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Implementation of an 11-Level Inverter with FACTS Capability for Wind 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. 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.

Index Terms— Modular multilevel converter (MMC); multilevel inverter (MLI); wind energy inverter (WEI)

I. 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.

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.

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. Traditionally, utilities have to use capacitor banks to compensate the PF issues, which will increase the total cost of the system. The modern ways of controlling the PF of these power lines is to use small distribution static synchronous compensators (D-STATCOMs). 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.

The proposed inverter in this paper is equipped with a D-STATCOM option to regulate the reactive power of the local distribution lines and can be placed between the wind turbine and the grid, same as a regular WEI without any additional cost. The function of the proposed inverter is not only to convert dc power coming from dc link to a suitable ac power for the main grid, but also to fix the PF of the local grid at a target PF by injecting enough reactive power to the grid.

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 [5], a complete list of the most important multilevel inverters was reviewed. Among all multilevel topologies [6]-[9], the cascaded H-bridge multilevel converter is very well known for STATCOM applications for several reasons [10]-[12]. The modular multilevel converter (MMC) was introduced in the early 2000s [13], [14]. Refer- ence [15] 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 submodules. In [9] and [16], a new single-phase inverter using hybrid- clamped topology for renewable energy systems is presented Several other applications of custom power electronics in renewable energy systems exist, including [17] an application of a custom power interface where two modes of operation, including an active power filter and a renewable energy STATCOM. Another application [18] looks at the current- source inverter, which controls reactive power and regulates voltage at the point of common coupling (PCC). [19], [20] propose an application of photovoltaic (PV) solar inverter as STATCOM in order to regulate voltage on three-phase power systems, for improving transient stability and power transfer limit in transmission systems.

In this paper, the proposed WEI utilizes MMC topology, which has been introduced recently for HVDC applications. Replacing conventional inverters with this inverter will eliminate the need to use a separate capacitor bank or a STATCOM device to fix the PF of the local distribution grids. 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.

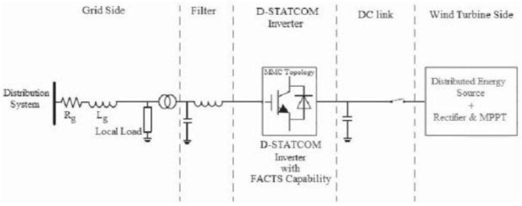

Fig. 1. Complete configuration of the proposed inverter with FACTS capability

II. MODULAR MULTILEVEL CONVERTER

MMC has gained increasing attention recently. A number of papers were published on the structure, control, and application of this topology [21], [22], but none has suggested the use of that for inverter + D-STATCOM application. This topology consists of several half-bridge (HB) submodules (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. 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.

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 (v_O) is either equal to its capacitor voltage (v_C) or zero, depending on the switching states. 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 submodule 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 submodule 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.

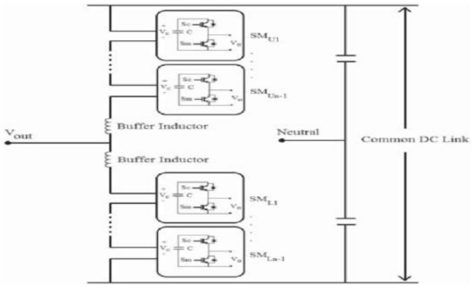

Fig 2: Structure of a single phase MMC inverter structure

Generally, when S_{ui} or S_{li} 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:

$$V_{\text{upper arm}} = \sum_{i=0}^{n-1} (S_{ui} v_{ci}) + v_{11} \qquad (1)$$

$$V_{\text{lower arm}} = \sum_{i=0}^{n-1} (S_{ui} v_{ci}) + v_{12} \qquad (2)$$

where v_{11} and v_{12} 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 SMs capacitor in upper arm or lower arm. A single-phase 11-level MMC 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

$$v_{DC} = v_{\text{upperArm}} + v_{\text{lower arm}}$$

III. PROPOSED CONTROL STRATEGY

The proposed controller consists of three major functions. The first function is to control the active and reactive power transferred to the power lines, the second function is to keep the voltages of the SMs' capacitors balanced, and the third function is to generate desired PWM signals. Fig. 3 shows the complete proposed controller system.

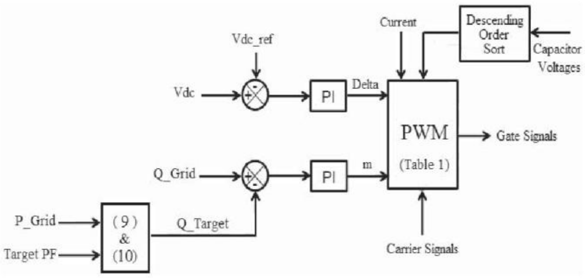

Fig. 3. Schematic of the proposed controller system

The aim of the designed inverter is to transfer active power coming from the wind turbine as well as to provide utilities with distributive control of volt-ampere reactive (VAR) compensation and PF correction of feeder lines. The application of the proposed inverter requires active and reactive power to be controlled fully independent. If there is no wind, the device should be only operating as a D-STATCOM (or capacitor bank) to regulate PF of the local grid. This translates to two modes of operation:
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 normal D-STATCOM to regulate the reactive power of the grid in order to control the PF of the grid and 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. Obviously, 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.

In the proposed control strategy, active and reactive power transferred between the inverter and the distribution grid is controlled by selecting both the voltage level of the inverter and the angle δ between the voltages of inverter and grid, respectively. The amplitude of the inverter voltage is regulated by changing the modulation index m and the angle δ by adding a delay to the firing signals.

In this paper, m is the key factor to control the reactive power compensation and its main task is to make the PF of the grid equal to the target PF. δ is the control parameter to adjust the active power control between the inverter and the grid.

IV. SIMULATION RESULTS

The design of an 11-level MMC inverter was carried out in MATLAB/Simulink. The simulation is 2s long and contains severe ramping and de-ramping of the wind turbine. The goal is to assess the behavior of the control system in the worst conditions. Figure 4 shows the simulation circuit of proposed 11-level inverter with wind turbine.

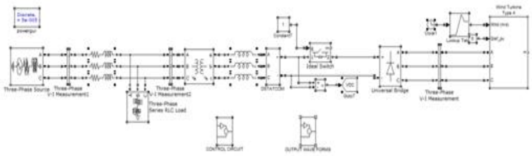

Fig.4 Simulation circuit of proposed inverter

Before t = 0.6 s, there is no wind to power the wind turbine; therefore, the dc link is open-circuited. At t = 0.6 s, the input power of the inverter is ramped up to 12 kW in 0.5 s, and then ramped down to 3.5 kW 0.4 s later. Fig. 5 shows the output active power from the wind turbine.

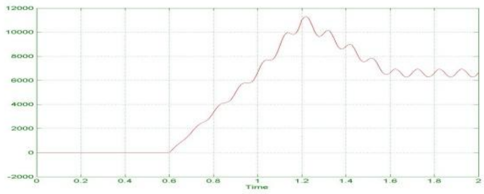

Fig 5. Simulated output active power from the wind turbine

In the simulation, the local load makes the PF 0.82. When the simulation starts, the inverter provides enough compensation to reach the target PF 0.90. Figure shows the output active and reactive power from the wind turbine and the grid.

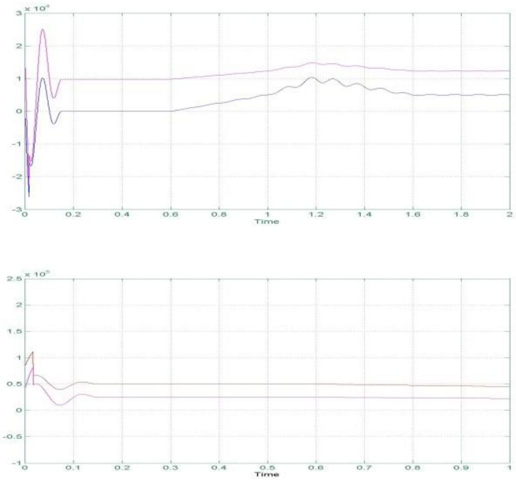

Fig. 6. Simulated active and reactive power of the inverter (top graph), active and reactive power of the power lines (bottom graph).

After t = 6 s, 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. The simulated output voltage of the inverter before the filter is shown in Fig. 8. Fig. 9 shows the PF of the grid. The PF of the grid is constant at 0.90 regardless of the active power from the wind turbine, showing that the main goal of the inverter is achieved.

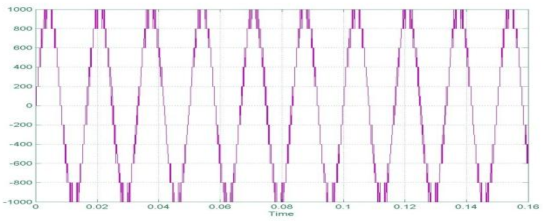

Fig.7. Simulated output voltage of an 11-level inverter

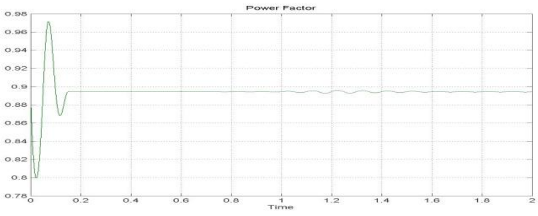

Fig. 8. Simulated PF of the grid.

The set-point for dc link voltage of the inverter is 2000 V and the RMS value of the output ac voltage is 600 V. The delta and modulation index graphs are shown in Fig. 10. As soon as the active power comes from the wind turbine, the controller system increases the value of the power angle in order to output more active power to the grid. Therefore, the active power provided from the feeder lines to the load is decreased, and as a result the reactive power from the feeder lines is decreased. Consequently, the modulation index is increased by the controller system to inject more reactive power needed by the load.

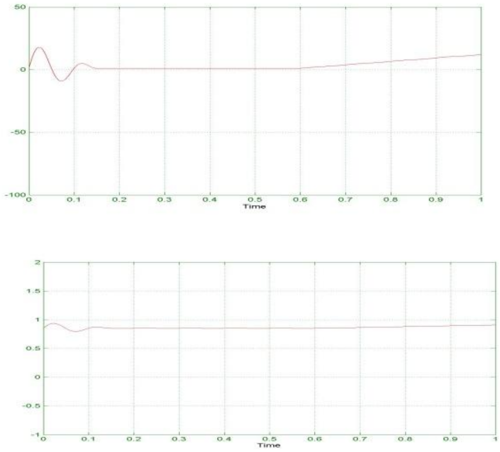

Fig. 9. Simulated delta and modulation index of 11-level inverter.

V. CONCLUSION:

In this paper, 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 renew- able 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.

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