A Sustainable, Portable, and Efficient Electricity Delivery (SPEED) System

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***Abstract*—In this paper, a sustainable, portable, and efficient electricity delivery (SPEED) system is designed and built for community emergency/disaster relief with sustainable power solutions. The system consists of a 180W PV array with six serial-connected solar panels, a 1.8kWh battery system, a SYNDEM power converter, and a human-machine interface. Advanced power electronics control technologies are designed and implemented to guarantee the autonomous operation of the SPEED system at either islanded mode or grid-tied mode to cope with emergency/disaster relief scenarios. Field testing is conducted to validate the effectiveness and efficiency of the SPEED system.**

Keywords—Portable, sustainable, and efficient electricity delivery (SPEED); Emergency relief; Disaster relief; Advanced power electronics control.

I. Introduction

Incorporation of sustainable and portable electricity generation to support critical energy demands is important for improving community resiliency and energy independency. Traditional portable electricity delivery systems would face serious consequences when the electric grid is not available for a longer period, and fuels (e.g., diesel, gasoline, hydrogen) is insufficient or not available. Such a scenario would be an aftermath of a natural disaster. It was reported that 20 deaths occurred as an exacerbated result of existing medical conditions due to the power outage, when the hurricane Irma knocked out power in Florida [1]. Also, it took a week to restore the power in hospitals in Puerto Rico after the hurricane Maria [2]. There are tremendous critical needs of power preparation for the community's survival from the effects of the extreme emergency, and thus, the portable and sustainable electricity delivery system is becoming a critical need. Moreover, such systems could facilitate other human energy needs related to off-grid activities such as outdoor recreational activities, and mobile charging stations for electric vehicles [3].

In responding to electricity demands for emergency/disaster relief, several solutions may be considered. In [4], a microgrid based solution has been discussed. In [6], a renewable energy powered mobile medical clinic is designed and developed. However, during an occurrence of a natural disaster, affected geographical area is usually large, and thus, there is a need of portable electricity units, which are capable of fulfilling the energy needs of a single family or a small group of people. Such units would be deployed as many as needed across the affected area during the recovery phase. Actually, the usage of such units is not limited to disaster relief but also can be seen as a potential solution for meeting the energy demands during public outdoor events, off-grid living and many more. There are portable electricity delivery systems in the current market, which are designed based on fossil fuels and battery storage systems. However, these systems heavily depend on the constant supply of fuel or frequent charging of batteries. As we pointed out earlier, during an emergency or a natural disaster, neither fuel supplies nor grid power is available to charge batteries or fuel generators. In this context, renewable energy in combination with battery storage systems offers a better solution for sustainable and portable electricity generation.

In designing a sustainable portable electricity delivery, solar radiation is the most recommended energy source due to its availability and inexhaustibility [5]. As we are interested in portable electricity generation applications, PV-based systems seem to be the right candidate due to its ability to generate power with a smaller surface area compared to other renewable energy generation, such as wind turbines. In this paper, we discuss the design and development process of a sustainable, portable, and efficient electricity delivery (SPEED) prototype based on PVs for community emergency/disaster relief. One of the important features of the system is the grid forming capability so that users could connect standard electrical appliances. Furthermore, advanced power electronics control technologies have been designed and implemented to guarantee the autonomous operation of the SPEED system at islanded mode or grid-tied mode. Moreover, real-time data acquisition is achieved via a raspberry-pi based human-machine interface (HMI), which consists of a graphical user interface and a dynamic web server. Furthermore, all components are mechanically mounted on a moving cart to facilitate its mobility.

The rest of the paper is organized as follows. Section II describes the SPEED system design. System control is presented in Section III, which includes the elaborations of operating functions and algorithms. Results of field experiments are discussed in Section IV. The final section concludes the whole paper.

II. SPEED System Design

In this work, the objective is to build a sustainable, portable, and efficient electricity delivery (SPEED) system for community emergency/disaster relief with sustainable power solutions.

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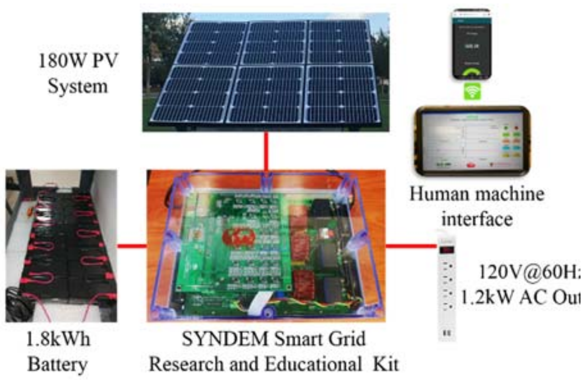

Fig. 1 The structure of the SPEED system.

As shown in Fig. 1, the SPEED platform consists of four major parts: six serial-connected solar panels, a battery system, a SYNDEM smart grid research and educational kit, and the human-machine interface (HMI). The solar panels absorb solar energy and convert it into DC power. The battery system is used for energy storage. The SYNDEM smart grid research and educational kit [7] is performed as a PV inverter and provides a power electronics interface for the PV panels, the battery, and AC outputs. The HMI system is developed for monitoring both energy data and real-time power flow.

In this SPEED platform, a total 180W PV array with six serial-connected solar panels (30W for each panel) is selected. The approximated model for this PV array is shown in Fig. 2, where the environment temperature is considered at $T = 25$ ℃. From Fig. 2, it can be observed that both the output current and the output power of the PV array are variable and susceptible, according to different solar irradiations and different load conditions. The maximum power point tracking (MPPT) algorithm is required to achieve maximum power acquisition of the PV array. It can be noticed that the PV output voltage is about 220 V, and the PV output current is about 0.9 A at the optimal point, when the solar irrational is $1000\ W/m^2$. The reason we design a high voltage, low current PV array is to increase the system efficiency will less power losses.

The battery storage system is integrated with 20 rechargeable lead-acid batteries (each one is with 12V@8Ah). The maximal, available energy storage in the battery is about 1.8kWh. The approximated battery discharging curve is shown in Fig. 3, which indicates that the battery system can support more than one hour with 5A output (about 1.2kW, within the power limitation of the SYNDEM PV inverter). The major function of the battery system is to balance the fluctuation of the PV power. Though the PV array can operate at the optimal point with the MPPT function, the optimal point still varies at different solar irradiations, such as daily changes or shading effects. In another aspect, the load consumption usually is different from the solar power generated. In this way, the battery can store the energy when the PV source is sufficient, and release the energy when more power is required by the loads.

In this work, the SYNDEM smart grid research and educational kit, a MathWorks third-party product [7], is performed as the PV inverter to integrate the PV panels, the battery, and AC outputs. The SYNDEM smart grid research and educational kit is a multifunctional power electronic converter. It can be used to facilitate research and education in grid integration of various renewable energy sources, such as solar power, wind power, and energy storage systems, and flexible loads. The kit can be reconfigured to obtain 10+ different power electronic converters, versatile for different applications. The kit includes both RS485 and CAN interface for data monitoring and HMI design. In the SPEED system, the SYNDEM PV inverter is configured as a DC/DC boost converter and a single-phase DC/AC converter. While the DC/DC boost converter converting DC power of the PV panel into the battery, and the single-phase DC/AC converter feeding the DC power from both the PV source and the battery into AC loads or AC grid.

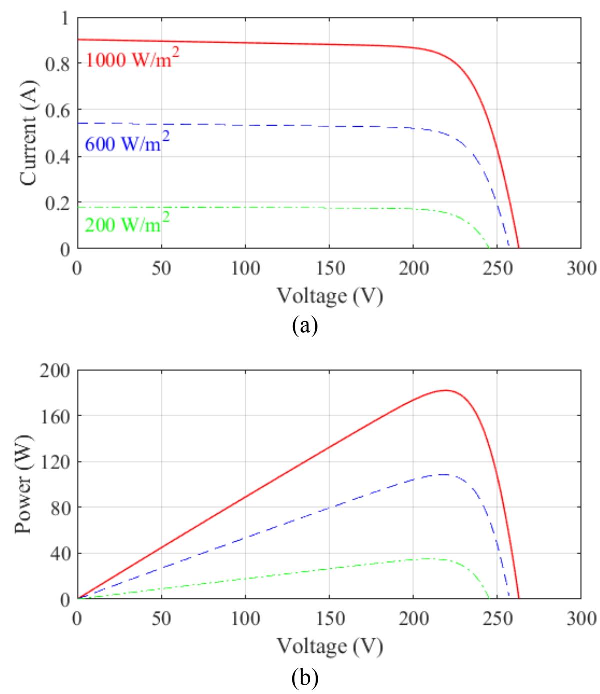

Fig. 2 The approximated model for the PV array at different solar irradiation conditions and = 25 ℃ : (a) Current-voltage curve; (b) Power-voltage curve.

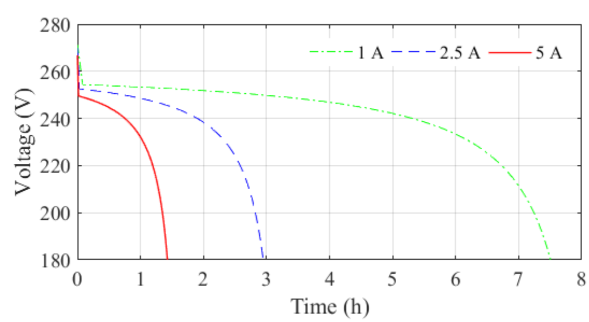

Fig. 3 The approximated battery discharging curve at different output currents.

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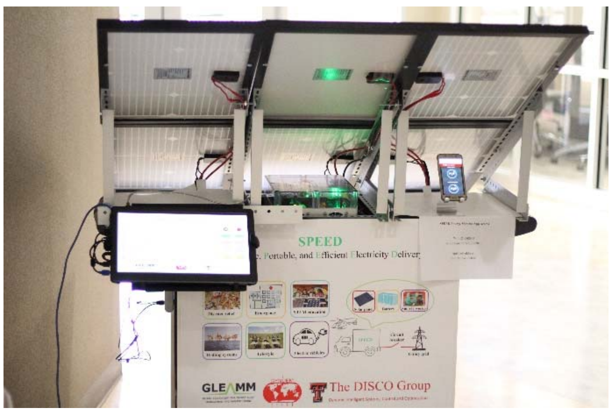
(a)



(b)

Fig. 4 The SPEED platform: (a) Front view; (b) Back

The aim of the HMI design is to acquire and visualize the real-time data of the SPEED platform. It consists of a graphical user interface and a dynamic web server running on a raspberry-pi single board computer. The raspberry-pi provides a low cost, compact, and open source embedded programming platform for data acquisition and monitoring. Data acquisition functions are implemented on the raspberry pi with a 100ms data sampling rate. However, the graphical user interface is updated only every 1 second in order to mitigate the execution overhead of the system. The graphical user interface is displayed on a 17” UHD monitor attached to the platform. In order to provide the remote logging capability, the raspberry pi operates as a Wi-Fi router and an access point. The user can monitor data on mobile devices via a web interface that displays the real-time data, which is hosted by the raspberry pi.

This SPEED platform can be operated at both island mode and grid-connected mode. If the SPEED platform is conducted for outdoor activities, such as emergency reliefs, or remote area applications, this system should be operated at islanded mode with the grid-forming capacities because there is usually no utility grid access in these scenarios. The grid-connected operation is also built inside the SPEED platform for normal daily scenarios, where the energy generated by the PV array can be sent back to the utility grid.

III. SPEED System Control

In order to achieve autonomous operation of the SPEED platform within a stable, reliable and adaptive way, advanced power electronics control technologies should be developed and embedded into the PV converter. There are three major functions of the control design for this SPEED platform as discussed below.

- DC/DC Boost Converter Control. As shown in Fig. 5(a), the output power of the PV panels varies, according to different conditions of both the sunlight and the load. In this work, an extremum seeking based control algorithm, as detailed in [8], is adopted for the DC/DC boost converter control to get the maximum power acquisition and charge the battery system.
- Islanded Mode Operation of the DC/AC Converter. For the islanded mode operation of the DC/AC converter, the major tasks of the control are to provide both voltage regulation and frequency regulation with the capabilities of grid-forming, and to keep the power balance between the loads and the source. Here, a robust droop control strategy, named the uncertainty and disturbance estimator (UDE)-based robust droop control technology [9] is adopted for islanded operation of the SPEED platform. Additionally, the UDE-based robust droop control also provides further advantages, e.g., self-synchronization, and scalability, which enables the potential parallel operation of multiple multi-scale SPEED platforms.
- Grid-connected Mode Operation of the DC/AC Converter. This SPEED platform also can be operated at grid-connection mode. In order to achieve robustness integration of the SPEED into electrical AC grid, the UDE-based robust power flow control [10] is embedded into the DC/AC converter control, which can achieve a grid-friendly manner and reject various disturbances, such as the fluctuations of the battery voltage, variations of output impedance/line impedance, and variations of the grid voltage. When the grid is detected, the DC/AC converter will be automatically operated at grid-connection mode.

IV. Field Testing

To enhance the mechanical robustness and portable capabilities of this SPEED platform, all hardware components, such as, the PV panels, the batteries, the SYNDEM PV inverter, and HMI system, are mechanically mounted on a moving cart, as shown in Fig. 4. The field testing of the SPEED platform was conducted on Texas Tech University campus. The SPEED platform was operated at islanded mode, as the off-grid scenario was considered. Several appliances, e.g., laptops, LEDs, cell phone chargers, iPad chargers, drone chargers, and electric kettle, were used as electrical loads to simulate conditions of the emergency relief or disaster relief.

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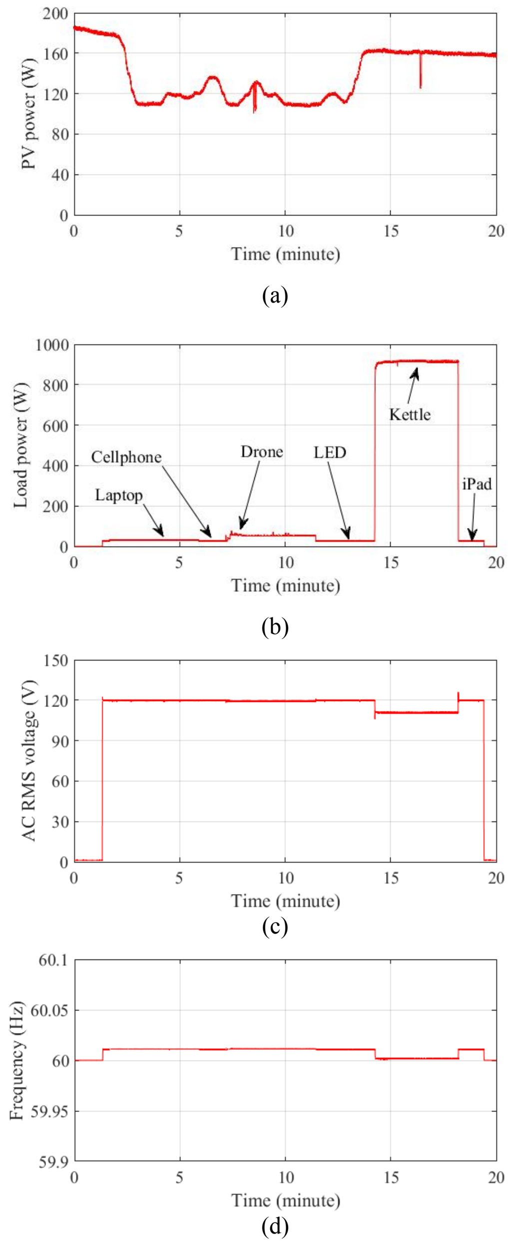

Fig. 5 Field testing results: (a) PV power generated from solar panels; (b) Load consumption (supported by both solar and battery); (c) AC output RMS voltage for the loads; and (d) AC output Frequency for the loads.

We have conducted extensive experiments on this SPEED platform. Two major scenarios are illustrated in Fig. 5, where Fig. 5(a) shows the PV power generated from solar panels. The proposed MPPT control can track the variations of the solar irradiations. The fluctuations in the curve are caused by different solar irradiations with shading effects. For example, during 3~14 minute, the sun is blocked by the cloud. The spike at about 16.5 minute is also caused by the shading effects of solar panels. Different types of load consumption are shown in Fig. 5(b). If the PV power is more than load consumption, the extra power is stored in the battery, e.g., during 0~14 minute, and 18 ~ 20 minute. From 14 minute to 18 minute, an electric kettle is added, the power consumption reaches 900W. Both solar and battery autonomously support this load together. The AC output RMS voltage and AC output frequency for the loads are shown in Fig. 5(c) and Fig. 5(d), respectively. As per result, the grid forming capabilities of this SPEED system are demonstrated at islanded conditions, where the AC output RMS voltage can always be regulated around 120 V, and the frequency is always regulated around 60 Hz. Both the voltage and the frequency change slightly during 14~18 minute, which is caused by the large electric kettle load. A video of the field testing can be found in the link [11].

V. Conclusion

In this paper, a sustainable, portable, and efficient electricity delivery system was designed and tested. The results have demonstrated the stable grid forming capability of the SPEED system. Islanded mode operation under different shading conditions and load changes has proven to be stable with good power quality. The power output of the system is compatible with the standard electrical appliances. In conclusion, the SPEED system has shown great potential in contributing to sustainable and portable electricity demand during emergency/disaster relief.

VI. Acknowledgment

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