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Analysis of star and delta connected modular multilevel cascaded converter-based STATCOM for load unbalanced compensation

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ABSTRACT

This paper compares the operating capabilities of STATCOMs based on Modular Multilevel Cascaded Converters (MMCC) using star and delta connections, with special attention to unbalanced load compensation. Zero sequence voltage for star connection, and zero sequence current for delta, need to be applied to overcome the phase cluster DC-voltage unbalance. Expressions are derived for both zero sequence elements as functions of the degree of load unbalance defined as the ratio of negative to positive sequence load current. They show that the zero sequence voltage in star connection reaches a very high level as the degree of load unbalance increases, making the MMCC DC-link voltage too high for correct functioning. However the delta connected MMCC can cope with the high level of load current unbalance. Experimental results are presented to validate this analysis.

1. Introduction

The Voltage Source Converter (VSC) based-Static Synchronous Compensator (STATCOM) is now an established and highly effective device for voltage control and reactive power compensation in power networks [1–3]. Compared to its predecessors, such as the thyristor-controlled SVC, the STATCOM has the advantages of fast response, high flexibility and low harmonic injection to the grid. With continuing changes in power systems, notably electricity market deregulation, increasing interconnection and wider use of the less predictable renewable energy sources, the need for development of STATCOMs and other FACTS devices, such as Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), becomes ever more pressing. Important aspects are the selection of installation locations, the selection and optimal parameter tuning for STATCOM and other FACTS devices, to deliver high performance control of voltage and power and damp out disturbances during transient states [4–6]. On the other hand, worldwide interest has been drawn to Modular Multi-level Cascaded Converters (MMCC) as possible next-generation inverters for STATCOMs and many other applications [7–9] in medium and high voltage (11 kV up to 200 kV) power systems. The commonly accepted MMCC uses single-phase H-bridge VSCs as fundamental building blocks which are serially stacked to form a phase limb. The three-phase limbs of an MMCC may be in either star or delta connection, hence being classified as Single-Star Bridge Converter MMCC (SSBC-MMCC) and Single-Delta Bridge Converter MMCC [10–12].

With proper control, STATCOMs can be equally capable for unbalanced load mitigation. Typical causes of unbalance are large single-phase loads such as traction drives, arc furnaces, adjustable speed drives and switch-mode power supplies. Renewable energy sources frequently appear as unbalanced generators, rather than loads.

Such loads cause unbalanced line voltage drops, and hence unbalanced network voltages at the point of common coupling. All loads connected to the affected points would be supplied with distorted unbalanced voltages, causing undesired effects of equipment malfunction, resonance and even damage, and low power factor and increased line losses and harmonics in power systems. When using a STATCOM to compensate the unbalanced load current, it should identify and then actively supply the required negative-sequence component of the load current, thus rebalancing the currents at the point of common coupling (PCC). The STATCOM converters used for this application are typically two-level H-bridge types with step-up transformers, [13,14] while classical multilevel converters, such as Neutral Point Clamped

Abbreviations: STATCOM, Static Synchronous Compensator; MMCC, Modular Multilevel Cascaded Converter; SSBC, Single Star Bridge Converter; SDBC, Single Delta Bridge Converter; VSC, Voltage Source Converter; NPC, Neutral Point Clamped; 2L-HB, Two-level H-Bridge; 3L-FCC, Three-level Flying Capacitor Converter; PCC, Point of Common Coupling.

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Nomenclature

List of Symbols and Abbreviations

v_o, i_o	zero sequence voltage and current
k_{ir}	degree of Load unbalance, I_n/I_p
I_p, I_n	positive and negative sequence currents
φ_{ip}, φ_{in}	positive and negative sequence current phase angles
V_p	Supply side phase voltage
φ_{vp}	Voltage phase angle
I_{d_ref}	reference converter positive sequence active current
V_{DC_avg}	average value of three phase sub-module capacitor voltages
V_{DC_i}	average value of phase sub-module capacitor voltages, where *i = a, b, c or ab, bc, ca*
n_{mp}	number of sub-modules per phase
K_{p_dc}, K_{i_dc}	Active Current proportional and integral controller gains
K_{p_i}, K_{i_i}	cluster voltage balancing proportional and integral controller gains per phases
V_S	Maximum Supply side voltage
V_{DC}	nominal sub-module capacitor voltage
i_s	supply side current
v_{ci}	converter cluster reference voltages where *i = a, b, c or ab, bc, ca*
i_{ci}	converter cluster currents where *i = a, b, c or ab, bc, ca*

(NPC) types, have also been applied [15]. Recently both SSBC-MMCC and SDBC-MMCC-based STATCOMs have been investigated for use in unbalanced current compensation [16–21], though these treatments are all for unbalance caused by PV power generation. Benefits of MMCC-based STATCOMs over conventional topologies are modularity and hence scalability, using their modular nature to extend to any voltage level required without step-up transformers [19–21], and good output voltage waveform quality at low switching frequencies. The switching and clamping devices in an MMCC can be rated at modular level, enabling it to use devices rated at lower powers and withstanding lower voltage stresses. However when an MMCC-based STATCOM operates under unbalanced loading it faces the challenge of DC-link voltage imbalance. This is caused by non-zero active power flowing between the converter phase limbs. Where the STATCOMs of two-level or classical multilevel converters can have three phase limbs sharing a common dc-link, for MMCCs the stacked H-bridge modules have their respective DC-capacitors isolated from each other, so no active power exchange between phases is possible. Consequently DC-link voltages may drift away from their desired levels, resulting in STATCOM malfunction and excessive device stress or damage. Various methods for addressing this problem have been investigated [16,22,23]; one approach for SSBC MMCC is to inject a sinusoidal zero-sequence voltage to balance the power between phase clusters[23,24]. This, however, restricts the STATCOM's capability in load unbalance compensation since the total DC-link capacitor voltage available in each phase cluster is reduced. Other approaches being proposed for extending the compensation level are in the context of using MMCCs for grid-connected PV systems[25–28] where the idea is to inject a non-sinusoidal zero sequence voltage with harmonic contents across each cluster. In the case of the SDBC MMCC, the proposed approach has been to inject a zero sequence current [15,20]. In [29], the authors gave a detailed analysis on the limitations of various methods for both the SSBC and SDBC MMCCs, assuming applications requiring active power injection into the grid system and not yet treating reactive power and unbalanced load compensation. Authors in [23] illustrated the relationship between the cluster voltage references and the degree of current imbalance but not specifying the operating range of the SSBC inverter for unbalanced load compensation.

This paper investigates the MMCC STATCOM for both reactive power and unbalanced current compensations. A new result from the work is the detailed derivation of explicit expressions for the zero sequence voltage as a function of the degree of load current imbalance for the SSBC converter, and for zero sequence current as a function of load current imbalance for the SDBC. These equations will enable the quantifications of the converter ratings required or compensating a given degree of load unbalance. The analysis will give the operation range limits of both types of MMCC-STATCOMs when operating under unbalanced loading and while performing voltage and power factor regulation.

The paper is structured as follows. Section 2 presents the circuit configurations of the SSBC and SDBC MMCC when the building blocks are either two-level H-bridge or three-level full-bridge flying capacitor converters (3L-FCC). Section 3 presents the problems of unbalanced voltage caused by non-zero active power for both types of STATCOM when compensating an unbalanced load. Subsequently their individual control schemes are discussed in Section 4. In Section 5, the operating ranges of both SSBC and SDBC are analysed. To validate this analysis, experimental results are discussed in Section 6.

2. Circuit configurations of MMCC–based STATCOMS

An MMCC-based STATCOM may be in either star (SSBC) or delta connections (SDBC) as illustrated in Fig. 1(a) and (b) respectively. For SSBC the neutral points of the supply and converter sides are not connected together. The basic cells in the phase clusters can be either two level H-bridge (2L-HB) or three level flying capacitor cells (3L-FCC). Both topologies, outlined below, have been used for STATCOM applications [10,11].

3. Analysis of inter cluster DC-voltage imbalance

For both SSBC and SDBC MMCC-based STATCOMs, irrespective of their cell topology, when they are used for unbalanced load compensation, the problems of DC voltage imbalance between the three phase clusters (*inter-cluster*) occurs. This is due to the compensating negative sequence current generating a non-zero active power inside the converter clusters thus resulting in sub-module DC capacitor voltages to be unbalance. This imbalance can be analysed for both converter configurations as follows.

3.1. The SSBC MMCC-based STATCOM

The phase voltages at the point of common coupling (PCC) having magnitude V_P and phase angle φ_{VP} can be written as:

$$v_a = V_p e^{j\varphi_{VP}},\ v_b = V_p e^{j\left(\varphi_{VP}-\frac{2\pi}{3}\right)},\ v_c = V_p e^{j\left(\varphi_{VP}+\frac{2\pi}{3}\right)} \quad (1)$$

For unbalanced load compensation the STATCOM reference phase currents comprise a positive and negative sequence components, I_P and I_n, given as:

$$\begin{aligned} i^*_{ra} &= I_p e^{j\varphi_{ip}} + I_n e^{j\varphi_{in}} \\ i^*_{rb} &= I_p e^{j\left(\varphi_{ip}-\frac{2\pi}{3}\right)} + I_n e^{j\left(\varphi_{in}+\frac{2\pi}{3}\right)} \\ i^*_{rc} &= I_p e^{j\left(\varphi_{ip}+\frac{2\pi}{3}\right)} + I_n e^{j\left(\varphi_{in}-\frac{2\pi}{3}\right)} \end{aligned} \quad (2)$$