ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Harmonic Analysis in A Grid Connected Wind Energy Systems Using 13 -Level Inverter with Facts Controllers

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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 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.

INTRODUCTION:

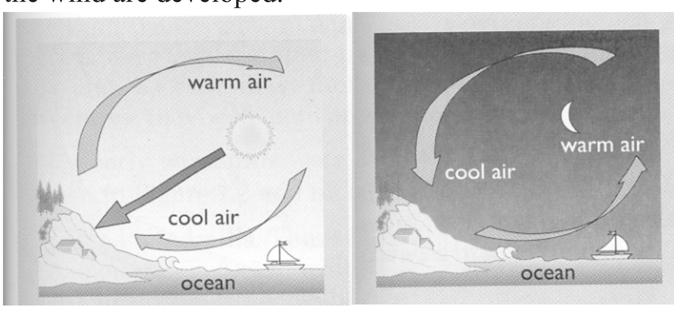
Recently, renewable energy systems have become a major part in modern power systems. The two major renewable energy sources, excluding hydro, are wind and solar which have some advantages such as being abundant and free. These are clean sources of energy which emit no greenhouse gas and are mostly free of political issues. The major disadvantage of these sources is that they are not available everywhere and are usually located in remote areas. In grid-connected applications, a power converter is needed between the renewable energy source and the main grid in order to improve the quality of output power of the renewable energy source, in terms of voltage and frequency. Regardless of the application for wind or solar systems, a renewable energy system needs an inverter right after its DC-link. In this paper, a new inverter with flexible AC transmission systems (FACTS) capability is proposed for renewable energy applications, especially for wind.

FACTS devices have been discussed in many papers due to their significant role in power systems. Briefly, FACTS devices are power electronic-based devices that are used to improve the power quality issues. One of the most important power quality issues is power factor (PF) of the grid. It is mostly desired to keep the PF of the grid near unity in order to be able to use the maximum capacity of the power systems. In common wind applications, an inverter is used to connect the wind turbine to the grid to transfer the active power coming from the wind turbine to the main grid. To improve the PF of the grid, a FACTS device is used to act as a sink or source of reactive power. The distribution static synchronous compensator (D-STATCOM) is a well-known member of the FACTS family, mostly used for distribution systems.

WIND ENERGY

Wind power:

Wind is abundant almost in any part of the world. Its existence in nature caused by uneven heating on the surface of the earth as well as the earth's rotation means that the wind resources will always be available. The conventional ways of generating electricity using non renewable resources such as coal, natural gas, oil and so on, have great impacts on the environment as it contributes vast quantities of carbon dioxide to the earth's atmosphere which in turn will cause the temperature of the earth's surface to increase, known as the green house effect. Hence, with the advances in science and technology, ways of generating electricity using renewable energy resources such as the wind are developed.



Features of wind power systems:

There are some distinctive energy end use features of wind power systems

i.Most wind power sites are in remote rural, island or marine areas. Energy requirements in such places are distinctive and do not require the high electrical power.

ii.A power system with mixed quality supplies can be a good match with total energy end use i.e. the supply of cheap variable voltage power for heating and expensive fixed voltage electricity for lights and motors.

iii.Rural grid systems are likely to be weak (low voltage 33 KV). Interfacing a Wind Energy Conversion System (WECS) in weak grids is difficult and detrimental to the workers' safety.

iv.There are always periods without wind. Thus, WECS must be linked energy storage or parallel generating system if supplies are to be maintained.

Power from the Wind:

Kinetic energy from the wind is used to turn the generator inside the wind turbine to produced electricity. There are several factors that contribute to the efficiency of the wind turbine in extracting the power from the wind. Firstly, the wind speed is one of the important factors in determining how much power can be extracted from the wind. This is because the power produced from the wind turbine is a function of the cubed of the wind speed. Thus, the wind speed if doubled, the power produced will be increased by eight times the original power. Then, location of the wind farm plays an important role in order for the wind turbine to extract the most available power form the wind. The next important factor of the wind turbine is the rotor blade. The rotor blades length of the wind turbine is one of the important aspects of the wind turbine since the power produced from the wind is also proportional to the swept area of the rotor blades i.e. the square of the diameter of the swept area. The relationship between the power produced by the wind source and the velocity of the wind and the rotor blades swept diameter is shown below.

$$P_{wind} = \frac{\pi}{8} dD^2 v_{wind}^3$$

The derivation to this formula can be looked up in [2]. It should be noted that some books derived the formula in terms of the swept area of the rotor blades (A) and the air density is denoted as

Wind power has the following advantages over the traditional power plants.

- •Improving price competitiveness,
- •Modular installation,
- •Rapid construction,
- •Complementary generation,
- •Improved system reliability, and
- •Non-polluting.

Wind Turbines:

There are two types of wind turbine in relation to their rotor settings. They are:

- •Horizontal-axis rotors, and
- •Vertical-axis rotors.

In this report, only the horizontal-axis wind turbine will be discussed since the modeling of the wind driven electric generator is assumed to have the horizontal-axis rotor.

STATCOM:

Flexible AC Transmission Systems, called FACTS, got in the recent years a well known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice.

- Power flow control,
- Increase of transmission capability,
- Voltage control,
- Reactive power compensation,
- Stability improvement,
- Power quality improvement,
- Power conditioning,
- Flicker mitigation,
- Interconnection of renewable and distributed generation and storages.

The development of FACTS-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the

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International Journal & Magazine of Engineering, Technology, Management and Research
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power system. Figure 1.2 shows a number of basic devices separated into the conventional ones and the FACTS-devices.

FUNCTIONAL REQUIREMENTS OF STATCOM:

The main functional requirements of the STATCOM in this thesis are to provide shunt compensation, operating in capacitive mode only, in terms of the following;

• Voltage stability control in a power system, as to compensate the loss voltage along transmission. This compensation of voltage has to be in synchronism with the AC system regardless of disturbances or change of load.
• Transient stability during disturbances in a system or a change of load.
• Direct voltage support to maintain sufficient line voltage for facilitating increased reactive power flow under heavy loads and for preventing voltage instability

In 1999 the first SVC with Voltage Source Converter called STATCOM (STATic COMpensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control.

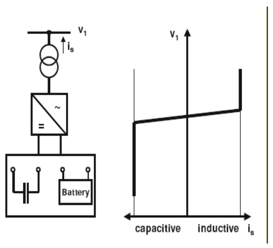

Fig2 STATCOM Structure And Voltage / Current Characteristic

STATCOMs are based on Voltage Sourced Converter (VSC) topology and utilize either Gate-Turn-off Thyristors (GTO) or Isolated Gate Bipolar Transistors (IGBT) devices. The STATCOM is a very fast acting, electronic equivalent of a synchronous condenser.

If the STATCOM voltage, Vs, (which is proportional to the dc bus voltage Vc) is larger than bus voltage, Es, then leading or capacitive VARS are produced. If Vs is smaller then Es then lagging or inductive VARS are produced.

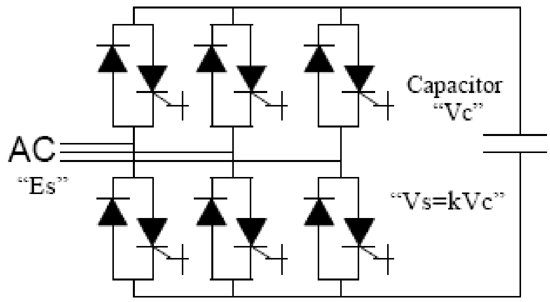

Fig 3 6 Pulses STATCOM

Several different control techniques can be used for the firing control of the STATCOM. Fundamental switching of the GTO/diode once per cycle can be used. This approach will minimize switching losses, but will generally utilize more complex transformer topologies. As an alternative, Pulse Width Modulated (PWM) techniques, which turn on and off the GTO or IGBT switch more than once per cycle, can be used. This approach allows for simpler transformer topologies at the expense of higher switching losses.

MULTI-LEVEL VSI:

It is possible to notice more and more publications concerning modernization and development, one of the basic directions in building DC/AC converters, which there are multi-level voltage inverters, formulating step voltages using few supply sources both isolated as sectioned. Absence in such inverters transformers takes off limitations in output voltage frequency control in range of low frequencies. In result it is possible to distinguish three basic solution directions of multi-level voltage inverters topologies:

- multi-level voltage inverters with levelling diodes (DC-Diode Clamped);

- multi-level voltage inverters with levelling capacitors (CC- Capacitor Clamped);

- multi-level voltage inverters as Isolated Series H-Bridges (ISHB), also called multi-level cascade inverters;

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On the base of above been mentioned structures, it is possible to create group of the new inverter topologies as connection of the standard three-phase inverters with one-phase bridge inverters.

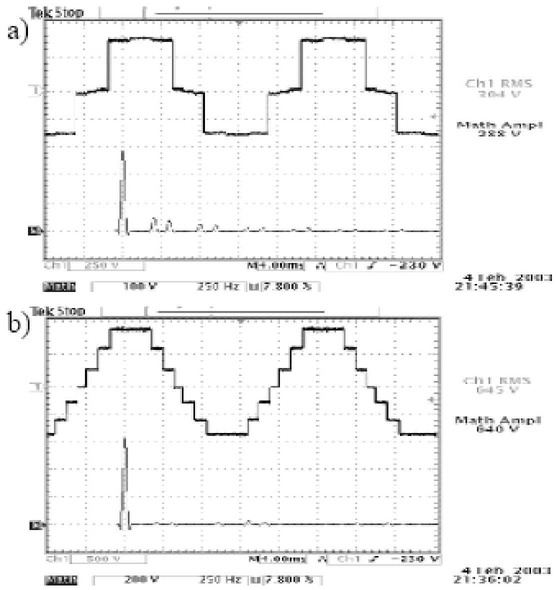

Fig.4 Phase-to-phase output voltage and its spectrum: a) standard VSI inverter; b) cascade topology multilevel VSI(without PWM).

EXTENSION:

Multilevel inverters include an array of power semiconductors and capacitor voltage sources, the output of which generate voltages with stepped waveforms. The commutation of switches permit the addition of capacitor voltages, which results as high voltage at output, while the power semiconductor must withstand only reduced voltages. The all different topologies presented in the multilevel inverter are cascaded, diode clamped and capacitor clamped. The main disadvantage associated with them is their circuit complexity, requiring a high number of power switches. This topology includes an H Bridge stage with an auxiliary bidirectional switch, drastically reducing the power circuit complexity, and a modulator and firing control circuit developed using a controller.

SIMPLIFIED 13 LEVEL INVERTER:

The different topologies presented in the multilevel inverter shows a number of characteristics in common. The main disadvantage associated with the multilevel inverter configuration is their circuit complexity, requiring a high number of power switches.

When we are entering the simplified H-Bridge multilevel inverter, power devices will be reduction and circuit complexity also reduction so circuit losses also reducing. Even taking into account the technological tendency to lower the prize at which multilevel inverter can compete with standard configuration. In the modulator circuit, the FPGA can perform all required modulation functions providing another important reduction in cost and circuit complexity.

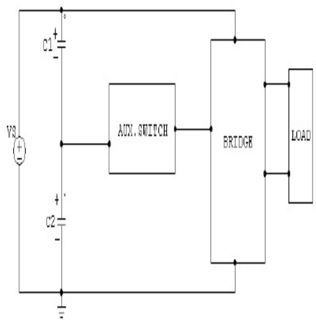

Fig 5: BLOCK DIAGRAM OF SIMPLIFIED 13 LEVELINV

PROPOSED CONTROL CIRCUIT OF A 13 LEVEL INVERTER:

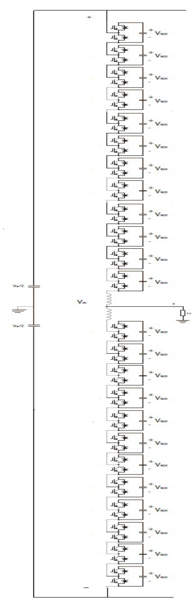

Fig 6.13 level inverter

CONFIGARATION OF A PROPOSED INVERTER WITH FACTS :

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 at target PF by injecting enough reactive power to the grid. In the proposed control strategy, the concepts of the inverter and the DSTATCOM have been combined to make a new inverter, which possesses FACTS capability with no additional cost.

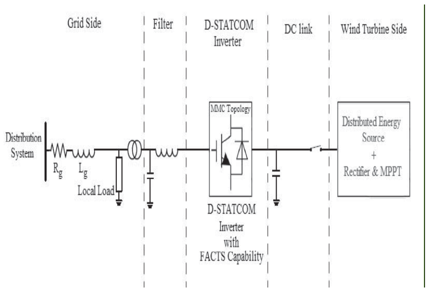

Fig 7 Complete configuration of the proposed inverter with Facts Capability

The proposed control strategy allows the inverter to act as an inverter with D-STATCOM option when there is enough wind to produce active power, and to act as a D-STATCOM when there is no wind. 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 [13], [14]. Reference [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 sub modules. In [9] and [16], a new single-phase inverter using hybrid clamped topology for renewable energy systems is presented.

MODULAR MULTILEVEL CONVERTER:

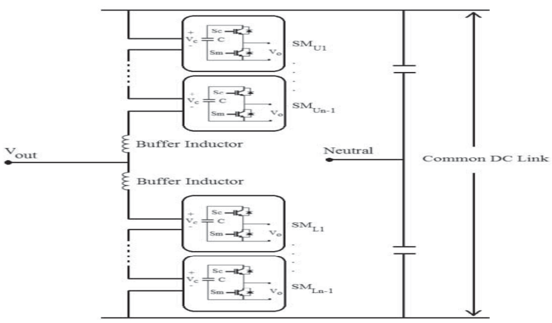

Fig 8 .Structure of a single-phase MMC inverter structure

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 possessestwo 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, thistopology 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 theGenerally, 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:

$$V\ upper\ Arm = \sum_{i=1}^{n-1} (Su1Vc1) + V11 \quad \ldots\ldots\ (1)$$

$$V\ lower\ Arm = \sum_{i=1}^{n-1} (S_{li}\, V_{c1}) + V_{12} \quad \ldots\ldots\ (2)$$

Where v11 and v12 are the voltages of the upper and lower buffer inductors, n is the number of voltage levels, and vci is the voltage of the i th SMs capacitor in upper arm or lower arm. A single-phase 13-level MMC inverter consists of 24 SMs which translates to 48 power switches, 20 capacitors, and 2 buffer inductors. The dc and ac voltages of the 13-level MMC are described by

$$V_{dc} = V\ upper\ arm + V\ lower\ arm$$

$$= \sum_{i=1}^{10} (S_{u1}\, v_{c_1}) + (V_{12} + V_{11}) \quad \ldots\ (3)$$

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 shows the complete 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.

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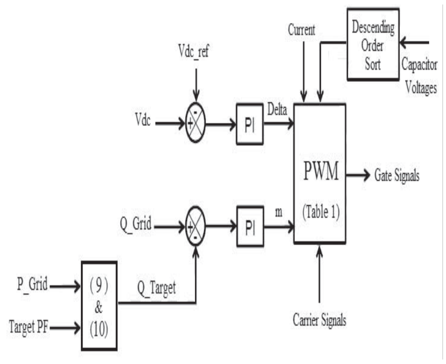

Fig 9 Schematic of the proposed controller system

The application of the proposed inverter requires active and reactive power to be controlled fully independent, so that if wind is blowing, the device should be working as a normal inverter plus being able to fix the PF of the local grid at a target PF (D-STATCOM option), and if there is no wind, the device should be onlyGenerally, (1) and (2) dictate the power flow between a STATCOM device and power lines

$$PS = \frac{-ESEL}{X} \sin\delta \qquad \text{………(1)}$$

$$QS = \frac{-\quad ESEL \cos\delta - El^2}{X} \qquad .(2)$$

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.Several assumptions should be considered for the proposed controller which is as:

1) The load on the feeder line should be considered fixed for a small window of time and there is no change in the load during a cycle of the grid frequency;

2) The feeder line can be accurately modelled as a constant P,Q load. This means that the power produced by a wind turbine will displace other power on the feeder line and not add to it; 3) Although making a change in m or δ has effect on both (3) and I

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	$-^{5v_{dc}}/_{10}$

The most critical issue to control MMC is to maintainthe 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, so that capacitors are being charged, nupperArmand nupperArm and of the SMs in upper arm and lower arm with the lowest voltages are selected, respectively. As a result, ten capacitors with lowest voltages are chosen to be charged
N upper Arm + n lower Arm = 12
In the 13 level inverter cpwm technique
Vr is compared to 6Vdc/12 and -6 Vdc/12

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

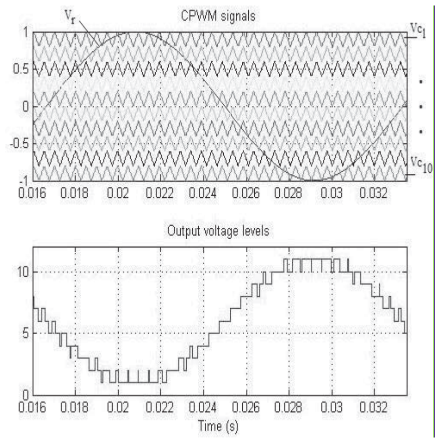

Fig 10 CPWM waveforms for an11-level MMC inverter, and the generated output voltage levels:
SIMULATION AND PRACTICAL RESULSTS

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The design of an 11-level MMC inverter was carried out in MATLAB/Simulink. The simulation is 20 s 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. Before t = 6 s, there is no wind to power the wind turbine;therefore, the dc link is open-circuited. At t = 6 s, the input power rampe up to 12 kW in 5 s d. Fig. 11 shows the output active power from the wind turbine. In the simulation, the local load makes the PF 0.82.

Wind power :

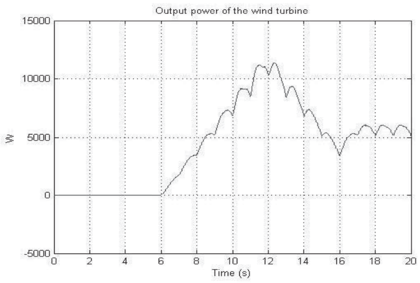

Fig 11 schematic output active power from wind turbine

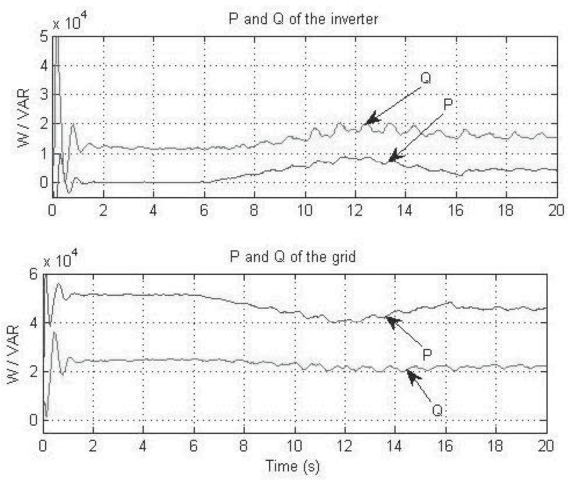

Fig. 12 . Simulated active and reactive power of the inverter (top graph), active and reactive power of the power lines (bottom grap

Simulated Pf Of The Grid

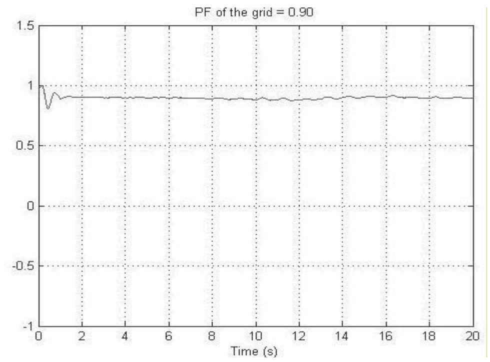

Fig 13   Simulated Pf Of The Grid THD:

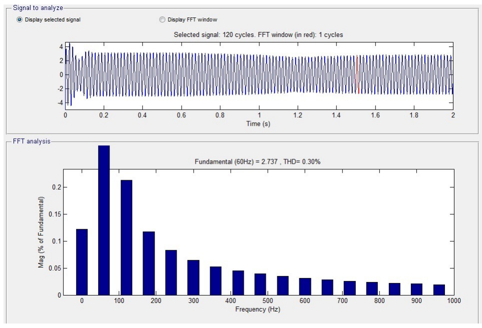

Fig 14 Thd Of The 13 Level Inverter

Simulated outout voltage of an 11 level inverter

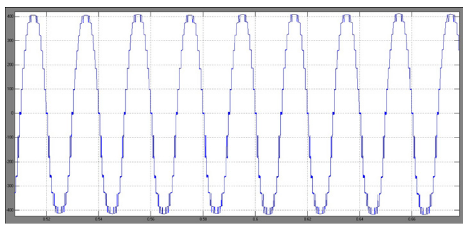

Fig 15 Simulated outout voltage of an 11 level inverter

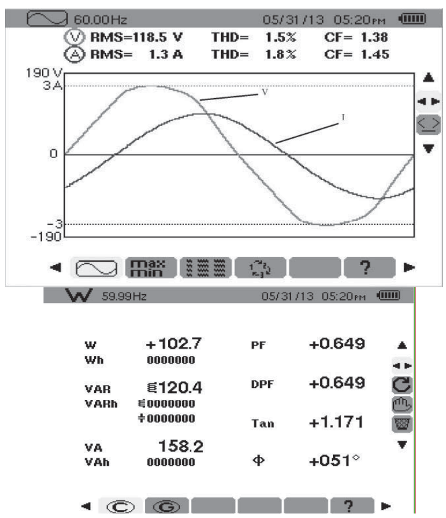

Fig. 16. Grid parameters before compensation where the compensator is disconnected from the grid. (a) Voltage and current. (b) Active power, reactive power, and PF

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 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.

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