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Design and Hardware Implementation of Laboratory-Scale Hybrid DC power System for Educational Purpose

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Abstract

The DC microgrid is an effective architecture that is utilized to achieve reliable power with high efficiency through the implementation of power electronics converters and energy storage devices. Many systems are currently using DC power. For instance, DC architecture is employed in data centers to provide efficient and reliable power distribution across large numbers of electrical loads. The proper utilization of the DC power system involves with many new challenges and requires development of new techniques for power flow control, energy management and protection. In this paper, we present the development of our educational DC microgrid platform which includes popular renewable energy sources and hybrid storage systems. This lab-scale platform provided an educational environment for senior students and graduate students to take part in laboratory experiments and to understand and develop new ideas for DC power system applications.

I. Introduction

Power system planning and its design are the major challenges of the future power system [1]-[3]. Recently, DC microgrid and hybrid DC power systems have gained a lot of popularity and interest. The importance of the DC power system is not only because of the fact that most of the renewable energy sources such as solar and fuel cell have a DC output but also because implementation of energy storage systems are easier and more efficient in DC power systems. Moreover, the recent advancement of power electronic converters made power regulation in DC architectures more efficient and effective [4]-[7].

In this paper, the laboratory-scale hybrid DC power system developed in the Energy Systems Research Laboratory at Florida International University is presented. The objective of this development is to study the challenges of the DC power system that includes renewable energy sources and a hybrid energy storage system in a laboratory scale. The practical issues involved with the implementation of the hybrid DC power system are discussed, including the limitation and the implementation challenges of the renewable energy sources and energy storage system. Also, the impacts of a load with a special profile on the performance of the DC power system are discussed. In section III, the description of the developed hybrid DC microgrid platform is presented. The energy storage devices and the load emulator system implemented in the test setup are detailed. Also, this section includes a description of the renewable energy source emulator and the power converter setups. The generation station, transformer and filters and the grid configuration implemented in the DC power system platform are described. Section IV discusses the real-time control and monitoring of the DC microgrid power system. The educational efforts being performed on the hybrid DC microgrid platform are presented in section V. This is followed by the conclusions in section VI.

II. Hybrid DC Microgrid Applications and Practical Issues

The DC microgrid is an effective architecture used to achieve more reliable power with higher efficiency. However, the implementation of the DC power system brings forth with many new challenges. In this section, the practical issues involved with the DC power system and hybrid DC microgrids in different applications are discussed.

A. Renewable Energy Sources

Due to the depletion of fossil fueled energy resources and their detrimental environmental impact, there is global attention for utilization of clean and renewable energy sources such as solar, wind and hydrogen energy. However, the main concern for increased utilization of the renewable energy resources is the means to control and integrate the renewable energy resources to the power grid [8]-[9].

One of the main issues for the implementation of the renewable energy sources is the choice between connecting these sources in an AC power system or a DC power grid. Most of the promising renewable energy technologies such as photovoltaic (PV) and fuel cells natively produce DC output. Moreover, the output power of the wind farm should be converted to DC for proper regulation. Thus, the DC power grid and DC distribution power system is a good choice to integrate and control the renewable energy resources. As the result, with the implementations of DC power system, the cost of the system can be considerably reduced and its efficiency improved.

Another issue for the implementation of the renewable energy resources is their intermittent characteristics. Most of the renewable energy sources such as PV and wind turbines have daily and seasonal patterns. For instance, the power versus voltage characteristic of a solar panel under different solar irradiations is shown in Figure 1. Under certain solar irradiations, the PV power-voltage curve would have only one peak. Assuming that a load is directly connected to the PV array, the system operation point will be at the intersection of the power-voltage profile of the load and the PV array. If the operation point is at the maximum power point (MPP), maximum power from the PV array will be achieved. However, since the MPP is irradiation dependent, installation of a power regulator and continuous MPP tracking control technique are essential.

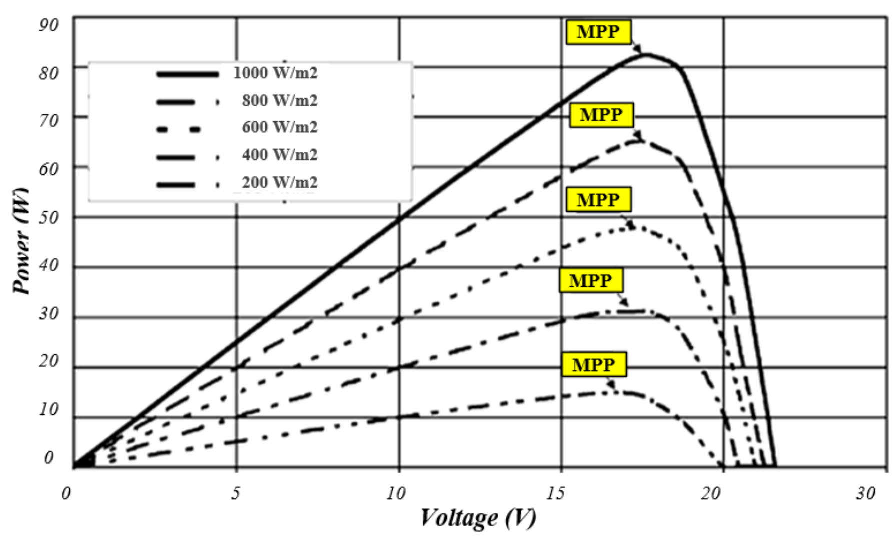


Figure 1: Electrical characteristics of a PV panel in different illumination.

B. Energy Storage Systems

Since renewable energy have intermittent characteristics, energy storage systems are necessary for a high penetration of energy into a power system. Energy storages are also of critical importance in power systems to meet peak demands and to improve the reliability of the power system. Moreover, energy storage system can be implemented to enhance the efficiency of the system and to make the system more environmentally friendly.

Most of storage devices such as batteries and supercapacitors are purely DC. Moreover, flywheels, as an electromechanical energy storage system, are commonly connected to a DC link through a permanent magnet synchronous machine (PMSM). Thus, the DC power system is the most prominent configuration for energy storage devices and their proper integration with the fewest number of conversion stages. As a result, the system efficiency will be improved and the system complexity and cost will be reduced.

Battery storage devices have been widely utilized for many applications. However, the storage systems come with several challenges. The power density of the battery storage is relatively low. As a result, a battery storage system alone is not able to meet the dynamic peak power demands effectively. Several battery banks can be connected in series and parallel to meet the load requirement. However, this will considerably increase the cost of the system and can cause thermal issues due to imbalances in battery cells.

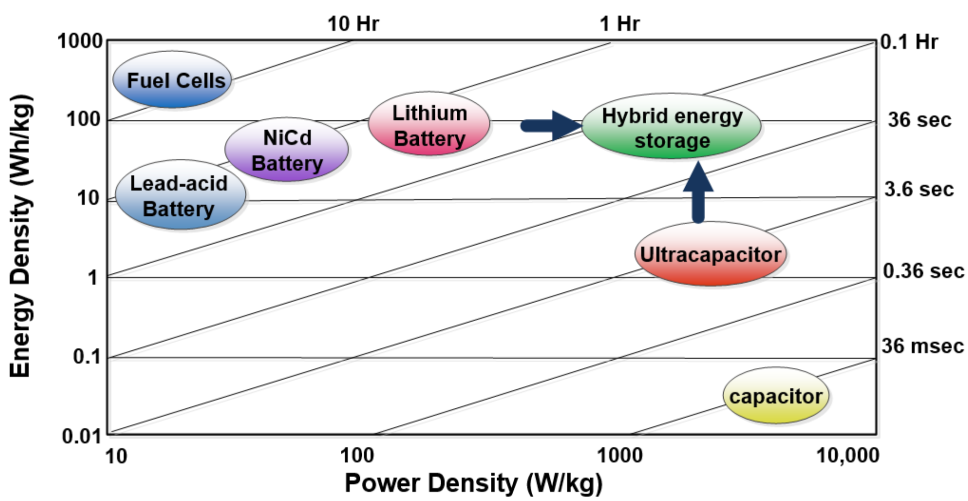


Figure 2: Power density vs. energy density for various electrochemical energy-storing devices.

Figure 2 shows the power density versus energy density of different energy storage devices. Lithium batteries have a power density of 100-500 W/kg which is the highest energy density of all modern batteries. In contrast, the power density of the supercapacitors is around ten times greater than the lithium battery, considering the power density of the supercapacitor is relatively low. As a result a hybrid battery/supercapacitor storage system can be utilized to retain the benefits of a high specific power and energy system. Also, the internal series resistance of the supercapacitors is much lower than that of the batteries. Therefore, hybrid storage system have a much higher charging/discharging efficiency than a battery alone storage system [5]-[6].

C. Loads and Drives Systems

Many loads are currently employing DC power. Household appliances such as computers, phones, telephones, microwave ovens, and lighting all consume electricity in DC form. Power systems requiring high reliability with a large number of electronic loads, such as data centers, protection systems and telecommunications benefit greatly from DC architectures [4]-[7]. One key advantage of a DC power system compared to an AC system is that loads can be connected through simpler and more efficient power-electronic interfaces.

In DC powered loads, the energy management and power control are fundamental concerns. The loads in systems such as spacecraft power systems and telecommunications have pulse characteristics where the load duration can range from hundreds of milliseconds to seconds, with varying power levels [5]-[6]. In order to meet the peak loads efficiently and to improve the power quality and stability of these systems, hybrid energy storages implementation is essential.

Consider the general power profile of a pulse load $P_L(t)$ as shown in Figure 3. As can be seen, the load is considered as a constant power changing between P_{Min} and P_{Max} with a period T where the frequency $f = 1/T$ and duty cycle D. The instantaneous load power, $P_L(t)$ for the first N pulses based on Figure 3, can be expressed as:

$$P_L(t) = P_{Min} + \sum_{k=0}^{N-1} (P_{Max} - P_{Min}) [\phi(t - kT) - \phi(t - (k + D)T)] \tag{1}$$

where ϕ is a unit step function. In order to describe the dynamic behavior of the pulse load, the instantaneous load power can be decoupled into an average power profile, P_{Lav} (dotted line) and a dynamic power profile, P_{Ldy} (dashed line).

It should be noted that the average of the P_{Ldy} over a period T is zero. In the case of a single source system, the source must supply the instantaneous power requirements i.e. both the dynamic and the average power components. In contrast, the dynamic and average power of a hybrid energy system can be distributed between different energy devices. A power source with high energy density can be utilized as a long-term source to provide P_{Lav} while a source with a high power density as a short-term power source is employed to satisfy the P_{Ldy}. This will allow the system to supply the loads over a wide range of time efficiently.

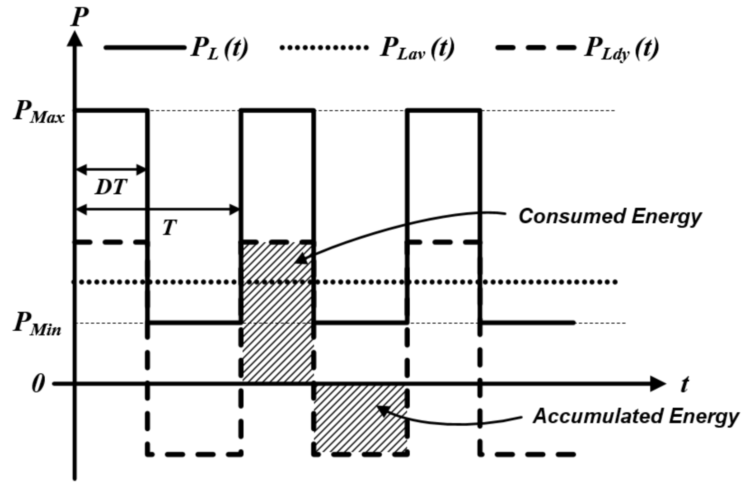


Figure 3. Consumption power profile of a pulse load.

D. Electric Vehicles and Hybrid Electric Vehicles

Due to the widespread concerns of global warming and high oil consumption rates in the transportation sector, the past decades have seen an increased interest in reducing fossil fuel consumption and emissions by government organizations. This act has urged many automotive companies to develop new environmentally friendly vehicles with higher fuel economy such as electric vehicles, hybrid electric vehicles and fuel cell vehicles.

The hybrid electric vehicle drive is mainly a DC power system which is powered by an energy storage system and an internal combustion engine. The electric vehicle drive system is only powered by the energy storage device/devices. The configuration of the hybrid electric vehicles includes parallel hybrid technology, with both batteries and/or engine propelling the vehicle through planetary gear, or series hybrids, with the engine simply charging the battery. Although electric and fuel cell vehicles have promising advantages compared to a conventional combustion engine vehicle, they have some limitations which make them a less attractive option than current combustion engine automobile technology [10]-[11].

One of the most important components of electric and fuel cell vehicles system is the electric motor. The key requirements for these systems are; (I) high efficiency over wide torque and speed ranges, (II) high torque and power density to reduce the weight and size of the vehicle, (III) high starting torque, (IV) wide speed range, (V) constant torque and constant power regions and (VI) reasonable cost [10]-[11].

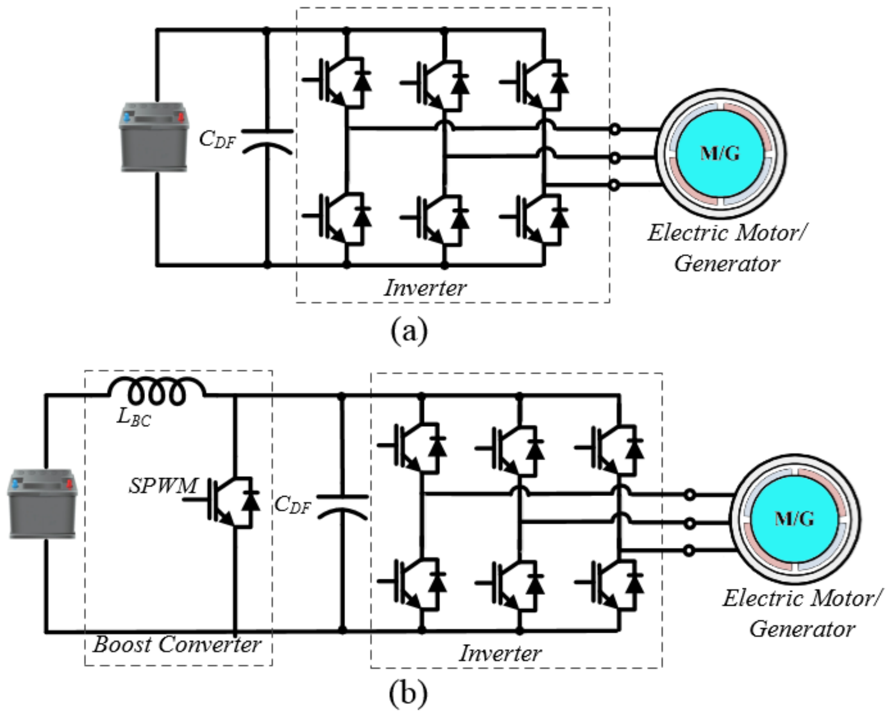


Figure 4: Electric drive topologies for electric vehicles: (a) Direct connection; (b) Active hybrid connection.

Another important design aspect of electric and fuel cell vehicles is the drive system. Figure 4 shows the two basic configurations utilized for electric vehicle applications. Figure 4 (a) shows the traditional battery-powered inverter using the pulse width modulation (PWM) technique. Figure 4 (b) shows the second topology in which the battery bank is connected to the inverter through bidirectional DC-DC converter. Implementation of the bidirectional DC-DC converter will minimize the stress of the inverter through bus voltage regulation. Also, the DC-DC converter allows separate design of the battery bank and the system voltage i.e. the system voltage can be designed based on motor output, while the number of battery cells can be varied to match the required power output and energy capacity. However, the active configuration (Figure 4 (b)) has some disadvantages such as increased system complexity, extra cost and power losses due to the implementation of the dc-dc converter. Thus, the cost optimization and size reduction of the power train and electronics components were a major concern in many studies. Also, the reliability improvement due to the introduction of an additional component needs to be taken into account. Moreover, hybrid combination of battery-supercapacitor is another major challenge in the design of the electric vehicle's DC power systems.

III. Implementation of Hybrid DC power System

The hybrid DC microgrid in the Energy Systems Research Laboratory at Florida International University is being developed as an educational platform for undergraduate and graduate electrical engineering students. The hybrid DC power system studies include system applications, microgrid design and power flow control, energy management systems, advanced protection, optimum efficiency and smart grid operation of the power system. In this section, the equipment used for this setup is presented and illustrated with their specifications and configurations.

A. Energy Storage Devices

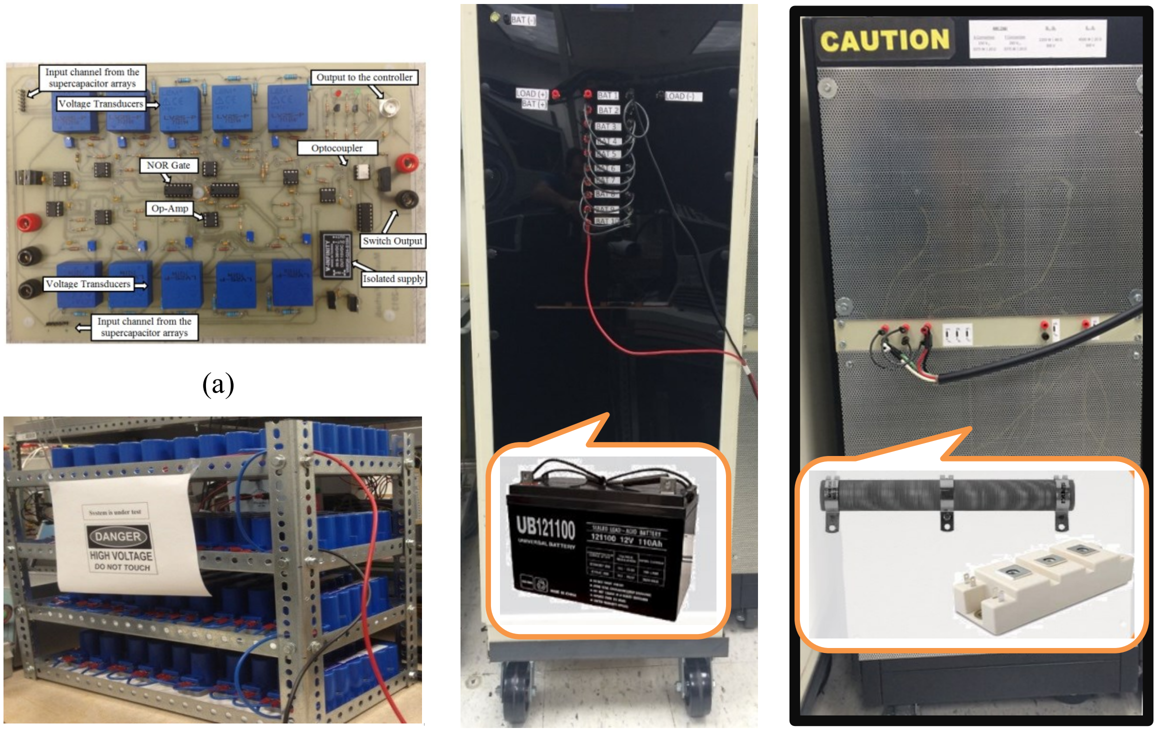
The energy storage devices of the implemented hybrid DC power system include a supercapacitor bank and a battery bank. The supercapacitor bank is built using 350-F, 2.7-V cells of Maxwell Technologies supercapacitors. Six supercapacitor cells connected in series form a 5.8-F, 16-V module. Twenty supercapacitor modules were connected in series to configure a 2.9-F, 320-V supercapacitor bank. This bank is protected via an analog hysteresis voltage protection board (Figure 5 (a)). Figure 5 (b) shows the supercapacitor bank implemented in the test setup. Two 2.9-F supercapacitor banks are available in our experimental test setup which can be connected in parallel to form 5.8-F, 320-V bank. Alternatively, they may be connected in series to form a 1.45-F, 650-V bank.

Also, the battery bank is composed of twelve lead-Acid battery cells rated 120-V, 110-Ah. Figure 5 (b) shows the battery bank implemented in the test setup. This bank is built using the UB121100 Universal 12-V, 110-Ah lead acid battery.

B. Load Emulator

The implemented hybrid DC microgrid includes three different types of loads. This includes the steady state load, the dynamic load and the pulse load. Figure 5 (c) shows the load module. The rated power of the steady state load is 2-kW at the rated 320-V DC bus voltage. The dynamic load is built using a 15-Ω resistor that is connected to the low voltage side of a buck converter, with a switching frequency of 2-kHz. This load is able to fully emulate the dynamic behavior of a load up to 6-kW. Also, in order to study the pulse load effects on the system, a 20-Ω resistor is connected to another buck converter. The switching frequency of this converter is 2-

kHz. The pulse load is completely programmable for the power up to 4-kW at different pulse frequencies and duty ratios.

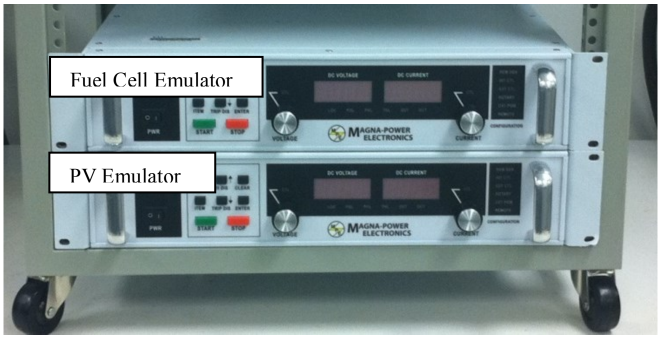


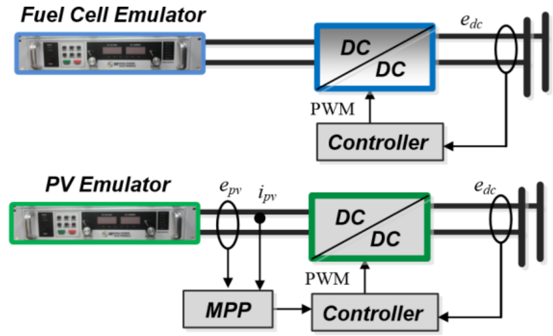
(a) (b) (c) (d)

Figure 5: Experimental test equipment: (a) supercapacitor voltage protection board; (b) supercapacitor bank; (c) battery bank; (d) load emulator.

C. Renewable Energy Source Emulator

Due to the limitation of energy availability in a laboratory environment, three major renewable energy resources, namely PV, fuel cell and wind are emulated in our hybrid DC microgrid. Figure 6 (a) shows the programmable power supplies which are utilized as a PV emulator and a fuel cell emulator. The PV system is able to fully emulate the nonlinear behavior of the PV system up to 5KW. Also the fuel cell system emulates solid oxide fuel cells (SOFC) characteristics. The power supply emulator is able to be programmed with lookup tables representing the relation between the voltage and current or voltage versus time. The emulator is also capable of representing sharp and sudden changes in the voltage value to examine the behavior of the system and its components under severe conditions. Figure 6 (b) shows the general schematic diagram of the PV and fuel cell system configuration. The PV system utilized MPP tracking algorithm and a DC to DC converter to extract the maximum power form the PV cell. Also, a DC to DC converter is employed in the fuel cell system to regulate the DC voltage terminal and the injected power to the DC bus.

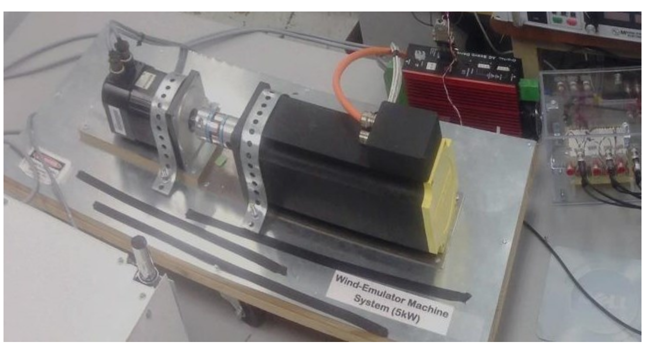


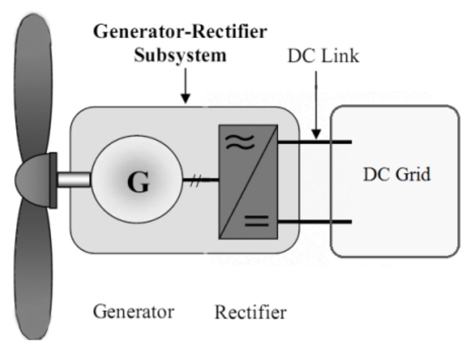


(a) (b)

Figure 6: PV and fuel cell system: (a) PV and fuel cell emulator; (b) System configuration of PV and fuel cell.

Figure 7 (a) shows the wind turbine emulator. This system is composed of a variable speed prime-mover and a brushless DC generator. A digital signal processor (DSP TMS320F240) has been employed as the main control system to emulate the wind speed pattern. In a realistic wind turbine system, the 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. Also, shown in Figure 7 (b) is the configuration of the wind system. As can be seen, the wind generator output terminal is connected to a DC bus through an AC to DC rectifier to convert and regulate the output power.





(a) (b)

Figure 7: Wind power system: (a) Wind emulator; (b) Wind system configuration.

D. AC/DC and DC/DC Power Converters

Four types of power converters are implemented in our hybrid DC microgrid system. Figure 8 (a) and (b) show the DC-DC boost converter configuration and its hardware test setup, respectively. The boost converters are mainly implemented as interfaces between different renewable energy sources and the DC grid. The PV interface converter is operating in MPP tracking mode while the fuel cell converter is used to integrate the fuel cell energy into the system and is operating in a current control mode.

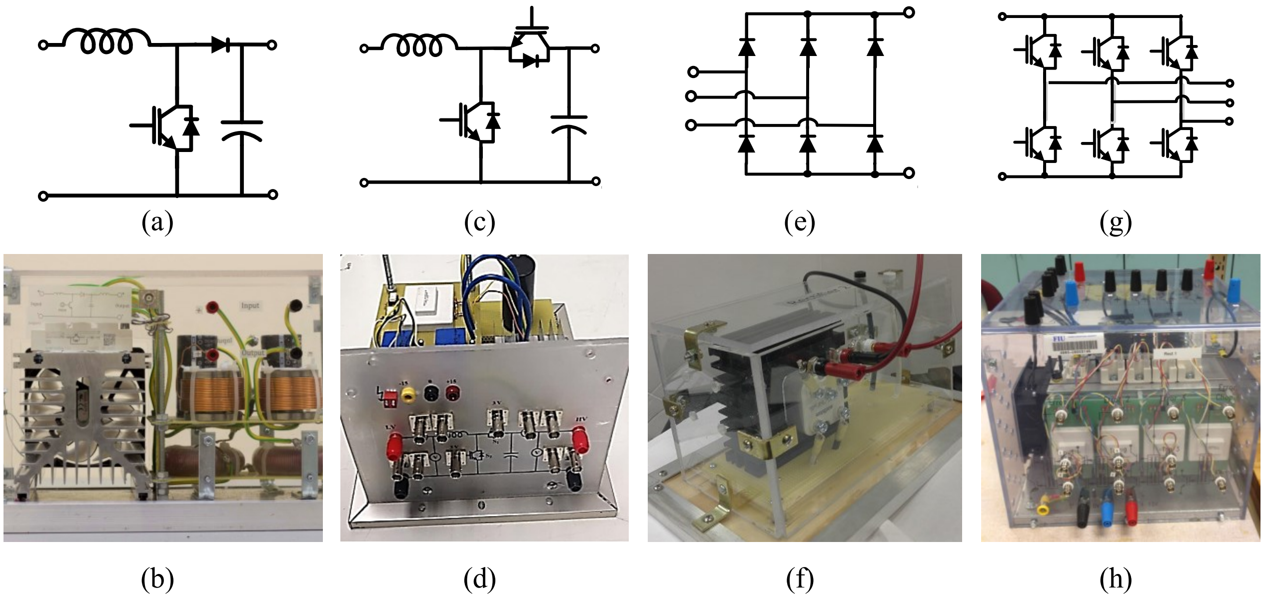


Figure 8: power converters implemented in hybrid DC power system. (a): DC-DC boost converter configuration; (b): DC-DC boost converter hardware; (c): DC-DC bidirectional converter configuration; (d): DC-DC bidirectional converter hardware; (e): uncontrolled rectifier configuration; (f): uncontrolled rectifier hardware (g): bidirectional AC-DC converter configuration; (h): bidirectional AC-DC converter hardware.

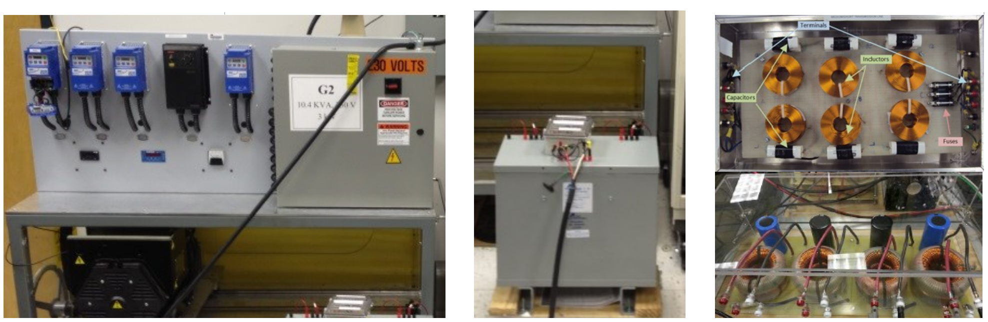
Figure 8 (c) and (d) show the topology of a bidirectional buck-boost convertor and its hardware test setup, respectively. This convertor has two modes of operation: In its first operation mode, the boost mode, the power from the left side, low voltage (LV) terminal is transferred to the right side, high voltage (HV) terminal. The second operation mode is the buck mode in which the power from the HV terminal is transferred to the LV terminal. The bidirectional converters are mainly implemented as a power regulator for charging and discharging of the battery bank. Also, it is implemented for the purpose of bidirectional power transfer between two DC microgrids.

Figure 8 (e) and (f) show the configuration of the full bridge uncontrolled rectifier and its hardware setup. This type of converter is very common in high power applications. The pair of diodes facing the highest amount of instantaneous line to line voltages will conduct for 120 degrees. As a result, the output contains six different ripple intervals per supply voltage time period. Thus, in order to reduce the ripple and control the power, implementation of the DC-DC power regulator at the output terminal is essential.

One of the most important converters implemented in the hybrid DC microgrid is the bidirectional AC-DC converter. Figure 8 (g) and (h) show the topology of this converter and its hardware setup. As can be seen, this converter is composed of six insulated-gate bipolar transistors (IGBTs) which are connected in bridge form and are controlled by sinusoidal pulse width modulation (SPWM) signals. These converters are implemented as a power regulator for charging and discharging of electric vehicle emulator and wind turbine generator system. Also, this converter is implemented as an interface between the hybrid DC microgrid and the main AC network.

E. Generation Station, Transformer and Filters

The AC generators are 3-kVA, 60-Hz, 208-V, 1800-RPM synchronous machines coupled to individual induction motors as prime movers. The generators are equipped with an automatic voltage regulator to maintain the terminal voltage magnitude. Detailed information about the operation of the generators can be found in [3].



(a) (b) (c)

Figure 9: Experimental test setup components. (a): AC generator; (b) Galvanic isolation transformer; (c) AC and DC filters.

In order to galvanically isolate the AC generator from the grid, a three phase 3-kVA Y/Δ transformer was connected between the generator and the AC filter. The AC filters are 12-mH inductors that filter out harmonics to the AC generators. Also, the DC filters are connected between the uncontrolled rectifiers and the boost converters. The inductor and the capacitor of the DC filter are 6-mH and 1200-μF, respectively. The filters are RC and RLC which are implemented to filter out the harmonics to the AC grid and generator and to improve the performance of the converter by reducing the DC voltage and current ripples.

F. Grid Configuration

Depending on the application, a hybrid DC microgrid can be designed to be supplied through internal energy sources and by an interconnected AC network. Also, a possible configuration for the hybrid DC microgrid is to be in a stand-alone operation mode in which the grid is only supplied through the internal energy sources. Figure 10 shows these two commonly used grid configurations that are implemented in our experimental test setup. As can be seen in Figure 10 (a) the hybrid DC microgrid is connected in a ring configuration and is connected via bidirectional AC-DC converter to a main 4 bus AC grid test-bed system. Also shown Figure 10 (b) is the stand alone configuration of the hybrid DC microgrid where the system is connected in a radial configuration and is supplied through its individual energy storage devices and the AC generators.

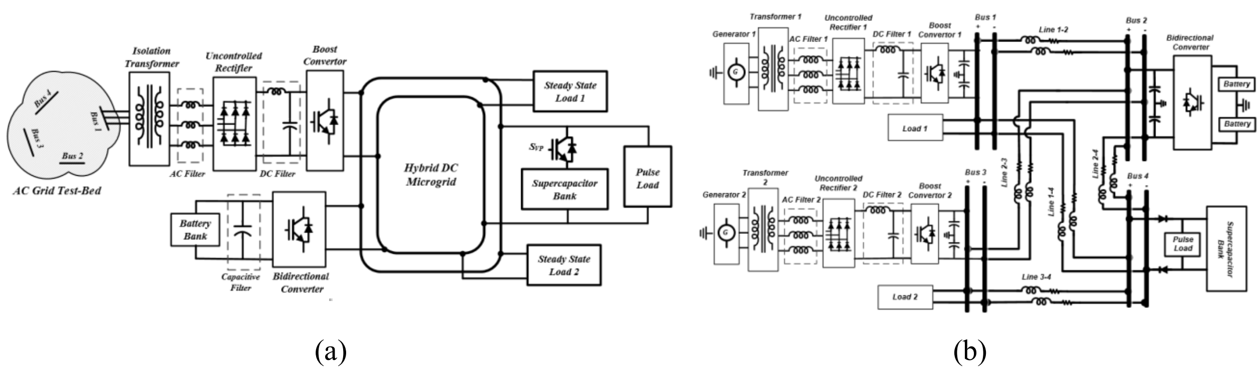


Figure 10: Schematic diagram of notional hybrid DC microgrid. (a): Hybrid DC microgrid Connected to a main AC network; (b): Stand-alone hybrid DC microgrid.

IV. Real-Time Control and Monitoring of the DC Microgrid

Figure 11 shows the strategy for the main control and monitoring system of the hybrid DC microgrid. As can be seen, the dSPACE 1103 real-time control module is utilized for the control of the power converters implemented in the hybrid DC microgrid. Also, in the notional DC microgrid shown in Figure 11, dSPACE 1103 board is utilized for the energy management and control of the DC-DC boost converter implemented in bus 1 and 3 and also for the control of the bidirectional converter implemented in bus 2. Moreover, this control board is utilized for the monitoring of the hybrid DC microgrid system.

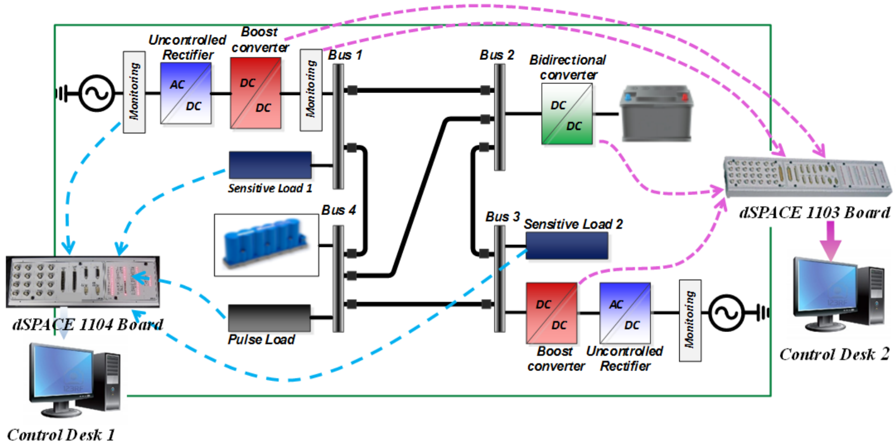


Figure 11: Monitoring and control infrastructure of the hybrid DC microgrid.

As shown in Figure 11, the dSPACE 1104 board was utilized to control and adjust the dynamic load, the pulse load and the steady state load. Also, this board is utilized for the control and monitoring of the power transferred to the AC generators. The experimental test setup of the hybrid DC microgrid including the control desk and monitoring system is shown in Figure 12.

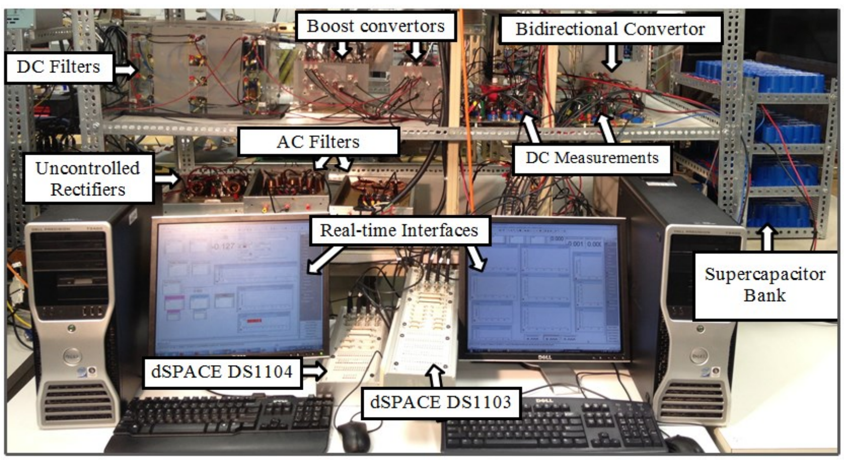


Figure 12: Control desk and monitoring system of the hybrid DC microgrid.

V. Students Involvement and the Developed Experiments

The developed hybrid DC microgrid setup is now being used as an educational platform for both undergraduate and graduate electrical engineering students. Two experiments were developed for undergraduate students and are included in the "Energy Conversion Lab" course. For each experiment, the students are asked to write a lab report stating their experience during the lab and answer the provided questions using the lab manual and also the U.S. Department of Energy website [12]. The first lab utilizes the test bed's wind turbine emulator in which the students are involved in learning the fundamental concepts behind its design, applications and operation. The students will understand the components of a wind turbine generator and the hardware/software infrastructure required to regulate the wind turbine output power. Moreover, the lab include the following topics: the importance of accurate prediction and measurement of wind speed and its direction, the advantages of larger wind turbines utilization and operating and installation cost comparison of a wind farm.

The second lab revolves around the power sharing control of hybrid DC systems and the objective of this experiment is to teach the students the fundamentals of fuel cells, PV systems, and their integration in hybrid DC systems. This lab also covers the following topics: the applications of the PV system and fuel cell, the environmental condition effects on the power generation of the PV plant, the difference between the concentrating thermal power (CSP) system and PV system, the components of the fuel cell, the factors that affect the produced power of a fuel cell and the required system to regulate the output power of the PV system and connect it to the grid.

In addition, this test-setup is utilized as a laboratory scale hybrid DC power system for individual or group projects. The senior undergraduate students can perform their final project by using the existing hardware-software infrastructures or built their own and evaluate it by connecting their development to the grid platform. Also, the graduate students utilize this setup for their voluntary experimental projects in the "Application of Intelligent Systems to Power System Operations" and "Power System Stability and Control" courses. The followings are the research areas that is selected and proposed by the students under the instructor's supervision:

- Renewable energy studies including wind turbine, PV system and fuel cell;
- Implementation and characteristics study of different energy storage technology including supercapacitor energy storage system, lead-acid battery bank and lithium battery;
- Study on the effects of galvanic isolation on the DC power system performance;
- Optimization of the energy storage system for hybrid DC power system applications;
- Study on the control and the energy management in a hybrid DC power train with regenerative braking capability;
- Accurate simulation model of the DC power system including different types of energy storage devises and evaluation of the model using the experimental results;

- Advanced power control for pulse load mitigation and analyzing the effects of the pulse load on the performance of the system;
- Protection of the DC microgrid with the capabilities of fault identification, fault area isolation and system restoration.

VI. Conclusion

This paper presented the laboratory-scale hybrid DC power system development in the Energy Systems Research Laboratory at Florida International University. This platform provided an educational environment for undergraduate and graduate student to take part in the laboratory experiments and to understand and develop new ideas with DC power system applications. The developed hybrid DC power system included three types of renewable energy source emulators including wind turbine, photovoltaic (PV) system and fuel cell. As essential components, a 5.4-F supercapacitor bank and 120-V, 110-Ah battery bank is implemented in the test setup. Also, this development includes three different load systems that can emulate steady state, dynamic and pulse load behaviors. Moreover, the developed hybrid DC power system is able to be connected in a ring, radial, stand-alone or grid connected configuration. The developed lab-scale platform along with the new experiments provided this opportunity for the students to understand many challenges and concepts of the hybrid DC power system. Also, the graduate students and the senior undergraduate students, as researchers, are able to develop new techniques and evaluate their ideas experimentally. As a future work, it is proposed to perform a survey to investigate the students' views about the lab projects, their learning and its impact on their future carrier. The feedback can be very beneficial to enhance the lab experiments and the defined projects.

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