STUDY ON POWER QUALITY IMPROVEMENT BY USING MODULAR MULTILEVEL CASCADE CONVERTER BASED STATCOM

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Abstract—the power quality associated problems are voltage sag, flicker, voltage imbalance, interruption and harmonics problems which results in the malfunctioning of equipments in the industries by affecting the microprocessor based loads, sensitive electric components which are highly sensitive to voltage level fluctuation. The power consumed by the heavy load creates unsymmetrical currents which results in reduced power quality in the electrical grid. The stimulating functions of Flexible AC Transmission system (FACTS) estimate the critical clearing time, voltage regulation, steady state power flow and oscillation damping control. The main objective of this paper is the application of modular multilevel cascade (MMC) converter based Static Synchronous Compensator (STATCOM) for reactive-power control and improved power quality. The complete simulation of this system is performed in the MATLAB software and the PI control is used for the controlling.

Keywords Flexible AC Transmission system (FACTS), Static synchronous Compensator (STATCOM), modular multilevel cascade (MMC), insulated-gate bipolar transistors (IGBT)

I. INTRODUCTION

J. S. Lai and F. Z. Peng [26] says the "multilevel converter" has drawn tremendous interest in the power industry [I]-[12]. The general structure of the multilevel converter is to synthesize a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The so-called "multilevel" starts from three levels. A three-level converter, also known as a "neutral-clamped" converter, consists of two capacitor voltages in series and uses the center tap as the neutral [13]. Each phase leg of the three-level converter has two pairs of switching devices in series. The center of each device pair is clamped to the neutral through clamping diodes. The waveform obtained from a three-level converter is a quasi-square wave output.

The diode clamp method can be applied to higher level converters [6] .As the number of levels increases, the synthesized output waveform adds more steps, producing a staircase wave which approaches the sinusoidal wave with minimum harmonic distortion [141. Ultimately, a zero harmonic distortion of the output wave can be obtained by an infinite number of levels. More levels also mean higher voltages can be spanned by series devices without device voltage sharing problems. Unfortunately, the number of the achievable voltage levels is quite limited not only due to voltage unbalance problems but also due to voltage clamping requirement, circuit layout, and packaging constraints. To date, hardware implementation has only been reported up to six levels for a back-to-back intertia application [9], in which the voltage unbalance problem has been successfully overcome.

The magnetic transformer coupled multipulse voltage source converter has been a well-known method and has been implemented in 18 and 48 pulse converters for battery energy storage and static condenser

(STATCON) applications, respectively, [15], [16]. Traditional magnetic coupled multipulse converters typically synthesize the staircase voltage wave by varying transformer turns ratio with complicated zigzag connections. Problems of the magnetic transformer coupling method are bulky, heavy, and lossy. The capacitor voltage synthesis method is thus preferred to the magnetic coupling method. There are three reported capacitor voltage synthesis based multilevel converters: 1) diode-clamp, 2) flying-capacitors, and 3) cascaded inverters with separated dc sources.

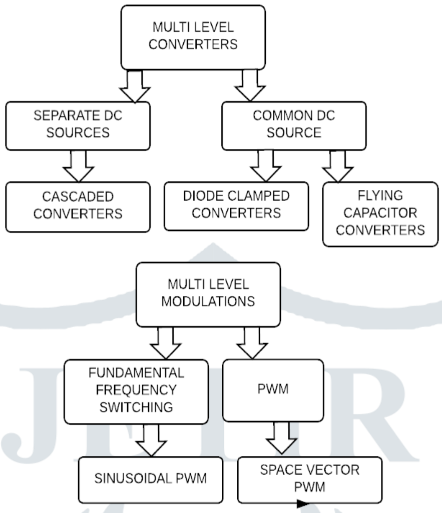

Fig. 1. Types of converters

Modular multilevel cascade converter (MMCC) family based on cascade connection of multiple bidirectional chopper cells or single-phase full-bridge cells. The MMCC family is classified from circuit configuration as follows: the single-star bridge cells (SSBC); the single-delta bridge cells (SDBC); the double-star chopper cells (DSCC); and the double-star bridge cells (DSBC). The term MMCC corresponds to a family name in a person while, for example, the term SSBC corresponds to a given name. Therefore, the term "MMCC–SSBC" can identify the circuit configuration without any confusion. Among the four MMCC family members, the SSBC and DSCC are more practical in cost, performance, and market than the others although a distinct difference exists in application between the SSBC and DSCC.

This paper presents application examples of the SSBC to a battery energy storage system (BESS), the SDBC to a static synchronous compensator (STATCOM) for negative-sequence reactive-power control, and the DSCC to a motor drive for fans and blowers.

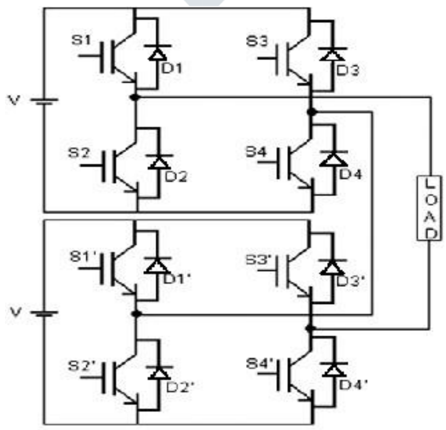

Fig. 2. Single-phase cascading VSI STATCOM.

According to Y. Liang and C. O. Nwankpa [27] Static compensators (STATCOM's) based on gate turn-off thyristors (GTO's) and a special zigzag trans-former have been developed and put into operation in recent years [17], [18]. It has been recognized that these STATCOM's have advantages over conventional static var compensator's (SVC's) of generating no harmonic or less harmonic current to the system and requiring a much smaller reactor. However, zigzag transformers used in these STATCOM's are bulky,expensive, and unreliable [22].

STATCOM's based on multilevel voltage source inverters (VSI's) have been widely studied due to their capability of eliminating the zigzag transformer. In this multilevel VSI-based STATCOM category, there are mainly three different system configurations: 1) diode-clamped converter configuration [19], [20]; 2) flying-capacitor converter configuration [21]; and 3) cascading converter configuration [22].

Basically, the STATCOM system comprises of three main parts: a multilevel-cascaded voltage source converter with separated dc capacitors, coupling reactors, and a controller. The multilevel-cascaded converter consists of a number of identical H-bridge converters, whose output terminal **is** connected in series. The output voltage is thus the summation of those H-bridge converters. The number of output line-to-neutral voltage levels equal **2 N + l .** In a very high voltage system, leakage inductances of coupling power step-up transformers can he functioned as the coupling reactors. The main purpose of the coupling inductors is to filter out current harmonic components mainly generated by modulation techniques of the power converters. The STATCOM is connected to the power networks at a point of common coupling (PCC). To make the entire system work effectively and properly, the controller needed to be carefully designed. All necessary voltages and currents arc measured and fed into the controller to he compared with the commands. The controller then performs feedback control and outputs a set of switching signals to drive the main valves of the power converter accordingly. The single-line diagram of the STATCOM system is illustrated. The multilevel-cascaded converter is in general represented by an ideal voltage source associated with internal **loss** connected to the ac power via coupling impedance.

The exchange of the real power and reactive power between the cascaded converter and the power system can he controlled by adjusting the amplitude and phase of the converter output voltage. In case of ideal converter, the output voltage of the converter is controlled to he in phase with that of the power system. To operate the STATCOM in capacitive mode, +Q, the magnitude of the converter output voltage is greater than that of the power system. On the other hand, the magnitude of the output voltage of the converter is controlled to be less than that of the power system to absorb reactive power or to operate the STATCOM in inductive mode, -Q. However, in practice, the converter associates with internal losses caused by non-ideal power semiconductor devices and passive components. As a result, without any control, the capacitor voltage will decrease. To regulate the capacitor voltage, a small phase shift delta between the converter voltage and the power system voltage **is** introduced.

II. DIODE-CLAMP MULTILEVELCONVERTER

A. Basic Principle

An m-level diode-clamp converter typically consists of m - 1 capacitors on the dc bus and produces m levels of the phase voltage.

Advantages:

1) When the number of levels is high enough, harmoniccontent will be low enough to avoid the need for filters.Efficiency is high because all devices are switched at the fundamental frequency.
2) Reactive power flow can be controlled.
3) The control method is simple for a back-to-back intertie system.

Disadvantages:

1) Excessive clamping diodes are required when the number of levels is high.
2) It is difficult to do real power flow control for the individual converter.

III. MULTILEVEL CONVERTER USING FLYING CAPACITOR

The voltage level defined in the flying-capacitor converter is similar to that of the diode-clamp type converter. The phase voltage of an m-level converter has m levels including the reference level, and the line voltage has (2 m - 1) levels. Assuming that each capacitor has the same voltage rating as the switching device, the dc bus needs (m- 1) capacitors for an m-level converter.

Advantages

1) Large amount of storage capacitors provides extra ride through capabilities during power outage.
2) Provides switch combination redundancy for balancing different voltage levels.
3) When the number of levels is high enough, harmonic content will be low enough to avoid the need for filters.
4) Both real and reactive power flow can be controlled

Disadvantages

1) An excessive number of storage capacitors is required when the number of converter levels is high. High level systems are more difficult to package and more expensive with the required bulky capacitors.
2) The inverter control will be very complicated, and the switching frequency and switching losses will be high for real power transmission.

Cascaded H-bridge Multilevel Inverter

Each Separate DC Source (SDCS) is connected to a single phase full bridge or H-bridge inverter. Each inverter level can generate three different voltage outputs, +Vdc, 0 and –Vdc by connecting the DC source to the AC output by different combinations of the four switches, S1, S2, S3 and S4.
The AC outputs of different full bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs.

Advantages :

1) The number of possible output voltage levels is more than twice the number of DC sources (NL = 2s + 1).
2) The series of H-bridges makes for modularized layout and packaging. This will make the manufacturing process to be done more quick and cheap.

Disadvantages :

1) It needs separate DC sources for real power conversions, thereby limiting its applications.

Table .1. Components required for different MLI topologies

Components	Inverter Type		
	Diode Clamped	Flying Capacitors	Cascaded H-bridge
Main Switching devices	(NL-1) * 2	(NL -1) * 2	(NL -1) * 2
Main diodes	(NL -1) * 2	(NL -1) * 2	(NL -1) * 2
Clamping diodes	(NL -1) * (NL -2)	0	0
DC bus capacitors	(NL -1)	(NL -1)	(NL -1) / 2
Balancing capacitors	0	(NL -1) * (NL -2) / 2	0

STATCOM

STATCOM is made up of a coupling transformer, a VSC and a dc energy storage device. STATCOM is capable of exchanging reactive power with the transmission line because of its small energy storage device i.e. small dc capacitor, if this dc capacitor is replaced with dc storage battery or other dc voltage source, the controller can exchange real and reactive power with the transmission system, extending its region of operation from two to four quadrants.

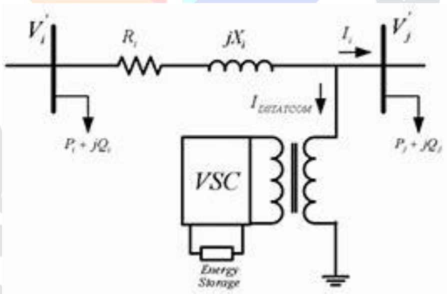

Fig.3. Basic Operation of STATCOM

A. Control of Reactive Power

It is well known that the amount and type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage. The reactive power supplied by the STATCOM is given by

$$Q = \frac{V_{STAT} - V_S}{X} V_S \qquad (1)$$

where V_{STAT} and V_S are the magnitudes of STATCOM output voltage and system voltage, respectively, and X is the equivalent impedance between STATCOM and the system.

When Q is positive, the STATCOM supplies reactive power to the system. Otherwise, the STATCOM absorbs reactive power from the system. Since the modulating signals are the same for the H-bridge inverters in the system, the fundamental component of the STATCOM output voltage is N times that of each H-bridge inverter, provided that the voltage across the dc capacitor of each inverter is the same. As a result, the STATCOM output voltage can be controlled by the modulating index (MI) (m_a) . $V_{STATCOM}$ is proportional to m_a, as long as the individual H-bridge inverter is in the linear modulating region. Due to its ability to control the output voltage by the MI, the proposed STATCOM has extremely fast dynamic response to system reactive power demand.

B. Control of DC Capacitor Voltages

If all the components in Fig. 1 were ideal and the STAT-COM output voltage were exactly in phase with the system voltage, there would have been no real power exchange between the STATCOM the and system, therefore, the voltages across the dc capacitors would have been able to sustain. However, a slight phase difference between the system voltage and the STATCOM output voltage is always needed to supply a small amount of real power to the STATCOM to compensate the component loss, so that the dc capacitor voltages can be maintained. This slight phase difference is achieved by adjusting the phase angle of the sinusoidal modulating signal. If the real power delivered to the STATCOM is more than its total component loss, the dc capacitor voltage will rise, and vice versa. The real power exchange between the STATCOM and the system is described by

$$P = \frac{V_S V_{STAT}}{X} \sin(\delta) \quad (2)$$

where δ is the phase angle difference between STATCOM voltage and the system voltage. The proportional plus integral (PI) controller presented in [12] is adopted to regulate and equalize the dc capacitor voltage. The basic idea of this controller is to use the error between the reference and the actual dc voltage as feedback signal. This signal is then fed to a PI regulator to produce the phase angle δ to control the real power exchange between the STATCOM and the system and, thus, regulate the dc capacitor voltage. Interested readers are referred to [12] for a detailed description of this PI regulator.

IV. RIPPLE OF DC CAPACITOR VOLTAGES AND SIZING OF THE DC CAPACITORS

DC capacitors not only play an important role in STATCOM system performance, but comprise a large part of the total system cost, as well. Hence, proper sizing of the dc capacitors is essential to low system cost and high performance of the proposed STATCOM. Since the inverters in the STATCOM are identical, the equations are based on a one inverter system

A. System Differential Equations

Equations (3) and (4) describe the system behavior of the one-inverter system.

$$(3) \qquad C\frac{dv_c}{dt} = sw.i_L$$

$$(4) \qquad L\frac{di_L}{dt} + Ri_L = e(t) - sw.v_c$$

In (3) and (4), $e(t)$ is the system voltage, v_c is the capacitor voltage, and w is the switching function.

B. DC Capacitor Voltage

Under the assumptions that: 1) the harmonic components centered around the switching frequency and its multiples are negligible; 2) the dc capacitor voltage ripple is small; and 3) system voltage $e(t)$ is sinusoidal, we have, in steady state, the following:

$$(5) \qquad sw(t) = m_a \sin \omega t$$

$$(6) \qquad i_L(t) = I \sin(\omega t + \varphi_i)$$

In (5) and (6), I is the inductor peak current, m_a is the MI, and

when the resistor R approaches zero. Equations

$\varphi_i = \pm 90°$

(3) , (5), and (6) result in (7)

$$C\frac{dv_c}{dt} = m_a \sin \omega t . I \sin(\omega t + \varphi_i) = \pm \frac{1}{2} m_a I \sin 2\omega t \qquad (8)$$

$$v_c(t) = V_{DC} + \frac{1}{4\omega C} m_a I \cos 2\omega t$$

C. **Sizing of the DC Capacitors**

From (8), we know that the DC capacitor peak±peak voltage ripple is $\Delta V_c = \frac{m_a I}{4\omega C}$. Once this ripple value is specified, the size of the dc capacitor can be calculated by

$$C = \frac{m_a I}{2\omega \Delta V_c} \qquad (9)$$

To keep the ripple voltage within the specified value in the full range of reactive power of the STATCOM, m_a in (9) should be set to one.

REJECTION OF CURRENT HARMONICS CAUSED BY DC CAPACITOR VOLTAGE RIPPLE

From (4), (5), and (8), we know that the dc capacitor voltage ripple will cause inductor current i_L to have third-order harmonic component. If this harmonic component can be rejected, the size of the inductor L and dc capacitors can be further reduced. A technique to reject harmonic caused by dc voltage ripple was proposed in [9], where the dc voltage ripple is independent of the inverter current. Unfortunately, the dc voltage ripple is proportional to the inverter current in the proposed STATCOM. Nevertheless, the basic idea in [9] enlightened the authors to develop a new method to tackle the problem.

In (4), if the switching function can be expressed

$$sw(t) = \frac{V_{STATCOM} \sin \omega t}{v_c(t)} \qquad (10)$$

the inductor current will be purely sinusoidal. Equations (3), (6), and (10) will result in

$$\frac{d(v_c^{\,2})}{d(2\omega t)} = \pm \frac{1}{2\omega C} V_{STATCOM} I \cos 2\omega t \qquad (11)$$

$$v_c(t) = V_{DC}(1 \pm k \cos 2\omega t)^{1/2} \qquad (12)$$

Where

$$k = \frac{m_a I}{2\omega C V_{DC}} \qquad (13)$$

$$m_a = \frac{V_{STATCOM}}{V_{DC}} \qquad (14)$$

As we can see, (8) is the first-order approximation of (12). From (10), (12), and (14), we have

$$sw(t) = m_a \sin \omega t . (1 \pm k \cos \omega t)^{1/2}$$

s chosen as the modulating signal. In this case, the inductor current will have no low-order harmonic components.Another option to reject the harmonic component is to use (10) directly as the modulating signal. Since the dc voltage ripple frequency is much lower compared to the resultant STATCOM switching frequency $(2Nf)$, the switching function will approach (10), if (10) is used as the modulating signal.

Depending on system implementation, either one of the above proposed methods can be used.

DC Capacitor Voltage Balance Control Approaches

Obviously, the primary attractive of the cascaded-multilevel converter-based is its modularity. However, this topology requires excessive amount of dc voltage sources. In STATCOM applications, the main challenge is how to, not only statically but also dynamically, balance those dc capacitors. There are two main factors regarding the dc voltage unbalance among these three dc capacitors.The first issue is these dc capacitors must have the same amount of power utilization in a period of time. Suitable modulation techniques can serve this concern. A technique so-called the phase-shifted carrier sinusoidal PWM was proposed to improve the quality of output waveforms of multi-converter modules in HVDC applications. Because of the use of equally distributed carrier signals, the fundamental components of the waveform in different levels are theoretically identical; therefore, the amount of reactive currents are drawn in and out of the capacitors in a period of time are equal. However, because of non-ideal converters, their internal losses are not identical and introduces unbalance problem. With only the use of the modulation technique itself cannot keep those dc voltages balance; therefore, a small amount of real power is needed to compensate the voltage differences. To simplify the explanation, the H-bridge converter operates with line switching frequency. The idea is that if the current and the voltage are exactly 90" phase shifted, the total charge of the capacitor **is** zero. Therefore, there is no net change in the capacitor voltage. However, if a small phase shift is introduced to the voltage waveform, the total charge in the capacitor is not zero. The voltage of the capacitor is thus either increased or deceased. By adjusting the phase of the output voltage, the capacitor voltages can be corrected.

The modeling techniques of the cascaded-multilevel converter-based STATCOM in abc and dq0 coordinators have been proposed. Based on the proposed models, the feedback control scheme is analyzed and designed to perform reactive power compensations as well as capacitor voltage balancing. . The proposed controller is designed according to the simplified models.

Future Scope

Higher device switching loss is a disadvantage of the proposed STATCOM . However, this disadvantage will diminish when low-loss and high-power switching devices are developed and used in the H-bridge inverters.

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