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Design and Implementation of an 11-Level Inverter with FACTS Capability for Distributed Energy Systems

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Abstract:

In this paper, a new single-phase wind energy inverter (WEI) with flexible AC transmission system (FACTS) capability is presented. The proposed inverter is placed between the wind turbine and the grid, same as a regular WEI, and is able to regulate active and reactive power transferred to the grid. This inverter is equipped with distribution static synchronous compensators option in order to control the power factor (PF) of the local feeder lines. Using the proposed inverter for small-to medium- size wind applications will eliminate the use of capacitor banks as well as FACTS devices to control the PF of the distribution lines. The goal of this paper is to introduce new ways to increase the penetration of renewable energy systems into the distribution systems. This will encourage the utilities and customers to act not only as a consumer, but also as a supplier of energy. Moreover, using the new types of converters with FACTS capabilities will significantly reduce the total cost of the renewable energy application. In this paper, modular multilevel converter is used as the desired topology to meet all the requirements of a single-phase system such as compatibility with IEEE standards, total harmonic distortion (THD), efficiency, and total cost of the system. The proposed control strategy regulates the active and reactive power using power angle and modulation index, respectively. The function of the proposed inverter is to transfer active power to the grid as well as keeping the PF of the local power lines constant at a target PF regardless of the incoming active power from the wind turbine. The simulations for an 11-level inverter have been done in MATLAB/Simulink. To validate the simulation results, a scaled prototype model of the proposed inverter has been built and tested.

INTRODUCTION:

The role of power electronics in distribution systems has greatly increased recently. The power electronic devices are usually used to convert the nonconventional forms of energy to the suitable energy for power grids, in terms of voltage and frequency. In permanent magnet (PM) wind applications, a back-to-back converter is normally utilized to connect the generator to the grid. A rectifier equipped with a maximum power point tracker (MPPT), converts the output power of the wind turbine to a dc power. The dc power is then converted to the desired ac power for power lines using an inverter and a transformer. Recent developments in wind energy, utilizing smarter wind energy inverters (WEIs) has become an important issue. There are a lot of single-phase lines in the United States, which power small farms or remote houses [1], [2]. Such customers have the potential to produce their required energy using a small-to-medium-size wind turbine. Increasing the number of small-to-medium wind turbines will make several troubles for local utilities such as harmonics or power factor (PF) issues.

1. A high PF is generally desirable in a power system to decrease power losses and improve voltage regulation at the load. It is often desirable to adjust the PF of a system to near 1.0. When reactive elements supply or absorb reactive power near the load, the apparent power is reduced. In other words, the current drawn by the load is reduced, which decreases the power losses. Therefore, the voltage regulation is

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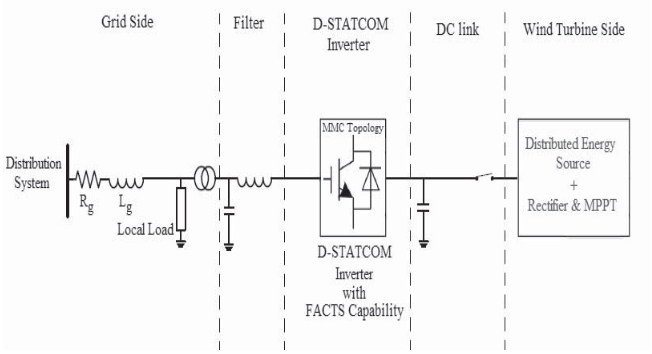
improved if the reactive power compensation is performed near large loads. Traditionally, utilities have to use capacitor banks to compensate the PF issues, which will increase the total cost of the system.

2. The modern ways of controlling the PF of these power lines is to use small distribution static synchronous compensators (D-STATCOMs). The D-STATCOMs are normally placed in parallel with the distributed generation systems as well as the power systems to operate as a source or sink of reactive power to increase the power quality issues of the power lines. Using regular STATCOMs for small-to-medium size single-phase wind applications does not make economic sense and increase the cost of the system significantly. This is where the idea of using smarter WEIs with FACTS capabilities shows itself as a new idea to meet the targets of being cost-effective as well as compatible with IEEE standards.



Complete configuration of the proposed inverter with FACTS capability

There are a large number of publications on integration of renewable energy systems into power systems. A list of complete publications on FACTS applications for grid integration of wind and solar energy was presented in [3]. In [4], new commercial wind energy converters with FACTS capabilities are introduced without any detailed information regarding the efficiency or the topology used for the converters. In, a complete list of the most important multilevel inverters was reviewed. Also, different modulation methods such as sinusoidal pulse width modulation (PWM), selective harmonic elimination, optimized harmonic stepped waveform technique,and space vector modulation were discussed and compared. Among all multilevel topologies, the cascaded H-bridge multilevel converter is very well known for STATCOM applications for several reasons. The main reason is that it is simple to obtain a high number of levels, which can help to connect STATCOM directly to medium voltage grids.

The modular multilevel converter (MMC) was introduced in the early 2000s .Reference describes a MMC converter for high voltage DC (HVDC) applications. This paper mostly looks at the main circuit components. Also, it compares two different types of MMC, including H-bridge and full-bridge sub modules. In and, a new single-phase inverter using hybrid clamped topology for renewable energy systems is presented. The proposed inverter is placed between the renewable energy source and the main grid. The main drawback of the proposed inverter is that the output current has significant fluctuations that are not compatible with IEEE standards. The authors believe that the problem is related to the snubber circuit design.

In this paper, the proposed WEI utilizes MMC topology,Bwhich has been introduced recently for HVDC applications. Replacing conventional inverters with this inverter will eliminatethe need to use a separate capacitor bank or a STATCOM device to fix the PF of the local distribution grids. Obviously, depending on the size of the power system, multiple inverters might be used in order to reach the desired PF. The unique work in this paper is the use of MMC topology for a single phase voltage-source inverter, which meets the IEEE standard 519 requirements, and is able to control the PF of the grid regardless of the wind speed Fig. 1 shows the complete grid-connected mode configuration of the proposed inverter. The dc link of the inverter is connected to the wind turbine through a rectifier using MPPT and its output terminal is connected to the utility grid through a series-connected second-order filter and a distribution transformer.

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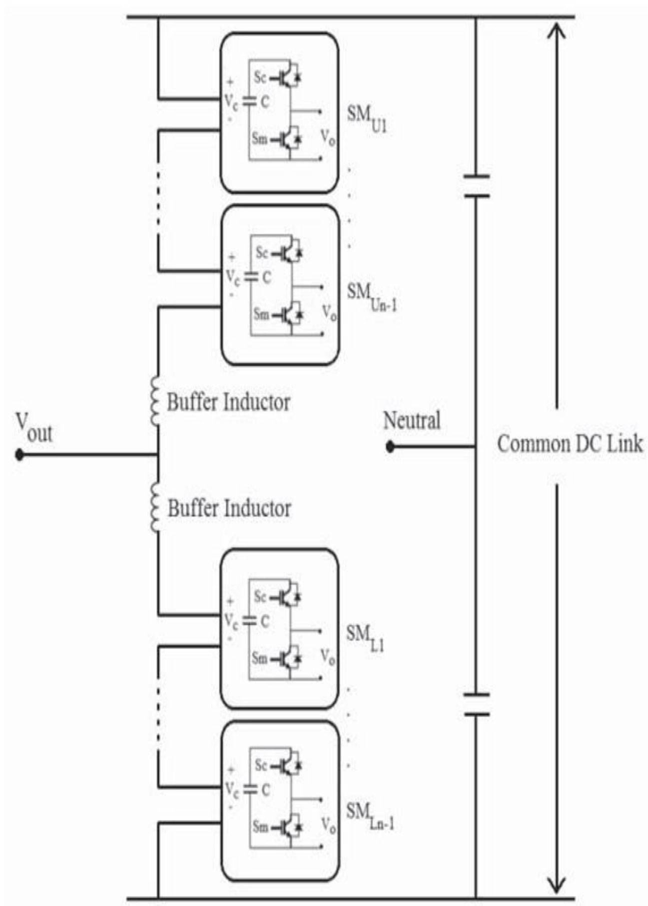
MODULAR MULTILEVEL CONVERTER:



Structure of a single-phase MMC inverter structure

MMC has gained increasing attention recently. A number of papers were published on the structure, control, and application of this topology, but none has suggested the use of that for inverter + D-STATCOM application. This topology consists of several half-bridge (HB) sub modules (SMs) per each phase, which are connected in series. An n-level single phase MMC consists of a series connection of 2(n − 1) basic SMs and two buffer inductors. Each SM possesses two semiconductor switches, which operate in complementary mode, and one capacitor.

The exclusive structure of MMC becomes it an ideal candidate for medium-to-high-voltage applications such as wind energy applications. Moreover, this topology needs only one dc source, which is a key point for wind applications. MMC requires large capacitors which may increase the cost of the systems; however, this problem is offset by the lack of need for any snubber circuit. The main benefits of the MMC topology are: modular design based on identical converter cells, simple voltage scaling by a series connection of cells, simple realization of redundancy, and possibility of a common dc bus. Fig. 2 shows the circuit configuration of a single-phase MMC and the structure of its SMs consisting of two power switches and a floating capacitor.

The output voltage of each SM (vo) is either equal to its capacitor voltage (vc) or zero, depending on the switching states. The buffer inductors must provide current control in each phase arm and limit the fault currents. To describe the operation of MMC, each SM can be considered as a two pole switch. If Sui, which is defined as the status of the i thsub module in the upper arm, is equal to unity, then the output of the i th SM is equal to the corresponding capacitor voltage; otherwise it is zero. Likewise, if Sliwhich is defined as the status of the i thsub module in the lower arm, is equal to unity, then the output of the i th lower SM is equal to the corresponding capacitor voltage; otherwise it is zero. Generally, when Sui or Sli is equal to unity, the i th upper or lower SM is ON; otherwise it is OFF. Therefore, the upper and lower arm voltages of the MMC are as follows:

$$v_{\text{upperArm}} = \sum_{i=1}^{n-1} (S_{\text{ui}} v_{\text{ci}}) + v_{11}$$

$$v_{\text{lowerArm}} = \sum_{i=1}^{n-1} (S_{\text{li}} v_{\text{ci}}) + v_{12}$$

wherev11 and v12 are the voltages of the upper and lower buffer inductors, n is the number of voltage levels, and vciis the voltage of the i th SMs capacitor in upper arm or lower arm. A single-phase 11-levelMMC inverter consists of 20 SMs which translates to 40 power switches, 20 capacitors, and 2 buffer inductors. The dc and ac voltages of the 11-level MMC are described by

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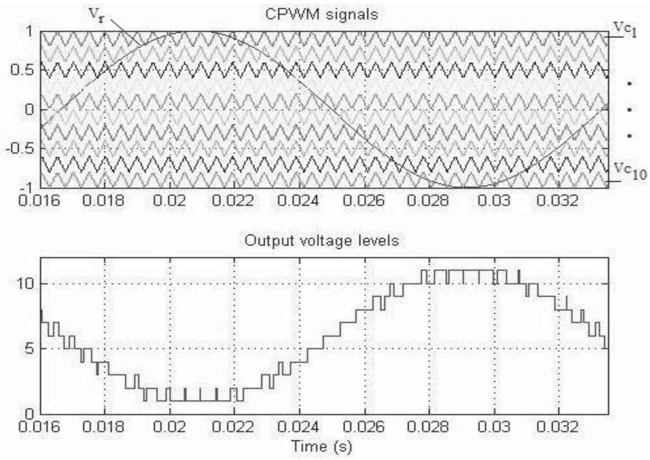
$$
\begin{aligned}
v_{DC} &= v_{upperArm} + v_{lowerArm} \\
&= \sum_{i=1}^{10} (S_{ui} v_{ci}) + \sum_{i=1}^{10} (S_{ui} v_{ci}) + (v_{11} + v_{12}) \\
v_{out} &= \frac{v_{DC}}{2} - v_{upperArm} = -\frac{v_{DC}}{2} + v_{lowerArm}.
\end{aligned}
$$

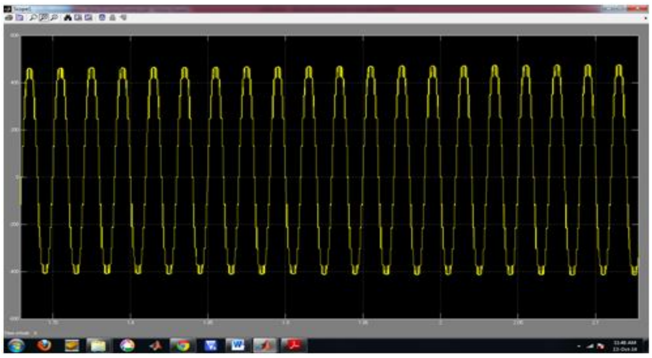
OPERATING REGIONS FOR AN 11-LEVEL MMC INVERTER:

Voltage level	Status	$n_{UpperArm}$	$n_{lowerArm}$	V_{out}
1	$v_r \geq v_{c1}, v_{c2}, v_{c3}, v_{c4}, v_{c5}, v_{c6}, v_{c7}, v_{c8}, v_{c9}, v_{c10}$	0	10	$5v_{dc}/10$
2	$v_r < v_{c1}$ $v_r \geq v_{c2}, v_{c3}, v_{c4}, v_{c5}, v_{c6}, v_{c7}, v_{c8}, v_{c9}, v_{c10}$	1	9	$4v_{dc}/10$
3	$v_r < v_{c1}, v_{c2}$ $v_r \geq v_{c3}, v_{c4}, v_{c5}, v_{c6}, v_{c7}, v_{c8}, v_{c9}, v_{c10}$	2	8	$3v_{dc}/10$
4	$v_r < v_{c1}, v_{c2}, v_{c3}$ $v_r \geq v_{c4}, v_{c5}, v_{c6}, v_{c7}, v_{c8}, v_{c9}, v_{c10}$	3	7	$2v_{dc}/10$
5	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}$ $v_r \geq v_{c5}, v_{c6}, v_{c7}, v_{c8}, v_{c9}, v_{c10}$	4	6	$v_{dc}/10$
6	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}, v_{c5}$ $v_r \geq v_{c6}, v_{c7}, v_{c8}, v_{c9}, v_{c10}$	5	5	0
7	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}, v_{c5}, v_{c6}$ $v_r \geq v_{c7}, v_{c8}, v_{c9}, v_{c10}$	6	4	$-v_{dc}/10$
8	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}, v_{c5}, v_{c6}, v_{c7}$ $v_r \geq v_{c8}, v_{c9}, v_{c10}$	7	3	$-2v_{dc}/10$
9	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}, v_{c5}, v_{c6}, v_{c7}, v_{c8}$ $v_r \geq v_{c9}, v_{c10}$	8	2	$-3v_{dc}/10$
10	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}, v_{c5}, v_{c6}, v_{c7}, v_{c8}, v_{c9}$ $v_r \geq v_{c10}$	9	1	$-4v_{dc}/10$
11	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}, v_{c5}, v_{c6}, v_{c7}, v_{c8}, v_{c9}, v_{c10}$	10	0	$-5v_{dc}/10$

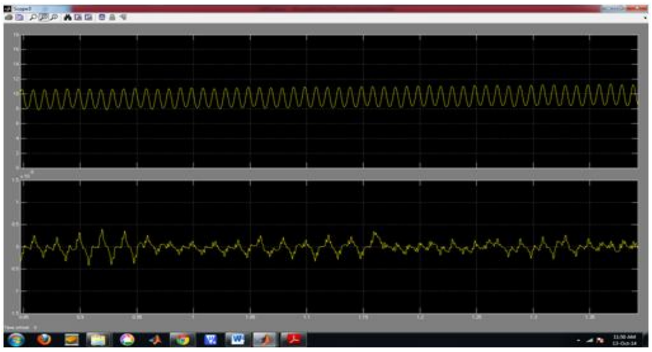


CPWM waveforms for an11-level MMC inverter, and the generated output voltage levels.

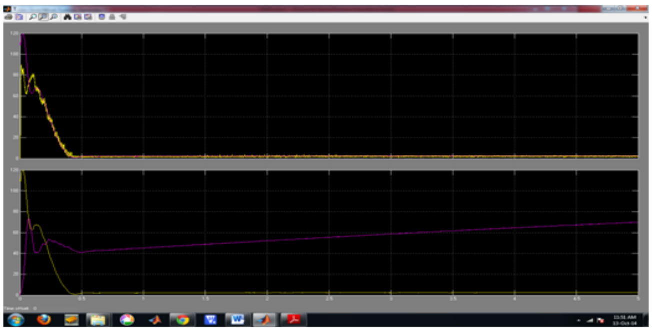
SIMULATION RESULTS:



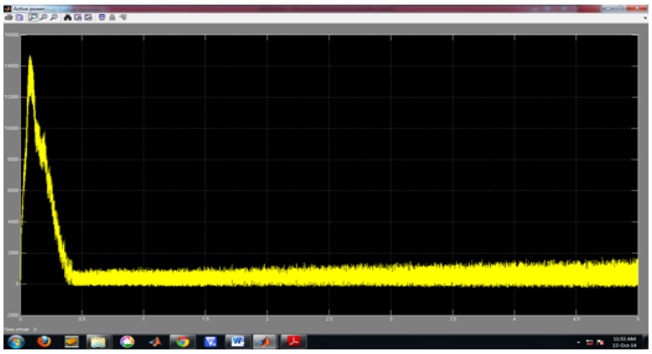
Simulated output voltage of an 11-level inverter.



Simulated active and reactive power of the inverter



Torque of the wind turbine generator



Active power of the wind generator turbine

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Conclusion:

In this project, the concept of a new multilevel inverter with FACTS capability for small-to-mid-size wind installations is presented. The proposed system demonstrates the application of a new inverter with FACTS capability in a single unit without any additional cost. Replacing the traditional renewable energy inverters with the proposed inverter will eliminate the need of any external STATCOM devices to regulate the PF of the grid. Clearly, depending on the size of the compensation, multiple inverters may be needed to reach the desired PF. This shows a new way in which distributed renewable sources can be used to provide control and support in distribution systems. The proposed controller system adjusts the active power by changing the power angle (delta) and the reactive power is controllable by the modulation index m. The simulation results for an 11-level inverter are presented in MATLAB/Simulink. To validate the simulation results, a scaled prototype of the proposed 11-level inverter with D-STATCOM capability is built and tested. Practical results show good performance of the proposed control strategy even in severe conditions.

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