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A Novel Single-Phase Inverter With D-STATCOM Capability for Wind Applications

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Abstract— **The modular multilevel converter (MMC) is an attractive topology for HVDC/FACTS systems. In this paper a new single-phase MMC-based D-STATCOM inverter for grid connection is proposed. The proposed inverter is designed for grid-connected wind turbines in the small- to mid-sized (10kW-20kW) range using the most advanced multi-level inverter topology. The proposed MMC D-STATCOM inverter controls the DC link voltage as well as the active and reactive power transferred between the renewable energy source, specifically wind turbine, and the grid in order to regulate the power factor (PF) of the grid regardless of the input active power from wind turbine. The goal of this paper is to present a new inverter with FACTS capability in a single unit without any additional cost. The 5-level D-STATCOM inverter is simulated and the results are presented to verify the operation of the proposed system. The simulation studies are carried out in the MATLAB/Simulink environment. To validate the simulation results, an experimental configuration of a 5-Level MMC D-STATCOM inverter has been built and tested.**

Index Terms-- **D-STATCOM, Modular Multi-level Converter (MMC), Wind Applications**

I. INTRODUCTION

Distributed energy sources such as wind and solar have been attracting increasing interest in recent years [1]-[3]. Recently, distributed generation (DG) has been introduced to the modern power systems in order to avoid generating power and transmitting it over a long distance. Relatively small power generation, such as small wind or solar system, is an approach to penetrate renewables to the power

systems. Small renewable energy sources are connected to the low side of the distribution systems. The general idea is that in modern power systems, end customers do not act only as consumers, but as active power supplier as well. Deploying small renewable energy sources in distribution systems requires paying more attention to the power quality at the end point, specifically when the amount of installed renewable energy becomes significant compared to the total power of that system.

Among all power quality concerns, controlling the active and reactive power transferred to or from the grid requires major attention. Nowadays, this attention is possible using power electronics. Power electronic-based flexible AC transmission System (FACTS) devices have been developed in order to provide more knowledge and control on power systems. In this paper, a new single-phase multilevel D-STATCOM inverter is presented. A D-STATCOM inverter is a power electronic device that is placed between a renewable energy source and the distribution grid not only to provide active power, but to control reactive power on system. The proposed D-STATCOM inverter in this work could replace existing inverters used for renewable energy systems, specifically for small wind applications.

Multi-level inverters have recently gained more attention for applications such as large-scale utility applications, and inverters for renewable energy systems. A multi-level converter has several advantages compared to the conventional two-level converter. It has the capability to perform at a lower switching frequency, it has lower total harmonic distortion (THD), it has better efficiency, and it possesses less dv/dt and therefore less voltage stress on the devices [4-8].

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 has been presented in [9]. In most of the STATCOM-related publications, the STATCOMs stand in parallel with the DG and power systems as an external device in order to mitigate the undesirable effects of the renewable energy sources. In [10] new commercial wind energy converters with FACTS capabilities are introduced without any detailed information regarding the efficiency or the topology used for the converters. The converter proposed in [10] is able to control reactive power while operating as a power

converter. In [4] a complete list of the most important multi-level inverters was reviewed. Also, different modulation methods such as sinusoidal PWM, selective harmonic elimination (SHE), optimized harmonic stepped waveform technique (OHSW), and space vector modulation (SVM) were discussed and compared. Among all multi-level topologies, the cascaded H-bridge multi-level 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. There are a large number of publications on different aspects of H-bridge STATCOM. For instance, [11-13] present new control methods for multi-level H-bridge cascaded STATCOMs to improve the power quality. The modular multilevel converter (MMC) was introduced in the early 2000s. Reference [14] describes a MMC converter for 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 [8] and [15] a new single-phase D-STATCOM inverter using hybrid-clamped topology for renewable energy systems is presented. The proposed inverter with D-STATCOM capability 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.

Among all new multi-level D-STATCOM topologies, the MMC topology has gained more and more attention specifically for mid- to high-voltage applications. The unique work in this paper is the use of MMC topology for a single-phase voltage source inverter (VSI) with D-STATCOM capability in a single unit for small to mid-sized wind applications. The proposed wind converter is capable of controlling the PF of the grid with or without active power from the wind turbine, and meets IEEE standard 519 for grid-connected devices.

II. CONCEPT OF THE MMC TOPOLOGY

The modular multilevel converter (MMC) is the most advanced topology for large scale commercial deployment. MMC is the topology used by SIEMENS for HVDC Plus technology [16-17]. The structure

of this topology is based on several modules in which each module consists of a floating capacitor and two switches. This topology is an ideal choice for FACTS applications if the capacitors voltages maintain balanced. MMC is able to transfer active and reactive power regardless of the load characteristics. The main drawback of this topology is that it requires large capacitors in comparison with similar topologies which may affect the total cost of the inverter. However, no need for any type of snubber circuit for MMC can alleviate this problem.

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 [18-20]. Figure 1(a) shows the circuit configuration of a single-phase MMC. The converter is composed of an arbitrary number of identical sub-modules (SMs). An n-level single-phase MMC consists of a series connection of $2(n-1)$ basic SMs and two buffer inductors. Figure 1(b) shows the structure of each SM consisting of two power switches and a floating capacitor.
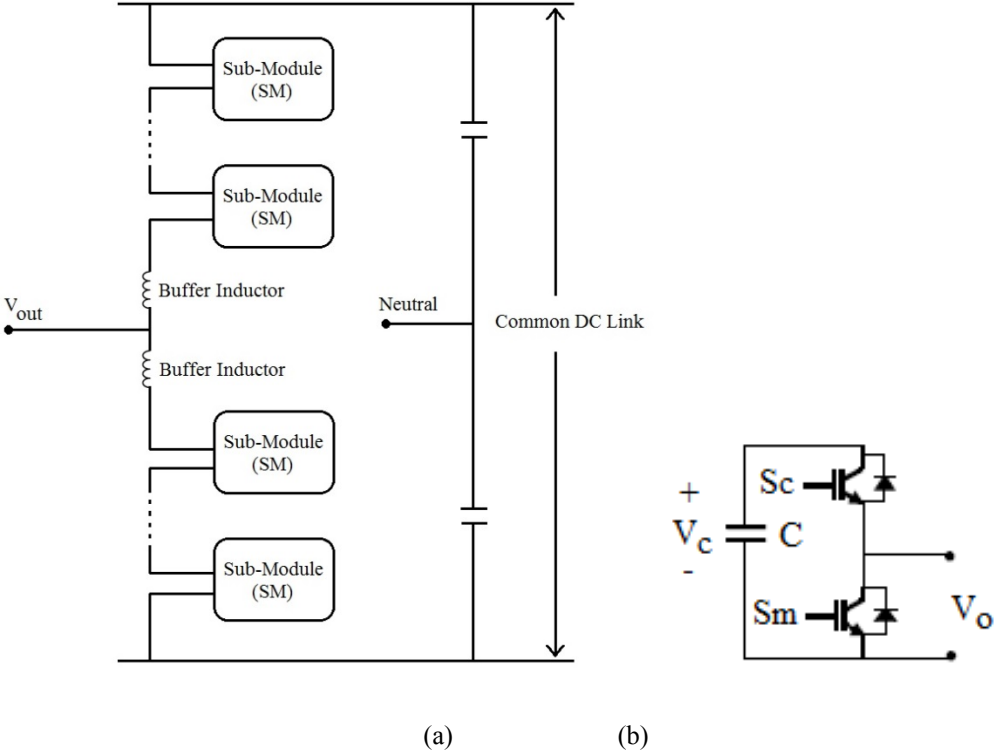

(a)   (b)
Fig.1. a) Configuration of the MMC topology, b) A sub-module (SM)

The output voltage of each SM (V_o) is either equal to its capacitor voltage (V_c) or zero, depending on the switching states. The buffer inductors must provide current control in each phase arm and limit the fault currents. The DC link of the MMC is connected to the distributed energy source (i.e., a wind turbine) through a rectifier using maximum power point tracker (MPPT). The output terminal of the MMC is connected to the utility grid through a series-connected second-order filter and a distribution transformer. Figure 2 shows the complete configuration of a grid-connected D-STATCOM inverter.
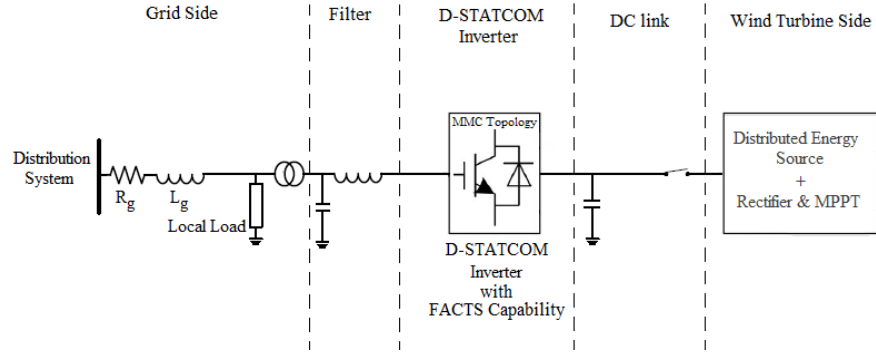

Fig. 2. Configuration of a grid-connected D-STATCOM inverter

To describe the operation of MMC, each SM can be considered as a two-pole switch. If S_{ui}, which is defined as the status of the i_{th} sub-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 S_{li}, which is defined as the status of the i_{th} sub-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 S_{ui} or S_{li} is equal to unity, the i_{th} upper or lower SM is ON (S_c is ON and S_m is OFF in figure 1(b)); otherwise it is OFF. Therefore, the upper and lower arm voltages of the MMC are as follows:

$$v_{upperArm} = \sum_{i=1}^{n-1}(S_{ui}v_{ci}) + v_{l1} \tag{1}$$

$$v_{lowerArm} = \sum_{i=1}^{n-1}(S_{li}v_{ci}) + v_{l2} \tag{2}$$

Where v_{l1} and v_{l2} are the voltages of the upper and lower buffer inductors, n is the number of voltage levels, and v_{ci} is the voltage of the i_{th} SM's capacitor in upper arm or lower arm. Therefore, the output DC and AC voltages of the 5-level MMC are described by:

$$v_{dc} = v_{upperArm} + v_{lowerArm} = \sum_{i=1}^{4}(S_{ui}v_{ci}) + \sum_{i=1}^{4}(S_{li}v_{ci}) + (v_{l1+}v_{l2)} \qquad (3)$$

$$v_{out} = \frac{v_{dc}}{2} - v_{upperArm} = -\frac{v_{dc}}{2} + v_{lowerArm} \qquad (4)$$

The carrier-based pulse width modulation (CPWM) method [21-22] is used in this paper to control the SMs' voltages. Fig. 3 shows the reference and the carrier waveforms for a 5-level CPWM.
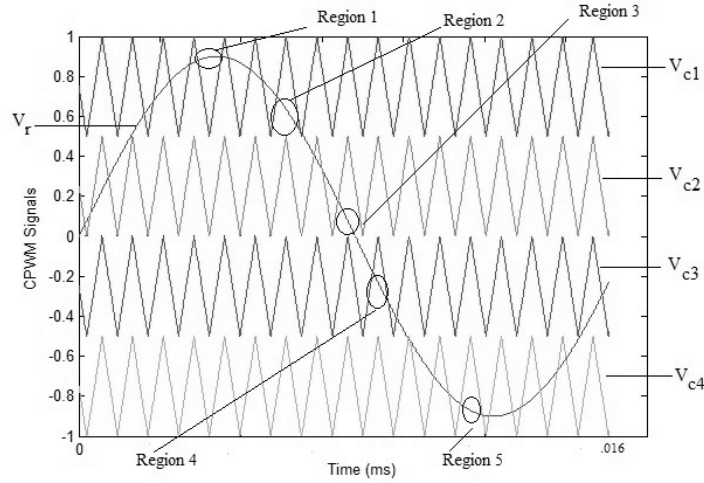

Fig. 3. CPWM waveforms for a 5-level MMC

In figure 3, based on the phase of the reference signal (v_r), there are five operating regions for a 5-level MMC inverter defined in table 1 where each region defines a voltage level.

Table1. Operating regions for a 5-level MMC

Region	Status	$n_{UpperArm}$	$n_{lowerArm}$	V_{out}
1	$v_r \geq v_{c1}, v_{c2}, v_{c3}, v_{c4}$	0	4	$\frac{v_{dc}}{2}$
2	$v_r < v_{c1}$ $v_r \geq v_{c2}, v_{c3}, v_{c4}$	1	3	$\frac{v_{dc}}{4}$
3	$v_r < v_{c1}, v_{c2}$ $v_r \geq v_{c3}, v_{c4}$	2	2	0
4	$v_r < v_{c1}, v_{c2}, v_{c3}$ $v_r \geq v_{c4}$	3	1	$\frac{-v_{dc}}{4}$
5	$v_r < v_{c1}, v_{c2}, v_{c3}, v_{c4}$	4	0	$\frac{-v_{dc}}{2}$

where $n_{upperArm}$ and $n_{lowerArm}$ are the numbers of SMs which are ON in the upper arm or lower arm, respectively. The total number of SMs with the status of ON is:

$$n_{upperArm} + n_{lowerArm} = 4 \tag{5}$$

In a 5-level MMC inverter, there are four upper and four lower SMs where each SM has a capacitor. For instance, in region 1 of figure 3, all the upper SMs should be OFF and all the lower SMs should be ON, which translates to the fact that the main switches (S_m) of all upper SMs and the auxiliary switches (S_c) of all lower SMs should be ON and all the other switches should be OFF. In this case, the input DC voltage is applied only to the four lower capacitors, so that the output voltage is $^{V_{dc}}/_2$.

The most critical issue to control MMC is to maintain the voltage balance across all the capacitors. Therefore, the SMs' voltages are measured and sorted in descending order during each cycle. If the current flowing through the switches is positive, $n_{upperArm}$ and $n_{lowerArm}$ of the SMs in upper arm and lower arm with the lowest voltages are selected, respectively. As a result, 4 capacitors with lowest voltages are chosen to be charged. Likewise, if the current flowing through the switches is negative, $n_{upperArm}$ and $n_{lowerArm}$ of the SMs in lower arm with highest voltages are selected, respectively. As a result, 4 capacitors with highest voltages are chosen to be discharged. Consequently, the voltages of the SMs' capacitors are maintained balanced.

III.   CONTROLLER DESIGN

The aim of the designed inverter is to provide utilities with distributive control of VAR compensation and power factor (PF) on feeder lines. To enhance the reactive power control of the proposed inverter, it is equipped with the additional D-STATCOM option. This option permits the inverter to deliver reactive power fully independent from the wind speed. The inverter is able to control the active and reactive power regardless of the input active power from the renewable energy source. Generally, there are two modes of operation for the proposed inverter when it is connected to the grid: 1) when wind is blowing and active power is coming from the wind turbine: the "inverter plus D-STATCOM" mode. In this mode, the device is working as a regular inverter to transfer active power from the renewable energy source to the grid as well as working as a D-STATCOM to regulate the reactive power of the grid in order to control the PF of the grid. 2) When wind speed is zero or too low to generate active power: the "D-STATCOM" mode. In

this case, the inverter is acting only as a source of reactive power to control the PF of the grid, as a D-STATCOM. Generally, regular renewable energy inverters are able to control only the active power transferred to the grid, but the proposed inverter is also equipped with a D-STATCOM option to control the reactive power and PF of the grid fully independent of the wins speed. This option eliminates the use of additional capacitor banks or external STATCOMs to regulate the PF on the feeder lines. The device is capable of outputting up to its rated maximum real power and/or reactive power, and will always output all real power generated by the wind turbine to the grid. The amount of reactive power, up to the design maximum, is dependent only on what the utility asks the device to produce.

The power flow between a STATCOM and a line is governed by the equations below that describe the power flow between two active sources separated by an inductive reactance. For normal transmission lines this inductive reactance is the inductance of a transmission line. For a STATCOM the modeled inductance is the inductance of the transformer that connects the STATCOM to the line which is denoted X. The RMS voltage of the STATCOM is given as E_s and is considered to be out of phase by an angle of δ to the RMS line voltage E_l. The active power transferred from the STATCOM to the line is given by (6) and the reactive power transferred from the STATCOM to the line is given by (7).

$$P_S = -\frac{E_S E_L}{X}\sin\delta \tag{6}$$

$$Q_S = \frac{E_S E_L \cos\delta - E_L^2}{X} \tag{7}$$

Control over the reactive power provided by the STATCOM is achieved by selecting both the voltage level of the STATCOM and the angle between the two voltages δ. By using power electronics it is possible to control the amplitude of the STATCOM voltage by adjusting the modulation index m and the angle δ by adding a delay to the firing signals. Adding the modulation index into (6) and (7) gives:

$$P_S = -\frac{m E_S E_L}{X}\sin\delta \tag{8}$$

$$Q_S = \frac{m E_S E_L \cos\delta - E_L^2}{X} \tag{9}$$

These two equations govern the operation of the STATCOM device. The steady state operation of the inverter is controlled by adjusting m and δ, so that it provides the desired amount of active power and reactive compensation. In this paper, the modulation index is used to control the reactive power and the power angle is used to control the active power transferred between the renewable energy source and the grid. The modulation index of a STATCOM is the primary governor of the reactive power compensation that is provided, and its main task is to make the power factor of the grid equal to the target power factor.

The proposed controller system depends on several assumptions. The first is that the load on the feeder line can be considered fixed for a small window of time. This assumes the load will not vary within one cycle of the grid frequency. Second, the feeder line can be accurately modeled as a constant P, Q load. This means the power produced by a wind turbine will displace other power on the feeder line and not add to it. Third, a change in the modulation index will predominantly affect Q, while a change in delta will predominantly affect P. Any effect on Q from a small change in delta is thus ignored. This assumes that P and Q are independently controlled.

The first step is to create an equation that relates the target Q to the target power factor. This relationship is shown in (10).

$$P_G = \left(\sqrt{P_G^2 + Q_T^2} \right) * PF_T \tag{10}$$

where P_G is the amount of active power on the grid, Q_T is the target amount of reactive power, and PF_T is the target power factor desired by the utility. So, Q_T can be calculated as:

$$Q_T = \sqrt{\left(\frac{P_G}{PF_T} \right)^2 - P_G^2} \tag{11}$$

Fig. 4 shows the complete control system. The proposed controller consists of three major functions. The first function is to find the desired modulation index and the power angle. By using equations (10) and (11), the target reactive power for the grid is determined and is compared with the actual value of the reactive power on the grid. Using a PI compensator will determine the desired value for the modulation

index. The power angle is determined by comparing the actual DC voltage of the inverter with a reference value. A PI compensator determines the desired value for power angle. The modulation index is applied to the reference sinusoidal signal to generate PWM signals. The second function of the controller system is to keep the capacitors' voltages balanced. The capacitors' voltages are sorted in descending order. Based on the direction of the current flowing through the switches, the proper algorithm will be selected to maintain capacitor balance. If the current is positive, it charges the capacitors and increases their voltages and if the current is negative, it discharges the capacitors and decreases their voltages. The third function of the controller is to generate the PWM signals. Based on the desired modulation index, power angle, voltages of the capacitors, direction of the current flowing through the switches and using table 1, the controller generates the PWM signals in order to meet all the system requirements.
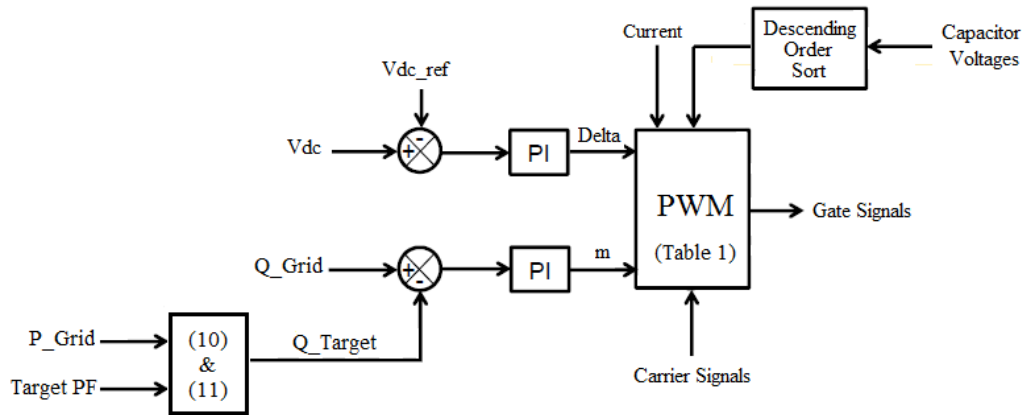
Fig. 4. Control System Schematic

IV.   SIMULATION RESULTS

The design of a 5-level D-STATCOM inverter was carried out in MATLAB/Simulink using the SimPowerSystems toolbox. The simulation is 20 seconds long and contains severe ramping and de-ramping of the distributed renewable energy source, which is a wind turbine; outputs are illustrated in Figs. 6-7. Before t=7s, there is no wind to power the wind turbine. At t=7s the input power to the inverter is ramped up to 17 kW in three seconds, and then ramped down to 12 kW four seconds later. The goal is to assess the behavior of the control system in the worst conditions. In this case, the load is 50 kW and 34.8 kVAR making the power factor 0.82. When the simulation starts, the D-STATCOM inverter

provides enough compensation to compensate the PF and reach to the target PF which is set to 0.90. As soon as the D-STATCOM provides VAR compensation, the amount of VARs provided by the feeder line to the load is decreased to 22kVAR. After t=7s, the output power of the wind turbine is increased, and as a result the level of active power provided by the feeder line is decreased by the same amount. Table 2 shows the values of the parameters used for the simulation.

Table 2. The parameters used for the simulation

Parameter	Value
L_{line}	10 mH
R_{line}	1 Ohm
L_{Filter}	10 mH
Transformer primary voltage	12000 V
Transformer secondary voltage	600 V
Switching frequency	2 kHz
Load active power	50000 W
Load reactive power	34800 VAR
Target PF	0.9
DC link Voltage	2500 V

The simulated output voltage of the proposed inverter before and after filter is shown in figure 5.
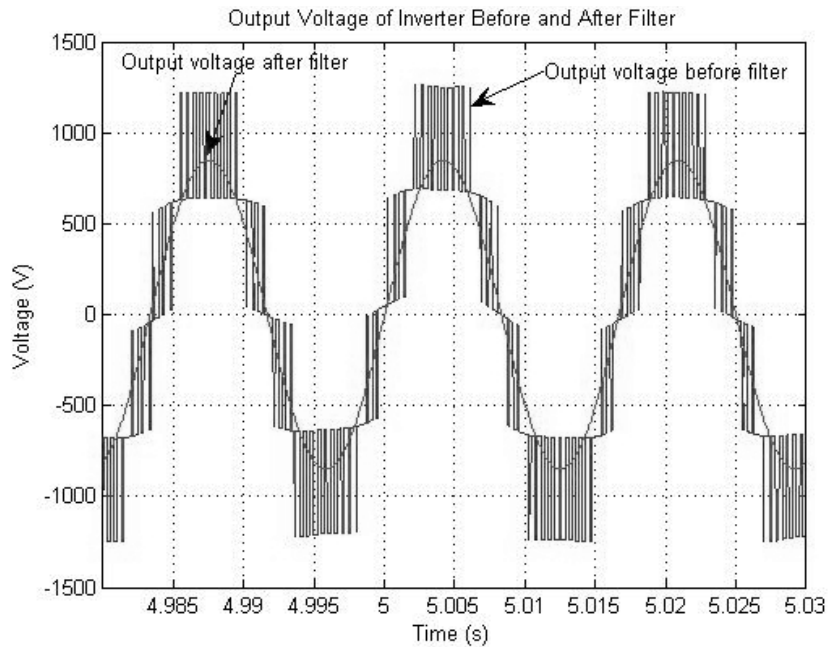

Fig. 5. Output voltage of the D-STATCOM inverter before and after filter

The target power factor on the grid is set to 0.90 while the load is making the power factor of 0.82. Therefore, D-STATCOM tries to inject reactive power to the grid to increase the power factor of the grid regardless of the input active power from wind turbine. Figure 6(a) shows the power factor of the grid, which is constant at 0.90 regardless of the input power from wind turbine. Power angle (delta) and modulation index (MI) are shown in figure 6(b).
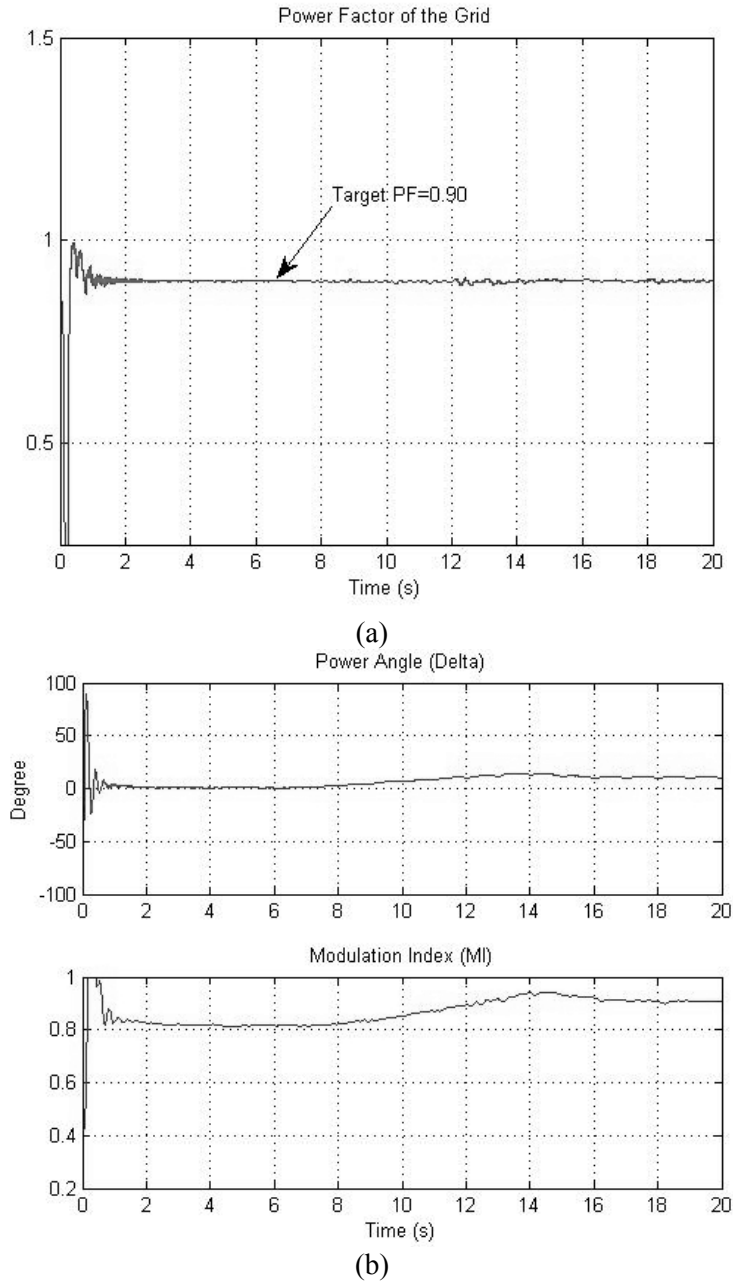

(a)

(b)

Fig. 6.(a) Power factor of the grid, (b) Power angle and modulation index

The PF of the grid is constant at 0.90 before and after t=7s, showing that the main goal of the inverter is achieved. The set-point for dc link voltage of the inverter is 2500 V and the rms value of the output ac voltage is 750 V. Active and reactive power of the feeder line, active and reactive power of the D-STATCOM inverter are shown in figure 7(a), and the output power of the renewable energy source is shown in figure 7(b).
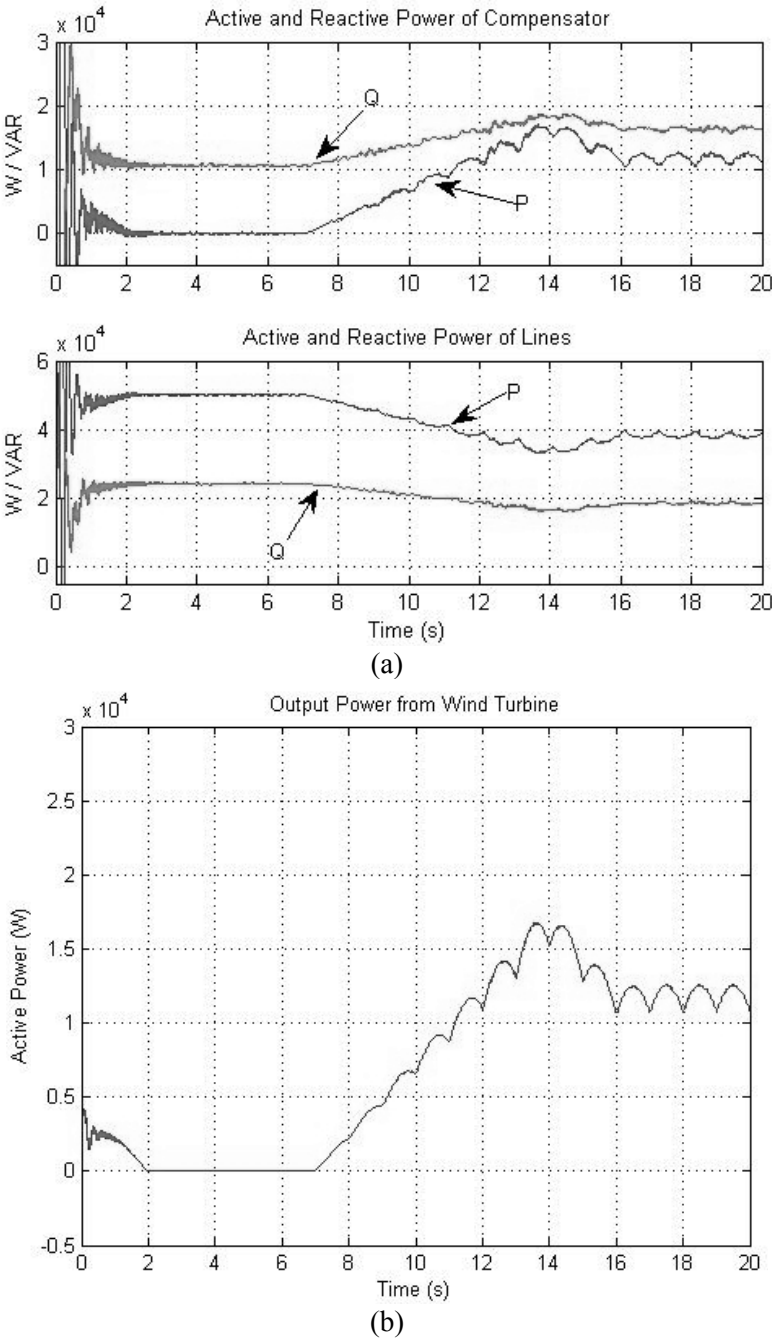

(a)

(b)

Fig. 7.(a) Active and reactive power of the inverter and the feeder lines, (b) Output power of the wind turbine

V. Experimental Results

To validate the simulation results, a 5-level model of the system has been built and tested. In laboratory-scale experiments a CLP1103 dSPACE system hosts the controllers and feedback signals from the sensors. The controllers were run from the Simulink model linked to the dSPACE. The measurements were performed using a 600 MHz LeCroy 64Xi-A oscilloscope with one CP030 current probe, and two ADP305 differential voltage probes. A three phase permanent magnet (PM) generator driven by a variable speed induction motor is used to emulate the wind speed changes. The variable output is connected to the DC link through a three-phase rectifier. In practical tests, due to the low ratings of the switches and capacitors, all the voltages and currents have been scaled down and the goal is only to show the proof of concept. Figure 8 shows the 5-level prototype model, and the experimental configuration and table 3 gives some information on the experimental parameters.
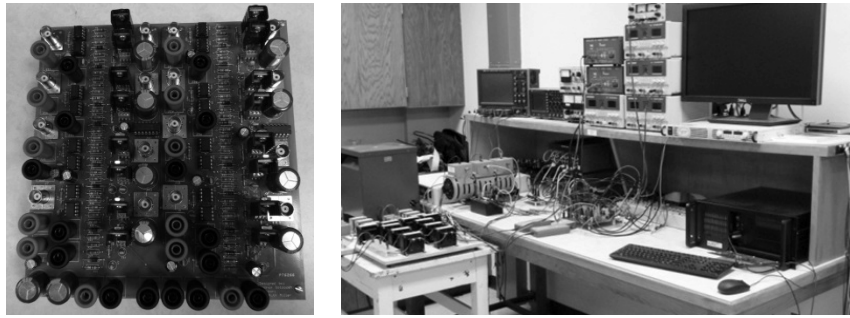

Fig. 8. The 5-level prototype model of the MMC D-STATCOM inverter, and the experimental configuration

Table 3. Specification of the experimental setup

Parameter	Value
C_{Filter}	30 uF
L_{Filter}	10 mH
Transformer primary voltage	120 V
Transformer secondary voltage	6 V
Switching frequency	2 kHz
Load resistance	54 Ohm
Load inductance	75 mH
Target PF	0.92
DC link Voltage	24-27 V
Power Switch	IRF 510

The 5-level prototype model has been tested in stand-alone mode and grid-connected mode. In stand-alone mode, the DC-link voltage is set to 24 V and the inverter is connected to a purely resistive load of 54 Ohms through a second-order low-pass filter of 10mH and 30uF. The SMs' capacitor voltages captured by the ControlDesk software, a program associated with dSPACE, are shown below.
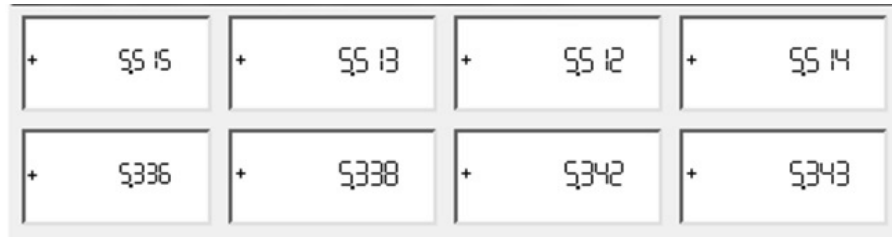

Fig. 9.Practical result for voltage balancing in the 5-level prototype MMC inverter. The displayed values are the voltages of the upper and lower sub-module capacitors during inverter operation

The main key to control the MMC inverter is to balance the voltages of the SMs' capacitors. Fig. 9 shows that the voltages of all 4 upper capacitors are the same and are close to the voltage of all 4 lower capacitors. The output waveform of the inverter before and after the filter for a purely resistive load is as shown in Fig. 10. In this case, the voltage drop over the filter is 2% which is compatible with standards, the modulation index is 0.91, and the efficiency of the inverter is 95%.
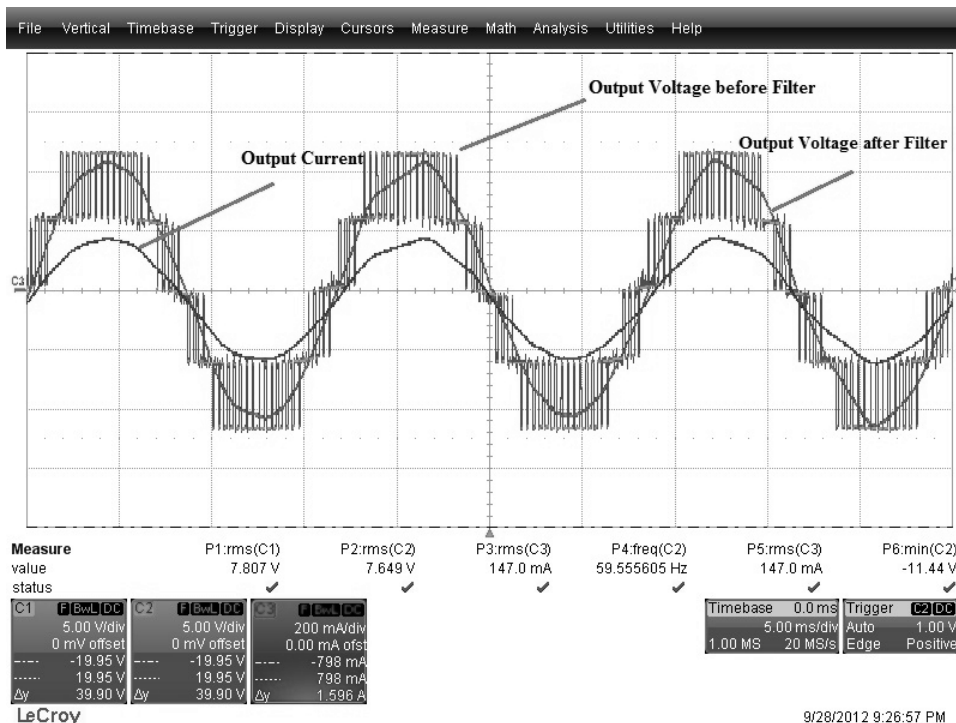

Fig. 10. Practical results for output voltage and current of the 5-level MMC inverter in stand-alone mode

In grid-connected mode the D-STATCOM inverter is connected to the grid through a distribution transformer with the ratio of 120:6, and the load resistance and inductance are 54 Ohms and 75 mH respectively, making the load PF 0.91. In this mode, the target power factor of the grid is 0.92 and the active and reactive power drawn from the grid are 213 W and 97 VAR making the PF 0.91. Fig. 11 shows the results after connecting the D-STATCOM inverter to the grid. In the top chart of figure 11, the dc link is open-circuited and the device is operating in D-STATCOM mode. Therefore, there is no active power from the wind emulator. In this case the power angle Delta is negative and 1.5 W active power drawn from the grid (P_Comp) is consumed by the non-ideal components as well as to charge the capacitors. The D-STATCOM corrects the PF of the grid by injecting 5.6 VAR (Q_Comp) to the grid. In the second chart of figure 11, the dc link is connected to the wind emulator and the device is operating in inverter+ D-STATCOM mode. In this case the active and reactive power drawn from the grid (P_Grid and Q_Grid) are 205 W and 87 VAR, showing that the compensator is able to reach the target PF 0.92 by injecting 10 VAR (Q_Comp) to the grid. In this case, the DC link voltage V_DC_Target is set to 27 V and it is supposed that the wind speed is constant and the wind turbine provides a constant active power of 10 W (P_Comp plus 1.5W to power the inverter).
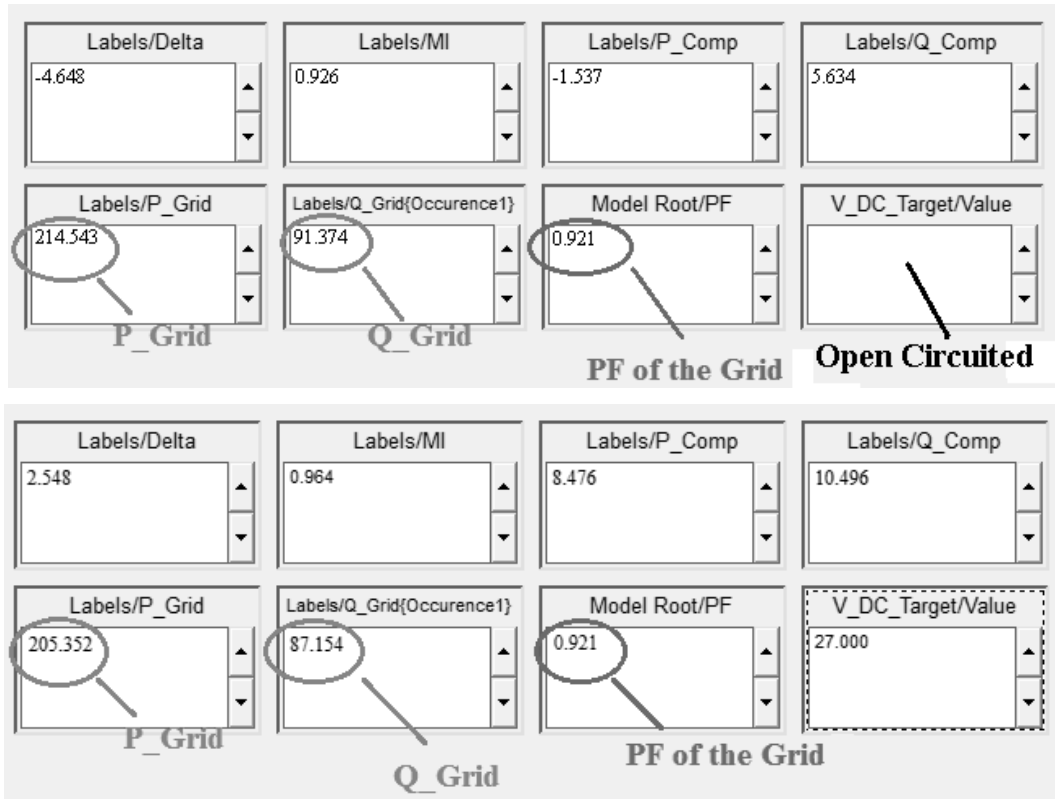
Fig. 11. Practical results for the grid-connected D-STATCOM inverter

The output voltage and current of the 5-level D-STATCOM inverter in capacitive mode is as below.
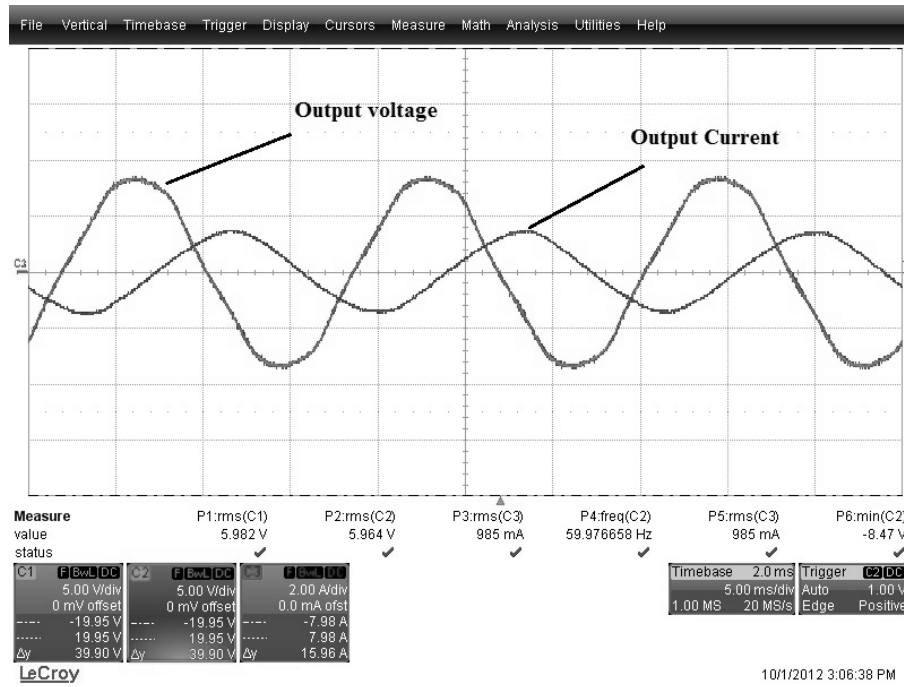

Fig. 12. Output voltage (after filter) and current of D-STATCOM inverter in capacitive mode

The practical results show that the THD of the output voltage and current in grid-connected mode are 3.9% and 4.1%, respectively, shown in figure 13, which is compatible with IEEE519 standard. In order to improve the THD, higher levels for the inverter are needed.

(a)   (b)

Fig. 13.(a) Practical output voltage THD, (b) Practical output current THD

VI.   CONCLUSION

In this paper, the concept of a multi-level D-STATCOM inverter for small- to mid-sized (10-20kW) wind installations is presented and shows a new way in which distributed renewable sources can be used to provide control and support in distribution systems. The proposed single-phase D-STATCOM inverter using MMC topology can actively regulate the reactive power on individual feeder lines while providing the variable output power of the renewable energy source. The aim is to provide utilities with distributive control of VAR compensation and power factor correction on feeder lines. The proposed D-STATCOM inverter performs in two modes: 1) inverter+D-STATCOM mode, in which there is a variable active power from the wind turbine, 2) D-STATCOM mode, in which the DC link is open-circuited and no active power is gained from the renewable energy source. The simulation results for a 5-level inverter are presented in MATLAB/Simulink. To validate the simulation results, a 5-Level MMC D-STATCOM inverter has been built and tested in stand-alone mode and grid-connected mode. The proposed system demonstrates the application of a new inverter with FACTS capabilities in a single unit without any additional cost.

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