X_l}) (s +\frac{wX_{c1}}{R_1}) + w^2 (s+ \frac{wX_{c1}}{R_1}) (s+\frac{wX_{c2}}{R_2}) + (\frac{m_1 m_2 w}{X_l})^2 w^2 X_{c1} X_{c2} \sin^2(\delta_{10} - \delta_{20})\} \quad (25)$$

$$\mathrm{num}_1(s) = \{(-\frac{3}{2} m_1^2 w^3 \frac{X_{c1}}{X_l} V_{dc10}(s + \frac{wX_{c2}}{R_2})) + \frac{3}{2} m_1 w X_{c1}(-i_{d0}' \sin\delta_{10} + i_{qo}' \cos\delta_{10}) \times [(s+ \frac{wR}{X_l})^2 (s+\frac{wX_{c2}}{R_2}) + \frac{3}{2}(m_2 w)^2)\frac{X_{c2}}{X_l} (s+ \frac{wR}{X_l}) + w^2 (s+\frac{wX_{c2}}{R_2}) + \frac{1}{2} (\frac{m_1 m_2 w}{X_l})^2 w^2 X_{c1} X_{c2} \sin 2(\delta_{20} - \delta_{10})] \quad (26)$$

$$\mathrm{num}_2(s) = \{-(\frac{3}{2} m_2^2 w^3 \frac{X_{c2}}{X_l} V_{dc20}(s+ \frac{wX_{c1}}{R_1})) + \frac{3}{2} m_2 w X_{c2} (i_{d0}' \sin\delta_{20} - i_{qo}' \cos\delta_{20}) \times [(s + \frac{wR}{X_l})^2 (s+ \frac{wX_{c1}}{R_1}) + \frac{3}{2}(m_1 w)^2 \frac{X_{c1}}{X_l} (s+ \frac{wR}{X_l}) (s +\frac{wX_{c1}}{R_1})] + \frac{1}{2} (\frac{m_1 m_2 w}{X_l})^2 w^2 X_{c1} X_{c2} \sin 2(\delta_{10} - \delta_{20})\} \quad (27)$$

## REFERENCES


[1] B.singh,R.Saha,A.Chandra,andK. Al-Haddad,"Staticsynchronous compensators (STATCOM): Areview,"*IETPowerElectron.*, vol.2, no.4,pp.297–324,2009.

[2] H.Akagi,S.Inoue,andT.Yoshii,"Controlandperformanceofatransformerlesscascaded PWMSTATCOMwithstarconfigeration,"*IEEE Trans.Ind.Appl.*,vol. 43,no.4, pp. 1041–1049,Jul./Aug.2007.

[3] Y. Liu, A. Q. Huang, W. Song, S. Bhattacharya, and G. Tan, "Small signal model-based control strategy for balancing individual dc capacitor voltages in cascade multilevel inverter-based STATCOM," *IEEE Trans. Ind. Electron.*, vol. 56, no. 6, pp. 2259–2269, Jun. 2009.

[4] H. P. Mohammadi and M. T. Bina, "A transformerless medium-voltage STATCOM topology based on extended modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 26, no. 5, pp. 1534–1545, May 2011.

[5] H. Akagi, H. Fujita, S. Yonetani, and Y. Kondo, "A 6.6-kV transformerless STATCOM based on a five-level diode-clamped PWM converter: System design and experimentation of a 200-V 10-kVA laboratory model," *IEEE Trans. Ind. Appl.*, vol. 44, no. 2, pp. 672–680, Mar./Apr. 2008.

[6] A. Shukla, A. Ghosh, and A. Joshi, "Hysteresis current control operation of flying capacitor multilevel inverter and its application in shunt compensation of distribution systems," *IEEE Trans. Power Del.*, vol.22, no. 1, pp. 396–405, Jan. 2007.

[7] X. Kou, K. A. Corzine, and M. W. Wielebski, "Overdistention operation of cascaded multilevel inverters," *IEEE Trans. Ind. Appl.*, vol. 42, no. 3, pp. 817–824, May/Jun. 2006.

[8] N.N.V Surendra Babu and B.G. Fernandes, "Cascaded two level inverter based multilevel STATCOM for high power application", IEEE trans. on Power delivery, pp. 993-1001, 2014.

[9] D.G. Holmes and T.A. Lipo, IEEE series on power engineering, in "Pulse width modulation for power converters: Principle and Practice". IEEE, 2003.

[10] A. Leon, J.M. Mauricio, J.A. Solsonna, and A. Gomez-Exposito, "Software Sensor based STATCOM control under unbalanced condition", IEEE trans. Power Del., Jul. 2009.