



## Hardware Implementation of Hybrid AC-DC Power System Laboratory Involving Renewable Energy Sources

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# **Hardware Implementation of Hybrid AC-DC Power System Laboratory Involving Renewable Energy Sources**

## **Abstract**

Future power system will highly rely on renewable energy sources. The need for expert designers and operators for such systems is increasing. The concept of renewable energy sources have been discussed by evolving new platforms for design, development and integration of renewable energy sources such as photovoltaic and wind for research and educational efforts. This includes the implementation of energy source emulators and related control issues. Laboratory experiments and their analysis prepare a suitable environment for students to achieve a high level of knowledge and deep understanding of the fundamentals of renewable energy concepts in the real world. This research and education environment involves techniques such as ac-dc power system design, real time operation, analysis and control that provide a state of the art platform to solve most challenges of actual renewable sources in modern power systems.

## **Introduction**

During the past 20 years, energy costs have increased annually. In addition, the need for an efficient, less environmentally damaging, renewable energy resource is significantly growing. Generating electricity from sources such as fossil fuels, biomass and nuclear power requires a lot of water which may intensify the drying of more lands and warming of earth. However, renewable energy resources such as wind and solar energy can provide electricity with the lowest pollution and solve many of the problems leading to global warming and impacts on energy demands in the near future. This is especially problematic for developed and industrial nations.

A renewable energy education platform in lectures that include both theory and practice will be the key point to providing effective training for future job demands in the energy industry.

The objective of this paper is to apply the concepts of integrating two main renewable energy sources into power grids with implementation examples in laboratory based test bed. The smart grid test bed developed at the energy systems research laboratory at Florida International University is presented. The techniques for integrating and emulating renewable energy sources, such as wind and solar energy generation, identifying the requirements and educational initiatives for educating and training students are explained in the following sections. An overview of developed hybrid smart power system including renewable energy resources is explained in section 4. The development of software and hardware implementation processes in ac/dc grid of the emulated power system will be identified. Section 5 discusses the ac/dc grid architecture, operation and control strategies. Section 6 highlights some of the educational efforts being developed on the smart grid test bed. This will be followed by conclusions.

## **Need, implementation and concerns of renewable energy sources**

Utilizing renewable energy sources will reduce the consumption of fossil resources for energy generation and transportation for the reduction carbon emission and air pollutants. They can be used to enhance the reliability, resiliency, efficiency and finally security of microgrids. In the customer's side, resources for energy generations can cut the peak loads of customers and consequently the costs of electricity. This will be improved when the renewable energy sources are used along with energy storage systems. It can be mentioned that in the area of integration of renewable energy sources into interconnected power systems, energy storage systems are important enabling factor. This is due to uncertainty of solar and wind energy resources. The stored energy is used when it is needed. This can improve the transmission capacity; reduce the requirements for generation units and maximize the use of variable sources such as PV and wind. The negative aspects of energy storage systems are losses due to multiple conversions in ac/dc or dc/ac stages, cost of energy storage devices and the complexity of the conversion process.

Large penetration of distributed generations and implementation of HEV into the grid provide a great opportunity of using idle battery storage of electric cars to be used as distributed energy storage systems.

From a technical point of view, large implementation of variable resources will make the grid more complex to operate. Future power system engineers should consider these distributed generations and should be greatly familiar with the many technical aspects. Utilizing renewable energy sources not only provides an excellent opportunity for students to have a deep and realistic understanding on this subject, but also prepares and train them to test their ideas in a highly technical research and development atmosphere. The implementation of operational regimes and conducting verification experiments will be necessary for future students to get into this area:

- a) Introduction to hybrid power grids
- b) Emulation and development of renewable energy sources (in particular wind and solar)
- c) Integrating techniques and approaches for optimally control and operation of PV and wind emulators along with energy storage system
- d) Real time energy transfer techniques, converters and tools in hybrid power systems with emphasis in dc micro grids connectivity

## **Overview of integrated hybrid power system platform**

### **A. AC Power Grid**

Energy transfer systems are relied on the basis of ac network along with bulk energy generations. Distributed generations will be added to this system through the micro grids. It is required to have the ac infrastructure as a basis for integrating any micro grids or for grid connected application of renewable energy resources, and also to analyze their performance and evaluate

innovative ideas. In the emulated ac grid system, the cost, flexibility of operation and safety (compared to actual high voltage systems) is the main advantage. The developed ac grid consists of generating stations, various programmable dynamic load modules, overhead transmission lines or cable models, synchronizers, ac measurement buses and feeders also in addition to wide area control, monitoring and operation package<sup>1</sup>. This particular ac system has the flexibility to work in either 50 or 60 Hertz in three phases four wires connectivity basis. Complimentary information is described in details and available in <sup>2</sup>.

## B. PV Emulation

One of the main research topics studied in our hybrid ac-dc power system laboratory is development of techniques for implementation and energy management of large and small scale photovoltaic power plant. Photovoltaic arrays have a nonlinear voltage-current characteristic that its output power varies with solar radiation and cell temperature. Due to the limitation on solar energy availability in a laboratory environment, an alternative photovoltaic emulator was used. The emulator is a 6 kW Magna Power Electronics dc programmable power supply (Figure 1) and its maximum output voltage and current are 375 V and 15.9 A, respectively. The Photovoltaic Power Profile Emulator (PPPE) software is used to calculate voltage and current profiles of a specific solar array based on predefined parameters. These profiles are sequentially sent to the power supply via RS232 serial communication interface. A power profile can be generated manually based on voltage-current curve of a photovoltaic cell or it can be defined based on short circuit current, open circuit voltage and maximum power point (MPP) of a cell.



Figure 1. Programmable power supplies.

Figure 2 shows typical voltage-current and voltage-power characteristic of a PV module. As it can be seen, the power curve has only a single maximum point and it is always desired that the PV module operate close to this point. Different maximum power point tracking (MPPT) techniques can be used to maintain the operation point at the MPP under varying conditions such as load, temperature, and insolation. The MPPT algorithms can be classified into direct and indirect categories. The indirect methods are the “open-circuit voltage method”, the “short-circuit method”, the “look-up table method” and the “curve-fitting method”. These methods are based on the data which show the characteristics of the PV panel at different environmental and working conditions. The direct methods include “artificial intelligence method”, “differentiation method”, “P&Q method”, and so on. The direct methods are more robust i.e. prior knowledge of the PV parameters is not required. However, voltage or current measurement and a feedback loop are necessary for the converter control circuit <sup>2</sup>.

Figure 3 shows the schematic diagram of photovoltaic system with MPPT controller. The PV module and the dc bus are interfaced with each other through a dc/dc converter, which can be a step-down or step-up converter depending on the dc bus voltage and the panel size. The controller circuit samples the voltage and the current at the output of the photovoltaic panel. Then the switching signal is sent to the converter to regulate the output current and to maximize the power transfer.

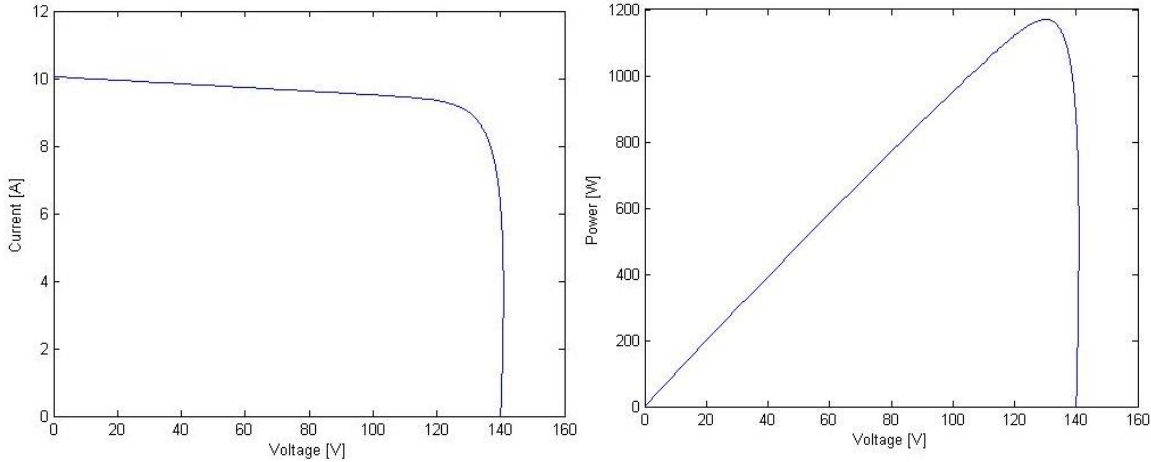


Figure 2. Voltage-current and voltage-power curve of a photovoltaic module.

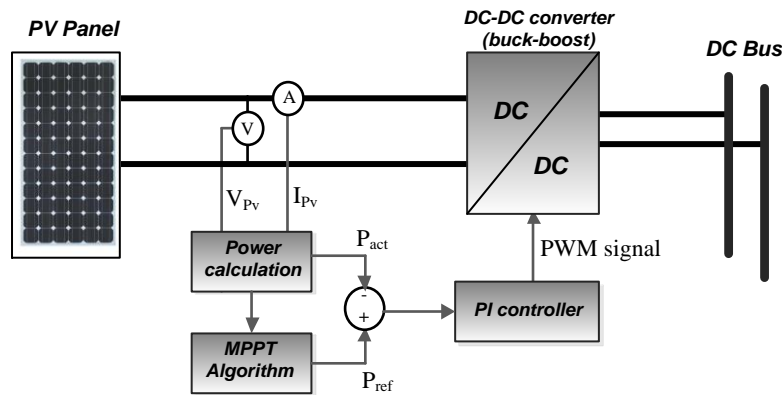


Figure 3. Block diagram of a photovoltaic system with MPPT controller.

### C. Wind Turbine Emulator

For wind turbines, ac induction or synchronous generators are often used to convert the kinetic energy of the wind into electric power. Permanent Magnet Synchronous Generators (PMSG) has good advantages because of stable and secure behavior during normal operation and does not need any additional DC supply for excitation circuit. In this machine, for modeling the generator the following equations has been considered:

$$\frac{di_d}{dt} = \frac{1}{L_d} [u_d + p\omega_g L_q i_q - R_d i_d] \quad (1)$$

$$\frac{di_q}{dt} = \frac{1}{L_q} [u_q + p\omega_g(L_d i_d + M i_f) - R_q i_q] \quad (2)$$

Where  $i_d$  and  $i_q$  are the stator currents,  $u_d, u_q$  are the stator voltages,  $p$  is the number of pairs of poles,  $L_d, L_q$  are the stator inductances,  $R_d, R_q$  are the stator resistances,  $M$  is the mutual inductance, and  $i_f$  is the equivalent rotor current.

Due to wind speed variation, the output of the wind turbine is not constant; hence a rectifier should be utilized to convert the variable ac voltage output of the generator into constant dc voltage. The generated dc power can be utilized in a standalone dc microgrid locally or it can be converted into ac to be connected to the main ac grid. Figure 3 demonstrates these two configurations. In dc grid connection, an isolated dc-dc converter may be implemented to provide galvanic isolation for the wind turbine. Similarly, a transformer is usually implemented for ac grid connection to boost up the voltage level and also isolate the wind farm from the utility grid.

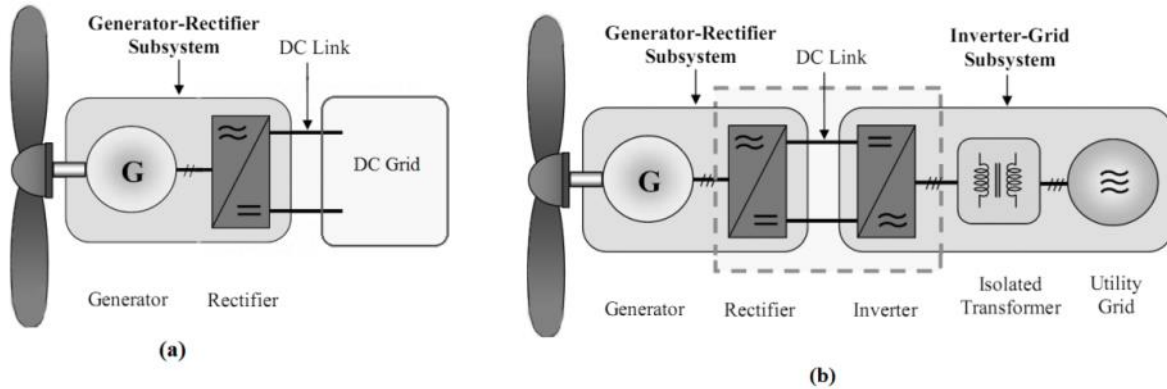


Figure 3. Wind generator electrical system: (a) dc grid connection (b) ac grid connection

The boost converter configuration is implemented as an experimental setup in our hybrid ac-dc power system laboratory (Figure 4.b)<sup>4</sup>. The wind source is imitated by a variable speed prime-mover and it is mechanically coupled with self-excited induction generator. A digital signal processor (DSP TMS320F240) on a digital platform has been employed as the control heart of the system. For dc to ac inverter system, space vector pulse width modulation (SVPWM) has been employed with a 5-kHz switching frequency.

The wind speed could be constant or varying in the form of pulses, sinusoidal or step change. Different patterns can be implemented on the DSP to emulate the wind turbine. In the real system, wind speed has a random variation according to the wind turbine location and its atmospheric conditions, but it can be set to operate within a given variation of speed. As an example to see the unpredictable pattern and range of variations, Figure 5 shows the monthly average wind speed at La Venta station.

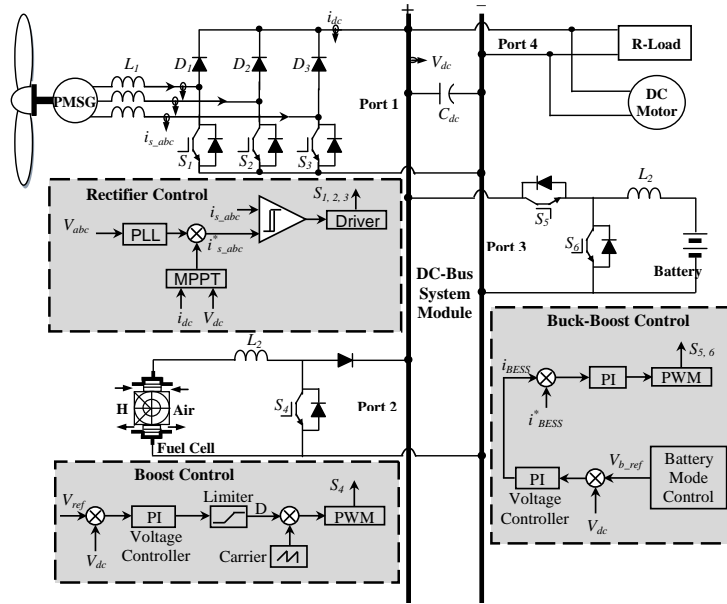


Figure 4.a. The overall hybrid system configuration <sup>4</sup>.

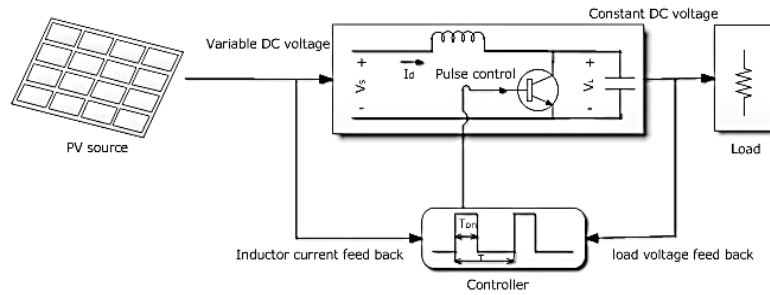


Figure 4. b. Boost converter circuit

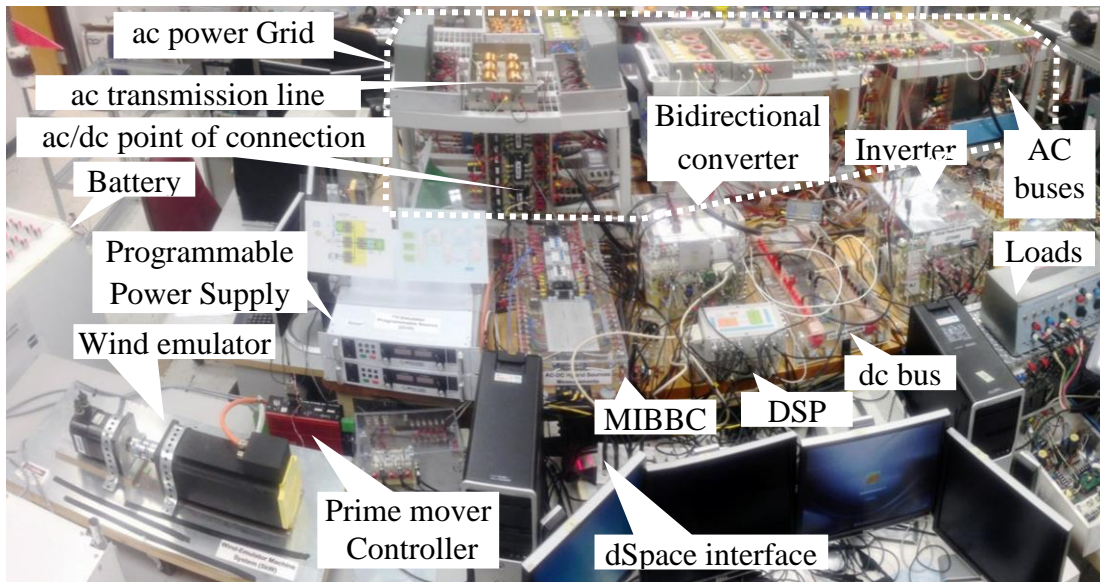


Figure 4.c. Experimental test setup for wind turbine and PV emulator.

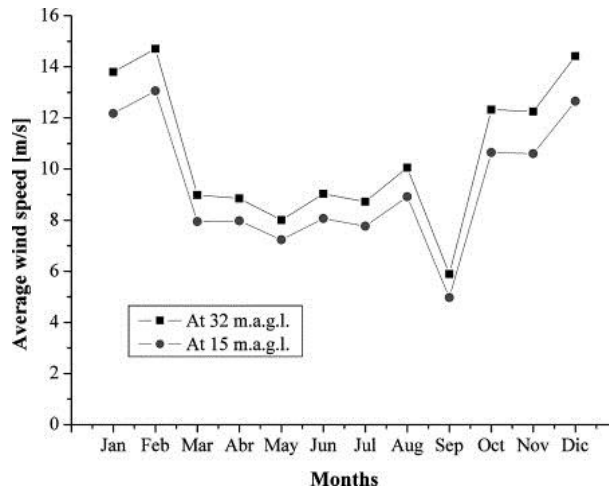


Figure 5. Monthly average wind speed at La Venta station <sup>5</sup>

The wind test setup can provide the vision of the future power system and it offers the following educational and research ideas:

- 1) Integration of wind turbine and also the other energy sources like PV, fuel cell and diesel.
- 2) Efficiency improvement of power converters in wind turbine system for battery charger and ac power.
- 3) Mathematical modeling and simulation of power systems under uncertainty
- 4) Installations of small wind turbine and grid connection
- 5) Design, fabrication, and testing of permanent magnet machines in wind turbine system
- 6) Monitoring, diagnostics, and control of wind generator
- 7) Impact of equipment aging and maintenance on wind turbine
- 8) Power system studies considering different level of wind energy penetration

#### D. Software packages for analysis and hardware interface

In addition to the DSP system in the wind emulator, most control setups for performing ac/dc conversion system were performed within the Matlab/Simulink environment and physically implemented by using dSpace interface. They present a proper infrastructure for users to emulate the wind and solar energy conversion systems behavior and create control platform interfaces in real time operation.

National Instrument LabVIEW is also one of the interfaces utilized in laboratory implementations, industry projects and educational applications. Using the data acquisition modules and its ease of use makes it a suitable choice for our application.



These software packages were selected due to their popularity for education purposes in control designs and simplicity of hardware implementation in research laboratory applications and feasibility of interface and communication with other software packages. Detailed information regarding each test setup was explained within the experiments clarification.

## Hybrid grid control and operation

### A. Isolated micro grid architecture and operation

Islanding is the situation when a portion of the power system which includes generations and loads are isolated from the main system but stays energized. The ac Micro grids which turn into islanded status, usually cannot maintain their frequency. In islanded micro grids, the main issue is to satisfy the balance between generation and demand in the ac grid to keep the frequency fixed. Since the islanding usually supposed to recover in a short time, utilization of storage systems to keep them working will be very efficient. In this case, the battery will be charged when generation is more than demand and frequency likes to increase. On the other hand, discharging batteries can provide the grid the missed energy at the point of connection to main grid. The first goal after maintaining the islanded area under normal electrical situation is to reconnect it to the main grid. For this purpose same voltage characteristics are required at the both side of reclosing breaker. Although synchronizers will make decision on ideality of reconnecting, but microgrid status should be controlled and reach to main grid and this will be done by the help of generation and storage systems <sup>6</sup>.

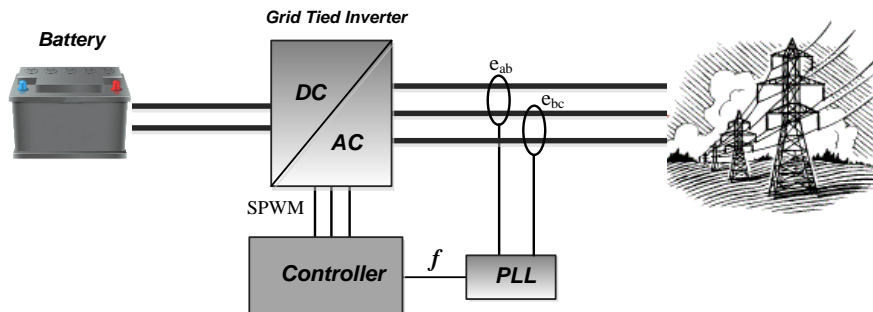


Figure 6: Battery energy storage for frequency regulation in islanded power system

### B. Developing procedures for power balancing in dc grid

Interconnected ac-dc micro grid is using the rectifier circuit to maintain the voltage criterion within the boundaries. Particularly controllable type of rectifier is used for that purpose. In this case the renewable sources with dc connectivity will participate in feeding the load through current or power control mode of operation. Depending on how fast they can react to new reference command, they have different priorities in balancing the generation and demand response <sup>8</sup>.

Unintentionally islanding of micro grid will lose voltage stability due to absence voltage control parameter. To keep the system stable, one of the units should take action fast and with high

reliability. It is recommended to use storage systems for this purpose <sup>8</sup>. In case of current injection from dc grid into ac grid, the story is totally different. Charging limit of battery storage systems are usually smaller than the discharge limit due to power electronic limitations <sup>9</sup>. The system should have enough inertia to delay the voltage rise and this is provided by capacitor banks and dc capacitive characteristic of the dc grid.

### C. Bidirectional Energy Conversion in dc Microgrid

There are many applications in dc power system that need transfer energy in both directions between two or more dc buses or sources. For instance, in an electric vehicle, the power should transfer from battery to the electric motor in acceleration mode of operation. But in deceleration condition, called regenerative braking, the energy of the wheels could be sent back into the battery. In this mode, the electric motor will act as a generator and the battery will receive power. The two modes of operation are shown in Figure 7.

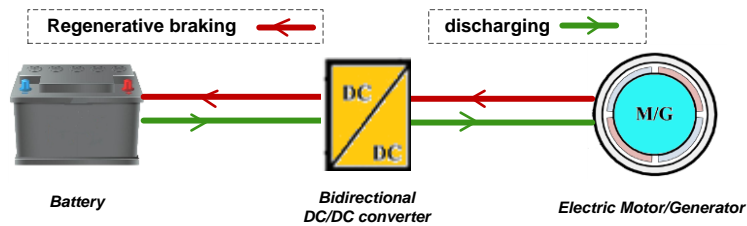


Figure 7. Energy transfer in electric vehicle

Moreover, several systems are currently employing dc distribution systems already. For instance, in systems that require high reliability and are involving a big number of electronic loads such as data centers, dc provides a more efficient solution for electric power distribution. Further applications of dc distribution systems include telecommunication, traction and spacecraft power systems. Figure 8 shows the schematic diagram for connection of two dc buses through bidirectional dc-dc converter.

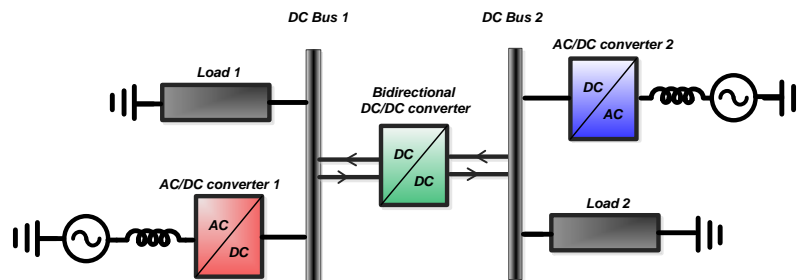


Figure 8. A schematic diagram for bidirectional energy transfer among two dc buses

Figure 9 shows the topology of bidirectional buck-boost converter that is implemented in our hybrid ac-dc power system. This convertor basically has two modes of operation:

- i. In the boost operation mode, power is transferred from the low voltage terminal (LV) to the high voltage terminal (HV). In this mode, the first switch,  $S_1$ , is turned off while the second switch is controlled by a PI controller to regulate the energy transfer. The steady state voltage and current can be given by <sup>11</sup>:

$$V_{HV} = \frac{V_{LV}}{1-\delta} \quad (3)$$

$$I_{HV} = \frac{V_{SLV} / (1-\delta) - V_{SHV}}{R_{HV} + R_{LV} / (1-\delta)^2} \quad (4)$$

Where, the  $\delta$ ,  $R_{HV}$  and  $R_{LV}$  are the duty cycle, the equivalent resistor of the HV source and the equivalent resistor of the LV source respectively. Also,  $V_{LV}$ ,  $V_{SLV}$  and  $V_{SHV}$  are the LV terminal voltage, the equivalent voltage of the source connected to the LV side and the equivalent voltage of the source connected to the HV side respectively.

- ii. In the buck operation mode, power from HV terminal is transferred to the LV terminal. In this mode, the PI controller regulates the power by continually adjusting the switching cycle of the  $S_1$ . The necessary condition for buck operation is that the  $\delta V_{SHV}$  should be higher than the  $V_{SLV}$ . During this mode, the voltage and current of the low voltage terminal can be given by (5) and (6) respectively.

$$V_{LV} = kV_{HV} \quad (5)$$

$$I_{LV} = -\frac{kV_{SHV} - V_{SLV}}{k^2 R_{HV} + R_{LV}} \quad (6)$$

- iii. In the Buck mode, power from HV will be transferred to the LV. In this mode the second switch,  $S_2$ , will work as diode and the first switch,  $S_1$ , will be controlled by PI controller and PWM to control the energy flow.

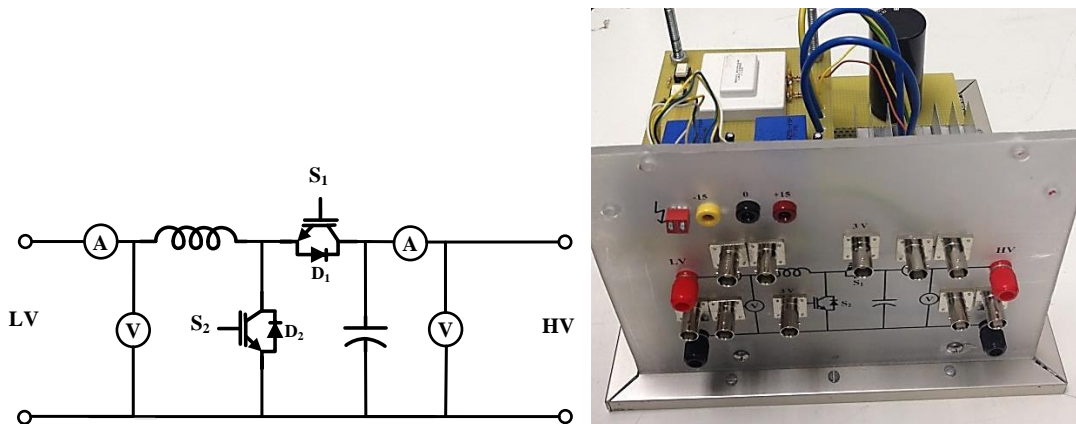


Figure 9. Bidirectional buck boost converter schematic

The inductor and capacitor used in the converter are 2.7 mH and 1200  $\mu$ F, respectively. The maximum input current into the LV side is 12 A and it is mainly limited by the inductor capacity. For control and monitoring purposes, two voltmeters and two ammeters were connected to measure the current and voltage at the two terminals. In practice, for bidirectional energy flow, the dc-dc converters are usually operated in current control mode. In this case, one of the ammeters may be enough for control of the current. However, the other meters can be used for monitoring purposes.

There are many issues attached with bidirectional dc-dc converter: To realize the benefits of bidirectional energy transfer, these converters must be capable of regulating of their output voltages at different load, while maintaining high efficiency. Also, there are connectivity issue linking two different dc buses, whose voltages are at different levels and containing significantly different content of ripple.

#### D. Bidirectional power flow in the interconnected ac/dc grid for controlling the active and reactive power flow

High penetration of renewable energy sources, yielding dc output, and also the increased number of electronic loads and machine drives operating with dc input, made the dc microgrid very important. In case that the generation in dc microgrid is not balanced, the excess power can be stored during low consumption times and be available during high utilization times. Also, grid-tied inverter can be implemented to provide bidirectional power flow between the dc microgrid and the existing ac grid. In this case, any excess dc power can be sent to the transmission grid, and also power from the ac grid can be drawn to make up for any power shortfalls in the dc microgrid.

While storage system is an advantage in areas that are disposed to power outages, grid-tied-inverter systems are much more cost-effective. This is because the grid-tied-inverter operates using fewer components, and also since the sizing of the system is not dependent on the electrical load. Nonetheless, compound system of the battery storage and grid-tied-inverter can provide both advantages with proper sizing.

Bidirectional grid-tied-inverter test setup is implemented in our hybrid ac-dc power system laboratory<sup>10</sup>. A vector decoupling control technique with sinusoidal pulse width modulation (SPWM) is implemented to regulate the active and reactive power flow between the dc and ac grid. Figure 10 shows the circuit diagram of the system and its control. The dynamic model of this system in the state space can be represented by (7)<sup>10</sup>.

$$\begin{bmatrix} \frac{di_q}{dt} \\ \frac{di_d}{dt} \\ \frac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & \omega & \frac{-s_q}{L} \\ \omega & \frac{-R}{L} & \frac{-s_d}{L} \\ \frac{3s_q}{2C} & 0 & \frac{-1}{CR_L} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{-1}{L} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} e_q \\ 0 \\ 0 \end{bmatrix} \quad (7)$$

Vector decoupling technique is used for autonomous control of the active and reactive power flow. The controller is built base on the state space model of the system and the equations are given by (8) and (9).

$$v_{rq}^{cont} = \omega Li_d + e_q + k_p (i_q^{ref} - i_q) + k_i \int (i_q^{ref} - i_q) dt \quad (8)$$

$$v_{rd}^{cont} = -\omega Liq + k_p (i_d^{ref} - i_d) + k_i \int (i_d^{ref} - i_d) dt \quad (9)$$

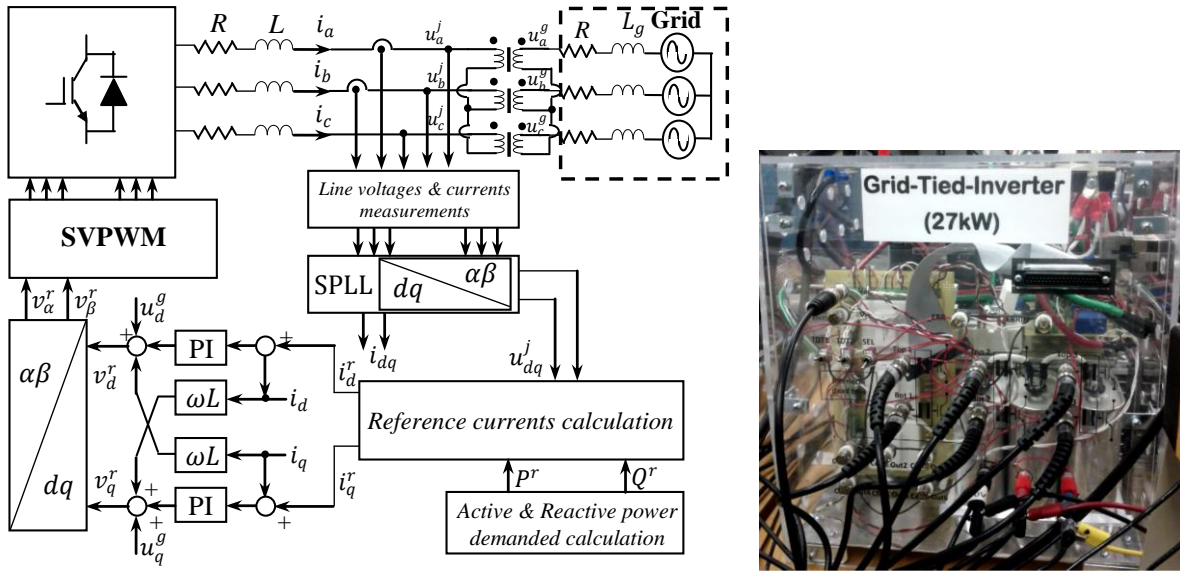


Figure 10. Vector decoupling control of the bidirectional converter for power sharing of hybrid ac/dc systems <sup>10</sup>

The controller can work at unity power factor if the reference value of  $i_d$  is set to zero. The grid-tied-inverter is operating at 8 kHz switching frequency and sampling time 0.3 ms, which allows fast response of the system to different load demands at either the ac or dc sides. Corresponding active and reactive power flow can be driven from equations (10) and (11).

$$P(t) = \frac{3}{2} [u_d^j(t) \cdot i_d(t) + u_q^j(t) \cdot i_q(t)] \quad (10)$$

$$Q(t) = \frac{3}{2} [u_q^j(t) \cdot i_d(t) - u_d^j(t) \cdot i_q(t)] \quad (11)$$

## Experiments for student training

For educational purposes, this material can be valuable for students majored in energy systems. In addition, the complementary course involves students in practical techniques which are not available in theoretical course work coverage. The developed system can also be used to implement protection and control ideas associated with new developments in smart grid. There are several experiments which were designed for the student's involvement with practical aspects of hybrid energy systems. These experiments are listed as:

- 1) Designing and speed control of wind emulator machine system
- 2) Power sharing control of hybrid ac/dc systems
- 3) Bidirectional energy conversion of power sources in dc microgrid systems
- 4) Designing and building of transmission line models and ac bus model
- 5) Wide area measurement and operation of the ac grid
- 6) Bidirectional power flow between ac and dc systems using grid tied inverters

## Conclusion

This test setup was developed by our research group to be used as an educational platform to simulate most common types of renewable energy resource in the modern power systems. By implementing different hardware and software components, we can evaluate different techniques and scenarios in operation of power grids involving automation, control, monitoring and analysis in presence of renewable resource.

Important practical knowledge in this context were gained including wind turbine and generator system behavior as well as the speed control of motor-generator sets through the inverter-drive electronics. We also gained experience in the design and control of power sharing control program using Matlab/Simulink. The control of the dc-bus voltage and the evaluation of the bidirectional dc-dc convertors performance were important knowledge gained. We have also utilized advanced power electronics techniques for distributed generation and demand side management. Finally we have utilized renewable energy resources for secure operation of islanded micro grids.

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