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High Power Capacitor Clamped Modular Resonant Dc/Dc Converter for Offshore Wind Energy Systems

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ABSTRACT

Recently, the interest in offshore wind farms is powerful resource, has been increased significantly because of the stronger and more stable winds at sea, which will lead to an increase power production. DC/DC power conversion solutions are becoming more popular for fulfilling the growing challenges in the offshore wind power industry. This paper presents several multilevel modular DC/DC conversion systems based on the capacitor-clamped module concept for high power offshore wind energy applications. Two types of the capacitor-clamped modules, the double-switch module and switchless module, are discussed. A soft-switching technique is adopted to achieve minimal switching losses and the maximum system efficiency. Theoretical analysis is carried out for the 2n+1 level cascaded configurations based on the capacitor-clamped modules. The inherent interleaving property of the proposed configurations effectively reduces the output voltage ripple without adding extra components. A cascaded hybrid topology is developed by the combination of double-switch and switchless modules. The experimental results of two 5-kW prototype capacitor-clamped converters are presented to validate the theoretical analysis and principles as well as attest the feasibility of the proposed topologies.

Keywords : Capacitor-clamped module, cascaded configuration, double-switch module, offshore wind energy, soft switching technique, and switchless module.

I. INTRODUCTION

Offshore wind energy systems have emerged as one of the most promising options among the renewable energy resource technologies to satisfy the growing urban and industrial demand. The reasonable economics of offshore wind farms are driving toward the development of larger wind turbines but high installation costs and maintenance difficulties are critical issues for minimizing the operating and maintenance (O&M) costs With increasing distances from the shore, the wind turbine industry faces new challenges, such as long distance electrical transmission on high-voltage submarine cables and the reliability of turbine equipment. Therefore, an optimized design is needed to reduce the size and weight of the components, O&M costs, and power losses of offshore wind turbines.

With the increasing penetration of decentralized offshore wind generation into high voltage power grids, the transmission of electrical energy to the load centers is a major challenge. In this regard, larger wind turbines are leading to increased interest in high power DC/DC converters to boost the turbine output voltage to the high voltage level and to provide efficient transmission over long distances.

High voltage transmission using DC technology allows decreases in power losses and cabling cost necessary for large current flow caused by the relatively low voltage of wind turbines. One of the most important concerns for the converters used in offshore wind farms is their reliability due to the inherent lack of turbine access at sea. Using the modularity, if a single module fails, the converter can still function at a reduced power level. In a modular structure, the total power handling can be allocated equally to multiple modules, allowing the use of cheaper components with low voltage/current stress in the system. Therefore, high power DC/DC conversion systems should be efficient, more compact, and highly reliable due to the more difficult equipment transportation from shore to the installation sites and maintainability of the wind turbines.

In this regard, multiple-module boost converters were proposed to achieve a high voltage conversion ratio for offshore wind energy applications. Never the less, because of the large duty ratio of the main switch to achieve high voltage gain, the switching frequency is limited to reduce losses and obtain sufficient turn-off time for switches. Therefore, increasing the size of the passive components, such as boost inductors and filter capacitors, is inevitable due to the low switching frequency. In a step-up resonant (SR) converter was introduced, in which only one inductor and a single capacitor are used to achieve the high voltage gain and provide a soft-switching technique for the main switches. However, the converter suffers from large power device conduction losses and a high peak-to-peak voltage across the passive components. Switched-capacitor (SC) or capacitor-clamped (CC), DC/DC converters have attracted considerable attention in the field of high power applications owing to their high efficiency, high power density, and control simplicity. A range of topologies and control methods have been proposed and applied in low power applications. In an switched capacitor DC/DC converter with exponential voltage gain for offshore systems was introduced based on the Marx concept. However, large voltage stress of the switches will increase the series connection of power devices, which results in significant conduction loss and complex balancing circuit. Motivated by these challenges, this paper extends the CC module concept and proposes two different CC module structures, the double-switch (DS) module and active switchless (SL) module. Each module provides a high degree of modularity by the combination of two top and bottom cells. The cascaded SL- and DS-based topologies are introduced to achieve a high voltage gain for offshore wind energy systems. The cascaded hybrid approach is evaluated in terms of the power device count, voltage and current stress of the switching devices, and efficiency. The cascade SL- and Double switch based topologies were implemented on two 5-kW prototype converters to confirm their feasibility.

II. DESCRIPTION OF THE GENERATOR/CONVERTER SOLUTION

A. High-Voltage Generator Concept

Generator Insulation Concept: A solution for handling high common mode voltages in an ironless generator has earlier been proposed by the author. The high-voltage generator is based on an axial-flux ironless-stator permanent-magnet synchronous generator (AF-IL-PMSG) design. Its stator is made of several identical segments. Each stator segment is connected to a medium-voltage converter unit, and the phase-to-phase voltage imposed on the segment windings is equal to the converter unit output. Additionally, electrical screens connected to the converter unit dc buses are introduced around each stator segment, switched capacitor(sc). These decouple the isolation levels in the stator segment into one turn-to-turn level and one from the segment screen to ground. The dc insulation outside the screen can withstand a higher field stress than HVAC insulation, which enables a further reduction in the generator insulation thickness. The two main effects of the solution can be summarized as follows.

1) Modularization reduces the line voltages in the windings significantly and, hence, the insulation requirement between coils in the same segment.
2) More of the voltage stress is moved from the ac field to the dc field, which requires thinner insulation. This can be exploited to make a high-voltage compact generator with a higher fill factor since the turn insulation thickness will be decided by the module ac voltage only, and regular machine insulation can be utilized. Hence, it is beneficial to increase the number of levels (modules) the output voltage is divided in, for a given turbine output voltage. An estimate presented to indicated that N = 9 modules yields an acceptable tradeoff between machine size increase and system complexity for a 10 MW wind turbine with 100 kvdc output voltage. Another consequence of the link between stator winding insulation thickness and the dc voltage in a converter unit is that knowledge of the maximum voltage variations a module may experience will allow an insulation thickness optimization. Hence, dc bus voltage control is essential.

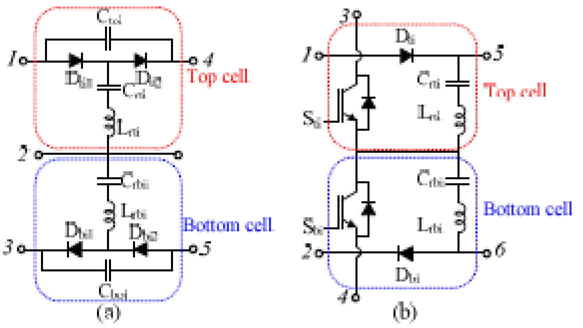


Figure 1. SL based module (b)DS based module

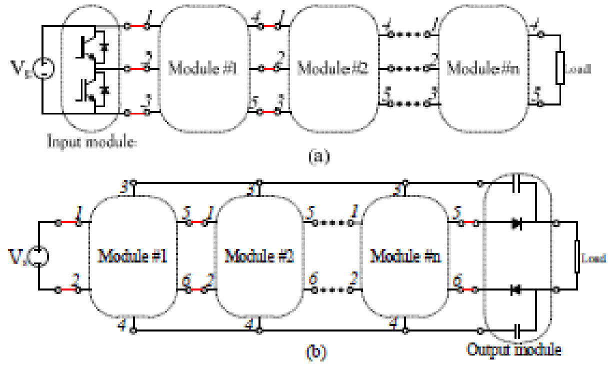


Figure 2. 2n+1 level cascaded configuration (a)SL based module (b)DS based module

B. General Topology

The general configuration with a three-phase generated ac voltage and an ac/dc converter in the front-end of the proposed RSC converter. A large capacitor is assumed to be used for energy storage at the output of the ac/dc converter. The RSC converter consists of two modular cells which use a new arrangement of the solid-state switches, diodes, capacitors, and inductors.

C. Principle of the Proposed RSC Converter Operation

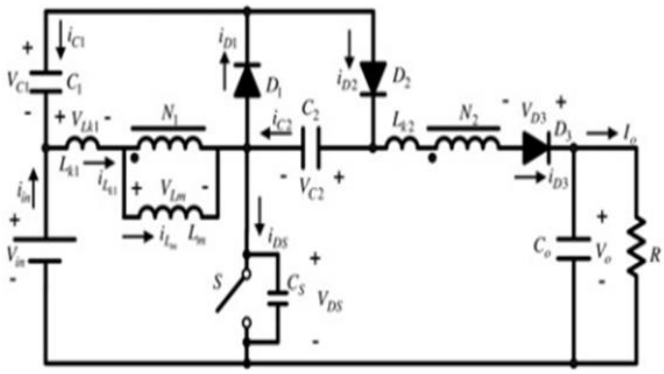
A seven-level RSC converter with two stages. The RSC converter is composed of four resonant capacitors (C_{rt1} , C_{rt2} , C_{rb1} ,and C_{rb2}), two output filter capacitors (C_{to} and C_{bo}), four resonant inductors (L_{rt1} , L_{rt2} , L_{rb1} , and L_{rb2}), two output resonant inductors and , six diodes (D_{t1} , D_{t2} , D_{to} , D_{b1} , D_{b2} , and D_b), and four switches (S_{t1} , S_{t2} , S_{b1} , S_{b2}). In this paper, subscripts "t" and "b" represent the corresponding variables to the circuit components at the top and bottom cells, respectively. The switches (S_{t1} , S_{t2}) (S_{b1} , S_{b2}) are controlled complementarily with a 50% duty cycle to minimize the conduction losses in the power devices and passive components. Here, the following assumptions are made to simplify the analysis:

1) all the switches, diodes, capacitors, and inductors are ideal;
2) all the capacitances are equal and the inductors have the same values;

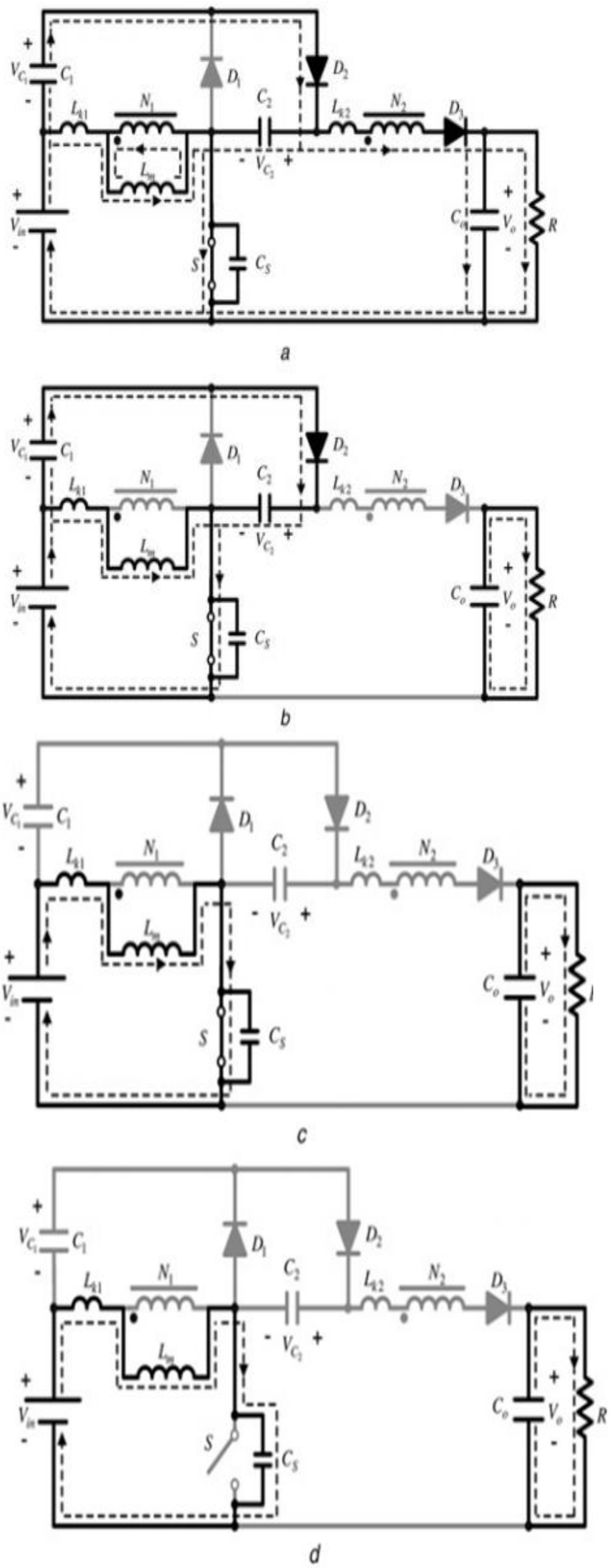
D. High step-up dc/dc converter

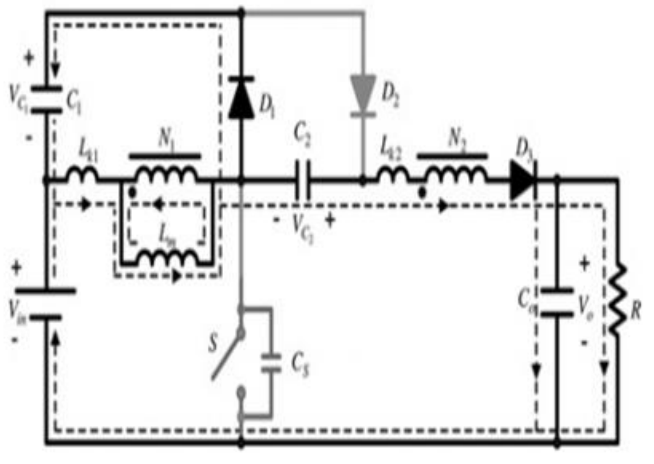
High step-up DC–DC converters are widely used in many applications, such as in high-intensity discharge (HID) lamp ballasts for automobile headlamps, DC back-up energy systems for uninterruptible power supplies. Theoretically, the conventional boost converter can be used for high step-up voltage conversion with a large duty ratio. However, the conversion efficiency and step-up voltage gain of the boost converter are limited under a large duty ratio condition owing to the loss of power switches and rectifier diodes, as well as the equivalent series resistance of inductors and capacitors . A very large duty ratio results in serious reverse-recovery problems and increases the rating of the output diode leading to very low efficiency. Additionally, a power converter operating at a duty ratio of greater than 50% requires a slope compensation in current mode pulse width modulation (PWM) to overcome the instabilities with load disturbances. Therefore a step-up converter with a reasonable duty ratio to achieve high efficiency and high voltage gain performance is very important for high voltage gain applications. Fly back and forward converters generally achieve high step-up voltage gains by adjusting. However, the active switch of this converter produces high voltage spike and poor efficiency because of the leakage inductance. To reduce the voltage spike, the resistor –capacitor –diode (RCD) snubber is adopted to limit the voltage stress on the active switch. However, this approach reduces the efficiency.Hence,non-dissipative snubber have been applied to recycle the leakage inductance energy and to suppress the voltage spike on the active switch. Since the energy regeneration snubber circuit requires additional components, it has an increased cost. Many boost converters have been presented to improve the conversion efficiency and raise the step-up voltage gain.

Various high step-up converters with low current ripple using the coupled inductor have been developed. However, leakage inductance issues relating to voltage spike and efficiency remain significant. proposed a very simple topology for a high efficiency DC– DC converter with a high step-up voltage gain. An integrated boost-fly back converter based on a coupled inductor has been presented. The energy stored in the leakage inductance is recycled into the output during the switch-off period, increasing the efficiency and limiting the voltage spike. Several counterpart converters have been proposed based on this converter integration and output stacking concept. presented a high step-up DC– DC converter with integrated coupled inductor and common-mode electromagnetic interference reduction filter. All developed a sepic-flyback converter with a coupled inductor and output voltage stacking. Introduced a high step-up gain converter that uses coupled inductor and voltage-double technique on output stacking to achieve high voltage gain. proposed a high step-up gain boost converter that utilizes multiple coupled inductors for output voltage stacking. Moreover, a simple and effective converter has been presented for high step-up voltage gain. Presented a switching converter, which recycles the leakage inductor energy stored to increase the conversion efficiency and suppress the switch voltage stress. Also, the converter alleviates the problem of the reverse-recovery time on the output diode. However, since most of the energy is stored in the coupled inductor, a large magnetic core is required for the demand of high output power application. switching mode of operation.



High step-up application of proposed converter systems. capacitor energy stored in them leakage inductance. Higher efficiency. For capacitor clamped module and double switch modeled considered of this systems. Two capacitors are turned on and diode is them reverse bias of this d1 and d2.Number of turns are available in them N1,N2.Effective converter has been presented for a high step-up application are proposed systems.





Current flow path of the operating modes

a) Mode 1
b) Mode 2
c) Mode 3
d) Mode 4
e) Mode 5, 6

III. CONCLUSION

High voltage step-up DC/DC conversion systems are the key-enabling components for offshore wind energy systems to interface with high voltage transmission networks. In this paper, two CC modules are introduced: the SL- and DS-based modules. The inherent interleaving property of the proposed modules effectively reduces the output voltage ripple without adding extra components. The cascaded SL- and DS-based topologies are introduced to achieve the high voltage gains at high efficiency in offshore wind applications. These results show that it is possible to develop a cascaded hybrid topology. By a combination of the SL- and DS-based modules. Conceptual comparisons of the cascaded hybrid topology with other high voltage DC/DC approaches show that the proposed converter is well suited for high power offshore systems that require a high efficiency and reliability. The test results have highlighted the performance and feasibility of the proposed topologies.

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