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Study of Cascaded H-Bridge Converter Control Strategies and their Impact on Switching Harmonics

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Abstract: **The Cascaded H-Bridge (CHB) multilevel static synchronous compensator (STATCOM) has been widely accepted in the industry [1]-[8]. An outstanding advantage of the CHB multilevel topology is their modular structure. This enables higher-level STATCOM to be easily implemented through series connection of more cells. since the pulse-width modulation (PWM) signals of each cell are generated all by the central controller instead of their own controller, the cell does not look like an "independent module". To achieve "true" modular implementation, a distributed control system (DCS) for the CHB multilevel STATCOM should be developed.**

Keywords: Cascaded H-Bridge, FACTS devices, STATCOM, Harmonics

1. INTRODUCTION

In recent years, due to more intransigent regulations in the area of power quality, much more interest has been devoted to the Flexible AC Transmission Systems (FACTS) as a means to improve the power quality [1,2]. Among the FACTS devices, static compensator (STATCOM) is an indispensable component to the grid voltage stability which is connected in shunt to the network for injecting or absorbing reactive power [2,3]. STATCOM can be installed whether on transmission or distribution network. The latter is called D-STATCOM and it operates in voltage and power ratings lower than the transmission system STATCOM. So, many efforts have been done to realize it without bulky and heavy coupling transformer and to reduce the size of bulky inductive filters, using multilevel converters [4]. In this case, STATCOM is composed of one multilevel converter with dc sources or energy storing capacitors on its dc side and coupling line inductances [1]. Multilevel converters are divided to three categories:
neutral point clamped (NPC), flying capacitor (FC) and cascaded H-bridge (CHB) converters [5]. Among the mentioned topologies, the cascaded H-bridge converter is more interested due to its extreme modularity, easier dc voltage balancing, and minimum number of required components for a specific number of voltage levels.

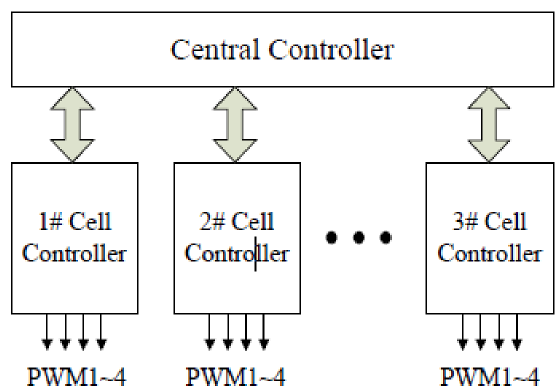

Fig. 1. General structure of DCS.

They have different functions. There are three main control tasks for the CHB multilevel STATCOM: (1) output current close-loop control; (2) each cell dc voltage balancing control; (3) each cell PWM signals generation.

2. LITERATURE REVIEW

[1] This paper presents a new control method for cascaded connected H-bridge converter-based static compensators. These converters have classically been commutated at fundamental line frequencies, but the evolution of power semiconductors has allowed the increase of switching frequencies and power ratings of these devices, permitting the use of pulse width modulation techniques. This paper mainly focuses on dc-bus voltage balancing problems and proposes a new control technique (individual voltage balancing strategy), which solves these balancing problems, maintaining the delivered reactive power equally distributed among all the H-bridges of the converter.

[2] The aim of this paper is to group and review these recent contributions, in order to establish the current state of the art and trends of the technology, to provide readers with a comprehensive and insightful review of where multilevel converter technology stands and is heading. This paper first presents a brief overview of well-established multilevel converters strongly oriented to their current state in industrial applications to then center the discussion on the new converters that have made their way into the industry. In addition, new promising topologies are discussed. Recent advances made in modulation and control of multilevel converters are also addressed.

[3] This paper deals with a cascaded multilevel converter which has multiple dc voltage values (multi-voltage cascade converter) for a 6.6-kV transformer less distribution static synchronous compensator (D-STATCOM). A control method is proposed to realize dc voltage regulation of series-connected three cells in the STATCOM operation, making it possible to remove dc sources from all H-bridge cells. The simplified configuration without the dc sources makes the STATCOM small and lightweight.

[4] This paper compares four power converter topologies for the implementation of flexible AC transmission system (FACTS) controllers: three multilevel topologies (multipoint clamped (MPC), chain, and nested cell) and the well-established multi pulse topology. In keeping with the need to implement very-high-power inverters, switching frequency is restricted to line frequency. The study addresses device count, DC filter ratings, restrictions on voltage control, active power transfer through the DC link, and balancing of DC-link voltages. Emphasis is placed on capacitor sizing because of its impact on the cost and size of the FACTS controller.

[5] This paper presents the most important topologies like diode-clamped inverter (neutral-point clamped), capacitor-clamped (flying capacitor), and cascaded multi cell with separate DC sources. Emerging topologies like asymmetric hybrid cells and soft-switched multilevel inverters are also discussed. This paper also presents the most relevant control and modulation methods developed for this family of converters: multilevel sinusoidal pulse width modulation, multilevel selective harmonic elimination, and space-vector modulation.

[6] This work presents the state of the art in the field of regenerative rectifiers with reduced input harmonics and improved power factor. Regenerative rectifiers are able to deliver energy back from the dc side to the ac power supply. Topologies for single- and three-phase power supplies are considered with their corresponding control strategies. Special attention is given to the application of voltage- and current-source PWM rectifiers in different processes with a power range from a few kilowatts up to several megawatts.

[7] This paper presents a survey of different topologies, control strategies and modulation techniques used by these inverters. Regenerative and advanced topologies are also discussed. Applications where the mentioned features play a key role are shown. Finally, future developments are addressed.

[8] This paper gives an overview of medium-voltage (MV) multilevel converters with a focus on achieving minimum harmonic distortion and high efficiency at low switching frequency operation. As a preferred option for future research and application, an inverter configuration based on three-level building blocks to generate five-level voltage waveforms is suggested. This paper shows that such an inverter may be operated at a very low switching frequency to achieve minimum on-state and dynamic device losses for highly efficient MV drive applications while maintaining low harmonic distortion.

[9] This paper discusses energy storage systems (ESSs) integrated with conventional and multilevel bidirectional power converters for a hybrid STATCOM/ESS. Conventional, diode-clamped, and cascaded multilevel converter-based STATCOM/ESSs are developed, and their performances for a variety of power system applications are compared using battery energy storage.

[10] In this paper, a new type of static compensator (STATCOM) is proposed. This new STATCOM is constructed by cascading several identical full-bridge (H bridge) voltage-source inverters (VSIs). A so-called phase-shifted sinusoidal pulse width modulation (SPWM) unipolar voltage switching scheme is applied to control the switching devices of each VSI.

[11] This paper presents a three-phase transformer less cascade pulse width-modulation (PWM) static synchronous compensator (STATCOM) intended for installation on industrial and utility power distribution systems. It proposes a control algorithm that devotes itself not only to meeting the demand of reactive power but also to voltage balancing of multiple galvanically isolated and floating dc capacitors. The control algorithm based on a phase-shifted carrier modulation

strategy is prominent in having no restriction on the cascade number.

[12] This paper presents a simple controller integrating a new reactive current reference algorithm for enhancing the transient performance of static synchronous compensator (STATCOM). A multilevel cascaded inverter with separated dc capacitors which is driven by carrier-based pulse width modulation is used to implement the STATCOM. The voltage across each dc-link capacitor is regulated by the rotated switching swapping scheme. In this paper, the STATCOM is controlled to provide both reactive power (VAR) compensation and grid power factor correction at the point of common coupling with a dynamically varying reactive load system. The proposed algorithm enhances the transient performance of the closed-loop system with only proportional controller and minimizes the STATCOM reactive current ripples

[13] A Fundamental Frequency Sorting Algorithm (FFSA) based on Carrier Phase Shift PWM (CPS-PWM) is proposed to balance the floating DC capacitors. The main idea is to change the corresponding relationship between the CPS-PWM carriers and the sub modules according to the capacitor voltage increments during the previous fundamental period. It utilizes no current detection, avoids the excessive frequent sorting and saves calculating resources for the controller so that more sub modules can be dealt with.

[14] The DC capacitors' voltage balancing strategy is one of the key technique of cascaded H-bridge STATCOM, because the DC capacitors of cascaded H-bridge STATCOM playing an important role in supporting DC voltage. The impact of H-bridge parameters on the DC capacitors' voltage has been analyzed based on then static mathematical model of DC capacitors of cascaded STATCOM. And traditional pulse rotation control method can make capacitors' voltage balance in the premise of no change of reactive current's THD

[15] This paper presents an analysis of how the switching frequency affects the capacitor voltages, circulating currents, and alternating voltages using phase-shifted carrier modulation. It is found that switching frequencies that are integer multiples of the fundamental frequency should be avoided as they can cause the capacitor voltages to diverge.

[16] This paper presents a three-phase transformerless cascade pulsewidth-modulation (PWM) static synchronous compensator (STATCOM) intended for installation on industrial and utility power distribution systems. It proposes a control algorithm that devotes itself not only to meeting the demand of reactive power but also to voltage balancing of multiple galvanically isolated and floating dc capacitors. The control algorithm based on a phase-shifted carrier modulation strategy is prominent in having no restriction on the cascade number.

[17] This paper presents a technology review of voltage-source-converter topologies for industrial medium-voltage drives. In this highly active area, different converter topologies and circuits have found their application in the market. This paper covers the high-power voltage-source inverter and the most used multilevel-inverter topologies, including the neutral-point-clamped, cascaded H-bridge, and flying-capacitor converters. This paper presents the operating principle of each topology and a review of the most relevant modulation methods, focused mainly on those used by industry.

[18] A control scheme for star-connected cascade static synchronous compensators (STATCOMs) operating under unbalanced conditions is proposed. The STATCOM is assumed to be connected to an equivalent three-phase star-connected power supply. By selecting the line-to-neutral voltages of the equivalent power supply, zero average active power in each phase can be obtained under unbalanced compensation currents or unbalanced supply voltages. Furthermore, to implement a separate control for the three-phase dc-link voltages, the average active power in each phase can also be adjusted to a target value determined by the dc-link voltage control loop.

[19] 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.

[20] The paper begins by detailing the development and control of an integrated power bridge, designed with its own digital signal processor and associated control circuitry. Details describing the networked control algorithm and signal protocol needed for synchronizing the multiple power bridges through a dynamically fast data communication network, are then presented to achieve optimum harmonic cancellation and reduced common-mode voltage.

[21] This paper explores the fundamental limitations of the neutral-point voltage balancing problem for different loading conditions of three-level voltage source inverters. A new model in the DQ coordinate frame utilizing current switching functions is developed as a means to investigate theoretical limitations and to offer a more intuitive insight into the problem. The low-frequency ripple of the neutral point caused by certain loading conditions is reported and quantified.

[22] This paper presents the most important topologies like diode-clamped inverter (neutral-point clamped), capacitor-clamped (flying capacitor), and cascaded multi cell with

separate DC sources. Emerging topologies like asymmetric hybrid cells and soft-switched multilevel inverters are also discussed. This paper also presents the most relevant control and modulation methods developed for this family of converters: multilevel sinusoidal pulsewidth modulation, multilevel selective harmonic elimination, and space-vector modulation.

[23] This paper presents the simulation design and implementation of 3D space vector modulation (SVM) for multilevel converters. The algorithm easily calculates the appropriate switching sequence and switching frequency of power devices. All simulations are performed using Matlab-Simulink® Power System Blockset.

[24] This paper introduces a general space-vector modulation algorithm for n-level three-phase converters. The algorithm is computationally extremely efficient and is independent of the number of converter levels. At the same time, it provides good insight into the operation of multilevel converters.

[25] This paper presents a similar equivalence between the phase disposition (PD) carrier and space vector modulation strategies applied to diode clamped, cascaded N-level or hybrid multilevel inverters. By analysis of the time integral trajectory of the converter voltage, the paper shows that the optimal harmonic profile for a space vector modulator occurs when the two middle space vectors are centered in each switching cycle. The required zero sequence offset to achieve this centring for an equivalent carrier based modulator is then determined. The results can be applied to any multilevel converter topology without differentiation

[26] This paper demonstrates that pulse-width modulation (PWM) based on space vector modulation (SVM), and using low switching frequencies (a few hundred Hertz) can be implemented in multimodule power converter systems. The proposed scheme is based on a delayed sampling technique and allows output voltage control and minimization of harmonic components. Pattern generation options are analyzed and system waveforms are presented for different switching frequencies and number of modules. Results are validated by simulation and confirmed by experiments on a 5-kVA prototype unit.

[27] This paper proposes a feed-forward space vector modulation method for a single-phase multilevel cascade converter. Using this modulation technique, the modulated output voltage of the power converter always generates the reference determined by the controller, even in worst case voltage unbalance conditions. In addition, the possibility of optimizing the DC voltage ratio between the H-bridges of the power converter is introduced. Experimental results from a 5-kVA prototype are presented in order to validate the proposed modulation technique.

[29] The aim of this paper is to group and review these recent contributions, in order to establish the current state of the art and trends of the technology, to provide readers with a comprehensive and insightful review of where multilevel converter technology stands and is heading. This paper first presents a brief overview of well-established multilevel converters strongly oriented to their current state in industrial applications to then center the discussion on the new converters that have made their way into the industry.

[30] A novel multi-pulse optimal PWIM technique for STATCOM based on cascade H-bridge inverters is proposed. The harmonics are suppressed using optimization techniques. Furthermore the fundamental output voltages of all the inverter cells are controlled to be equal to make all the inverter cells equally share the exchanged power with power system, which is to maintain the dc voltages as balance as possible. At the same time the switching-pattern swapping technique is used, and the dc voltages can be fairly balanced.

[31] This work presents an analysis of four topologies of Phase Locked Loop-PLL, applied in wind power inverters. The SRF-PLL, DDSRF-PLL, DSOGI-PLL and a MATLAB/Simulink PLL model are compared when there are harmonics in the point of common coupling (PCC). The simulations represent a wind farm with one synchronous generator of 1.5 MW using full converters. The results show that the harmonic produced by the wind farm depends on the PLL model used.

[32] Various multicarrier pulse width modulation (PWM) techniques suitable for high power converter structures and capable of generating multilevel output voltage waveforms are discussed in this paper. Several interesting characteristics of the multicarrier disposition PWM techniques are revealed. A hybrid multicarrier PWM technique combining the disposition and the phase shifted concepts is considered. The performance of the various techniques with respect to the total harmonic distortion (THD) of the output line voltage in the linear and over-modulation regions is reported.

[33] In this paper, an indirect current control method is proposed for cascaded H-bridge-based multilevel converter to operate as a STATCOM. As the indirect control approach does not need any current sensor, the system reliability increases. Using the proposed control strategy, dc link voltages are balanced, although the H-bridge cells have different amounts of losses. The reactive power is also equally distributed between the cells, independent of the active power distribution. The proposed STATCOM can be connected directly to a 3.3 kV distribution network, and work as a distribution network

STATCOM (D-STATCOM), eliminating the bulky and heavy coupling transformer

[34] In this paper a new control method for voltage balancing of distinct DC buses in cascaded H-bridge rectifier has been proposed. The voltage balancing will be guaranteed even if the load values aren't equal. This structure with the proposed control method is applicable for arbitrary number of series H-bridges, different voltage levels, and different power levels. For reducing current harmonics and distortion, the input current is programmed to be in sinusoidal form and in phase with the input voltage. Besides, it is possible to change the phase angle between input current and input voltage to transfer active or reactive power between load and mains.

[35] A new transformerless four-leg topology is suggested for shunt compensation, the modular multilevel converters (MMC) based on the half-bridge converters, to achieve higher performance as a STATCOM in a distorted and unbalanced medium-voltage large-current (MV-LC) system. Further, an extended MMC (EMMC) is proposed in order to manage more accurate compensation for high-power applications. Both proposals can be controlled for various purposes such as reactive power and unbalance compensation, voltage regulation, and harmonic cancellation.

3. CONCLUSION

Multicarrier phase-shifted sinusoidal pulse-width modulation can be used for modulation purpose, since it is naturally the best option for CHB converter. In this way, low-order harmonics are eliminated from the line side current and the current THD is below 5%, which satisfies IEEE-519 standard. A phase shifted PWM technique may have following advantages:

(1) the algorithm is based on single H-Bridge space vector modulation, and it makes implementation more easier compared with the conventional multilevel SVPWM schemes, and can be easily extended to *n*-level converters, without extra computational difficulty and complexity;

(2) high performance of output voltage and current can be achieved with low switching frequency of each cell, and it is suitable for utility applications.

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