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Coordinated Control and Energy Management of Distributed Generation Inverters in a Microgrid

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***Abstract*—This paper presents a microgrid consisting of different distributed generation (DG) units that are connected tothe distribution grid. An energy-management algorithm is implemented to coordinate the operations of the different DG units inthemicrogridforgrid-connectedandislandedoperations. The proposed microgrid consists of a photovoltaic (PV) array which functions as the primary generation unit of the microgrid and a proton-exchange membrane fuel cell to supplement the variability in the power generated by the PV array. Alithium-ion storage battery is incorporated into the micro grid to mitigate peak demands during grid-connected operation and to compensate for any shortage in the generated power during islanded operation. The control design for the DG inverters employs a new model predictive control algorithm which enables faster computational time for large power systems by optimizing the steady-state and the transient control problems separately.**

***Index Terms*—Distributed generation (DG), energy management, microgrid, model predictive control (MPC).**

I.INTRODUCTION

The ever-increasing energy consumption, fossil fuels' soaring costs and exhaustible nature, and worsening global environment have created a booming interest in renewable energy generation systems, one of which is photovoltaic. Such a system generates electricity by converting the Sun's energy directly into electricity. Photovoltaic-generated energy can be delivered to power system networks through grid-connectedinverters.A single-phase grid-connected inverter is usually used for residential or low-power applications of power ranges that are less than 10 kW. Types of single-phase grid-connected inverters have been investigated. A common topology of this inverter is full-bridge three-level.

1.1. Photovoltaic technology

Photovoltaic is the field of technology and research related to the devices which directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic effect involves the creation of voltage in a material upon exposure to electromagnetic radiation

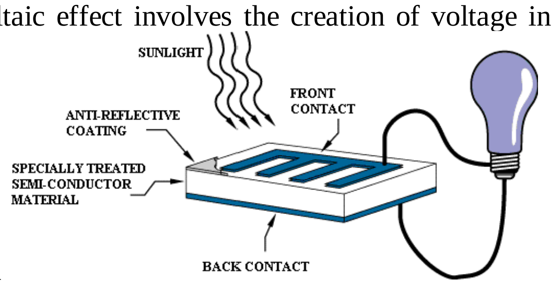

Fig: 1. 1. Basic model of photovoltaic system

1.2. Solar cell:

The photovoltaic effect was first reported by Edmund Becquerel in 1839when he observed that the action of light on a silver coated platinum electrode immersed in electrolyte produced an electric current. Forty years later the first solid state photovoltaic devices were constructed by workers investigating the recently discovered photoconductivity of selenium. In1876 William Adams and Richard Day found that a photocurrent could be produced in a sample of selenium when contacted by two heated platinum contacts. The photovoltaic action of the selenium differed from its photoconductive action in that a current was produced spontaneously by the action of light.

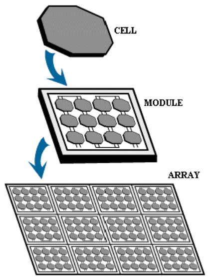

Fig:1.2.Basic solar cells

1.3. Electrical connection of the cells

The electrical output of a single cell is dependent on the design of the device and the Semi-conductor material(s) chosen, but is usually insufficient for most applications. In order to provide the appropriate quantity of electrical power, a number of cells must be electrically connected. There are two basic connection methods: series connection, in which the top contact of each cell is connected to the back contact of the next cell in the sequence, and parallel connection, in which all the top contacts are connected together, as are all the bottom contacts. In both cases, this results in just two electrical connection points for the group of cells.

1.3.1Series connection:

Figure shows the series connection of three individual cells as an example and the resultant group of connected cells is commonly referred to as a series string. The current output of the string is equivalent to the current of a single cell, but the voltage output is increased, being an addition of the voltages from all the cells in the string (i.e. in this case, the voltage output is equal to 3Vcell).It is important to have well matched cells in the series string, particularly with respect to current. If one cell produces a significantly lower current than the other cells (under the same illumination conditions), then the string will operate at that lower current level and the remaining cells will not be operating at their maximum power points.

1.3.2Parallel connection

Figure shows the parallel connection of three individual cells as an example. In this case, the current from the cell group is equivalent to the addition of the current from each cell (in this case, 3 I cell), but the voltage remains equivalent to that of a single cell.As before, it is important to have the cells well matched in order to gain maximum output, but this time the voltage is the important parameter since all cells must be at the same operating voltage. If the voltage at the maximum power point is substantially different for one of the cells, then this will force all the cells to operate off their maximum power point, with the poorer cell being pushed towards its open-circuit voltage value and the better cells to voltages below the maximum power point voltage. In all cases, the power level will be reduced below the optimum.

1.4. The Photovoltaic array

A PV array consists of a number of PV modules, mounted in the same plane and electrically connected to give the required electrical output for the application. The PV array can be of any size from a few hundred watts to hundreds of kilowatts, although the larger systems are often divided into several electrically independent sub arrays each feeding into their own power conditioning system.

II. PHOTOVOLTAIC INVERTER

The inverter is the heart of the PV system and is the focus of all utility-interconnection codes and standards. A Solar inverter or PV inverter is a type of electrical inverter that is made to change the direct current (DC) electricity from a photovoltaic array into alternating current (AC) for use with home appliances and possibly a utility grid. Since the PV array is a dc source, an inverter is required to convert the dc power to normal ac power that is used in our homes and offices. To save energy they run only when the sun is up and should be located in cool locations away from direct sunlight. The PCU is a general term for all the equipment involved including the inverter and the interface with the PV (and battery system if used) and the utility grid. It is very important to point out that inverters are by design much safer than rotating generators. Of particular concern to utility engineers is how much current a generator can deliver during a fault on their system. Inverters generally produce less than 20% of the fault current as a synchronous generator of the same nameplate capacity. This is a very significant difference.

2.1. Inverter classification:

Solar inverters may be classified into three broad types:

2.1.1 Stand-alone inverters, used in isolated systems where the inverter draws its DC energy from batteries charged by photovoltaic arrays and/or other sources, such as wind turbines, hydro turbines, or engine generators.

2.1.2 Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available. Normally these do not interface in any way with the utility grid, and as such, are not required to have anti-islanding protection.

2.2. Anti-islanding protection

Normally, grid-tied inverters will shut off if they do not detect the presence of the utility grid. If, however, there are load circuits in the electrical system that happen to resonate at the frequency of the utility grid, the inverter may be fooled into thinking that the grid is still active even after it had been shut down. This is called islanding.

Islanding refers to the condition of a distributed generation (DG) generator continuing to power a location even though power from the electric utility is no longer present. Consider for example a building that has solar panels that feed power back to the electrical grid; in case of a power blackout, if the solar panels continue to power the building, the building becomes an "island" with power surrounded by a "sea" of unpowered buildings.

2.3. Detection methods

Detecting the absence of power from the grid is complicated by two items:

2.3.1 The distributed generator itself is a source of power whose voltage is by definition identical to the voltage from the grid, so it is hard to distinguish the two.

2.3.2 A nearby motor may continue to spin and act as a generator, creating a frequency similar to the original line frequency (50 or 60 Hz).

2.3.3 That may be also true if the load in the building forms a resonant circuit at the line frequency.

2.4. Maximum power point tracking (MPPT)

Maximum power point tracking is a technique that solar inverters use to get the most possible power from the PV array. Any given PV module or string of modules will have a maximum power point: essentially, this defines current that the inverter should draw from the PV in order to get the most possible power (power is equal to voltage times current).

A maximum power point tracker (or MPPT) is a high efficiency DC to DC converter that presents an optimal electrical load to a solar panel or array and produces a voltage suitable for the load.

2.5. Grid tie inverters

Many solar inverters are designed to be connected to a utility grid, and will not operate when they do not detect the presence of the grid. They contain special circuitry to precisely match the voltage and frequency of the grid.

2.6. Charge controllers

Stand-alone inverters thatis, inverters that are designed to be used without the presence of the electrical utility grid can be run from PV panels and batteries using a charge controller. The charge controller regulates the input from the PV and the batteries, regulates the battery output, and handles charging the batteries.

III.INVERTER

An **inverter** is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.Static inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utilityhigh-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries.The electrical inverter is a high-power electronic oscillator. It is so named because early mechanical AC to DC converterswere made to work in reverse, and thus were "inverted", to convert DC to AC.The inverter performs the opposite function of a rectifier

3.1. Cascaded H-Bridges inverter

A single-phase structure of an m-level cascaded inverter is illustrated in Figure. Each separate dc source (SDCS) is connected to a single-phase full-bridge, or H-bridge, inverter. Each inverter level

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can generate three different voltage outputs, $+V_{dc}$, 0, and $–V_{dc}$ by connecting the dc source to the ac output by different combinations of the four switches, S_1, S_2, S_3, and S_4. To obtain $+V_{dc}$, switches S_1 and S_4 are turned on, whereas $–V_{dc}$ can be obtained by turning on switches S_2 and S_3. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs.

3.2. Diode-Clamped Multilevel Inverter

The neutral point converter proposed by Nabae, Takahashi, and Akagi in 1981 was essentially a three-level diode-clamped inverter [5]. In the 1990s several researchers published articles that have reported experimental results for four-, five-, and six-level diode-clamped converters for such uses as static var compensation, variable speed motor drives, and high-voltage system interconnections [18-31].

3.3. Flying Capacitor Multilevel Inverter

Meynard and Foch introduced a flying-capacitor-based inverter in 1992 [32]. The structure of this inverter is similar to that of the diode-clamped inverter except that instead of using clamping diodes, the inverter uses capacitors in their place. The circuit topology of the flying capacitor multilevel inverter is shown in Figure 31.7. This topology has a ladder structure of dc side capacitors, where the voltage on each capacitor differs from that of the next capacitor. The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform.

3.4. Multilevel Converter PWM Modulation Strategies

Pulse width modulation (PWM) strategies used in a conventional inverter can be modified to use in multilevel converters. The advent of the multilevel converter PWM modulation methodologies can be classified according to switching frequency as illustrated in Figure 3.6.

The three multilevel PWM methods most discussed in the literature have been multilevel carrier-based PWM, selective harmonic elimination, and multilevel space vector PWM; all are extensions of traditional two-level PWM strategies to several levels. Other multilevel PWM methods have been used to a much lesser extent by researchers; therefore, only the three major techniques will be discussed in this chapter.

3.5. Multilevel converter design example

In a multilevel inverter, determining the number of levels will be one of the most important factors because this affects many of the other sizing factors and control techniques. Tradeoffs in specifying the number of levels that the power conditioner will need and the advantages and complexity of having multiple voltage levels available are the primary differences that set a multilevel filter apart from a single level filter.

As a starting point, known is the nominal RMS voltage rating, V_{nom}, of the electrical system to which the diode clamped power conditioner will be connected. The dc link voltage must be at least as high as the amplitude of the nominal line-neutral voltage at the point of connection, or2·Vnom.

3.6. Applications:

3.6.1. DC power source utilization

Inverter designed to provide 115 VAC from the 12 VDC source provided in an automobile. The unit shown provides up to 1.2 amperes of alternating current, or enough to power two sixty watt light bulb.

IV.PULSE WIDTH MODULATION

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller's power devices. When in PWM regulation, the current from the solar array tapers according to the battery's condition and recharging needs Consider a waveform such as this: it is a voltage switching between 0v and 12v. It is fairly obvious that, since the voltage is at 12v for exactly as long as it is at 0v, then a 'suitable device' connected to its output will see the average voltage and think it is being fed 6v - exactly half of 12v. So by varying the width of the positive pulse - we can vary the 'average' voltage.

4.1. Pulse Width modulator

So, how do we generate a PWM waveform? It's actually very easy, there are circuits available in the TEC site. First you generate a triangle waveform as shown in the diagram below. You compare this with a d.c voltage, which you adjust to control the ratio of on to off time that you require. When the triangle is above the 'demand' voltage, the output goes high. When the triangle is below the demand voltage, the

4.2. Dither

Static friction, station, and hysteresis can cause the control of a hydraulic valve to be erratic and unpredictable. Station can prevent the valve spool from moving with small input changes, and hysteresis can cause the shift to be different for the same input signal. In order to counteract the effects of station and hysteresis, small vibrations about the desired position are created in the spool.

4.3. Why the PWM frequency is important:

The PWM is a large amplitude digital signal that swings from one voltage extreme to the other. And, this wide voltage swing takes a lot of filtering to smooth out. When the PWM frequency is close to the frequency of the waveform that you are generating, then any PWM filter will also smooth out your generated waveform and drastically reduce its amplitude. So, a good rule of thumb is to keep the PWM frequency much higher than the frequency of any waveform you generate.

4.4. PWM Controller Features:

This controller offers a basic "Hi Speed" and "Low Speed" setting and has the option to use a "Progressive" increase between Low and Hi speed. Low Speed is set with a trim pot inside the controller box. Normally when installing the controller, this speed will be set depending on the minimum speed/load needed for the motor.

Normally the controller keeps the motor at this Lo Speed except when Progressive is used and when Hi Speed is commanded (see below). Low Speed can vary anywhere from 0% PWM to 100%.

4.5. How does this technology help :

The benefits noted above are technology driven. The more important question is how the PWM technology Jumping from a 1970's technology into the new millennium offers. This signal can be generated from a throttle position sensor, a Mass Air Flow sensor, a Manifold Absolute Pressure sensor or any other way the user wants to create a 0-5 volt signal.

4.5.1 Longer battery life:

–reducing the costs of the solar system

– reducing battery disposal problems

4.5.2 More battery reserve capacity:

– increasing the reliability of the solar system

– reducing load disconnects

– Opportunity to reduce battery size to lowerthe system cost

4.5.3 Greater user satisfaction:

– get more power when you need it for lessmoney!!

V. TOTAL HARMONIC DISTORTION

Harmonic problems are almost always introduced by the consumers' equipment and installation practices. Harmonic distortion is caused by the high use of non-linear load equipment such as computer power supplies, electronic ballasts, compact fluorescent lamps and variable speed drives etc. which create high current flow with harmonic frequency components. The limiting rating for most electrical circuit elements is determined by the amount of heat that can be dissipated to avoid overheating of bus bars, circuit breakers, neutral conductors, transformer windings or generator alternators.

5.1. Definition

THD is defined as the RMS value of the waveform remaining when the fundamental is removed. A perfect sine wave is 100%, the fundamental is the system frequency of 50 or 60Hz. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiplies of the fundamental i.e.3rd harmonic is 3x the fundamental frequency / 150Hz. Total harmonic distortion is a measurement of the sum value of the waveform that is distorted.

5.2.Power Measurement

Despite the use of good quality test meter instrumentation, high current flow can often remain undetected or under estimated by as much 40%. This severe underestimation causes overly high running temperatures of equipment and nuisance tripping. This is simply because the average reading test meters commonly used by maintenance technicians, are not designed to accurately measure distorted currents, and can only provide indication of the condition of the supply at the time of checking. Power quality conditions change continuously, and only instruments offering true RMS measurement of distorted waveforms and neutral currents can provide the correct measurements to accurately determine the ratings of cables, bus bars and circuit breakers.

5.3. Neutral Currents

High harmonic environments can produce unexpected and dangerous neutral currents. In a balanced system, the fundamental currents will cancel out, but, triple- N's will add, so harmonic currents at the 3rd, 9th, 15th etc. will flow in the neutral. Traditional 3 phase system meters are only able to calculate the vector of line to neutral current measurements, which may not register the true reading. Integra 1530, 1560 and 1580 offer a 3 phase 4 wire version with a neutral 4th CT allowing true neutral current measurement and protection in high harmonic environments.

5.4. Harmonic Profiles

There is much discussion over the practical harmonic range of a measurement instrument, however study of the harmonic profiles of typically installed equipment can guide the system designer to the practical solution. A typical harmonic profile graph will show a logarithmic decay as the harmonic frequency increases. It is necessary to establish the upper level at which the harmonic content is negligible.

5.5. PROPOSED MULTILEVEL INVERTER TOPOLOGY

The proposed single-phase seven-level inverter was developed from the five-level inverter. It comprises a single-phase conventional H-bridge inverter, two bidirectional switches, and a capacitor voltage divider formed by *C*1, *C*2,and *C*3, as shown in Fig. 1. The modified H-bridge topology is significantly advantageous over other topologies, i.e., less power switch, power diodes, and less capacitor for invertersof the same number of levels. Photovoltaic (PV) arrays were connected to the inverter via a dc–dc boost converter. The power generated by the inverter is to be delivered to the power network, so the utility grid, ratherthan a load, was used. The dc–dc boost converter was required because the PV arrays had a voltage that was lower than the grid voltage. High dc bus voltages are necessary to ensure that power flows from the PV arrays to the grid. A filtering inductance *Lf* was used to filter the current injected into the grid.

5.6. PWM modulation

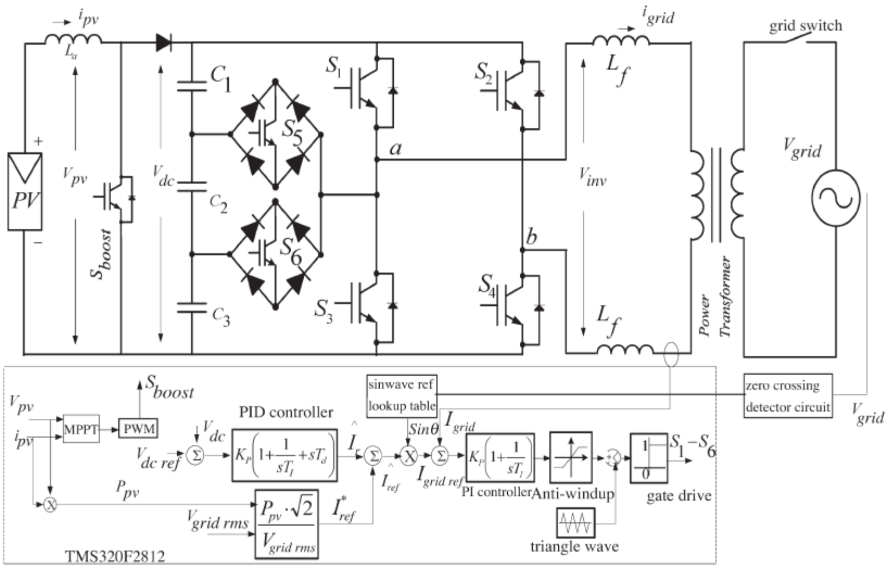
A novel PWM modulation technique was introduced to generate the PWM switching signals. Three reference signals (*V*ref1, *V*ref2, and *V*ref3) were compared with a carrier signal (*Vcarrier*). The reference signals had the same frequency and amplitude and were in phase with an offset value that was equivalent to the amplitude of the carrier signal. The reference signals were each compared with the carrier signal. If *V*ref1 had exceeded the peak amplitude of *V*carrier, *V*ref2 was compared with *V*carrier until it had exceeded the peak amplitude of *V*carrier. Then, onward, *V*ref3 would take charge and would be compared with *V*carrier until it reached zero.

VI. CONTROL SYSTEM

The control system comprises a MPPT algorithm,a dc-bus voltage controller, reference-currentgeneration,and a current controller. The two main tasks of the controlsystem are maximization of the energy transferred from the PVarrays to the grid, and generation of a sinusoidal current withminimum harmonic distortion, also under the presence of gridvoltage harmonics.The proposed inverter utilizes the perturb-and-observe(P&O) algorithm for its wide usage in MPPT owing to itssimple structure and requirement of only a few measured parameters, It periodically perturbs (i.e., increment or decrement)the array terminal voltage and compares the PV output powerwith that of the previous perturbation cycle. If the power as increasing, the perturbation would continue in the samedirection in the next cycle; otherwise, the direction would bereversed. This means that the array terminal voltage is perturbedevery MPPT cycle; therefore, when the MPP is reached, theP&O algorithm will oscillate around it.

VII. MATLAB CASE STUDY & SIMULATION RESULTS

MATLAB SIMULINK simulated the proposed configuration before it was physically implemented in a prototype. The PWM switching patterns were generated by comparing three reference signals (*V*ref1, *V*ref2, and *V*ref3) against a triangular carrier signal (see Fig. 7.1).



7.1 Seven-level inverter with closed-loop control algorithm

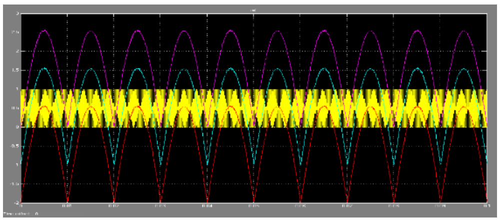


Fig.7.2. PWM switching signal generation.

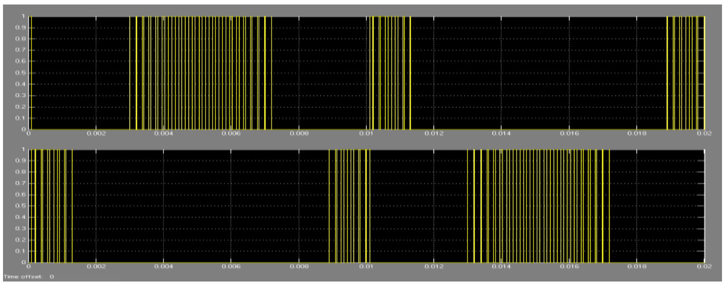


Fig.7.3. PWM signals for *S*1 and *S*3.

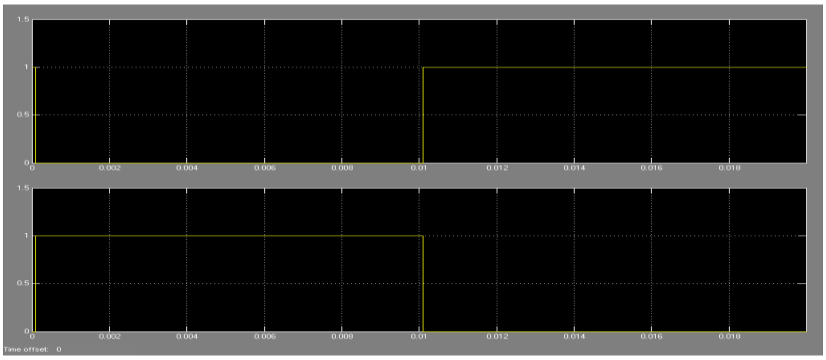


Fig.7.4. PWM signals for *S*2 and *S*4.

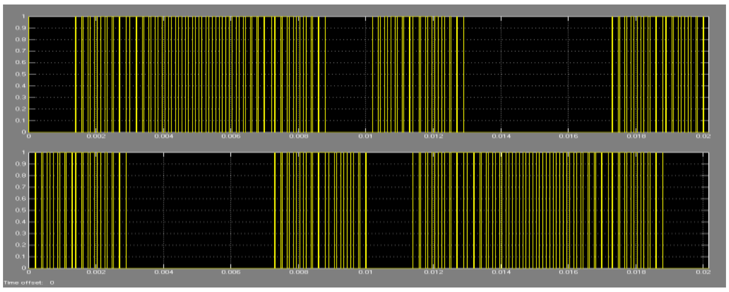


Fig.7.5. PWM signals for *S*5 and *S*6.

Subsequently, the comparing process produced PWM switching signals for switches *S*1–*S*6, as Figs.7.2–7.5 show. One leg of the inverter operated at a high switching rate that was equivalent to the frequency of the carrier signal, while the other leg operated at the rate of the fundamental frequency (i.e., 50 Hz). Switches *S*5 and *S*6 also operated at the rate of the carrier signal. Fig.7.6. Inverter output voltage (*V*inv). Fig.7.7. Grid voltage (*V*grid) and grid current (*I*grid).of the carrier signal. Fig. 10 shows the simulation result of inverter output voltage *V*inv. The dc-bus voltage was set at 300 V (>√2*V*grid; in this case, *V*grid was 120 V). The dc-bus voltage must always be higher than √2 of *V*grid to inject current into the grid, or current will be injected from the grid into the inverter. Therefore, operation is recommended to be between *Ma* = 0.66 and *Ma* = 1.0. *V*inv comprises seven voltage levels, namely, *V*dc, 2*V*dc/3, *V*dc/3, 0, −*V*dc, −2*V*dc/3, and −*V*dc/3.The current flowing into the grid was filtered to resemble a pure sine wave in phase with the grid voltage see Fig.7.7).

As *I*grid is almost a pure sine wave at unity power factor, the total harmonic distortion (THD) can be reduced compared with the THD.

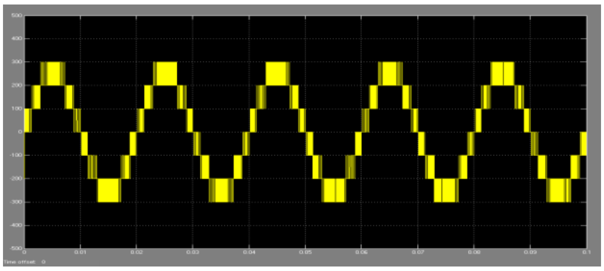


Fig.7.6. Inverter output voltage (*V*inv).

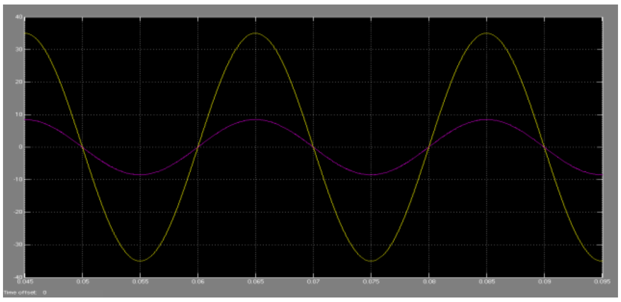


Fig.7.7. Grid voltage (*V*grid) and grid current (*I*grid).

VII. CONCLUSION

Multilevel inverters offer improved output waveforms and lower THD. This paper has presented a novel PWM switching scheme for the proposed multilevel inverter. It utilizes three reference signals and a triangular carrier signal to generate PWM switching signals. The behavior of the proposed multilevel inverter was analyzed in detail. By controlling the modulation index, the desired number of levels of the inverter's output voltage can be achieved. The less THD in the seven-level inverter compared with that in the five- and three-level inverters is an attractive solution for grid-connected PV inverters.

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