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Reactive Power Compensation using a 11 Level Inverter

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Abstract- The Modern world runs on naturally obtained combustible resources. They are easy to use but are depleted quickly. Thus the use of renewable resources is increasing in our daily lives. The main drawback for these resources is that they are costly. Their production plants have high initial capital and large transmission and distribution costs. The following paper relates to one such renewable source and its transmission i.e. wind energy. Wind energy is harnessed with the help of turbines. The turbines are used to run generators to produce electrical power. The produced electrical power is then transmitted via electrical transmission lines. Wind energy cannot be used commercially in big cities as the plant output is low compared to other plants. They are mainly used to supply power in villages. Thus there is a need to decrease the transmission cost of the line. The lines used to transmit power at high power factor use synchronous compensators or other similar FACTS devices. The idea of the project is to control the power factor without the installation of FACTS devices. The output of the turbine-generator combination is a low frequency ac output. In order to supply the said output in a transmission line a wind energy inverter is used. The wind energy inverter changes the low frequency output to a suitable input frequency of the transmission line. Now if the wind energy inverter can also change the power factor of the line, then extra FACTS devices will not be required for the line. This is the purpose of the proposed inverter i.e. "to make the wind energy inverter also change the power factor of the line" so as to do away with the installation of FACTS devices and thereby decreasing the overall cost of the distribution system. This ensures easy injection of renewable power in our daily life.

Index Terms- *Modular Multilevel Inverter (MMC), Multilevel Inverter (MLI), Power Factor (pf), Total Harmonic Distortion (THD), Wind Energy Inverter (WEI).*

I. INTRODUCTION

What is wind energy?

Wind energy is the power that is generated through the conversion of kinetic energy in the wind into other forms of energy that are more practically useful, such as electricity.

Wind energy or wind power is extracted from air flow using wind turbines or sails to produce mechanical or electrical energy. Windmills are used for their mechanical power, wind pumps for water pumping, and sail to propel ships. Wind power as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation, and uses little land. The net effects on the environment are far less problematic than those of nonrenewable power sources.

Wind farms consist of many individual wind turbines which are connected to the electric power transmission network. Onshore wind is an inexpensive source of electricity, competitive with or in many places cheaper than coal or gas plants. Offshore wind is steadier and stronger than on land, and offshore farms have less visual impact, but construction and maintenance costs are considerably higher. Small onshore wind farms can feed some energy into the grid or provide electricity to isolated off-grid locations.

Wind power is very consistent from year to year but has significant variation over shorter time scales. It is therefore used in conjunction with other electric power sources to give a reliable supply. As the proportion of wind power in a region increases, a need to upgrade the grid and a lowered ability to supplant conventional production can occur. Power management techniques such as having excess capacity, geographically distributed turbines, dispatch able backing sources, sufficient hydroelectric power, exporting and importing power to neighboring areas, using vehicle-to-grid strategies or reducing demand when wind production is low, can in many cases overcome these problems. In addition, weather forecasting permits the electricity network to be readied for the predictable variations in production that occur.

As of 2014, Denmark has been generating around 40% of its electricity from wind, and at least 83 other countries around the world are using wind power to supply their electricity grids. Wind power capacity has expanded to 369,553 MW by December 2014, and total wind energy production is growing rapidly and has reached around 4% of worldwide electricity usage.

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II. Small scale turbine and inverter

A. Wind energy Inverter

Compared with MW system, small wind generators are used mainly to recharge batteries, applications in a separate power supply network or system near a lake to fetch water. For the application domain, there are a lot of the machines whose prices are reasonable. However, with the development of small wind power system, it applied the trend of a new machine in recent years. It can produce electric power and directly provide for the regular network or independent off-grid system. The new application for electricity becomes more flexible and can also provide indirect power for electricity users. In order to save costs for expensive and maintenance costs of the battery group, these wind of the grid-connected technology to save a lot of expenditure costs. Small wind turbine grid-connected power system contains wind driven generator port controller, grid-connected inverter power distribution equipment. When the wind speed reaches the cut-in wind speed, after rectification, inversion the AC power generated from the wind generator feeds into the grid.

B. Wind Turbines

A wind turbine is a device that converts kinetic energy from the wind into electrical power. The term appears to have migrated from parallel hydroelectric technology (rotary propeller). The technical description for this type of machine is an aerofoil-powered generator.

A quantitative measure of the wind energy available at any location is called the Wind Power Density (WPD). It is a calculation of the mean annual power available per square meter of swept area of a turbine, and is tabulated for different heights above ground. Calculation of wind power density includes the effect of wind velocity and air density. Color-coded maps are prepared for a particular area described, for example, as "Mean Annual Power Density at 50 Meters". The larger the WPD calculation, the higher it is rated by class. Classes range from Class 1 (200 watts per square meter or less at 50 m altitude) to Class 7 (800 to 2000 watts per square m). Commercial wind farms generally are sited in Class 3 or higher areas, although isolated points in an otherwise Class 1 area may be practical to exploit.

Wind turbines are classified by the wind speed they are designed for, from class I to class IV, with A or B referring to the turbulence.

Class	Average wind speed (m/s)	Turbulence
I A	10	18%
I B	10	16%
II A	8.5	18%
II B	8.5	16%
III A	7.5	18%
III B	7.5	16%
IV A	6	18%
IV B	6	16%

Table 1: Classification of wind turbine based on turbulence

Turbine Construction:

Wind turbines are designed to exploit the wind energy that exists at a location. Aerodynamic modeling is used to determine the optimum tower height, control systems, number of blades and blade shape. Wind turbines convert wind energy to electricity for distribution. Conventional horizontal axis turbines can be divided into three components:

i. The rotor component, which is approximately 20% of the wind turbine cost, includes the blades for converting wind energy to low speed rotational energy.
ii. T he generator component, which is approximately 34% of the wind turbine cost, includes the electrical generator, the control electronics, and most likely a gearbox, adjustable-speed drive or continuously variable transmission component for converting the low speed incoming rotation to high speed rotation suitable for generating electricity.
iii. The structural support component, which is approximately 15% of the wind turbine cost, includes the tower and rotor yaw mechanism.

A 1.5 MW wind turbine of a type frequently used has a tower 80 meters high. The rotor assembly weighs 22,000 kilograms. The nacelle, which contains the generator component, weighs 52,000 kilograms. The concrete base for the tower is constructed using

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26,000 kilograms of reinforcing steel and contains 190 cubic meters of concrete. The base is 15 meters in diameter and 2.4 meters thick near the center.

Among all renewable energy systems wind turbines have the highest effective intensity of power-harvesting surface because turbine blades not only harvest wind power, but also concentrate it.

Turbine Efficiency:

Not all the energy of blowing wind can be used, but some small wind turbines are designed to work at low wind speeds. Conservation of mass requires that the amount of air entering and exiting a turbine must be equal. Accordingly, Betz's law gives the maximal achievable extraction of wind power by a wind turbine as 59% of the total kinetic energy of the air flowing through the turbine.

Further inefficiencies, such as rotor blade friction and drag, gearbox losses, generator and converter losses, reduce the power delivered by a wind turbine. Commercial utility-connected turbines deliver 75% to 80% of the Betz limit of power extractable from the wind, at rated operating speed.

Efficiency can decrease slightly over time due to wear. Analysis of 3128 wind turbines older than 10 years in Denmark showed that half of the turbines had no decrease, while the other half saw a production decrease of 1.2% per year.

DC Link:

A DC link exists between a rectifier and an inverter.

On one end, the utility connection is rectified into a high voltage DC. On the other end, that DC is switched to generate a new AC power waveform. It's a link because it connects the input and output stages.

Two high power AC networks can be connected via a DC link, as that does not require both networks to be synchronized in frequency and phase, which is often difficult or impossible.

The switching network on the output side generates very large transients at the switching frequency. The DC link capacitor helps to keep these transients from radiating back to the input. This can also help prevent the switching network from oscillating or triggering inadvertently at an inappropriate moment and causing a short. Additionally, if the input is not multiple-phase, the capacitor helps provide a source of energy when the input waveform is near zero.

Filter:

Electronic filters are analog circuits which perform signal processing functions, specifically to remove unwanted frequency components from the signal, to enhance wanted ones, or both.

This is mainly done to remove the unwanted harmonics generated in the electrical signal due to the inverter action.

C. D-STATCOM Inverter

A static synchronous compensator (STATCOM), also known as a static synchronous condenser (STATCON), is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. It is a member of the FACTS family of devices. It is inherently modular and electable.

Uses:

Usually a STATCOM is installed to support electricity networks that have a poor power factor and often poor voltage regulation. There are however, other uses, the most common use is for voltage stability. A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. The voltage source is created from a DC capacitor and therefore a STATCOM has very little active power capability. However, its active power capability can be increased if a suitable energy storage device is connected across the DC capacitor.

The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source. For example, if the terminal voltage of the VSC is higher than the AC voltage at the point of connection, the STATCOM generates reactive current; conversely, when the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power. The response time of a STATCOM is shorter than that of a static VAR compensator (SVC), mainly due to the fast switching times provided by the IGBTs of the voltage source converter.

The STATCOM also provides better reactive power support at low AC voltages than an SVC, since the reactive power from a STATCOM decreases linearly with the AC voltage (as the current can be maintained at the rated value even down to low AC voltage)

A static VAR compensator can also be used for voltage stability. However, a STATCOM has better characteristics than an SVC. When the system voltage drops sufficiently to force the STATCOM output current to its ceiling, its maximum reactive output current will not be affected by the voltage magnitude. Therefore, it exhibits constant current characteristics when the voltage is low under the limit.

In contrast the SVC's reactive output is proportional to the square of the voltage magnitude. This makes the provided reactive power decrease rapidly when voltage decreases, thus reducing its stability. In addition, the speed of response of a STATCOM is faster than that of an SVC and the harmonic emission is lower, however STATCOMs typically exhibit higher losses and may be more expensive than SVCs, so the (older) SVC technology is still widespread.

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III. Power factor control using a D-STATCOM device

A. Power factor and FACTS Inverter

The role 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. With 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. 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. 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 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. 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.

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.

In the proposed control strategy, the concepts of the inverter and the D-STATCOM have been combined to make a new inverter, which possesses FACTS capability with no additional cost. 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 active power is controlled by adjusting the power angle δ, which is the angle between the voltages of the inverter and the grid, and reactive power is regulated by the modulation index m.

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. In 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 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. Several other applications of custom power electronics in renewable energy systems exist, including an application of a custom power interface where two modes of operation, including an active power filter and a renewable energy STATCOM. Another application looks at the current source inverter, which controls reactive power and regulates voltage at the point of common coupling (PCC). Varma et al 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. The authors called their proposed system PV-STATCOM. Similar to wind farms (when there is no wind), solar farms are idle during nights. We proposed a control strategy that makes the solar farms to act as STATCOMs during night when they are not able to produce active power. The main purpose of the PV-STATCOM system is to improve the voltage control and the PF correction on three-phase transmission systems.

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. Obviously, depending on the size of the power system, multiple inverters might be used in order to reach the desired

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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.

B. Using MATLAB Software.

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. Table III shows the values of the parameters used for the simulation. 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 of the inverter is ramped up to 12 kW in 5 s, and then ramped down to 3.5 kW 4 s later. Fig. 1 shows the 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. Fig. 2 shows the output active and reactive power from the wind turbine and the grid. 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. 3. Fig. 4 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. 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. 5. 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. To validate the simulation results, a scaled version of the proposed inverter has been built and tested. The power rating of the scaled prototype model is 250 W and/or VAR, which is limited by the rating of the semiconductor devices. The experimental results serve only as a proof-of-concept. In order to implement the control strategy and to handle the feedback signals, two CLP 1104 dSPACE systems have been synchronized. A three-phase PM generator driven by a variable speed dc motor is used to emulate the wind speed change. The test bench setup and the 11-level prototype inverter was made.The efficiency of the inverter is close to 0.95. The experimental output voltage THD and current TDD is 2.7 and 2.12%, respectively. In grid-connected mode, the inverter is connected to the grid through a transformer with the ratio 120:24. The load PF is set to 0.65 and the target PF is 0.90. In this case, the job of the inverter is to fix the PF at the target PF regardless of the input active power from the wind emulator.

In order to show the performance of the system conveniently, an AEMC 8230 power meter is used and the practical results are captured and shown using and the ControlDesk, which is a helpful tool associated with the dSPACE 1104 package. Fig. 6(a) shows the system parameters after compensation when there is no active power coming from the wind emulator. In this case, the inverter acts as a D-STATCOMto improve the PF of the grid. Ideally, there should be no active power transfer between the two sources, but due to the non ideality of the components and to charge the capacitors, 10 W is drawn from the grid. As it can be seen, the compensated PF of the local grid is constant at 0.90: the inverter is performing properly as a D-STATCOM. Fig. 6(b) shows the system parameters after compensation when there is active power from the wind emulator. In this case, the inverter is acting as an inverter with PF correction capability and the PF of the local grid is fixed at 0.90 with small oscillations. Figs. 13 and 14 show that the grid PF before compensation is 0.65 and after the compensation is constant at the target PF, which is 0.90 in this case, regardless of the input active power from the wind emulator. The amount of active power which is drawn from the grid changes with the amount of incoming active power from the wind emulator.

When the output power of the wind turbine is increased, the level of active power provided by the feeder line is decreased by the same amount. The inverter transfers the whole active power of the wind, excluding its losses, to the grid. The amount of reactive power is dictated by the target PF. When the active power from the wind turbine increases, the controller increases the power angle δ in order to output more active power to the grid in order to decrease the dc link voltage. The modulation index m is also increased when the inverter is supposed to inject more reactive power to the grid. The transient response of the PI controllers used to control the modulation index and delta can be adjusted by changing the proportional and integral coefficients of the controllers. The practical results show that the performance of the proposed controller strategy is sufficiently close to the simulation results. The PI controllers show a proper performance during severe changes in the wind speed, which is emulated by the wind emulator.

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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	$-5v_{dc}/10$

Table 2: Operating regions of the Inverter

Parameter	Value
L_{line}	15 mH
R_{line}	1 Ohm
L_{Filter}	5 mH
Transformer primary voltage	12000 V
Transformer secondary voltage	600 V
Switching frequency	2 kHz
Load active power	50 kW
Load reactive power	34.8 kVAR
Target PF	0.90
DC link Voltage	2000 V

Table 3: Parameters used for Simulation

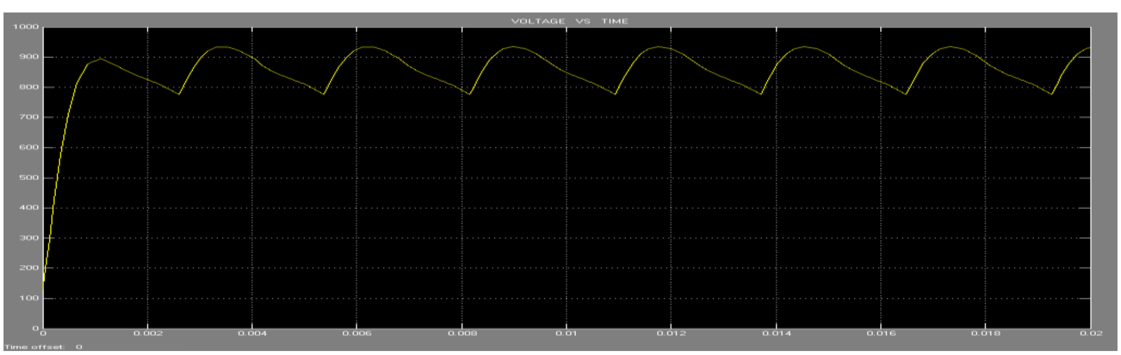

Figure 1: Simulated output active power from the wind turbine

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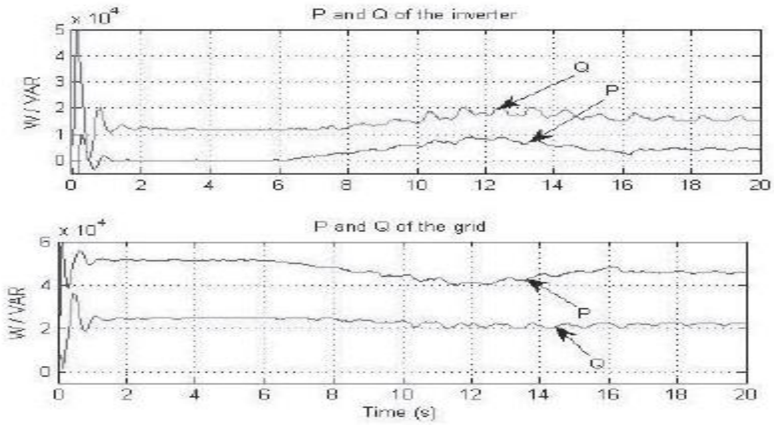

Figure 2: Simulated active and reactive power of the inverter (top graph), active and reactive power of the power lines (bottom graph).

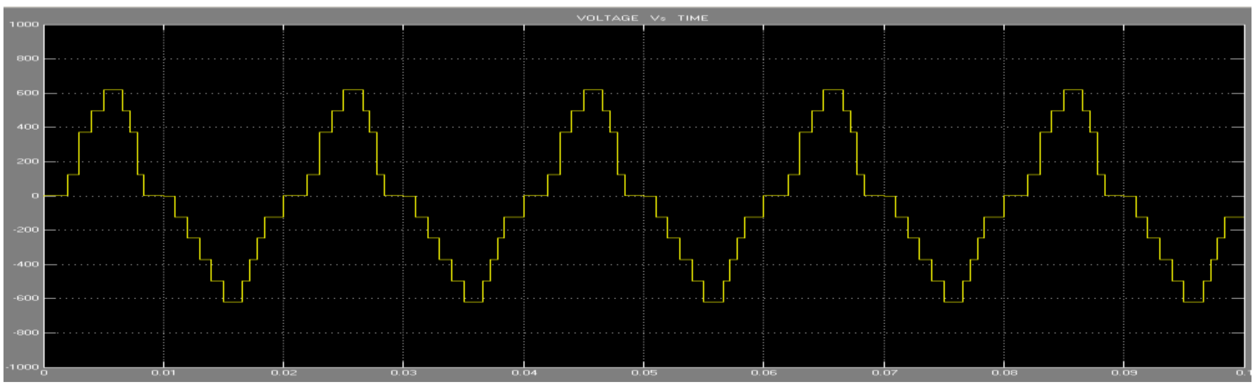

Figure 3: Simulated output voltage of an 11-level inverter

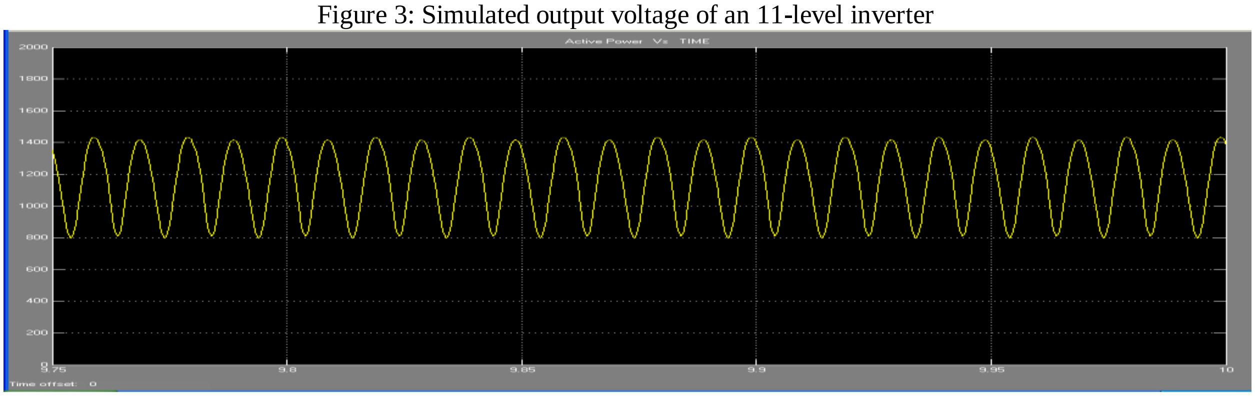

Figure 4: Simulated Active Power Output

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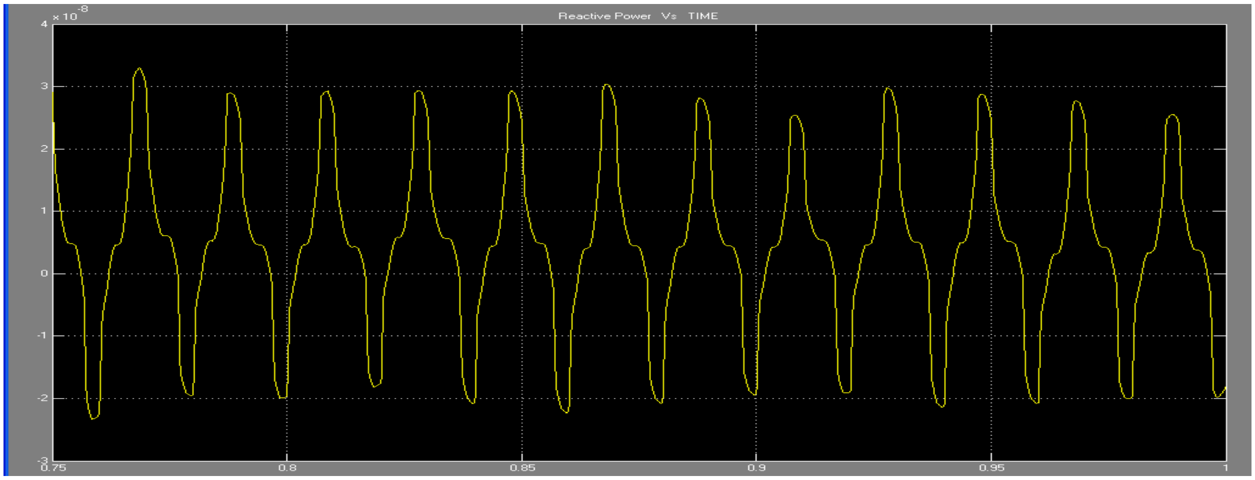

Figure 5: Simulated Reactive Power Output

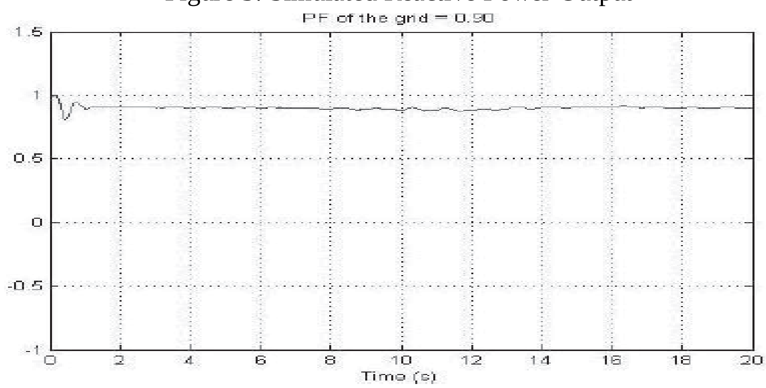

Figure 6: Simulated PF of the grid.

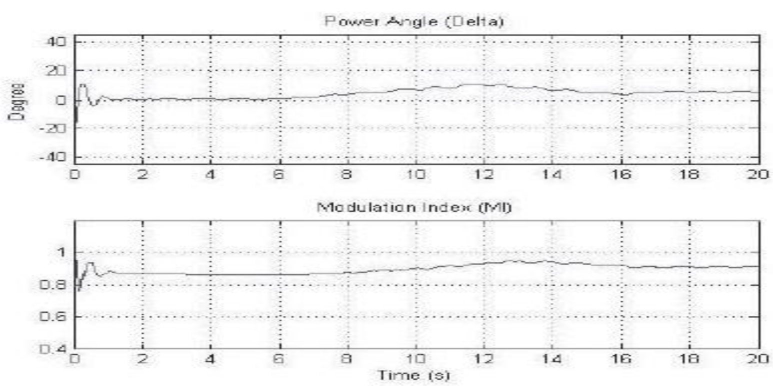

Figure 7: Simulated delta and modulation index of the 11-level inverter.

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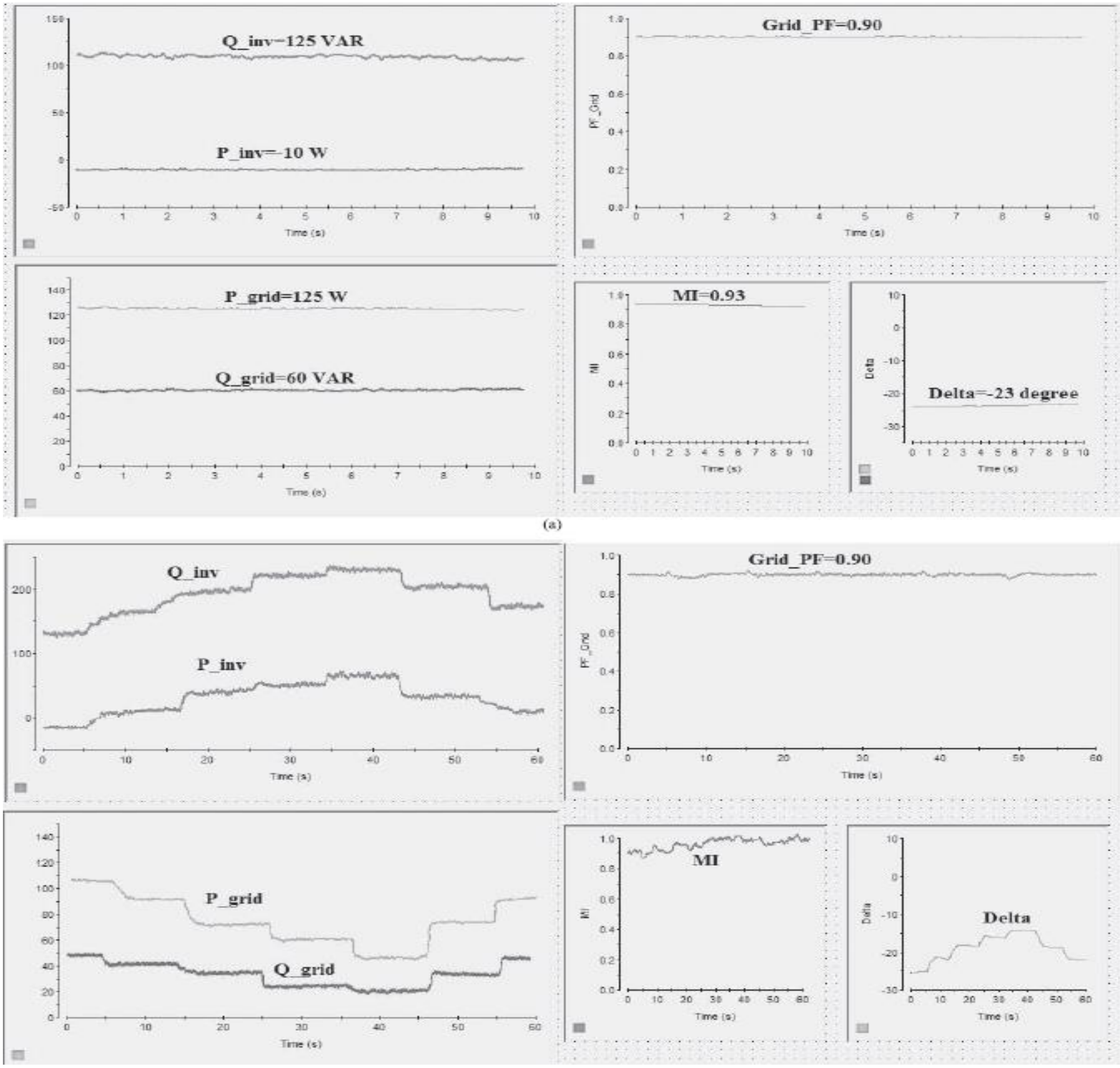

Figure 8: System parameters where the inverter is connected to the grid. (a) When wind speed is zero and there is no active power coming from wind emulator. (b) When wind speed is changing and the incoming active power from the wind emulator is changing.

IV. CONCLUSION

Thus as shown above we can control the power factor of the line by using the proposed inverter. This makes the addition of FACTS equipment in the distribution lines for reactive power compensation unnecessary. Hence they decrease the overall cost of the distribution system.

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