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Control Scheme of Multi Level Cascaded H-Bridge STATCOM

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Abstract: *This paper presents a control scheme of cascaded H-bridge STATCOM in three-phase power systems. Cascaded H-bridge STATCOM has merits in point of switching losses, output harmonics, and the number of circuit components. But every H-bridge cell has isolated dc capacitors. So the balancing problem of capacitor voltages exists. Since STATCOM is often requested to operate under asymmetrical condition by power system faults, capacitor voltage balancing between phase clusters is particularly important. Solving this problem, a technique using zero-sequence voltage and negative-sequence current is proposed.By this scheme, the STATCOM is allowed to operate under asymmetrical conditions by power system faults. The validity is examined by digital simulation under one line and two-lines fault circuit condition.*

IndexTerms: *Capacitor voltage balancing, cascaded H-bridge, multilevel converter, negative-sequence current, STATCOM, zerosequence voltage.*

I. INTRODUCTION

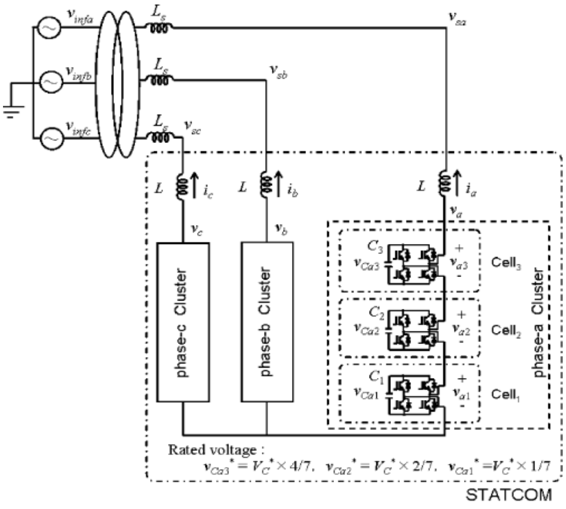
CASCADED H-bridge multilevel converter consists of series connected H-bridge cells. It has merits of switching losses of semiconductor device and harmonics in output voltage. And it is considered to be suitable for STATCOM in power system application, because it requires less number of circuit components compared with diode-clamped multilevel converter or flying capacitor multilevel converter and STATCOM does not have to handle real power [1]–[3]. But every H-bridge cell has isolated dc capacitor and balancing problem of capacitor voltages exists in this configuration [3]–[8]. STATCOM is often requested to operate under asymmetrical condition by power system faults, such as one line grounding or two-lines short circuit [9]. These kinds of faults cause unbalance of power system voltage [10] and unbalance current flows into each phase cluster. So capacitor voltage balancing between phase clusters is particularly important. Recently, several methods of voltage balancing between phase clusters are proposed [4], [5]. One method is based on zero-sequence voltage injection [4]. However it needs wide margin of dc capacitor voltage compared with rated power system voltage when the unbalance of power system voltage is large. The other method handles the capacitor voltage unbalance by independently controlling active power of individual phase cluster, but unbalance of power system voltage is not considered [5]. By these reasons, the circuit condition in which these methods are effective is considered to be limited in practical use.We also had proposed a capacitor voltage balancing method using negative-sequence current [11]. It does not need wide margin of dc capacitor voltage and can handle large unbalance of power system voltage. However the output current of the STATCOM using the method is uniquely determined by the unbalance of power system voltage and function of the STATCOM is limited.

So we introduce a different control method using zero-sequence voltage in this paper. By this method, the STATCOM can control output current almost freely. But it needs wide margin of dc voltage under large power system voltage unbalance, similar to the method proposed in [5]. To avoid this, we exclusively use the two methods depending on the extent of voltage unbalance. The validity is examined by digital simulation under one line and two-lines fault circuit condition.

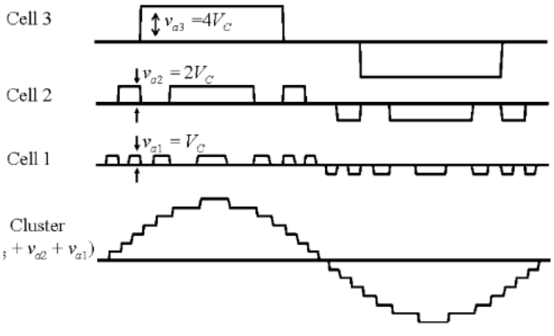
II. MAIN CIRCUIT AND CONTROL SCHEME

A. Main Circuit and Basic Operation

Fig. 1(a) shows the main circuit of cascaded H-bridge STATCOM in this paper [11]. It is composed of three-phase clusters. Each phase cluster consists of three H-bridge cells. The dc capacitor voltages are set to Vc,2vc , 4vc, in a phase cluster. Fig. 1(b) shows an example of output waveform. Voltage level from - 7 to +7 can be generated by combining the capacitor voltages. The level is decided according to the calculation flow shown in Fig. 1(c). Then the cluster outputs the nearest voltage level to reference. Conventional cascaded H-bridge multilevel converter may require high number of H-bridge cells for low current distortion.But the proposed circuit configuration can output 15-level voltage in spite of only three cells. So, lower conduction losses of semiconductor devices are expected.For dc voltage balancing in each phase cluster, the control Method proposed here uses the fact that several switching patterns are available when a phase cluster outputs particular voltage levels. An example is shown in Fig. 2. When a phase cluster outputs voltage “Vc”, “2Vc-Vc” “, 4Vc-2Vc-Vc” and charged or discharged capacitors are different. These patterns are selected



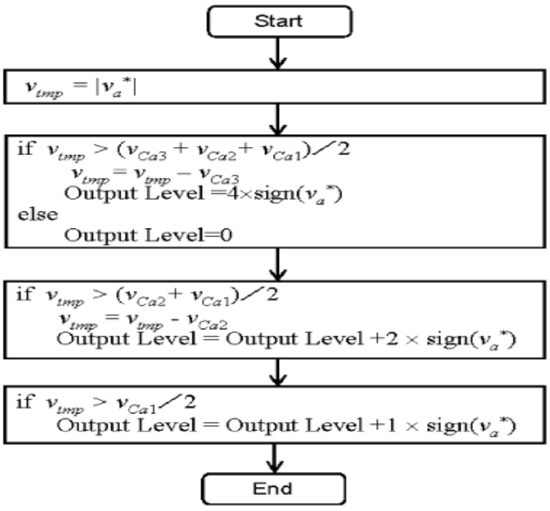
(a)



(b)

Figure1 Circuit configuratio and operation, (a) Main circuit,(b) Example of output waveform, (c) Decision method of output level.

According to the relation between Vc1, Vc2, and Vc3. When 4Vc1≥2Vc2 andVc3, output pattern "Vc" is selected. When 2Vc2>4Vc1 and Vc3 out pattern



(c)

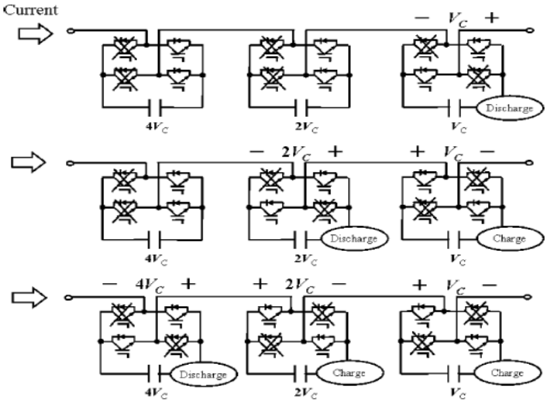


Figure2 An example of voltage balancing between the H-bridge cells

Output pattern "2Vc-Vc" is selected.when Vc3>2Vc2 and 4Vc1, out pattern "4Vc-2Vc-Vc" is selected. To use same switching pattern in 1/4 cycle, the capacitor voltages are measured [rad] of ac side phase angle. Table I shows the all operational patterns and decision method. It is used when the polarities of STATCOM output voltage and current are same. "1" indicates that the cell outputs voltage to positive direction and its capacitor is discharged. " -1" indicates that the cell output voltage to negative direction and its capacitor is charged. It is similar when the polarity of the output current is opposite. By this method, capacitor voltage ratio between H-bridge cells in a phase cluster is controlled.

TABLE I
DECISION TABLE OF OPERATIONAL PATTERN FOR VOLTAGE BALANCING

Output Level	$Cell_3$	$Cell_2$	$Cell_1$	Condition
1			1	$4v_{C1}\geqq 2v_{C2}$ and $4v_{C1}\geqq v_{C3}$
		1	−1	$2v_{C2}\geqq v_{C3}$ and $2v_{C2}>4v_{C1}$
	1	−1	−1	$v_{C3}>4v_{C1}$ and $v_{C3}>2v_{C2}$
2		1		$2v_{C2}\geqq v_{C3}$
	1	−1		$2v_{C2}<v_{C3}$
3		1	1	$2v_{C2}\geqq v_{C3}$ and $4v_{C1}\geqq v_{C3}$
	1		−1	$v_{C3}>4v_{C1}$ and $2v_{C2}>4v_{C1}$
	1	−1	1	$v_{C3}>2v_{C2}$ and $4v_{C1}\geqq 2v_{C2}$
4	1			
5	1		1	$4v_{C1}\geqq 2v_{C2}$
	1	1	−1	$4v_{C1}<2v_{C2}$
6	1	1		
7	1	1	1	

Table I shows the all operational patterns and decision method. It is used when the polarities of STATCOM output voltage and current are same. "1" indicates that the cell outputs voltage to positive direction and its capacitor is discharged. " -1" indicates that the cell output voltage to negative direction and its capacitor is charged. It is similar when the polarity of the output current is opposite. By this method, capacitor voltage ratio between H-bridge cells in a phase cluster is controlled.

B. Capacitor Voltage Balancing Between Phase Clusters: STATCOM is often requested to operate under symmetrical condition by power system faults, such as one line grounding or two-lines short circuit. These kinds of faults cause unbalance of power system voltage and unbalance current flows into each phase cluster. Then capacitor voltage unbalance between phase clusters occurs.

So we had proposed a capacitor voltage balancing method using negative-sequence current [11]. The negative-sequence current ,Ina, Inb, Inc , for capacitor voltage balancing is expressed as

$$\begin{pmatrix} ina \\ inb \\ inc \end{pmatrix} = \sqrt{\frac{2}{3}}\,Knvca \begin{pmatrix} \cos(wt) \\ \cos\left(wt+\frac{2\pi}{3}\right) \\ \cos\left(wt-\frac{2\pi}{3}\right) \end{pmatrix} + \sqrt{\frac{2}{3}}\,Knvca \begin{pmatrix} \cos\left(wt+\frac{2\pi}{3}\right) \\ \cos\left(wt-\frac{2\pi}{3}\right) \\ \cos(wt) \end{pmatrix} + \sqrt{\frac{2}{3}}\,Knvca \begin{pmatrix} \cos\left(wt-\frac{2\pi}{3}\right) \\ \cos(wt) \\ \cos\left(wt+\frac{2\pi}{3}\right) \end{pmatrix} \qquad (1)$$

Where *Kn* is a gain and *vca,vcb,vcc* are the sum of capacitor voltages in a phase cluster, as shown

$$VCa = \sum_{k=1,2,3} VCak$$

$$VCb = \sum_{k=1,2,3} VCbk \qquad (2)$$

$$VCc = \sum_{k=1,2,3} VCck$$

Here, it is assumed that the STATCOM shown in Fig. 1 operates under the asymmetrical circuit condition, as shown

$$\begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} = \sqrt{\frac{2}{3}}\,Vp \begin{pmatrix} \cos(wt) \\ \cos\left(wt - \frac{2\pi}{3}\right) \\ \cos\left(wt + \frac{2\pi}{3}\right) \end{pmatrix} + \sqrt{\frac{2}{3}}\,Vn \begin{pmatrix} \cos(wt+\varphi) \\ \cos\left(wt + \frac{2\pi}{3} + \varphi\right) \\ \cos\left(wt - \frac{2\pi}{3} + \varphi\right) \end{pmatrix} \qquad (4)$$

And its output current is controlled as shown in (4). Where, the first term is the active current to compensate converter losses. The second term is the reactive current output to power system. The third term is the negative-sequence current for voltage balancing, as shown in (1)

$$\begin{pmatrix} ia \\ ib \\ ic \end{pmatrix} = \sqrt{\frac{2}{3}}\,ipd* \begin{pmatrix} \cos(wt) \\ \cos[(wt - \frac{2\pi}{3}] @ \cos\left(wt + \frac{2\pi}{3}\right)) \end{pmatrix} + \sqrt{\frac{2}{3}}\,ipq* \begin{pmatrix} -\sin(wt) \\ -\sin[(wt - \frac{2\pi}{3}] @ -\sin\left(wt + \frac{2\pi}{3}\right)) \end{pmatrix} + \begin{pmatrix} ina \\ inb \\ inc \end{pmatrix}$$

(5)

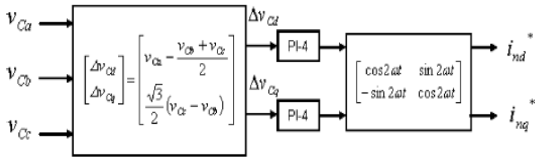


Fig. 3. Calculation method of negative-sequence current for voltage balancing between phase clusters.

Then, the average real powers of each phase clusters are calculated as

$$\begin{pmatrix} Pa \\ Pb \\ Pc \end{pmatrix} = \begin{pmatrix} \dfrac{w}{2\pi \int_0^{\frac{2\pi}{w}} va.ia\,dt} \\ \dfrac{w}{2\pi \int_0^{\frac{2\pi}{w}} vb.ib\,dt} \\ \dfrac{w}{2\pi \int_0^{\frac{2\pi}{w}} vc.ic\,dt} \end{pmatrix}$$

$$= \frac{VpKn}{2} \begin{pmatrix} Vca - Vc \\ Vcb - Vc \\ Vcc - Vc \end{pmatrix} + \begin{pmatrix} P \\ P \\ P \end{pmatrix} + \begin{pmatrix} Pna \\ Pnb \\ Pnc \end{pmatrix} \qquad (6)$$

Where

$$Vc = \frac{Vca + Vcb + Vcc}{3} \qquad (7)$$

$$P = \frac{Vpipd*}{3} + \frac{VnKn}{3}\left[vca\cos\varphi + vcb\cos\left(\varphi - \frac{2\pi}{3}\right) + vcc\cos\left(\varphi - \frac{2\pi}{3}\right)\right]$$

(8)

$$Pna = \frac{Vnipd*}{3}\cos(\varphi) + \frac{Vnipq*}{3}\sin(\varphi)$$

$$Pnb = \frac{Vnipd*}{3}\cos\left(\varphi - \frac{2\pi}{3}\right) + \frac{Vnipq*}{3}\sin\left(\varphi - \frac{2\pi}{3}\right)$$

(9)

$$Pnc = \frac{Vnipd*}{3}\cos\left(\varphi + \frac{2\pi}{3}\right) + \frac{Vnipq*}{3}\sin\left(\varphi + \frac{2\pi}{3}\right)$$

In (5), the first term is proportional to the error between the individual capacitor voltage ,Vca,Vcb,Vcc , and the average capacitor voltage Vc expressed as (6) and (2). The second term is the same for each phase cluster. The third term is almost independent of Vca, Vcb,Vcc,as expressed in (8). So the error of the individual capacitor voltage is decreased by use of the negative-sequence currents shown in (1)

Besides *ina,inb,inc* can be expressed on dq-axes, as shown

$$\begin{pmatrix} ind* \\ inq* \end{pmatrix} = \begin{pmatrix} \cos 2wt & \sin 2wt \\ -\sin wt & \cos 2wt \end{pmatrix} \mathbf{\mathit{Kn}} \begin{pmatrix} Vca - \frac{Vcb + Vcc}{2} \\ \frac{\sqrt{3}}{2}(Vcc - Vcb) \end{pmatrix} \qquad (10)$$

So PI controller is actually used to calculate , in the control block of proposed STATCOM, instead of gain , to make the error between the individual capacitor voltage and the average capacitor voltage zero, as shown in Fig. 3.However the output current of the STATCOM using the negative-sequence current method is uniquely determined by unbalance of power system voltage and function of the STATCOM is limited. For example, the STATCOM becomes impossible to compensate negative-sequence current by unbalanced loads. So we introduce a different control method using zero-sequence voltage in this paper.
The zero-sequence voltage for capacitor voltage balancing
Is expressed as

$$VO = \frac{\Delta Pa(ib.ic)ia + \Delta Pb(ic.ia)ib + \Delta Pc(ia.ib)ic}{ia2ib2 - (ia.ib)2}$$

$$\Delta Pa = Va'.ia - \frac{1}{3}\sum_{k=a,b,c} Vk'.ik$$

+*Kop*
$$\left(\frac{1}{3}\sum k = a,b,c \sum_{j=1,2,3}\frac{1}{2}CjVcaj - \sum_{j=1,2,3}\frac{1}{2}CjVcaj2\right)$$

$$\Delta Pb = Vb'.ib - \frac{1}{3}\sum_{k=a,b,c} Vk'.ik$$

+*Kop*
$$\left(\frac{1}{3}\sum k = a,b,c \sum_{j=1,2,3}\frac{1}{2}CjVckj2 - \sum_{j=1,2,3}\frac{1}{2}CjVcbj2\right)$$

$$\Delta Pc = Vc'.ic - \frac{1}{3}\sum_{k=a,b,c} Vk'.ik$$

$$+Kop\left(\frac{1}{3}\sum k = a,b,c \sum_{j=1,2,3}\frac{1}{2}CjVckj2 - \sum_{j=1,2,3}\frac{1}{2}CjVccj2\right)$$
(11)

where bold text means phasor,*va',vb',vc',* , are positive and negative-sequence components of STATCOM output voltage, ia,ib,ic are STATCOM output current,Kop is a gain, operator". " means scalar product of complex vector. To handle
Instantaneous value at time , it is substituted by the calculation as follows:

$$x.y = \frac{w}{2\pi}\int_{t-\left(\frac{2\pi}{3}\right)}^{t} x(t)\times y(t)d\tau \qquad \textbf{(12)}$$

where x and y are arbitrary phasor in (10) and x(t) and y(t)are their instantaneous value.w is angular frequency of power system.By using vo shown in (10), STATCOM output power from each phase is calculated as follows. See equation (12) at the bottom of the page. From (12), it is understood that the STATCOM outputs same power from each phase when the capacitor voltage of each phase is balanced. Even if capacitor voltage unbalance occurs, it is corrected by the second term of (12). It can be easily confirmed that the time constant to correct the capacitor voltage unbalance is 1/kop.

However, this method requires a wide dc voltage margin. For example, it is assumed that two-line short circuit occurs in power system and positive positive and negative sequence of STATCOM out put voltage becomes

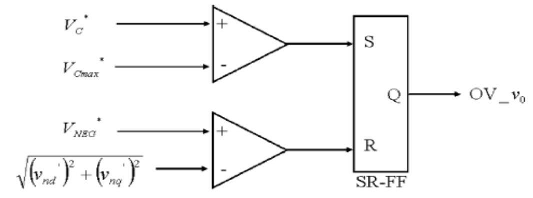


Fig. 4. Decision method of voltage balancing between phase clusters.

$$\left.\begin{aligned} Va' &= 1 + j0 \\ Vb' &= -0.5 + j0 \\ Vc' &= -0.5 + j0 \end{aligned}\right\} \qquad \textbf{(13)}$$

At this time vo shown in (10) is calculated as follows
Vo=0.5+j0 **(14)**

Then statcom output voltages becomes as followes:

$$\left.\begin{aligned} Va &= Va' + Vo = 1.5 + j0 \\ Vb &= Vb' + Vo = 0 + j0 \\ Vc &= Vc' + Vo = 0 + j0 \end{aligned}\right\} \qquad \textbf{(15)}$$

As mentioned before, the STATCOM using must output 1.5 times voltage compared with only using positive and negativesequence voltage at the circuit condition shown in (13). To avoid this, we exclusively use the two voltage balancing methods depending on the extent of voltage unbalance. The zero-sequence voltage method is used normally. The negative- sequence current method is used under large unbalance of power system voltage. The decision method shown in Fig. 4 is used to select these two methods. Input Vc* is capacitor voltage necessary for outputting reference voltage of the STATCOM. The calculation method of VC*is described in next section. Input *v'nd,v'nq* is the negative-sequence component of power system voltage on reverse rotated frame, described in the next section.

$$Pa = (Va' + Vo).ia = Va'.ia - \Delta P\ a$$

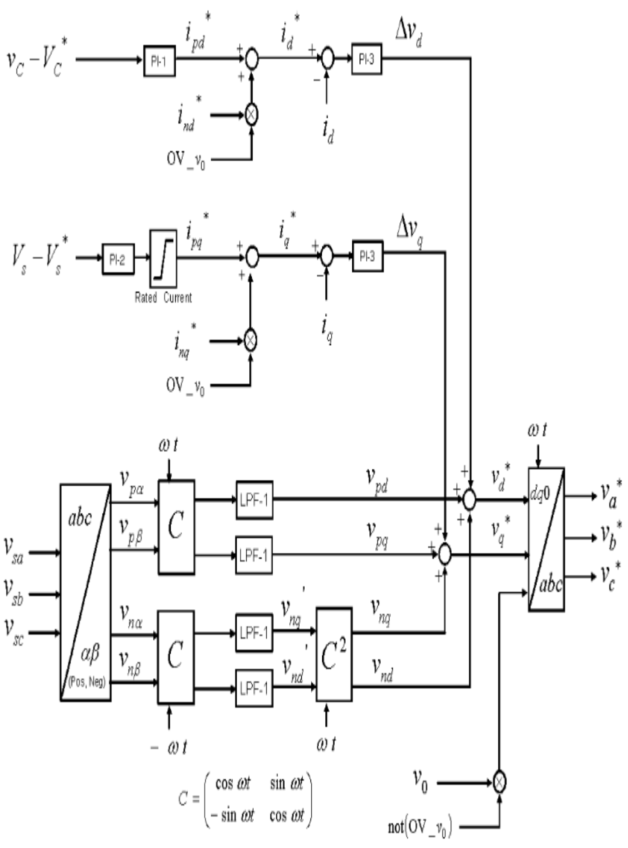
$$= \frac{1}{3}\sum_{k=a,b,c} Vk'.ik + Kop\left[\sum_{j=1}^{3}\frac{1}{2}CjVcaj2 - \frac{1}{3}\sum k = a,b,c \sum_{j=1}^{3}\frac{1}{2}CjVckj2\right]$$

$$Pb = (Vb' + Vo).ia = Vb'.ib - \Delta Pb$$

$$= \frac{1}{3}\sum_{k=a,b,c} Vk'.ik + Kop\left[\sum_{j=1}^{3}\frac{1}{2}CjVcbj2 - \frac{1}{3}\sum k = a,b,c \sum_{j=1}^{3}\frac{1}{2}CjVckj2\right]$$
(12)

$$Pc = (Vc' + Vo).ic = Vc'.ic - \Delta Pc$$

$$= \frac{1}{3}\sum_{k=a,b,c} Vk'.ik + Kop\left[\sum_{j=1}^{3}\frac{1}{2}CjVccj2 - \frac{1}{3}\sum k = a,b,c \sum_{j=1}^{3}\frac{1}{2}CjVckj2\right]$$



If power system voltage is balanced,$v'nd,v'nq$ is enough lower than limit value $V*NEG$ shown in Fig. 4. Then over voltage flag"OV-vo " shown in Fig. 4 is set to 0 and the zero-sequence voltage method is selected. Once asymmetrical power system fault occurs,vo shown in (10) may become rather high and may become higher than limit value $V*cmax$ shown in Fig. 4.At this time, the flag "OV-vo" is set to 1 and the negative-sequence current method is selected. After clearing the fault,$v'nd,v'nq$, returns to a value low enough and the zero-sequence voltage method restarts.

$V*cmax$ is set depending on withstand voltage of the STATCOM components such as dc capacitor. is set to a value low enough to use the zero-sequence voltage method

C. Control Scheme for STATCOM

Fig. 5 shows the control block of the STATCOM shown in
Fig. 1. The STATCOM is designed to control the positive sequence voltage Vs at the grid connection point to reference V*s by q-axis current $i*pq$.

The average capacitor voltage vc is ontrolled to reference V*c by d-axis current $i*pd$. Where,vc is from (6) and (2). The dc voltage is varied according to the STATCOM output voltage shown in Fig. 6. The reason why this method is adopted is to use as many voltage levels of the cascade H-bridge multilevel converter as possible, regardless of the peak of STATCOM output voltage. In addition, the control element " 7/6.5" shown in Fig. 6 acts to set the peak of reference $v*a,v*b,v*c$ in the middle of output level 6 and 7.

The zero-sequence voltage shown in (10) or the negative sequence current $i*nd,i*nq$ shown in Fig. 3 are used for capacitor voltage balancing between phase clusters. If over voltage flag 0V-vo shown in Fig. 4 is set to 0, then vo is transformed to

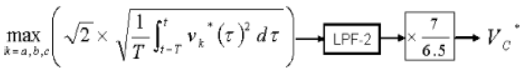


Fig. 6. Calculation method of capacitor voltage reference.

The detection method of the grid voltage, shown in under part of Fig. 5, is designed to control the STATCOM output currentaccurately under asymmetrical circuit conditions by power system faults. The grid voltage is once decomposed to positive sequence and negative sequence by the method shown in Fig. 7. The control element "lag90" delays the input, for 1/4 cycle at fundamental frequency of ac voltage and outputs For example, $v\alpha, v\beta$ these are expressed as

$$\begin{pmatrix} v\alpha \\ v\beta \end{pmatrix} = Vp\begin{pmatrix} \cos wt \\ \sin wt \end{pmatrix} + Vn\begin{pmatrix} \cos(wt+\varphi n) \\ -\sin(wt+\varphi n) \end{pmatrix} \quad \mathbf{(16)}$$

Then $v'\alpha, v'\beta$ are calculated as

$$\begin{pmatrix} v'\alpha \\ v'\beta \end{pmatrix} = Vp\begin{pmatrix} \sin wt \\ -\cos wt \end{pmatrix} + Vn\begin{pmatrix} \sin(wt+\varphi) \\ \cos(wt+\varphi) \end{pmatrix} \quad \mathbf{(17)}$$

From (16) and (17), positive sequence vp^{α} ,vp^{β} and negative sequence $vn\alpha, vn\beta$ are calculated as followes:

$$\begin{pmatrix} vp\alpha \\ vp\beta \end{pmatrix} = \frac{1}{2}\begin{pmatrix} v\alpha - v\beta' \\ v\beta + v\alpha' \end{pmatrix} = Vp\begin{pmatrix} \cos wt \\ \sin wt \end{pmatrix}$$

$$\begin{pmatrix} vn\alpha \\ vn\beta \end{pmatrix} = \frac{1}{2}\begin{pmatrix} v\alpha + v'\beta \\ v\beta - v'\alpha \end{pmatrix} = Vn\begin{pmatrix} \cos(wt+\varphi n) \\ -\sin(wt+\varphi n) \end{pmatrix}$$

(18)

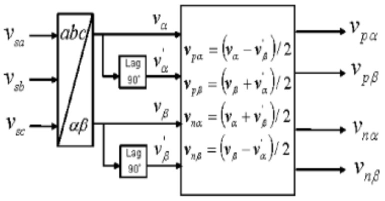


Fig. 7. Decomposition from grid voltage to positive and negative sequence.

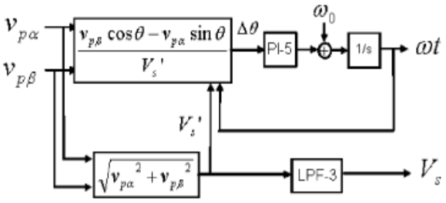


Fig. 8. Phase angle and voltage detection method.

TABLE II
CIRCUIT PARAMETERS

Rated AC Voltage	V_s^*	3 ϕ AC 6600V
Rated Reactive Power	Q	1MVA
Line angular frequency	ω_0	$2\pi \times 60$ rad/s
Line Inductance	L_s	4.64mH (4%)
AC link Inductance	L	11.6mH (10%)
DC Capacitance	C_3 C_2 C_1	1mF 2mF 4mF
Rated Capacitor Voltage	v_{C3}^* v_{C2}^* v_{C1}^*	3900V 1950V 975V

The feature of this method is that the appropriate values are obtained in about 1/4 cycle even if sudden change of occurs by power system faults. After transformation and low pass filtering, the positive sequence other hand are once rotated to reverse direction of transformation. Here, the negative-sequence voltage is also obtained as dc components. After low pass filtering, the output values are rotated two times to forward direction of transformation.

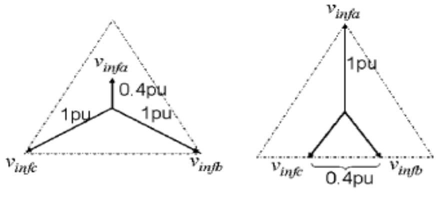
And the negative-sequence voltage are obtained accurately. The time constant of low pass filter does not have to be long, ie. the delay time of low pass filter is not long, because the filter is requested to eliminate only harmonic component of ac side voltage. As a result, the STATCOM can respond to power system faults quickly, and the error of capacitor voltage between phase clusters is expected to be small even in the transient state by the faults. In addition, these are used for PLL, shown in Fig. 8, to synchronize the phase angle to positive sequence of the grid voltage. And the positive sequence voltage at grid point is also obtained by this control block diagram.

III. SIMULATION RESULT

Digital simulation using EMTP (Electro Magnetic Transient Analysis Program) has been carried out to verify the effectiveness of the proposed scheme for the circuit shown in Fig. 1. The TABLE III CONTROL PARAMETERS

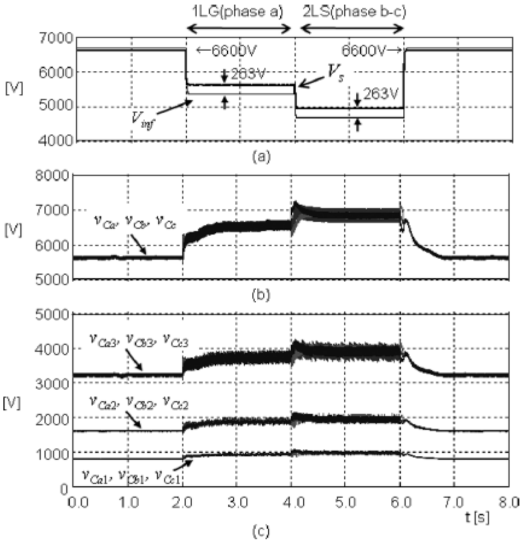
TABLE III
CONTROL PARAMETERS

PI-1 :	Proportional gain Integral gain	K_{Cp} K_{Ci}	0.1 1.0
PI-2 :	Proportional gain Integral gain	K_{Vp} K_{Vi}	0.5 50
PI-3 :	Proportional gain Integral gain	K_p K_i	25 100
PI-4 :	Proportional gain Integral gain	K_{mp} K_{mi}	0.1 1.0
LPF-1 :	Time constant	T_1	0.001
LPF-2 :	Time constant	T_2	0.2
LPF-3 :	Time constant	T_3	0.01
Proportional gain		K_{0p}	30
Limit for Zero Seq. Voltage		V_{Cmax}^*	7000
Limit for neg. seq. Current		V_{NEG}^*	1320

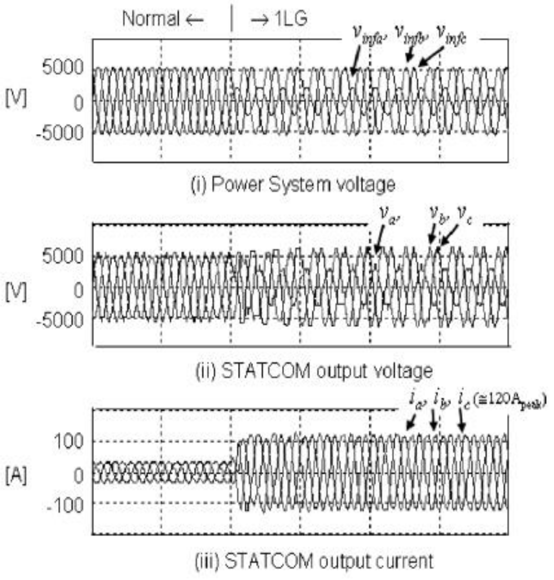


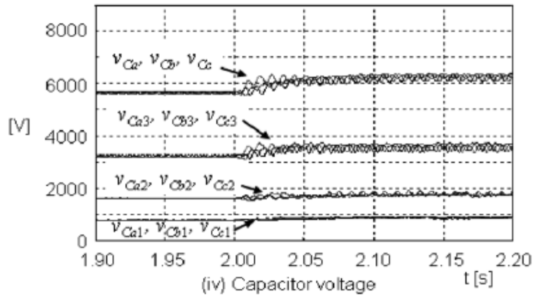
(a) (b)

Fig. 9. Source voltage under faults. (a) 1LG. (b) 2LS.



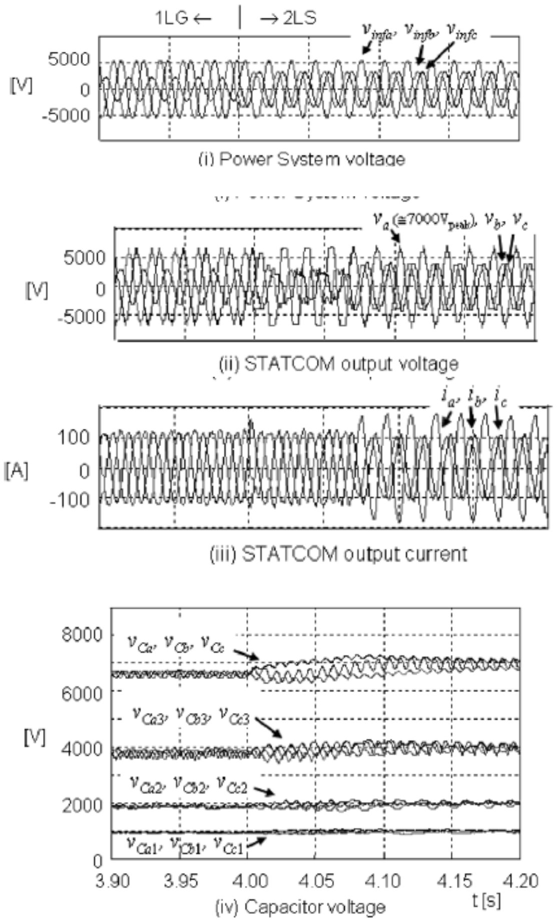
Circuit parameters are given in Table II. Rated reactive power is 1 MVA. The sum of rated capacitor voltage is 825V+1650V+3300V =5575V slightly higher than the peak voltage of ac system which is .5389V The capacitance 1 mF, 2 mF, 4 mF are chosen so that the capacitor voltage ripple are less than about 5% of their rated voltage at outputting rated reactive power. The ac reactance 11.6 mH is equivalent to 10% at rated reactive power. The control parameters are given in Table III.





(iv) Capacitor voltage

(a)



(i) Power System voltage

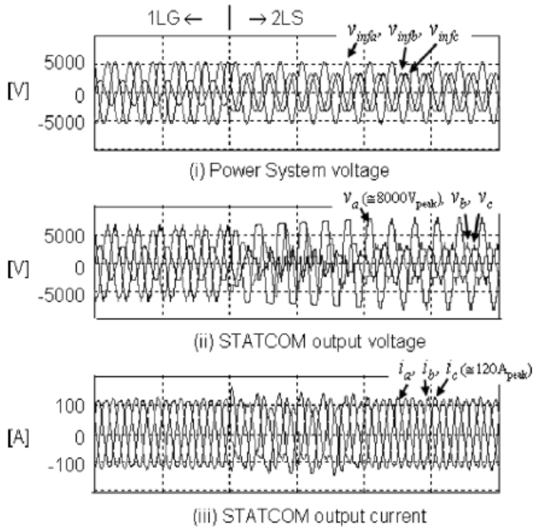
(ii) STATCOM output voltage

(iii) STATCOM output current

(iv) Capacitor voltage

(b)

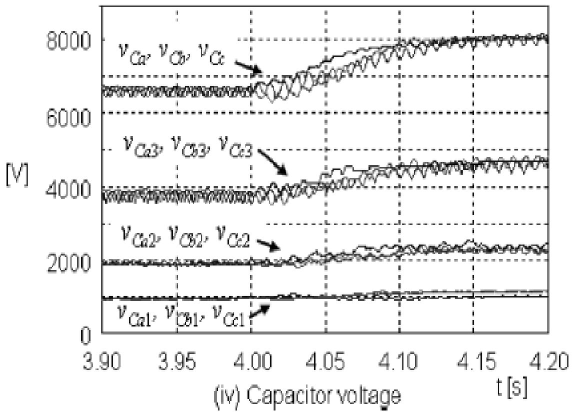
Fig. 11. Simulation result (Proposal: zero seq. voltage + negative seq. current control). (a) Normal → 1LG. (b) 1LG → 2LS.



(i) Power System voltage

(ii) STATCOM output voltage

(iii) STATCOM output current



(iv) Capacitor voltage

Fig. 12. Simulation result (only zero-sequence voltage control).

The simulation result of power system voltage and capacitor voltages are shown in Fig. 10. The STATCOM compensates power system voltage. As a result, grid connection voltage is 263 V higher than source voltage during 1LG and 2LS. Before 1LG the capacitor voltages of phase clusters are balanced and the voltage ratio of H-bridge cells is controlled to 1:2:4. At the starting point of 1LG and 2LS, the capacitor voltages of phase clusters are once unbalanced. But they are rebalanced soon. Fig. 11 shows the power system voltage, STATCOM output voltage, STATCOM output current and capacitor voltages. Under normal condition or 1LG the zero-sequence voltage method is used and balanced current are output, as shown in Fig. 11(a). The peak value of the currents is about 120 A. On the other hand, the negative-sequence current method is used and the STATCOM output unbalanced current under 2LS, as shown in Fig. 11(b). By this, the capacitor voltages are balanced. During this time, the peak value of STATCOM output voltage is about 7000 V. If the zero-sequence voltage method was used under 2LS, the STATCOM outputs balanced current, as shown in Fig. 12. But the peak value of the STATCOM output voltage is about 8000 V. Thus, the STATCOM had to output high voltage and a wide margin of dc capacitor voltage was needed. As described before, the combination of two capacitor voltage method realizes reasonable circuit design and flexible function of the STATCOM.

IV. CONCLUSION AND FUTURE SCOPE

This paper presented a configuration and control scheme of cascaded H-bridge STATCOM in three-phase power system. We proposed a control method using zero-sequence voltage and negative-sequence current. The two methods are used exclusively depending on the extent of voltage unbalance. By this method, STATCOM can operate flexibly under normal power system condition and does not need wide margin of dc capacitor voltage under large asymmetrical condition. The validity is examined by digital simulation under one line and two-lines fault circuit condition. The simulation results showed the effectiveness of proposed STATCOM. In addition, proposed control scheme can be used for other type of applications, such as PV(photovoltaic) inverter systems. It expands applicable scope of cascaded H-bridge multilevel converter.

REFERENCES

[1] F. Z. Peng, J. S. Lai, J. W. McKeever, and V. Coevering, "A multilevel voltage-source inverter with separate dc sources for static var generation," *IEEE Trans Ind. Appl.*, vol. 32, no. 5, pp. 1130–1138, Sep./Oct. 1996.

[2] J. Arrillaga, Y. H. Liu, and N. R. Watson, *Flexible Power Transmission*. Hoboken, NJ: Wiley, 2007, pp. 158–160.

[3] O. Alizadeh and S. Farhangi, "Voltage balancing technique with low switching frequency for cascade multilevel active front-end," presented at the 7th Int. Conf. Power Electronics, Daegu, Korea, Oct. 2007.

[4] R. E. Betz and T. J. Summers, "Using a cascaded H-bridge STATCOM for rebalancing unbalanced voltages," presented at the 7th Int. Conf. Power Electronics, Daegu, Korea, Oct. 2007.

[5] H. Akagi, S. Inoue, and T. Yoshii, "Control and performance of a transformerless cascade PWM STATCOM with star co figuration," *IEEE Trans Ind. Appl.*, vol. 43, no. 4, pp. 1041–1049, Jul./Aug. 2007.

[6] Q. Song, W. Liu, Z.Yuan, W.Wei, and Y. Chen, "DC voltage balancing technique using multi-pulse optimal PWM for cascade H-bridge inverters based STATCOM," in *Proc. IEEE 35th Power Electronics Specialists Conf.*, Aachen, Garmany, Jun. 2004, vol. 6, pp. 4768–4772.

[7] C. Cecati, A. Dell'Aquila, M. Liserre, and V. G. Monopoli, "A passivity-based multilevel active rectifier with adaptive compensation for traction applications," *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1404–1413, Sep./Oct. 2003.

[8] C. Cecati, A. Dell'Aquila, M. Liserre, and V. G. Monopoli, "Design of H-bridge multilevel active rectifier for traction systems," *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1541–1550, Sep./Oct. 2003.

[9] T. Fujii, S. Funahashi, N. Morishita, M. Azuma, H. Teramoto, N. Iio, H. Yonezawa, D. Takayama, and Y. Shinki, "A STATCOM for the Kanzaki substation," presented at the Int. Power Electronics Conf., Niigata, Japan, Apr. 2005.

[10] M. H. J. Bollen, "Voltage recovery after unbalanced and balanced voltage dips in three-phase system," *IEEE Trans. Power Del.*, vol. 18, no. 4, pp. 1376–1381, Oct. 2003.

[11] N. Hatano and T. Ise, "A configuration and control method of cascade H-bridge STATCOM," presented at the IEEE Power Energy Soc. General Meeting, Pittsburgh, PA, Jul. 2008.