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A Study on the Importance of Balance Control Strategies in Cascaded Multilevel STATCOM

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Abstract: This paper presents a study on dc capacitor voltage balance control method for cascade multilevel static synchronous compensator (STATCOM) and a general analytical method for balance control strategy. Imbalance of dc capacitor voltage is considered, which is caused by the inconsistency of active power absorbed and consumed by chain, a balance control strategy is discussed, based on Phase shift angle regulation. A general analytical method based on vector analysis is also presented, by which the performance of balance control strategy can be analysed, including regulation capacity. To find out the importance of balance control strategy, a comparison still based on vector analysis between balance control strategy and without using any balance control strategy is provided, from which importance of balance control strategy, based on Phase shift angle regulation, can be known which has the advantage of strong regulation capacity, and simulations are performed to prove it.

Index Terms : Cascade multilevel, dc capacitor voltage balance, static synchronous compensator (STATCOM), vector analysis

I. INTRODUCTION

FLEXIBLEac transmission systems, called FACTS, in the recent times is a well known name for higher controllability by help of power electronic devices in power systems. The STATCOM is a solid-state-based power converter version of the SVC. Its capacitive output currents or inductive output currents can be controlled independently from its terminal AC bus voltage.

The conventional 12-pulse voltage-sourced converter static synchronous compensator (STATCOM), first came into picture but the cascade multilevel STATCOM has gained importance because it offers greater efficiency, transformer less, minimalistic volume, redundancy, discreet phase control ability, etc. [1]–[3], it is a topic of great interest in recent times and has been widely studied. Because of independence of all dc capacitors of cascade multilevel STATCOM, the shunt losses, switching delay, and switching loss of every chain are different, the dc capacitors voltage will be unbalanced [4].

Thus, some problems are introduced due to unbalanced dc-link capacitor voltage, such as total harmonic distortion (THD) and raise the output voltage. When the degree of this unbalance boosts up, the capacitor voltage of few chains becomes greater than the others, which puts the safety of the devices in serious danger or could lead to serious system collapse [5].

Regulation capacity is one of the most important evaluation indexes of balance control strategy, where regulation capacity can be described by maximum range of active power absorbed in chain via the balance control algorithm. Every kind of balance control strategy has its own limits on regulation range, and at full range it positively cannot achieve dc capacitor voltage balance control; thus, it is essential to get maximum regulation range quantitatively, which is to play guiding task of components selection and system design; it is important to examine the constancy of balance control strategy because a worthy control method should have sturdy robustness.

Several dc capacitor voltage balance control methodologies have been under study in recent times for cascaded multilevel STATCOM in, but the comparison of with and without using any balance control strategies have been seldom discussed, it is necessary to make a comparison in order to determine the importance of balance control strategies.

In this paper, a dc capacitor voltage balance control strategy based on regulation of phase-shift angle, which changes the absorbed active power of each chain by changing the phase angle of its output voltage. Furthermore, vector analysis is presented; through this method, the regulation capability of control strategy is analyzed, and its regulation range is quantitatively specified. Thus, to find out the importance of balance control strategies, a comparison assessment based on vector analysis is presented, including regulation capability.

This paper concentrates on cascade multilevel STATCOM and its control of the dc capacitor voltage, which adopts carrier phase-shifting modulation strategy. The remaining paper is arranged as follows. In Section 2, three types of balance control strategies via vector analysis of a single chain are concluded for cascade multilevel

STATCOM, and the balance control strategy which is based on phase shift angle regulation is projected. Section 3 deals with hierarchal control structure of balance control strategy to present a new analytical way based on vector analysis, including regulation capability analysis. Section 4 discusses the control diagram of the balance control strategy. And Section 5 caters to regulation capability of the method. In Section 6, comparison of with and without using balance control strategy is done, and the conclusion is demonstrated by simulation, followed by conclusions in Section 7.

II. VECTOR ANALYSIS

The system illustration of delta-connected cascaded multilevel STATCOM is shown in Fig. 1. In Fig. 1, the phase voltage of point of common coupling (PCC) are u_{sa}, u_{sb}, and u_{sc}; u_{sab}, u_{sbc}, and $u_{sca}$are the line-to-line PCC voltages; The line-to-line voltages of STATCOM are u_{rab}, u_{rbc}, and u_{rca}; the phase current are i_{sab}, i_{sbc},and i_{sca}; the positive current direction is depicted in the schema; u_{c1}, u_{c2}, . . . , $u_{cN}$are dc capacitor voltages of arbitrary link; the joint inductance L; and N is the chain number.

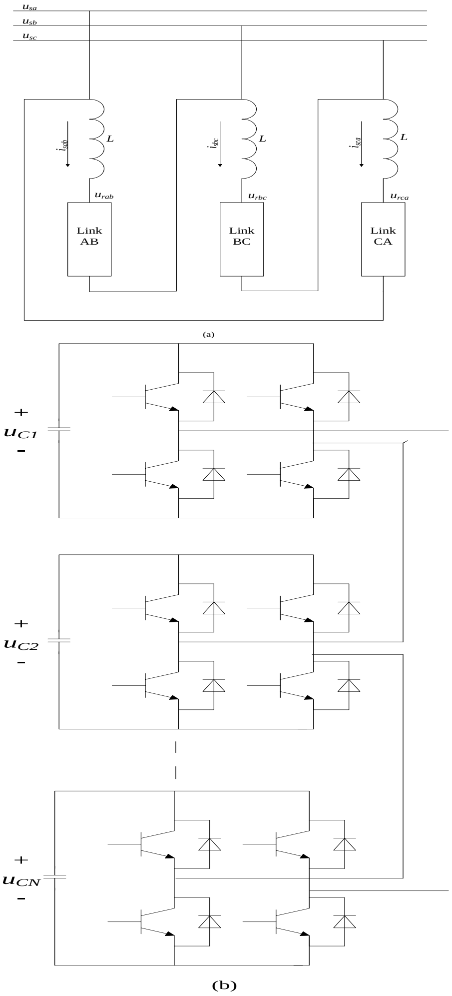


Fig -1: System diagram of cascade multilevel STATCOM. (a) System connection diagram. (b) Circuit of single-phase link.

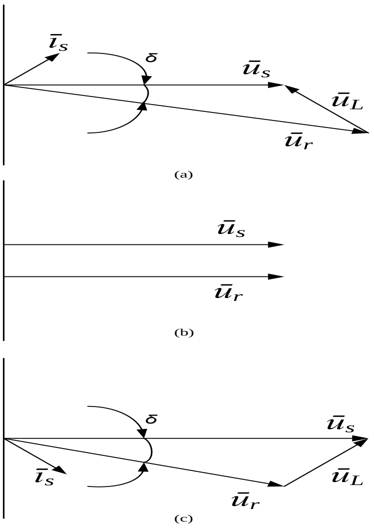


Fig -2: Vector diagram of cascade multilevel STATCOM. (a) Capacitive mode (b) No-load mode (c) Inductive mode

Escaping the series loss of cascaded multilevel STATCOM, we will have three operation modes as shown by the vector diagrams in Fig. 2: inductive mode, capacitive mode, and no-load mode, where system voltage is $\bar{u}_s$, $\bar{u}_r$is the output voltage of STATCOM, $\bar{\imath}_s$is the phase current, and $\bar{u}_L$is the joint inductance voltage. For minimalism, all the analyses are inductive mode based, as the other two modes also have the parallel analysis methods and conclusions. When as study object, an arbitrary link is considered, it can be correspondent to two series inverters through vector analysis of one single chain and the remaining N – 1 chains of this link.

When all the dc capacitor voltage are balanced, and all chains are alleged to be the same and their dc-side voltage are $u^*_{dc}$and $(N - 1)u^*_{dc}$, respectively, there will co-exist three vector operation modes with diverse modulation indexes, which is shown Fig. 3, where the output voltage range of the inverters is represented by the two circles. And steady-state operating point is depicted by P, which is articulated as follows:

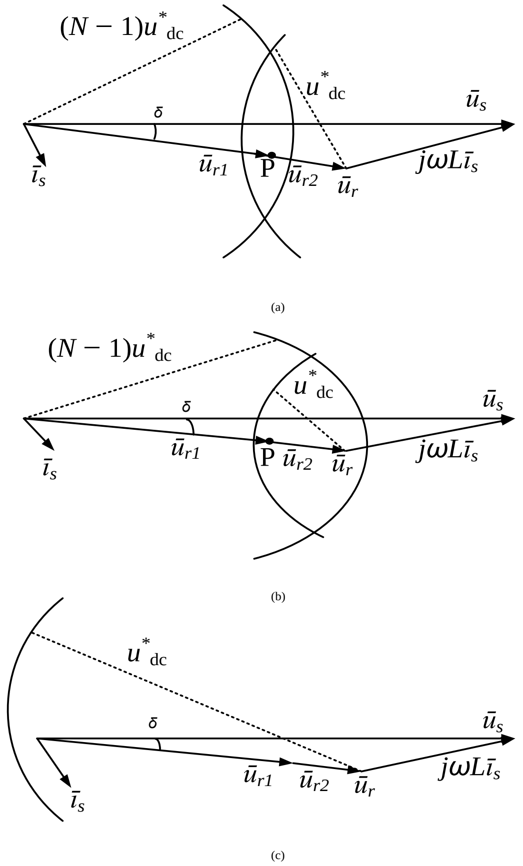
$$\bar{u}_{r1} = M\,(N - 1)u^*_{dc} \qquad (1)$$

$$\bar{u}_{r2} = M\,u^*_{dc} \qquad (2)$$

$$\bar{u}_r = \bar{u}_{r1} + \bar{u}_{r2} = MNu^*_{dc} \qquad (3)$$

where, the modulation index is represented by M and $u^*_{dc}$is the rated dc voltage of one single chain.

Generally, due to diverseness among chains it is unfeasible to work at point P for the system, which will produce an offset. For example, the steady-state operating point in Fig. 3(a) can be only positioned in the shadow area. This shadow area is the overlying part of two circles, which results into outcome that the output $\bar{u}_r$can only be synthesized in this portion, which is shown in Fig. 4(a) according to geometric analysis. In addition, the dc capacitor voltage level of cascade multilevel STATCOM can be only regulated when it absorbs active power from the system; and therefore, this absorbed active power of the arbitrary chain is meant positive, and Fig. 4(b) shows the stable operation portion of cascaded multilevel STATCOM.

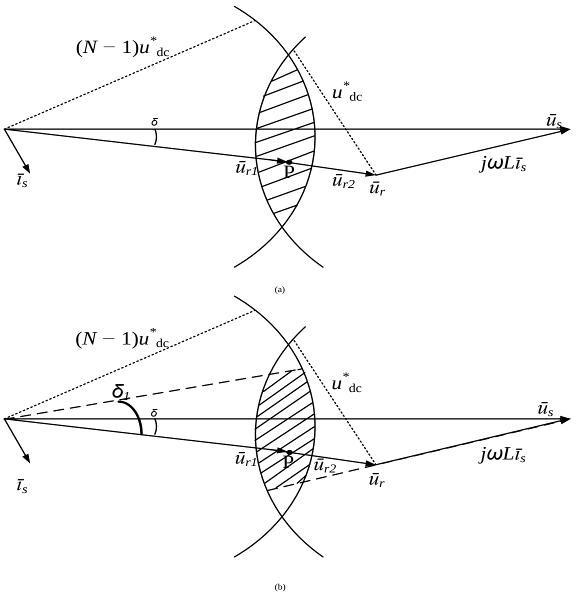


(a)

(b)

(c)

Fig -3: Vector diagram of operation depicted with different modulation index. (a) When (N-1)/N ≤ M ≤ 1. (b) When 1/N ≤ M ≤ (N-1)/N. (c) When 0 ≤ M ≤ 1/N.



(a)

(b)

Fig -4: Depiction of operation area of cascade multilevel STATCOM when (N-1)/N ≤ M ≤ 1. (a) Effective range of output voltage vector. (b) Stable operation area

III. HIERARCHICAL CONTROL STRUCTURE OF BALANCE CONTROL STRATEGY

Circuit of an arbitrary chain and also its vector diagram is illustrated in Fig. 2.17, where $\bar{u}_{rj}$is the chain output voltage, $i_s$is the phase current and $\theta_j$is the angle between them, $u_{cj}$is the voltage of dc-side, and $R_j$is the shunt resistance equivalent, where j = 1, 2, . . .N.

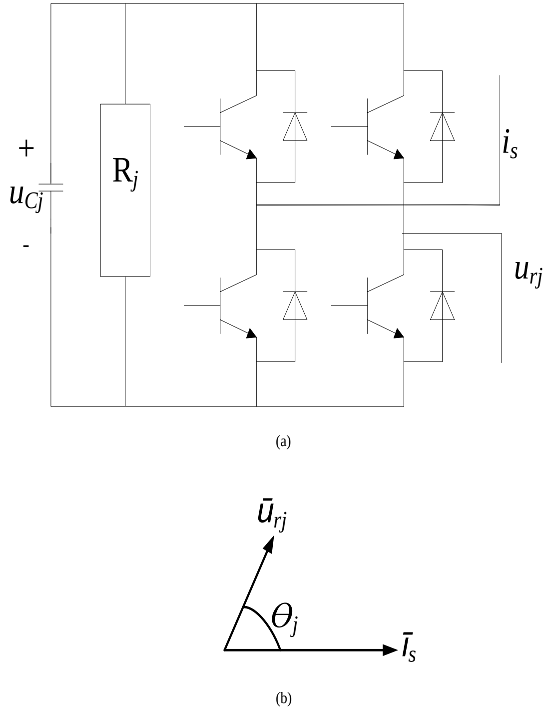
Active power balance put lights upon the fact that, the variation of energy which is stored in capacitor is dependent on the consumption of active power for the chain and actually absorbed active power.

$$P_{Cj} = P_{\text{absorb}} - P_{\text{loss}} = d(1/2Cu^2_{cj})/dt \qquad (4)$$

where $P_{\text{absorb}}$is the chain's absorbed active power, $U_{rj}$is the rms value for output voltage, $I_s$is the rms value for phase current, and power loss of the chain is represented by P_{loss}, which includes switching loss, dc-side power loss, etc.

$$P_{\text{absorb}} = U_{rj}\, I_s \cos\theta_j\,. \qquad (5)$$

Equation (4) provides us with two ideas to vary the dc-side voltage of the chain, which includes regulating the active power which is absorbed and regulating the active power which is consumed. As the compensation current is fixed so power loss is also fixed under its effect, thus the regulation of the absorbed active power realizes the dc capacitor voltage balance. According to Equation (5), there are three ways to vary the absorbed active power of chain, which includes regulation of the phase current magnitude, regulation of the output voltage magnitude, and regulating the angle between these two.



(a)

(b)

Fig -5: Diagrams for single chain. (a) Single chain circuit. (b) Single chain vector diagram

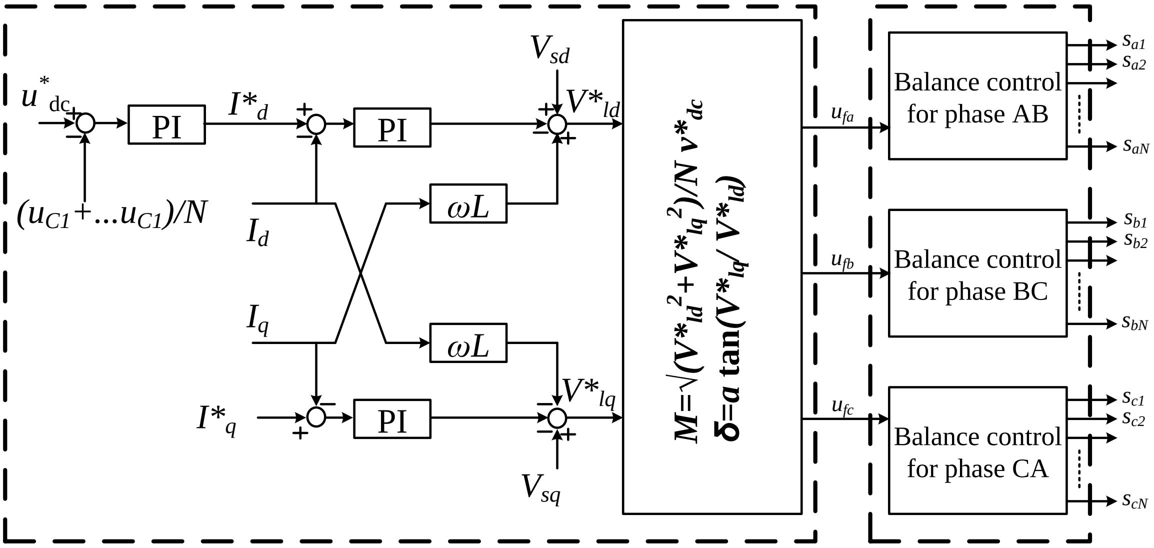


Fig -6: Hierarchical control structure for balance control strategies

As the direction as well as the magnitude of current is fixed, the direction and magnitude of chain output voltage can be altered only, which is equivalent to the chain controller output phase-shift angle and modulation index. Hierarchical control structure is generally adopted for cascade multilevel STATCOM when dc capacitor voltage balance control strategies are applied, in which the total active as well as reactive power control is gained by upper layer control; to realize dc voltage balance, the distribution of active power among chains of homophase is gained by lower layer control. Making it decouple control, [18]–[20], the control diagram is shown in Fig. 6. Therefore, according to the analysis above, the control strategy can be abridged as the following three types:

1) Phase-shift angle regulation and maintain modulation index;
2) Modulation index regulation and maintain phase-shift angle;
3) Regulation of both at the same time.

In recent times, most balance control strategies are based on these three methods mentioned and this paper the first one is discussed in priority.

IV. Phase Shift Angle Regulation and its Control Diagram

The angle between phase current and chain output voltage can be varied by altering the angle of phase-shift in the balance control strategy which is based on phase-shift angle regulation. The control diagram for respective is shown in Fig. 7.

As shown in Fig. 7, the average of homophase chains is the reference voltage, the feedback is the actual of each chain; when the reference is higher than actual voltage, the phase-shift angle is increased; otherwise when the reference is lower than actual voltage, and the phase-shift angle is hence decreased.

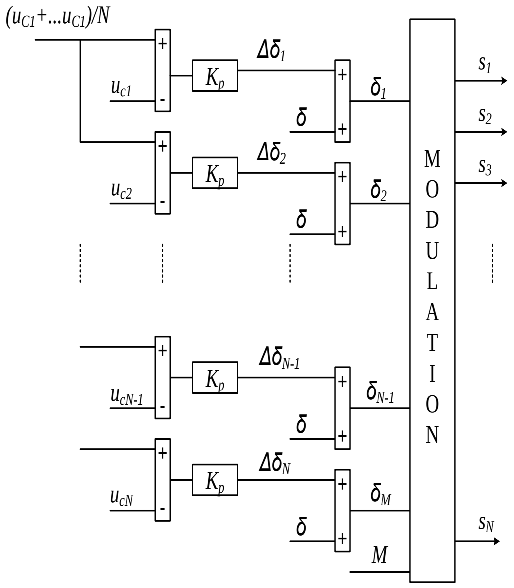


Fig -7: Control diagram for phase-shift angle regulation balance control strategy.

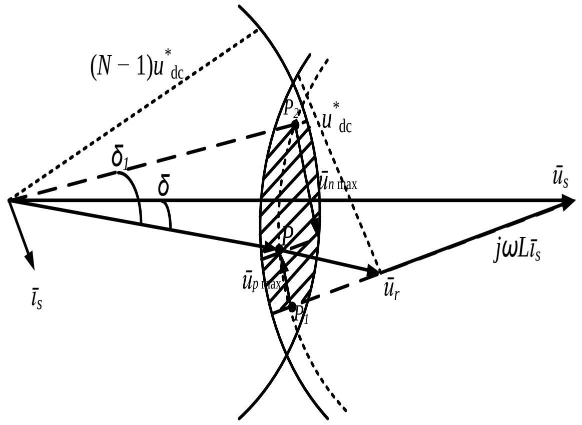


Fig -8: Regulation range for phase shift angle regulation balance control strategy

V. REGULATION CAPABILITY OF PHASE SHIFT ANGLE BALANCE CONTROL STRATEGY

For phase-shift angle regulation the maximum regulation range is as depicted in Fig. 8, the active component of regulation voltage are, correspondingly, $\bar{u}_{pmax}$ and $\bar{u}_{nmax}$. It can be achieved that

$$\bar{u}_{pmax} = (N - 1)Mu^{*}_{dc} \sin \delta_1 \quad (16)$$

$$\bar{u}_{nmax} = Mu^{*}_{dc} \sin \delta_1 \quad (17)$$

Assuming that the active range of regulation is $[-P\delta 1, P\delta 2]$, then we get,

$$P_{\delta 1} = \bar{u}_{pmax} I_s = (N - 1)\, M\, u^{*}_{dc} \sin {}_{\delta 1} I_s \quad (18)$$

$$P_{\delta 2} = \bar{u}_{nmax} I_s = M\, u^{*}_{dc} \sin {}_{\delta 1} I_s \quad (19)$$

Thus, we observe that regulation capability based upon phase shift angle regulation is worthy.

VI. VERIFICATION BY SIMULATION

A. Parameters of Simulation System

The control strategy is demonstrated by simulation, the system parameters are listed in Table 1.

Table -1: Specification of Simulation

Parameters	Values
Three phase line voltage u_s/V	6000
System frequency f_s/hz	50
Output inductor L_s/mH	28.6
Dc-side capacitor C_{dc}/uf	1840
Dc-side capacitor voltage u_{dc}/V	1000
Carrier phase-shifting with single polarity double frequency f_c/hz	250
Chain number N	12
Output reactive current reference	100

To validate the balance control strategies, we are taking the dc-side shunt resistor of single chain to be R and that of all other chains are 1 kΩ, which could be the reason for occurrence of difference of shunt loss among chains.

When cascade multilevel STATCOM is working in inductive mode and rated reactive current is absorbed by it, the modulation index is:

$$M = (u_s - I_{ref}\omega L) \times 1.414/N/u_{dc} = 0.61.$$

Figuring out the regulation range of balance control strategy according to modulation index,

$$\delta \in [0.1^\circ\ 1^\circ].$$

When we put, $R = 500\ \Omega$, the shunt loss difference among chains is:

$$\Delta P = (u^2_{dc}/500) - (u^2_{dc}/1000) = 1\text{kW}.$$

When we put, $R = 200\ \Omega$, the shunt loss difference among chains is:

$$\Delta P = (u^2_{dc}/200) - (u^2_{dc}/1000) = 4\text{kW}.$$

B. Simulation when no Balance Control Strategy is used

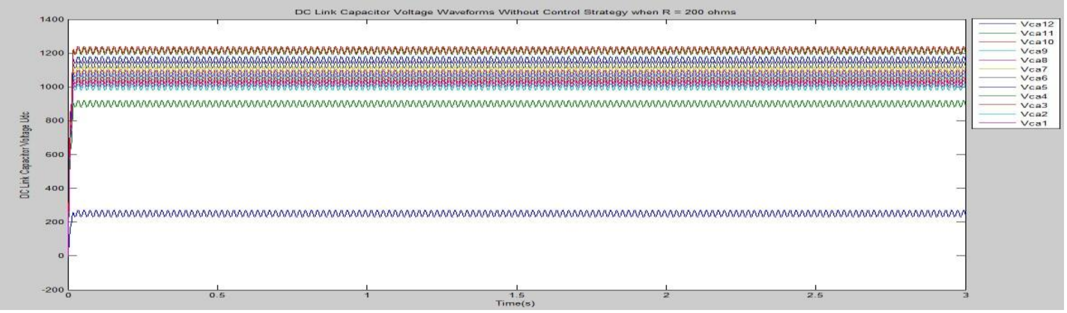
The waveforms for dc-side capacitor voltage are depicted in Fig. 9, when no balance control strategy is adopted and shunt loss difference among chains is also present. Fig. 9 illustrates that the shunt loss difference will lead up to serious dangerous consequences for cascade multilevel STATCOM as its capacitor voltage will be imbalanced.

When we take, R=200 Ω, the maximum difference of dc capacitor voltage among chains results to 973 V. And when we put, R = 500 Ω, the maximum difference of dc capacitor voltage among chains comes out to be 578 V.

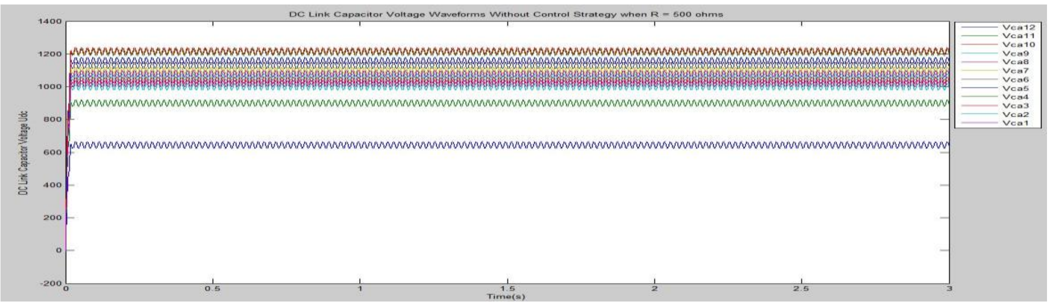
C. Simulation when Balance Control Strategy is used which is based on phase Shift Angle Regulations

Through the balance control strategy which is based on phase-shift angle regulation, the waveform for dc-side capacitor voltage is illustrated in Fig. 10.

The maximum difference of capacitor voltage results to 15, when the shunt resistance is put, R= 200 Ω; therefore, we can infer that the capacitor voltage of cascade multilevel



(a)



(b)

Fig -9**:** DC capacitor voltage waveforms without balance control strategy. (a) $R = 200\ \Omega$. (b) $R = 500\ \Omega$.

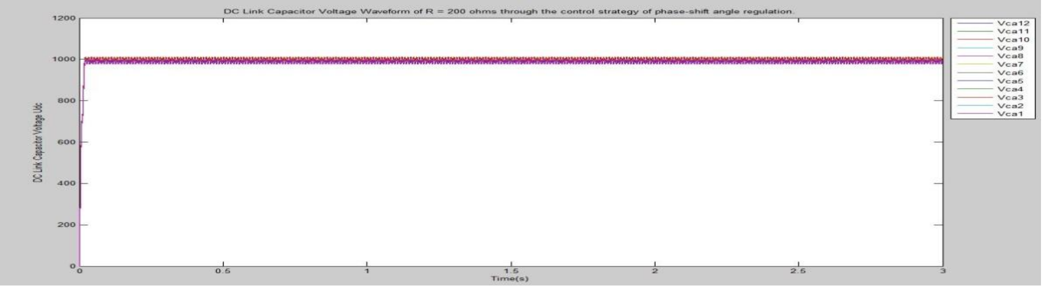


Fig -10: DC capacitor voltage waveforms of $R = 200\ \Omega$ through the control strategy of phase-shift angle regulation.

STATCOM can be controlled and balanced by the control methodology of Phase-shift angle regulation even when the shunt loss is quite varied among the chain.

VII. CONCLUSION

This paper studies the effect and importance of applying balance control strategy to cascaded multilevel STATCOM. Due to the variation of absorbed power and power loss between the chains the dc capacitor voltage imbalance occurs; hence, the dc capacitor voltage balance can be obtained via altering the absorbed power of chain. This approach is used and balance control strategy is discussed and one of method is presented which based on phase-shift angle regulation. The control diagram of proposed method is illustrated; in addition to it, regulation range is analysed with vector analysis also. When we compare the above mentioned method with the system where no balance control strategy is used; the studied method has the benefit of strong regulation capability, it means when the shunt loss is quite variable among the chain, then also it is effective in balancing capacitor voltage. In this paper, all the theoretical analysis is authenticated by simulation.

Simulation results show that the problem of dc capacitor voltage balance for cascade multilevel can be tried to be solved by the balance control strategy of phase-shift angle regulation.

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BIOGRAPHIES

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