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A 43-Level 33 kV 3-Phase Modular Multilevel Cascaded Converter for Direct Grid Integration of Renewable Generation Systems

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Abstract—This paper proposed a 43-level 3-phase 33 kV modular multilevel cascaded (MMC) converter for direct grid integration of renewable generation systems. A high-frequency magnetic-link is considered to generate isolated and balanced multiple dc sources for all of the H-bridge inverters of the MMC converter. The proposed converter is designed and analyzed taking into account the specified system performance, control complexity, cost and market availability of the semiconductors. The simulation results demonstrate the excellent feature of the proposed medium-voltage converter. It is expected that the proposed new technology will have great potential for future renewable power plants and smart grid applications.

Index Terms—Modular multilevel cascaded converter, medium-voltage, photovoltaic power plants, grid integration.

I. INTRODUCTION

Different power electronic converters have been developed using conventional topologies to fulfill the requirements of renewable generation systems [1], [2]. However, it is hard to connect the traditional converters to the grids directly, as the distortion in generated output voltages is high and a single switch cannot stand the grid voltage level. Many power semiconductor vendors such as Semikron, ASEA Brown Boveri (ABB), IXYS, Siemens and Mitsubishi Electric produce devices specially designed for the diode rectifier based converter and back-to-back converter for wind turbine generator systems. All of the devices are in a pack, which reduces the cost and complexity of the power conditioning system. Semikron developed compact modules SKS660FB6U+E1C+B6CI250V06 and IGDD6-4-426-D3816-E1F2-BL-FA for the diode rectifier based power conditioning systems. According to the internal circuit configuration, the

module SKS660FB6U+E1C+B6CI250V06 is suitable for permanent magnet synchronous generator (PMSG)-based wind turbine generator systems and IGDD6-4-426-D386-E1F2-BL-FA is suitable for wound rotor synchronous generator (WRSG)-based wind turbine generator systems. Mitsubishi Electric developed the module CM00MXA-24S with this converter topology which can be used for both the WRSG and PMSG-based wind turbine generator systems. Semikron also developed the module SKSC120GDD69/11-A3AWAB1B for power conditioning of synchronous and doubly-fed generator-based wind power systems.

ABB central inverters are especially designed for medium scale photovoltaic (PV) power plants. The PVS800 version is a 3-phase inverter with a power capacity in the range of 100–500 kW. The transformer steps-up the inverter output voltage from 300 V ac to grid voltage level (e.g., 6–36 kV). Siemens developed the SINVERT PVS inverter for medium scale PV power plants. The ac output voltage and power capacity of the PVS version inverters are in the range of 288–370 V and 500–630 kW, respectively.

With these converters, the conventional renewable generation systems possessing the power-frequency (i.e., 50 or 60 Hz) step-up transformer and the line filter and booster not only increase the size, weight and loss but also increase the cost and complexity of the system operation [1]. Today, the industrial trend is to move away from these heavy and large size passive components to power electronic systems that use more and more semiconductor elements controlled by a digital circuit. In such a way, smart operation is ensured. In comparison with conventional two level converters, multilevel converters present lower switching losses, lower voltage stress on switching devices, and better total harmonic

distortion (THD) [3]–[7]. These remarkable features enable the connection of renewable energy systems directly to the grid without using large, heavy and costly power transformers and also minimize the input and output filter requirements [8]–[14]. Although several multilevel converter topologies have been used in low voltage applications, most of the topologies are not suitable in medium voltage applications. Because of some special features (e.g., the number of components scale linearly with the number of levels and individual modules are identical and completely modular in construction hence enabling high level attainability), the modular multilevel cascaded (MMC) converter topology can be considered as the best possible candidate for medium-voltage applications [15], [16]. The high number of levels means that medium-voltage attainability is possible to connect the renewable generation units to the medium-voltage grid directly and it is also possible to improve the output power quality. The component number and control complexity increase linearly with the increase in the number of levels [1], [17]. Fig. 1 plots the component number and complexity of different level converters.

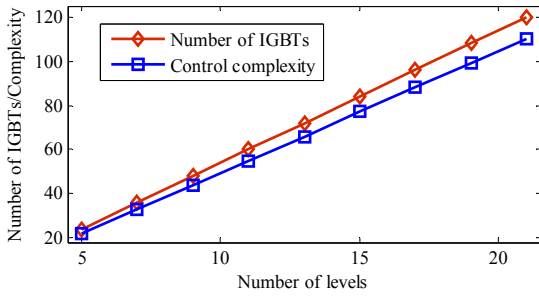


Fig. 1. Number of IGBTs/Control complexity versus converter level numbers of 11 kV system.

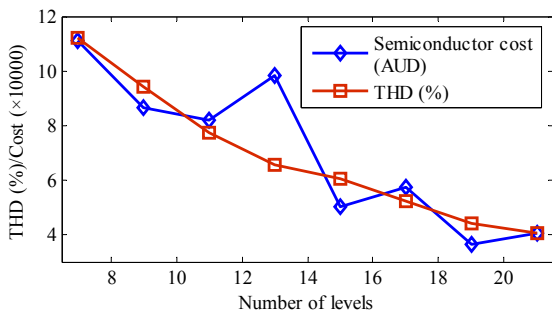


Fig. 2. THD (%) / Semiconductor cost versus converter level numbers of 11 kV system.

On the other hand, the distortion in generated output voltage and semiconductor cost of the converter decrease dramatically with the increase of the converter number of levels. Fig. 2 plots THD (%) and semiconductor cost of

different number of MMC converter levels for an 11 kV system. Due to the unavailability of rated insulated gate bipolar transistors (IGBTs), the 13 and 17 level converters used the IGBTs that are used in the 11 and 15 level converters, respectively. Hence, the semiconductor cost curve is up-and-down in nature. Moreover, lower switching frequency, even fundamental switching frequency, can be used with the high level number converter, which significantly reduces the switching losses of the converter. Therefore, the optimal selection in the number of converter levels is important for the best performance/cost ratio of the medium-voltage converter systems and this is one of the central contentions of this paper [17]. In this paper, a 33 kV system is designed and analyzed taking into account the specified system performance, control complexity, and cost and market availability of the power semiconductors. It is found that the 43-level converters are the optimal choice for the 33 kV systems. The design and analysis of a 33 kV MMC converter system is presented in detail in the following sections.

II. DESIGN OF 43-LEVEL 33 kV MODULAR MULTILEVEL CASCADED CONVERTER

A. Selection of Number of Level of 33 kV converter

Each H-bridge inverter cell commutation voltage of a 13-level converter is about 4044 V. The highest voltage rating of a commercially available IGBT is 6.5 kV, which is recommended for a maximum voltage of 3600 V. Therefore, a 13-level or lower level converter cannot be used to design the 33 kV converter. Each H-bridge inverter cell commutation voltage of a 15-level topology based 33 kV converter is 3467 V which may be supported by the 6.5 kV IGBT. Owing to this, at least 15-level topology is required to design a 33 kV converter. The output power quality of a 55-level inverter is good enough to directly feed into the 33 kV ac grid. The cheap 1.7 kV IGBT can be used to design the 55-level inverter. There are no significant performance improvements or cost reductions with converters of more than 55-levels. Moreover, the control complexity increases with the number of converter levels. Due to these, 15-level to 55-level MMC converter topologies are considered for a 33 kV inverter system.

The arithmetic and logic operations (ALOs) for switching section, THD of output power, and cost of semiconductors are calculated. The number of ALOs is used to compare the complexity of the converters. The THD are calculated through the MATLAB/Simulink environment. Fig. 3 plots the component number and complexity of different level converters for 33 kV system. Fig. 4 plots THD (%) and semiconductor cost of different number of MMC converter levels for a 33 kV system. Normalized index values are

calculated. Fig. 5 plots the normalized total index values of different converters. For the 33 kV converter, the total index value is the lowest at the 43-level, because there is no significant output power quality improvement and semiconductor cost reduction for converters with more than 43 levels. In addition, the component number and control complexity increase linearly with the increase in the number of levels. Therefore, 43-level topology is considered as optimal for 33 kV converter systems.

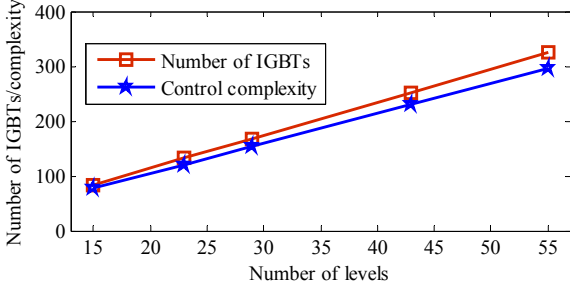


Fig. 3. Number of IGBTs/control complexity versus converter level numbers of 33 kV system.

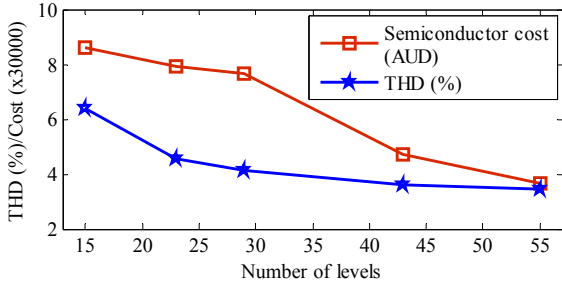


Fig. 4. THD (%)/Semiconductor cost versus converter level numbers of 33 kV system.

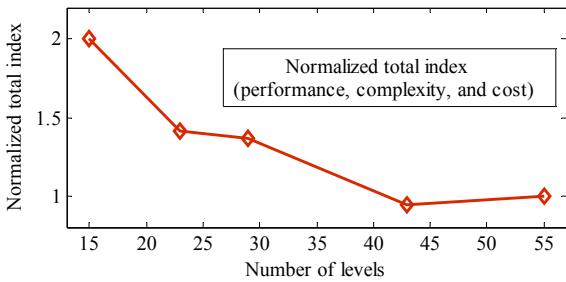


Fig. 5. Normalized total index versus converter level numbers of 33 kV system.

B. Power Circuit of 43-Level 33 kV MMC Converter

Each H-bridge inverter dc-link voltage rating of a 33 kV 43-level converter is 1156 V. The available cheap and mature 2.5 kV IGBT can be used to design the 33 kV 43-level converter, because this IGBT is recommended for 1200 V maximum applications. About 96% device voltage utilization factor (DVUF) can be obtained with the 2.5 kV IGBTs. In

total, 21 H-bridge inverter cells are on each phase-leg and 252 active switching devices are required for the 3-phase 43-level converter. Fig. 6 shows the circuit diagram of 43-level converter.

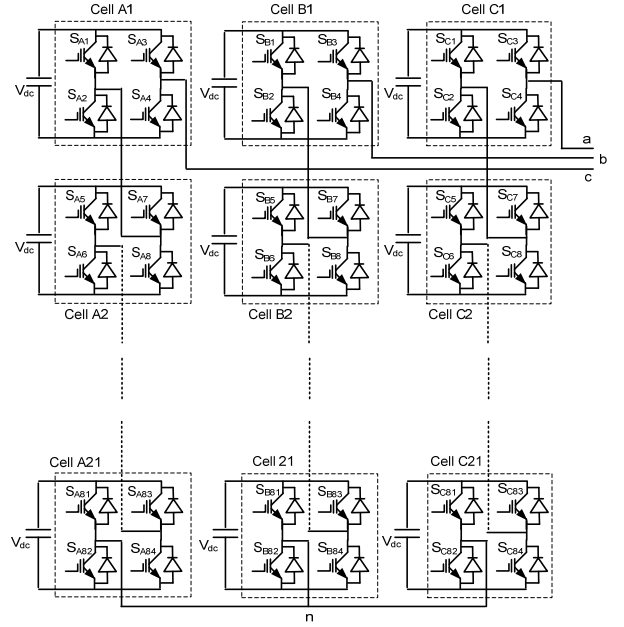


Fig. 6. Circuit diagram of a 43-level MMC converter.

However, the MMC converter requires multiple isolated and balanced dc sources. A high-frequency magnetic-link is considered to generate multiple isolated and balanced dc supplies for all of the H-bridge inverter cells of the MMC converter from a single or multiple renewable source. The grid electrical isolation and voltage imbalance problems are solved through the common high-frequency magnetic-link [18].

C. Switching Circuit of 43-Level MMC Converter

The phase-shifted carriers are specially conceived for FC [19] and MMC [20] converters. Since each FC cell is a two-level converter, and each H-bridge cell is a 3-level inverter, the traditional bipolar (using one carrier signal that is compared to the reference to decide between two different voltage levels, typically the positive and negative busbars of a voltage source converter) and unipolar pulse width modulation (PWM) techniques can be used, respectively. Due to the modularity of these topologies, each cell can be modulated independently using the same reference signal in a phase. If the peak to peak amplitude of the carriers is A_c , the amplitude modulation index can be calculated from

$$m_{ap} = \frac{A_m}{A_c}. \quad (1)$$

Fig. 7 shows the basic block diagram of the phase-shifted switching scheme for a 3-phase 43-level converter. If B_n is

the number of the H-bridge inverter cell or pair on a particular phase leg and m the number of converter levels, the carrier phase-shifting for that particular cell or pair can be calculated from

$$\theta_{ps} = \frac{360^\circ (B_n - 1)}{(m - 1)}. \quad (2)$$

Each compare unit generates one switching signal for the top switching device of a half-bridge cell or a pair. The inverted form of this switching signal drives the bottom switching device. For the left half-bridge cell, one is asserted when the reference signal value is greater than or equal to the carrier signal value, and the other is asserted when the reference signal value is less than the carrier signal value. For the right half-bridge cell, one is asserted when the inverted carrier signal value is greater than or equal to the reference signal value, and the other is asserted when the inverted carrier signal value is less than the reference signal value. Fig. 8 shows the gate pulse generation technique for the top switching device and the technique to generate gate pulse for the bottom switching device is illustrated in Fig. 9.

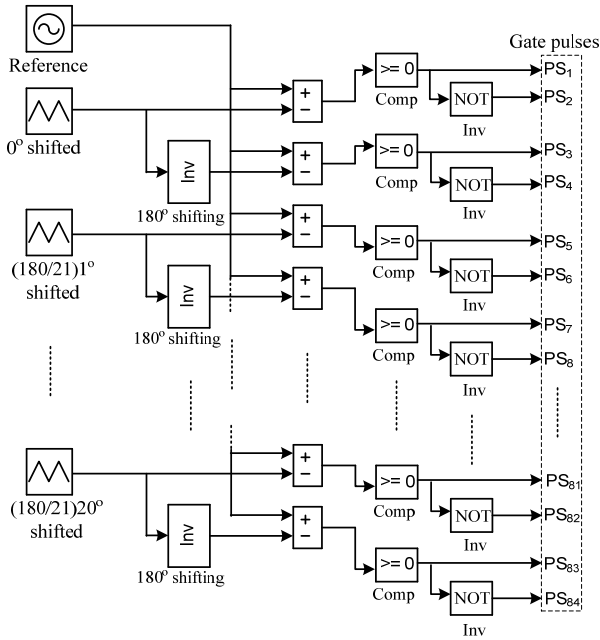


Fig. 7. Switching control scheme of 43-level MMC converter

For the flying capacitor (FC) multilevel converter, the advantage of the even power distribution is that once the flying capacitors are properly charged (initialized to their corresponding values) no imbalance will be produced due to the self balancing property of this topology [21], [22] and as a result there is no need to control the dc-link voltages. Another interesting feature is that the total output voltage has a switching pattern with k (number of the power cells) times the frequency of the switching pattern of each cell. This

multiplicative effect is produced by the phase shifts of the carriers. Hence, better THD is obtained at the output, using the k time's lower frequency carriers. With the phase-shifted carrier based modulation scheme, the control signal assignment to the appropriate semiconductor of the MMC converter is easy and this remains simple even when the level number increases to higher values.

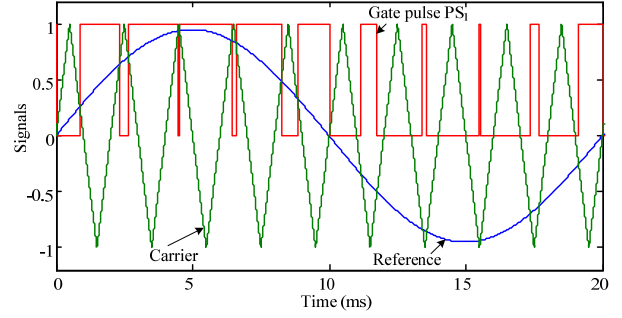


Fig. 8. Generation of gate pulse PS_1 with phase shifted carrier.

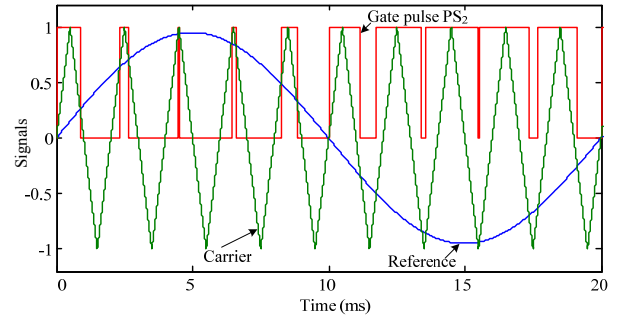


Fig. 9. Generation of gate pulse PS_2 with phase shifted carrier.

III. SIMULATION RESULTS

A total of 231 ALOs are involved with the switching scheme. Although three times more switching devices are used in the 43-level converter, the semiconductor cost is about 41% lower than that of the 15-level converter, due to the cheap cost of low voltage rated devices. The line peak to peak voltage consists of 84 voltage levels and each level contributes 1156 V to the peak to peak line voltage. Due to small step size, the line voltage waveforms are found to be very consistent with the reference sine waveforms. Fig. 10 plots the line voltage waveforms. The output power quality of a 43-level converter is good enough to feed into the grid. The line voltage THD is about 3.61%, which satisfies well the 5% limit by IEEE1547 and IEC61727 standards. The frequency spectrum of line voltage is shown in Fig. 11. Compared with the 15-level converter, the 43-level converter provides 44% better quality output power. As the number of active switching devices has increased three times, the complexity of the

control scheme of a 43-level converter has also increases three times more than that of a 15-level converter.

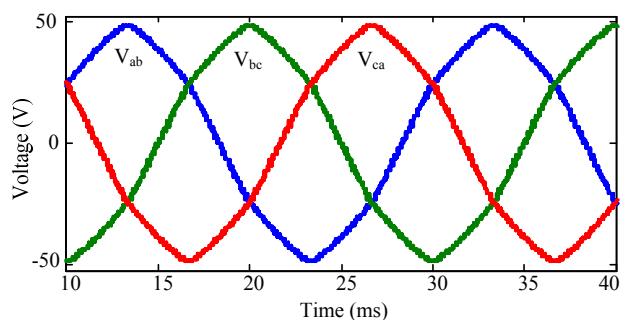


Fig. 10. Line-to-line voltages of 43-level MMC converter.

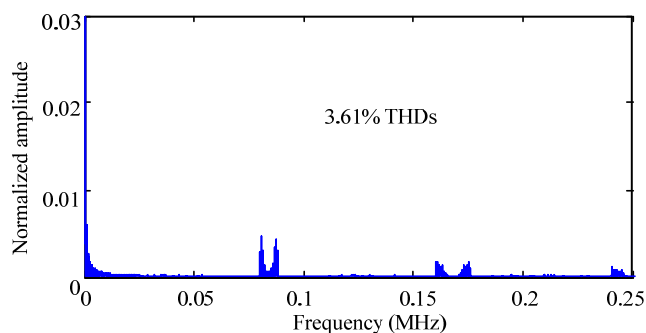


Fig. 11. Line voltage frequency spectrum of 43-level MMC converter.

CONCLUSION

In this paper, the designs of 33 kV converter systems have been analyzed, which helps in selecting the optimal number of levels for a medium-voltage converter. All possible MMC converter topologies have been considered for the 33 kV converter systems. In order to ensure a cost effective design, the DVUFs were calculated and only the selected converters with high DVUF were considered. During the design process, the availability of the semiconductor devices was considered in the first instance. After checking the availability of devices, the converter systems were designed taking into account three main factors: the specified converter output power quality, complexity of the switching controller, and cost of the semiconductors. The investigation has shown that the 43-level topology is the optimal choice for a 33 kV converter system.

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