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High-Gain Resonant Switched-Capacitor Cell-Based DC/DC Converter for Offshore Wind Energy Systems

Mr .K.Manoj Reddy & Ms.K.Lakshmi
1 PG Student, Dept. Of Power Electronics , SKR College Of Engineering & Technology, AP.
2 Asst. Professor, Dept. Of Power Electronics, SKR College Of Engineering & Technology, AP.

Abstract: *Recently, the interest in offshore wind farms has been increased significantly because of the stronger and more stable winds at sea, which will lead to a higher 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: High-Power Density, High-Voltage Gain, Offshore Wind Energy, Resonant Switched-Capacitor (RSC) Converter, Resonant Switching Transitions.

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 demands. 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. Nevertheless, 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 SC 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 Dsbased topologies were implemented on two 5-kW prototype converters to confirm their feasibility.

II. EXISTING AND PROPOSED SYSTEMS A. Existing System

High voltage dc (HVDC) transmission promises a very flexible and efficient technology for offshore wind farms that requires power conversion systems to step-up and control the wind turbine output. A conventional HVDC system uses an ac line frequency (50/60 Hz) transformer to boost the voltage and ac/dc converters for rectification and power flow control. This technology is robust and reliable, but it causes a considerable increase in weight and volume, which leads to higher installation cost. A high-power density can be obtained by replacing the bulky 50/60-Hz transformers with high-frequency transformers. Unfortunately, high-frequency transformers with large turn ratios are difficult to design at high voltages and mega power levels because of the enormous expense of the magnetic material, core, and dialectic losses. One of the key-enabling components for HVDC is the high power dc/dc conversion system because it has a rigid structure, is easy to control system and more compact

B. Proposed System

The paper presents a new high-gain RSC dc/dc converter for offshore wind energy systems. The proposed converter combines the output of two modular cells to reduce the device count, output capacitance requirements, and total capacitor power rating. The principle of a soft-switching operation and output voltage analysis of the proposed converter are described in detail. The output capacitors are charged and discharged continuously by an 180◦ phase shift with respect to each other to eliminate the output voltage ripples without adding extra components. In this paper, the series-modular and cascade RSC configurations are introduced to increase the reliability and reduce the control complexity. These configurations are verified by a simulation and their efficiency, volume, weight, and device count are compared with a counterpart to highlight its advantages for high voltage and high power offshore winds applications. A comprehensive collection of the experiments are carried out to evaluate the feasibility of the proposed converter.

III.PROPOSED MODULAR RESONANT CAPACITOR-

CLAMPED (MRCC) CONFIGURATIONS A. Module Structure

Fig1(a) presents a SL-based module, where a five-port system consists of two top and bottom cells. Each cell includes two capacitors, one inductor, and two diodes. The DS-based module is depicted in Fig. 1(b), which is a six-port system with two cells in the top and bottom of the module. Each cell of the DS-based module is composed of a single active switch, one diode, one inductor, and one capacitor. Fig. 2 shows the 2n+1 level cascaded configurations of the Sland DS-based modules. For the cascaded SL-based circuit, an input module is connected to module #1, as shown in Fig. 2

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(a). For the cascaded DS-based topology, ports 5 and 6 of module #n are connected to an output module that consists of two capacitors and two diodes (see Fig. 2(b)).

B. Operating Principles of the MRCC Voltage Tripler Converter

To understand the operational principle, the MRCC voltage tripler converter is selected as the topology under analysis. The MRCC converter consists of an SL-based module indicated by a red-colored box and an input module, as shown in Fig. 3(a). The MRCC voltage tripler can also be realized with a Dsbased module represented by a blue-colored box and an output module (see Fig. 3(b)). Therefore, both SL-and Dsbased configurations have the same circuit for the voltage tripler converter. To simplify the analysis, the following assumptions are made:

Fig.1. Structure of module #i. (a) SL-based module. (b) DS-based module.

- All the switches, diodes, capacitors, and inductors are ideal;
- The output capacitors, Cto1 and Cbo1, are large enough to be considered as voltage sources;
- The resonant capacitors, Crt1 and Crb1, have identical values;
- Vs is an ideal DC voltage source and the load is modeled by a pure resistor (Rload); and
- The switching frequency is less than the resonant frequency to achieve a zero-current switching (ZCS).
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4.Simulation Results

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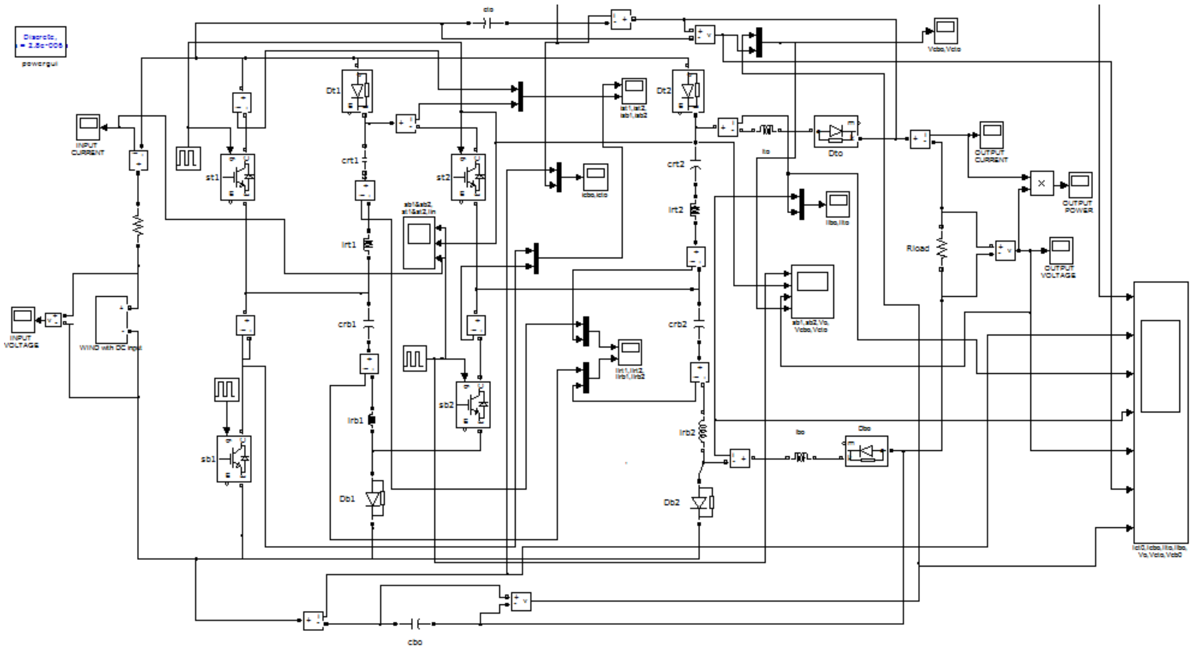

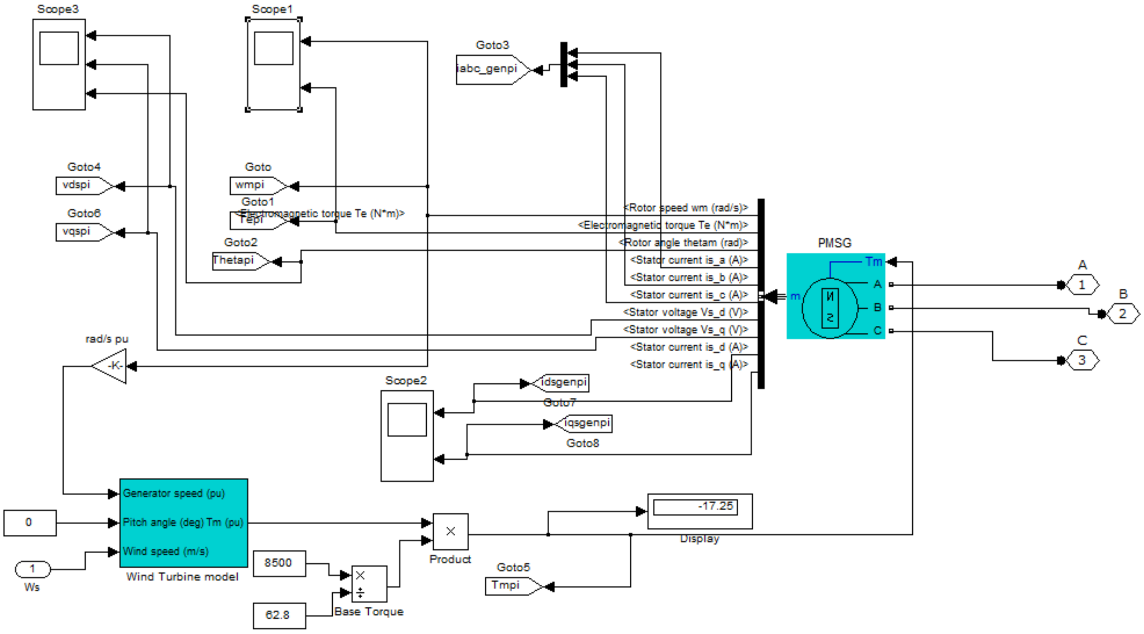

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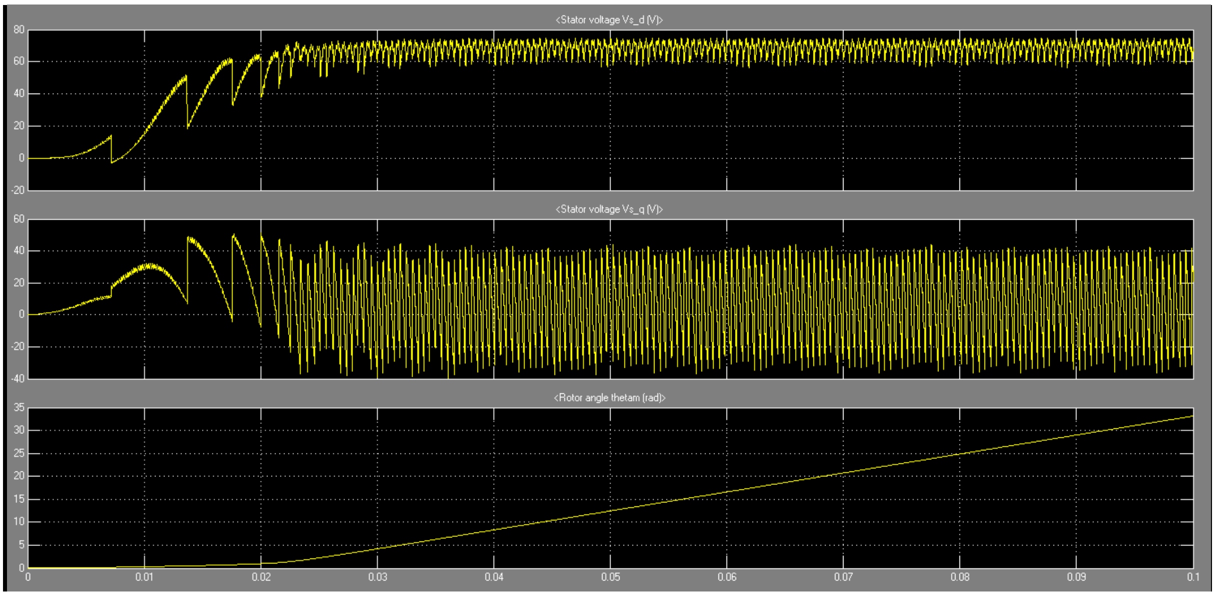

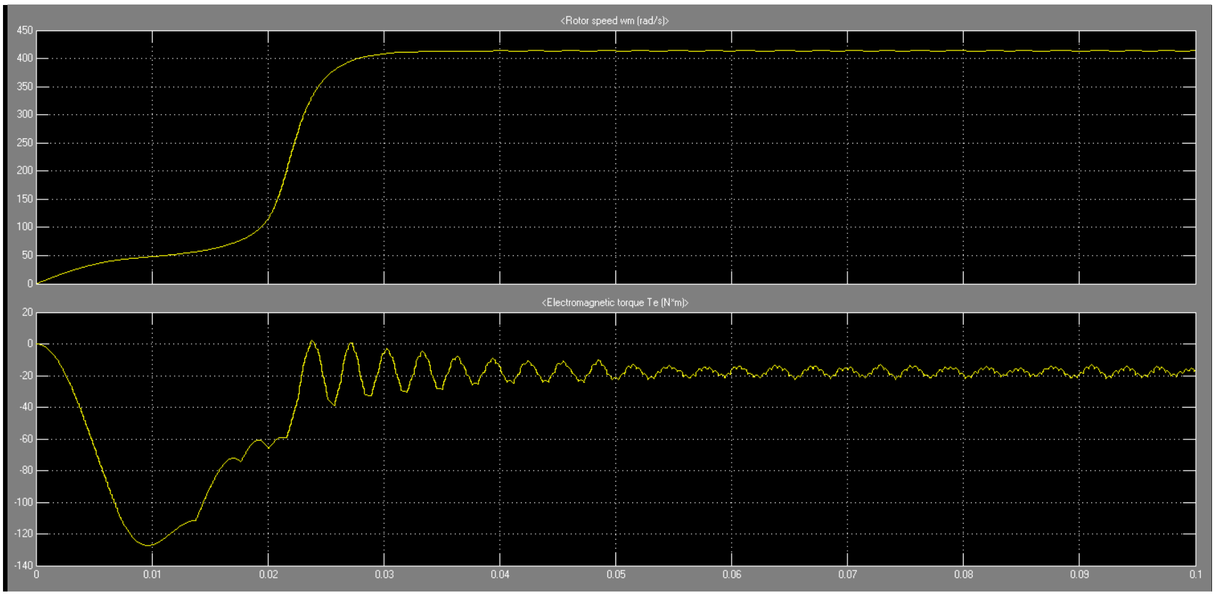

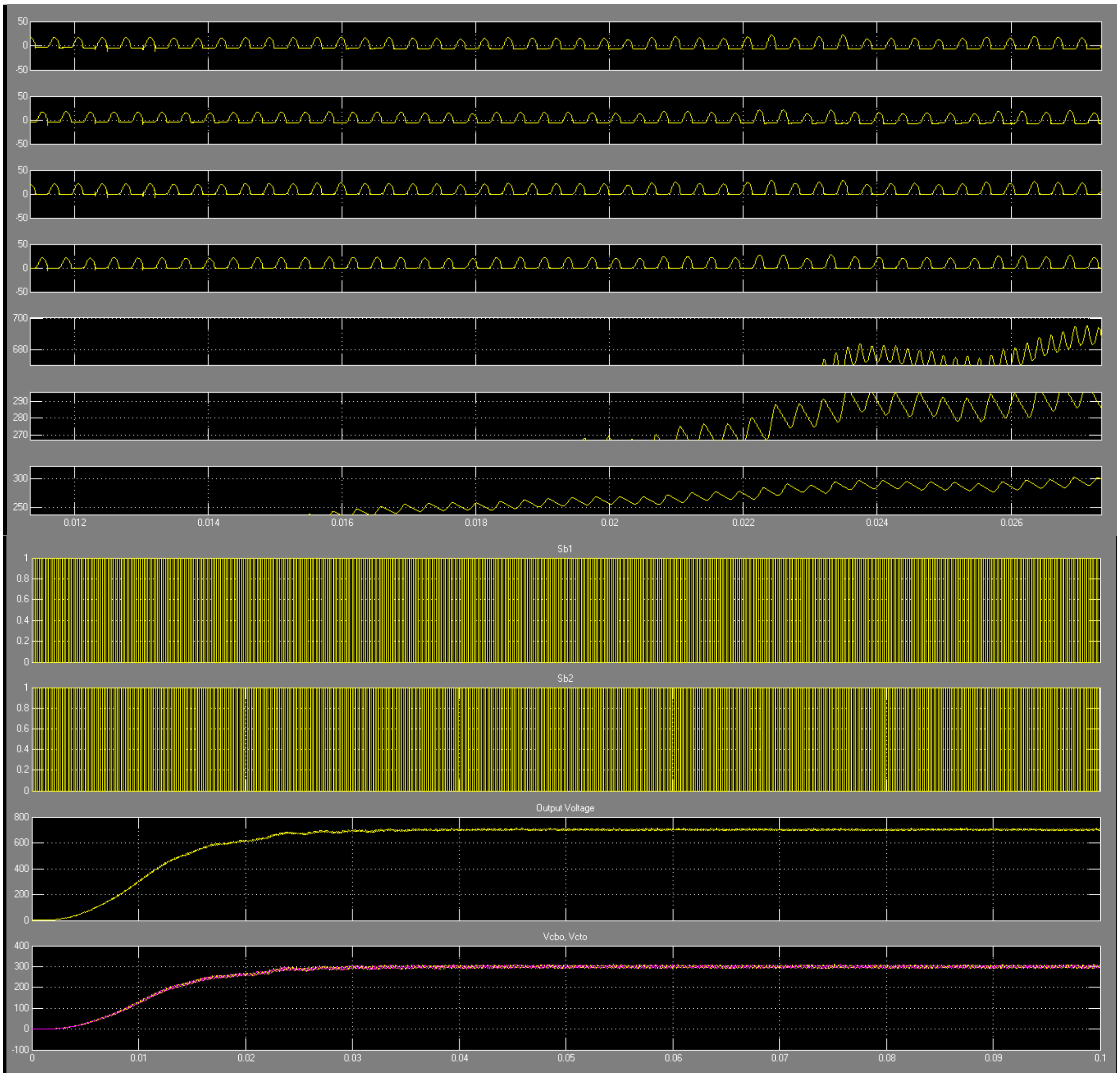

5.Conclusion

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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Author's Profiles

Mr. K.MANOJ REDDY received Btech in Electrical and Electronics Engineering from Sri raghavendra institute of science and Technology, Vinjamur (M), Nellore affiliated to the Jawaharlal Nehru technological university Anantapur in 2014, and pursing M. Tech in Power Electronics from SKR College of Engineering and Technology ,Konduru satram(v), Manubolu (M),affiliated to the Jawaharlal Nehru technological university Anantapur in 2017, respectively.

Ms.K.Lakshmi Has Received Her B.Tech In EEE In 2013 And M.Tech PG In Electrical Power Engineering from JNTU Ananthapur In 2016. She Has Guided 4 P.G Students And 8 U.G Students. Her Research Included Electrical Power Engineering At Present she Is Working As Asst Professor In SKR Engineering College, Kondurusatram (v), Manubolu (M), SPSR Nellore, AP. India.. she Is Highly Passionate And Enthusiastic About Teaching And Believes That Inspiring Students To Give Of Her Best In Order To Discover What She Already Knows Is Better Than Simply Teaching.