Active and Reactive Power Controller for Single-Phase Grid- Connected Photovoltaic Systems

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Abstract- **This paper at first presents a control algorithm for a single-phase grid-connected photovoltaic system in which an inverter designed for grid-connected photovoltaic arrays can synchronize a sinusoidal current output with a voltage grid. The active and reactive power are sequentially controlled by load angle and by inverter output voltage magnitude besides a maximum power point tracker (MPPT) always finds optimal power of the PV array in use. The controller feeds maximum active power into grid at unity power factor, whereas it also allows the adjustment of reactive power injected into the grid. Simulation and experimental results show that the control system has good performances. The second part of this paper presents briefly the Green Power Laboratory (Department of Electrical and Electronic Engineering in HoChiMinh City University of Technology), where the experimental set-ups are carried out. This lab has been developed and settled up in order to focus aiming of the converter design and various controls of the renewable energy systems like isolated or grid-connected photovoltaic systems, fuel-cells and wind power. This paper describes laboratory hardwares as well as the context of which they are used in the undergraduate and graduate teaching, and especially in research activities.**

***Index Terms* — grid connected, photovoltaic system, active power, reactive power, DSP TMS320F2812**

I. Introduction

IN PHOTOVOLTAIC SYSTEMS, a grid connected inverter converts the DC output voltage of the solar modules into the AC system. The grid-connected photovoltaic (PV) system extracts maximum power from the PV arrays. The maximum power point tracking (MPPT) technique is usually associated with a DC-DC converter. The DC-AC injects the sinusoidal current to the grid and controls the power factor.

An important aspect related to the photovoltaic system connected to the electric grid is that it can operate the double functions of active power generator and reactive power compensator. The proper power factor is selected according to active power and reactive power that the grid demands. At the same time, it can supply reactive power to the electrical grid when there is little or no solar radiation. That is important for compensing the reactive power at peak hours, when the main grid needs a amount of reactive power higher than average consumtion. Although the photovoltaic system does not generate active power in such period of time, it can supply reactive power up to its maximum.

This inverter control strategy is not only capable to control the active power, but also dynamically reconfigured to change the magnitude of the reactive power injected into the grid. Some solutions are proposed [1-6], [10], to obtain a high reliability inverter. The basic idea of the propose control is to obtain a low cost and simple controller. In this method, the active power is controlled by load angle and the reactive power is controlled by inverter output voltage magnitude. The controller feeds maximum active power into grid at unity power factor, whereas it also allows the adjustment of reactive power fed into the grid.

II. Operational Principles

The power stage of the single phase inverter connected to the grid in the Fig.1 explains the inverter output current.

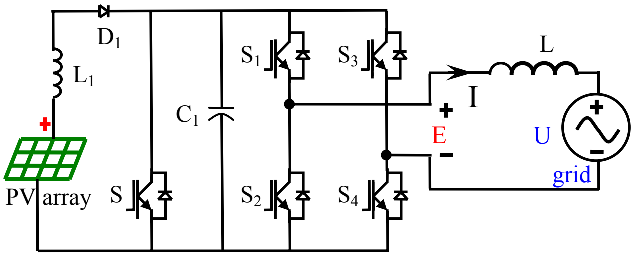

Fig. 1: Single-phase inverter topology.

The current of the inverter connected to the grid must be got from a PV panel. The analysis is based on inductor coupling and applied for other types of output filter configurations, such as L, LC, LCL, etc [1,4,9]. The equivalent electrical circuit is shown in Fig.2.

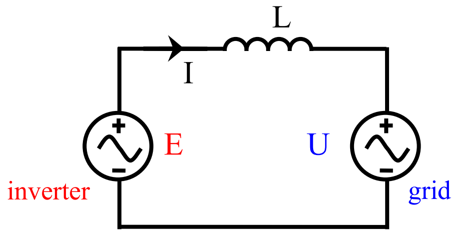

Fig. 2: Equivalent electric cirrcuit

In order to explain the circuit characteristics, the Fig. 3 represents the phase diagram of the fundamental components, including the inverter output voltage (E), the inverter output current (I), the drop voltage on the inductance L ($jX_sI=j\omega LI$), and the fundamental component of the grid voltage (U). [1].

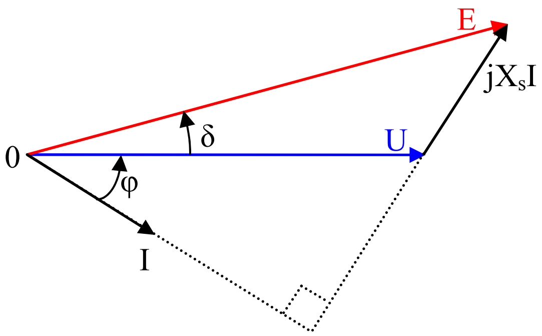

Fig. 3: Phase diagram with grid voltage (U) and load angle (δ).

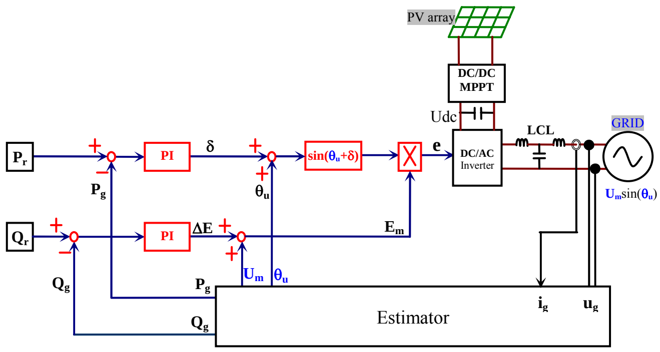

Fig. 4: Control structure for a single phase grid-connected PV system.

φ is represented as the power angle between the grid voltage and the inverter output current. And, δ is represented as the load angle between the grid voltage and the inverter output voltage. The phase diagram is shown in Fig. 3. The following relations can be represented:

$$\dot{E} = \dot{U} + jX_s\dot{I} \quad (1)$$

$$E\sin(\delta) = X_s I.\cos(\varphi) \quad (2)$$

The active power (P) provided by the converter to the grid can be expressed as:

$$P = UI\cos(\varphi) = \frac{UE}{X_s}\sin(\delta) \quad (3)$$

And the reactive power (Q) provided by the converter to the grid, can be expressed as:

$$Q = \frac{UE}{X_s}\cos(\delta) - \frac{U^2}{X_s} = \frac{U}{X_s}(E\cos(\delta) - U) \quad (4)$$

According to figure 3, equations (3) and (4), the power flow adjustment of the inverter is parallel connected to the main grid, can be performed by controlling the inverter ouput voltage magnitude (E) and load angle (δ). On the other hand, to inject power to the grid, the value of the DC voltage must be high enough so that the output voltage E can get a value which is equal or greater than the grid peak voltage.

From equation (3) and (4), the active and reactive power depend on both the inverter output voltage magnitude E and the load angle δ [6]. So, the active power injected into the grid can be controlled by the phase difference between grid voltage and inverter output voltage δ. At the same time, the reactive power can be controlled by the inverter output voltage magnitude E.

III. Proposed Control Implementation

The proposed control structure for a single-phase inverter connected to the grid is shown in Fig.4. The photovoltaic system consists of photovoltaic generator (PV array), DC/DC converter with maximum power point tracking (MPPT), a single phase inverter and an active and reactive power controller. The control circuit has two parts: the first one controls the active power injected into the grid by the load angle δ, and the second one controls the reactive power through the inverter output voltage magnitude E.

As show in figure 4, the controller compenses the reactive power injected into the grid (Q_g) and compares it with its reference (Q_r), originating an reactive power error. This error passes through an PI controller and it is added to grid voltage amplitude (U_m≈const), resulting the inverter output voltage amplitude (E_m). On the other hand, the controller produces the active power generated by the inverter (P_g) and compares it with a reference signal (P_r), generating an active power error. This error passes through another PI controller, originating reference load angle (δ). The load angle is added to grid voltage phase angle (θ_u), generating inverter output voltage phase angle ($\delta+\theta_u$). The inverter output voltage amplitude (E_m) is multiplied by $\sin(\delta+\theta_u)$, resulting the instantaneous value of the inverter output voltage (e) – the DC/AC inverter reference signal.

The grid voltage:	$u = U_m\sin(\omega t) = U_m\sin(\theta_u)$	(5)
and	$\delta \sim P$ and $\Delta E \sim Q$	(6)
Inverter output voltage:	$e = E_m\sin(\theta_u + \delta)$	(7)
where:	$E_m = U_m + \Delta E$	(8)

The main advantage of this control strategy is its simplicity related to the computational requirements of the control circuit and hardware implementation. By another way, it allows controlling not only an active power needs to be injected but also a reactive component. When the reactive power reference is zero, the power factor will approach to the unity.

IV. Simulation Results

MATLAB/Simulink software were used in all simulations accomplished here which show the results obtained for voltage and current waveforms, active, reactive and apparent powers on the AC side supplied to the grid. The rate value of grid voltage (U=220Vrms) and the inverter is connected to the grid through a coupling inductance L=10mH. Simulations at low-power scale (1 kVA) is implemented in predicting the behaviour of the system for the experiments to be performed on the laboratory test bench.

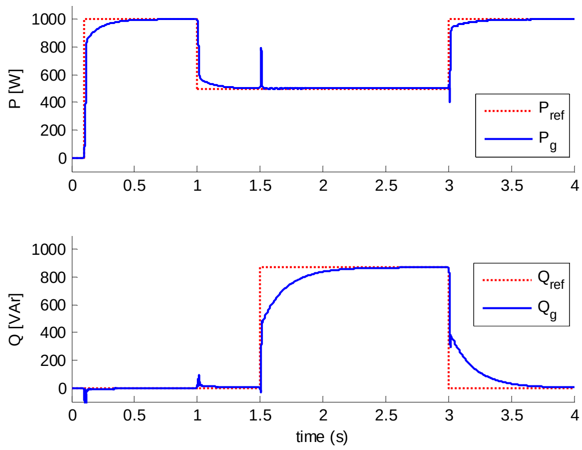

Fig. 5: Active and Reactive Power supplied by the inverter with 100%-50%-100% of photovoltaic system power.

The simulation results obtained for steady-state operation are shown in Fig. 5. Active and reactive power response has good performance. The active power and reactive power injected into the grid for four generation conditions: [P,Q]=[0%, 0%], [100%, 0%], [50%, 0%], [50%, 87%].

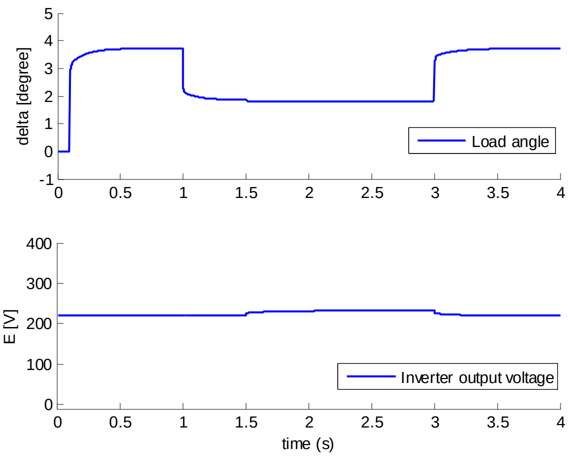

Fig. 6: Load angle δ [degree] and Inverter output voltage E [Vrms].

The load angle (δ) is proportional to the active power and the inverter output voltage (E) is proportional to the reactive power.

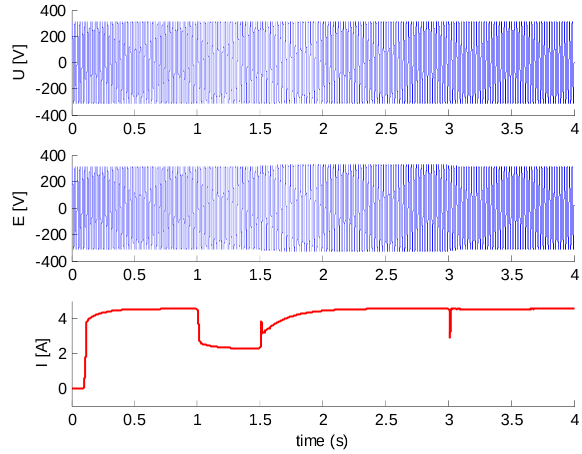

Fig. 7: Grid voltage [V], Inverter output voltage [V], and Inverter output current [Arms].

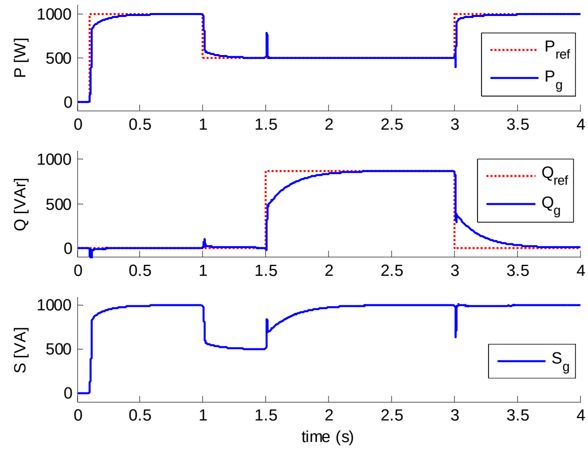

Fig. 8: Active, Reactive and Apparent power injected into the grid with four generation conditions: [P,Q]=[0%, 0%], [100%, 0%], [50%, 0%], [50%, 87%].

As observed in figures 5 to 8, when the active power is reduced, the control is adjusted to increase the reactive power supplied capacity. Hence, the values of inverter current and the apparent power injected into the grid can get the rate values whereas the solar radiation is low. [6].

The active power supplied by the photovoltaic system to the grid presented a agreeable performance, due to a resonable system response. When there is sunstroke variation, the system adjusts to a new reference of active power with a good performance. Moreover, it was observed an interaction between the active and reactive powers delivered to the grid. So, the system takes advantage of the moments of little active power generation to accomplish the compensation of reactive power.

V. Experimental Results and Remarks of Testing

A prototype of a single phase inverter (Fig.9), has been built to validate the performance of the digital control previously described and tested. A voltage source inverter has been developed in a DSP platform (DSP TMS320F2812) reconfigurating easily and simply the system [3]. It is possible to configure the inverter output voltage and the load angle shifting to the grid voltage reference. Two digital PI control-algorithms are implemented in DSP TMS320F2812 to optimize the performance of the control system. The proposed inverter is tested with a PV array of 80W.

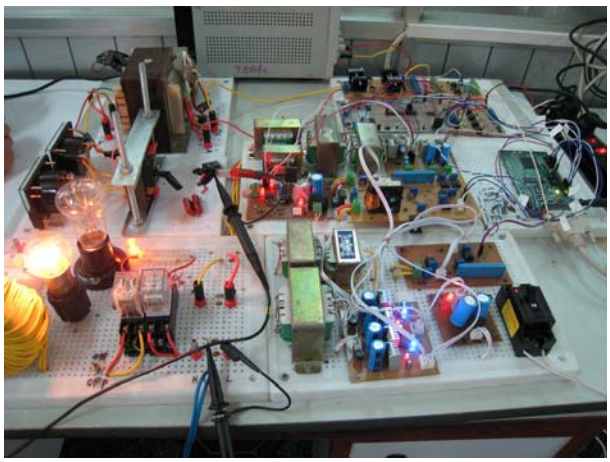

Fig. 9: Single-phase inverter prototype.

As first, the inverter output voltage and its phase must be synchronized to the grid voltage signal before the power output of the inverter is connected to the grid (Fig. 10).

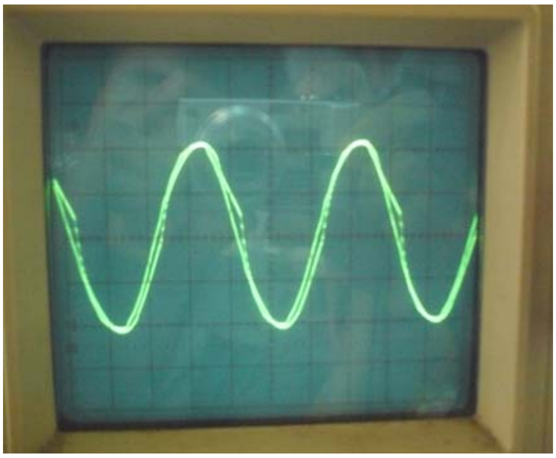

Fig. 10: Inverter output voltage generated in phase with the grid voltage in open loop.

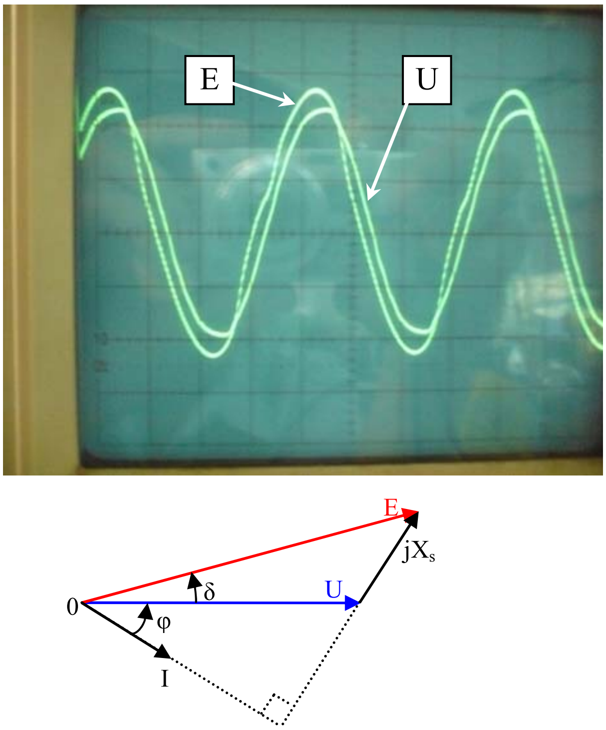

Fig. 11 & 12: E > U and δ > 0.

Second, the gid-connected algorithm is executed to control the power flow delivered into the grid. The controller varies magnitude and phase of the inverter output voltage (Fig. 11).

Code composer studio sofware of Texas Instruments's DSP allows drawing real-time measurement values. Fig. 13 and Fig.14 show the experimental results of inverter output current compared to the grid voltage emulator. The graph of figure 15 shows the active power injected into the grid, which has good performance.

The experimental result shows the feasibility of the propose control. And the control is applied to regulate the active and reactive power of low power PV systems. The propose implementation is very simple and not required a high speed hardware and computational resources.

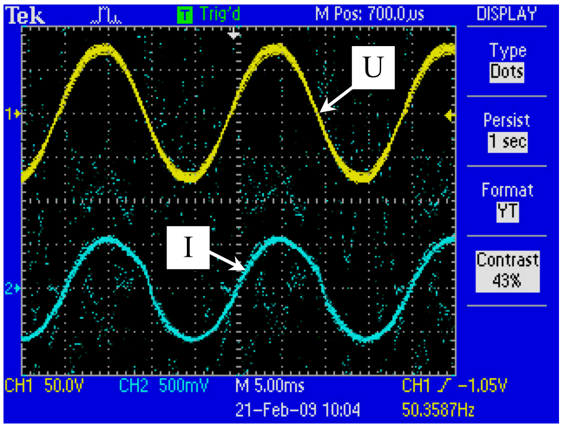

Fig. 13: Inverter output current in phase with the grid voltage emulator by Ocsillocope

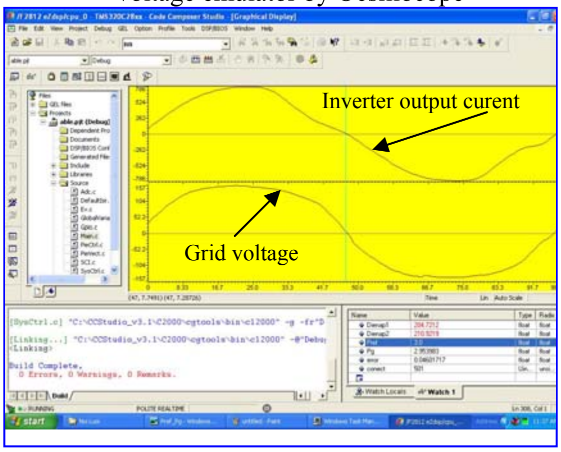

Fig. 14: Inverter output current in phase with the grid voltage emulator by Code composer tool.

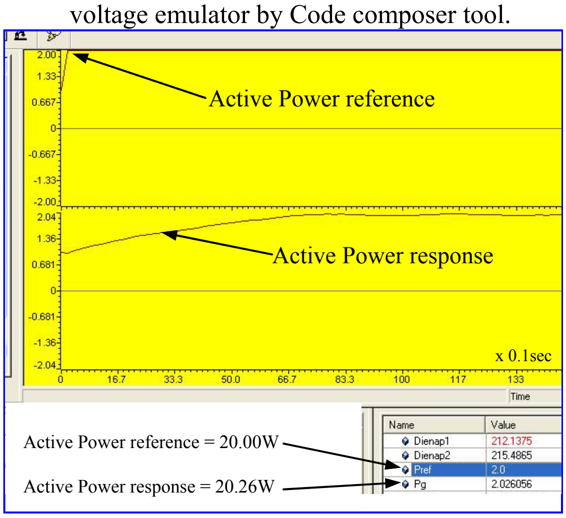

Fig. 15: Active power response.

REMARKS OF TESTING

In this part, the simulation and experiment results prove that the propose system has the ability of changing inverter output voltage amplitude as well as load angle. Consequently, the system is controllable for the active and reactive power injected into the grid with a good performance. Thus, it becomes possible to operate independently the photovoltaic system in any condition of the sunstroke level and supplies both the active and reactive powers according to the availability of solar radiation. This photovoltaic systems is neither complex to implement nor expensive to realise. It is a better cost-benefit ratio in the implementation for the other alterative energies.

VI. INTRODUCTION TO GREEN POWER LAB

All of the research activity, such as the first part of this paper, concerning the renewable energy are focused on the development of the Green Power Laboratory (GPL).

GPL now belongs to Faculty of Electrical- Electronics Engineering- HoChiMinh City University of Technology- is a fruitful collaboration between HCMUT and PFIEV-ENSEEIHT in the framework of the project NTEDD (Nouvelles Technologies Et Développement Durable = New Technologies and Sustainable Development) from 2007 in setting up a lab on Renewables, aiming at undergraduate and graduate teaching and researchs of new electrical-electronics technologies applied in green energy.

The objectives of this lab are to focus on renewable energy technologies (wind power, solar power, fuel cell) as well as on the design and control of the power electronic converters used in single-phase and three-phase renewable energy systems like photovoltaic, wind, fuel cells and water turbines connected to the utility grid or to a microgrid.

The laboratory comprises various equipments for student use and other research activities in the field of renewable energy. DSP technology, either Texas Instruments TMS320F2812 DSP from Texas Instruments, or dSPACE DS1104 cards are widely used in order to provide higher flexibility. Fig. 1 shows a photo of the Green Power Laboratory. The course Renewable Energy Systems given to undergraduate and graduate students is going in parallel with Green Power Labs includes (3 hous lecture per week):

1. *Introduction to Renewable Energy System*
- Need for more energy
- Renewable Energy Sources (solar, wind, hydro, tidal, waves)
- Fuel-cell introduction
- Cost and environmental impact
- Renewable energy in a sustainable future

2. *Stand alone and gird-connected Photovoltaic Systems*
- Solar cells technology (crystalline, amorphous, thin film)
- Electrical characteristics of silicon PV cells/modules
- Tracking maximum power point
- Grid-connected and off-grid PV systems (residential, farms, etc)
- Converter topologies for PV systems
- Control of dc-dc boost converters
- Control of single-phase and three-phase dc-ac inverters
- Compliance with power quality and safety systems

3. *Wind Energy Systems*
- Power and energy from wind turbines
- Wind turbine system configurations
- Converter topologies for variable-speed wind turbines
- Modeling and simulation of DFIG used in wind power

4. *Fuel Cell technology*
- Various technologies of Fule Cells
- Characteristics of Fuel Cells
- Fuel Cell Application as an energy vector

Matlab and Bondgraph (20SIM) softwares are extensively used by students to carry out modeling, simulations and study of renewable energy equipment performance and its behaviour when connected to power grid.

The laboratory exercises include:

1. Solar cells and panels
- Matlab simulation of solar cells and panels electrical characteristics (I-V, P-V, MPPT temperature dependence, irradiation-dependence, shadowing etc).

2. Grid-connected PV systems – System simulation
3. MPPT controller – experimental test
4. Control of single-phase grid converter used for PV residential application – experimental test
5. Control of three-phase Wind Turbine systems – experimental test

PROJECT EXAMPLES

GPL offers a variety of projects to undergrad or grad students in their program.

- Operation and simulation of stand alone PV system (of 300 W, BondGraph or Matlab, comparison of results obtained from experiments measurements and those from simulation)

- Operation and simulation of grid-connected PV system (of 960 W, BondGraph or Matlab, comparison of results obtained from experiments measurements and those from simulation)

- Operation and simulation of off- grid wind power system (of 400 W, BondGraph or Matlab, comparison of results obtained from experiments measurements and those from simulation)

- Operation and simulation of Fuel cell (principle of electrolysis, applications)

- Off- grid wind power system (of 400 W, BondGraph or Matlab, comparison of results obtained from experiments measurements and those from simulation)

Some specific themes are also offered as final projects for senior class students. Some of topics are as follows:

- Digital simulation of Three phase Grid-Connected PV system with improved performance: The concept of the instantaneous *p-q* (real-imaginary) power theory is presented in the control algorithm to design the system with features of separate control of active and reactive power, which results in the maximal transfer of the dc energy from PV array and improves the power factor of the electrical system. The whole system of PV array, dc-dc converter, MPPT, dc-ac PWM converter along with hysteresis current controller is designed and simulated in Matlab- Simulink environment. The results obtained from digital simulations will show dynamic system performances in terms of changing irradiance, power factor correction, as well as easy tracking of inverter currents fed into grid.

- Digital simulation and Experimental test of One-phase Grid-Connected PV system with improved performance. This topic presents a control algorithm for a single-phase grid-connected photovoltaic system. An inverter designed for grid-connected photovoltaic arrays can synchronize a sinusoidal current output with a voltage grid. This method controls active power by load angle and control reactive power by electromotive force. A maximum power point tracker (MPPT) always finds optimal power of the PV array in use. The controller feeds maximum active power into grid at unity power factor, whereas it also allows the adjustment of reactive power fed into the grid. Simulation and experimental results show that the control system has good performances.

- Modeling and simulation of wind power DFIG connected to power system

Various seminars, workshops are held in GPL offering basic knowledge and expertise in the field given by professors coming from INPT- ENSEEIHT, University of Dresden, ENS Cachan (Fig 2) on topics:

- Alternative Energy: technologies, impacts on sustainable development.
- Fuel Cell technology and Applications in the future as an energy vector.
- Wind power Generatos and Simulations.
- Small hydro power and exploitation operations.
- PV technology stand alone and grid connected operations and characteristics.
- Power converters in Green Power technology.
- Wind power: Operation and site selection estimation of wind potential economic side consideration.
- Power LED and efficient use of electric power.
- Power LED technology.
- BondGraph software applications in hybrid systems research.

VII. CONCLUSION

GPL shows its effectiveness and attraction when it draws a real interest of students majoring in Power. Engineering. Students are really interested in new concepts, new technologies introduced into the curriculum. In addition, the introduction of micro electronics and DSP techniques into the renewable energy field really makes the subject state-of-the art and more interdisciplinary. Power electronics, electrical machines, dsp, microelectronics, control techniques, all integrated in the discipline gives even more attractiveness to students.

Fig. 15: Green Power Laboratory.


Fig. 16: Three-phase inverter prototype.

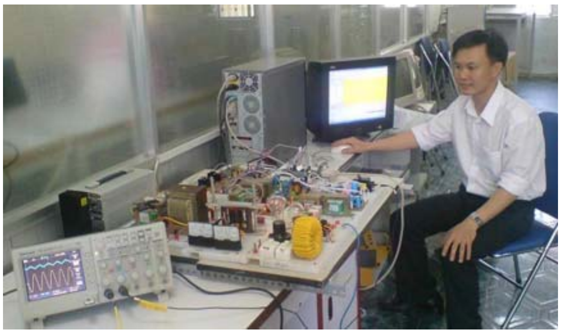
Fig. 17: Single-phase inverter prototype.

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