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A Self Sustaining Microgrid for Supplying Electrical Load in Rural Areas

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***Abstract*—A self-sustaining microgrid (MG) with alternating energy resources including renewable sources has been proposed in this paper. Based on the analysis and recent experimental results from a prototype system, we proposed control strategy for the MG's energy delivery to achieve higher efficiency, reliability and economy. Beside supplying traditional AC load, the proposed MG will supply DC load that will include battery charging facility. We are also proposing an algorithm for a MG to maximize the use of renewable energy at the same time controlling the battery charging/discharging to extend its life expectancy. An inverter-based backup generator has been included in the MG as an alternating energy source to ensure the quality and the reliability of the power delivery. The proposed MG is a potential sustainable solution for rural electrification.**

***Index Terms*—Battery energy storage systems, DC load, Microturbine, Inverter-based generator, Voltage control.**

I. Introduction

A microgrid is a viable and scalable approach to supply electrical energy to the essential load of a remote or off the grid areas [1], [2]. It provides a platform for two major aspects of sustainable energy management: one is energy harvesting from renewable sources which are distributed in nature and the other one is the energy management at the load side. Smarter control is required to ensure economic and reliable operation of MG [1]–[4]. Sensors for feedback signal generation, automatic switches, energy storage devices such as battery, generators, protection equipment, control systems, linear and nonlinear loads, smart metering etc. are some key physical components of a MG which need to be integrated to make it functional [2]. Study shows that the energy delivery within the MG facilitates consumer freedom at the demand side [4]–[6]. Depending on geographical location, energy resources, existing grid infrastructure, and available technology, MG control strategy needs to be decided to facilitate reliable but economic delivery of energy [4], [5]. To provide economy, it is expected that the MG will maximize the use of renewable energy. However, to ensure reliability the MG keeps the option of having multiple energy sources such as utility supply or stand-by generator [5]. Another important aspect of power delivery is the power quality that needs to be maintained according to the industry acceptable standards. Depending on the application, this becomes a critical issue for sensitive loads.

From the power delivery standpoint, reality is that often time the power utility cannot maintain high quality power to the customer living in the rural areas. It is primarily due to voltage drop and other associated issues such as handling nonlinear or switching load [2], [5]. To avoid the situation of having poor quality power, the stand-by generator should pick up load ensuring higher power quality. Currently, inverter based micro-turbine generators assure the good power quality and are commercially available [4]–[7]. Their energy is delivered through an advanced power electronics-based converter controlled by local as well as central control system [7]. Recently conducted test results from a campus MG shows that if distributed control mechanism has been adopted then the delivered power will possess higher quality [5]–[8]. However, considering above mentioned power delivery constraint it is challenging to integrate multiple sources/loads and control them. In this paper, we will be investigating the control algorithm based on the experimental finding in a prototype to achieve economic, reliable and high-quality power delivery in a MG established in a rural area. For overall control, it is an effort of controlling individual components and integrate in a distributed control system.

II. Microgrid Model and Control Strategy

The structure of the study MG is shown in Fig. 1. The considered system is a DC microgrid that consists of a photovoltaic (PV) generator and a battery energy storage system (BESS) which are interfaced to the point of common coupling (PCC) via boost dc/dc converters. The instantaneous energy stored in the PV output capacitor is $w_{\mathrm{Cpv}}(t) = \frac{1}{2}C_{\mathrm{pv}}v_{\mathrm{opv}}^{2}(t)$. The energy equation can be linearized about the nominal value $v_{\mathrm{opv}}^{\mathrm{ref}}$ which yields:

$$\begin{aligned} w_{\mathrm{Cpv}}(t) &= \frac{1}{2}C_{\mathrm{pv}}v_{\mathrm{opv}}^{2}(t) \\ &\approx \frac{1}{2}C_{\mathrm{pv}}v_{\mathrm{opv}}^{\mathrm{ref}^2} + C_{\mathrm{pv}}v_{\mathrm{opv}}^{\mathrm{ref}}(v_{\mathrm{opv}}(t) - v_{\mathrm{opv}}^{\mathrm{ref}}) \\ &= C_{\mathrm{pv}}v_{\mathrm{opv}}^{\mathrm{ref}}v_{\mathrm{opv}}(t) - \frac{1}{2}C_{\mathrm{pv}}v_{\mathrm{opv}}^{\mathrm{ref}^2}. \end{aligned} \quad (1)$$

The derivative of capacitor energy with respect to $v_{\mathrm{opv}}(t)$ is

$$\dot{w}_{\mathrm{Cpv}}(t) = C_{\mathrm{pv}}v_{\mathrm{opv}}^{\mathrm{ref}}\dot{v}_{\mathrm{opv}}(t) \quad (2)$$

By neglecting the switching losses, the power balance equation can be expressed as:

$$\dot{w}_{\mathrm{Cpv}}(t) = P_{Cpv}(t) = P_{\mathrm{pv}}(t) - P_{\mathrm{out}}(t) \quad (3)$$

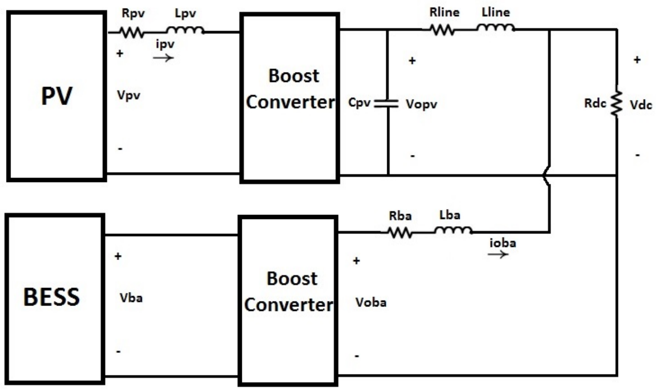

Fig. 1: Study MG circuit diagram

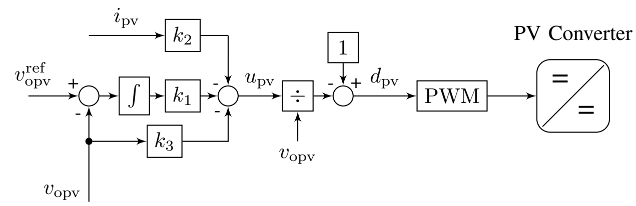

Fig. 2: PV Voltage Controller

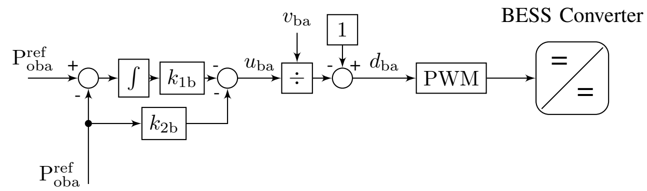

Fig. 3: BESS Power Controller

Assume $d_{\mathrm{pv}}(t)$ is the duty cycle of pulse width modulator (PWM) of the PV converter, then the average converter voltage is $v_{\mathrm{opv}}(t) = \frac{v_{\mathrm{pv}}(t)}{1-d_{\mathrm{pv}}(t)}$. The control input is given as $u_{\mathrm{pv}}(t) = (1 - d_{\mathrm{pv}}(t))v_{\mathrm{opv}}(t)$. Define $\dot{x}_1(t) = e(t) = v_{\mathrm{opv}}^{\mathrm{ref}} - v_{\mathrm{opv}}(t), x_2(t) = i_{\mathrm{pv}}(t)$, and $x_3(t) = v_{\mathrm{opv}}(t)$. The state space representation of the PV voltage controller can be expressed as:

$$\begin{aligned} \dot{x}_1(t) &= -x_3(t) + v_{\mathrm{opv}}^{\mathrm{ref}} \\ \dot{x}_2(t) &= \frac{v_{\mathrm{pv}}(t)}{L_{\mathrm{pv}}} - \frac{u_{\mathrm{pv}}(t)}{L_{\mathrm{pv}}} - \frac{R_{\mathrm{pv}}}{L_{\mathrm{pv}}} i_{\mathrm{pv}}(t) \\ \dot{x}_3(t) &= \frac{v_{\mathrm{pv}}(t)}{C_{\mathrm{pv}} v_{\mathrm{opv}}^{\mathrm{ref}}} i_{\mathrm{pv}}(t) - \frac{v_{\mathrm{dc}}}{C_{\mathrm{pv}} R_{\mathrm{dc}}} \end{aligned} \tag{4}$$

The tracking problem in (4) is then transformed into a linear quadratic regulating (LQR) problem by applying the time derivative $\frac{d}{dt}$ to both sides which yields

$$\begin{aligned} \dot{z}_1(t) &= -z_3(t) \\ \dot{z}_2(t) &= \frac{W_{\mathrm{pv}}}{L_{\mathrm{pv}}} - \frac{R_{\mathrm{pv}}}{L_{\mathrm{pv}}} z_2(t) \\ \dot{z}_3(t) &= \frac{v_{\mathrm{pv}}(t)}{C_{\mathrm{pv}} v_{\mathrm{opv}}^{\mathrm{ref}}} z_2(t) \end{aligned} \tag{5}$$

where $z_i(t) = \dot{x}_i(t)$ and $W_{\mathrm{pv}}(t) = \dot{u}_{\mathrm{pv}}(t)$. Assuming that v_{dc} and $v_{\mathrm{opv}}^{\mathrm{ref}}$ are constant, the PV system can be expressed in the state space form as $\dot{z}(t) = Az(t) + BW_{\mathrm{pv}}(t)$. The regulation problem is to find the control input W_{pv} that minimizes the following cost function

$$J(t) = \int_0^\infty (z^T Q z + W_{\mathrm{pv}}^2) dt \tag{6}$$

where Q is a symmetric positive semi-definite matrix.The elements of matrix Q are selected systematically to design the feedback gains k_1, k_2, and k_3 as described in [9]. The block diagram of the PV system voltage controller is shown in Fig. 2.

The BESS is connected to the common dc bus via a boost converter. Assume $d_{\mathrm{ba}}(t)$ is the duty cycle of the BESS converter PWM and $v_{\mathrm{ba}}(t)$ is the battery voltage, then the average output voltage is $v_{\mathrm{oba}}(t) = \frac{v_{ba}(t)}{1-d_{\mathrm{ba}}(t)}$. Define $v_{\mathrm{oba}}(t)$ as the control input $u_{\mathrm{ba}}(t)$, then the dynamics of the BESS can be written as

$$\dot{i}_{\mathrm{oba}}(t) = \frac{u_{\mathrm{ba}}(t)}{L_{\mathrm{ba}}} - \frac{v_{\mathrm{dc}}}{L_{\mathrm{ba}}} - \frac{R_{\mathrm{ba}}}{L_{\mathrm{ba}}} i_{\mathrm{oba}}(t) \tag{7}$$

Multiplying both sides by v_{dc} yields

$$\dot{P}_{\mathrm{oba}}(t) = \frac{v_{\mathrm{dc}}}{L_{\mathrm{ba}}} u_{\mathrm{ba}}(t) - \frac{v_{\mathrm{dc}}^2}{L_{\mathrm{ba}}} - \frac{R_{\mathrm{ba}}}{L_{\mathrm{ba}}} P_{\mathrm{oba}}(t) \tag{8}$$

Define $\dot{x}_1(t) = e(t) = P_{\mathrm{oba}}^{\mathrm{ref}} - P_{\mathrm{oba}}(t), x_2(t) = P_{\mathrm{oba}}(t)$. The state space representation of the battery power controller can be expressed as:

$$\begin{aligned} \dot{x}_1(t) &= P_{\mathrm{oba}}^{\mathrm{ref}} - x_2(t) \\ \dot{x}_2(t) &= \frac{v_{\mathrm{dc}}}{L_{\mathrm{ba}}} u_{\mathrm{ba}}(t) - \frac{v_{\mathrm{dc}}^2}{L_{\mathrm{ba}}} - \frac{R_{\mathrm{ba}}}{L_{\mathrm{ba}}} x_2(t) \end{aligned} \tag{9}$$

Similarly, the tracking problem in (9) is then transformed into an LQR problem by applying the time derivative $\frac{d}{dt}$ to both sides which yields

$$\begin{aligned} \dot{z}_1(t) &= -z_2(t) \\ \dot{z}_2(t) &= \frac{v_{\mathrm{dc}}}{L_{\mathrm{ba}}} W_{\mathrm{ba}}(t) - \frac{R_{\mathrm{ba}}}{L_{\mathrm{ba}}} z_2(t) \end{aligned} \tag{10}$$

where $z_i(t) = \dot{x}_i(t)$and $W_{\mathrm{ba}}(t) = \dot{u}_{\mathrm{ba}}(t)$. The BESS power system can be expressed in the state space form as $\dot{z}(t) = Az(t)+BW_{\mathrm{ba}}(t)$. The regulation problem is to find the control input W_{ba} that minimizes the following cost function

$$J(t) = \int_0^\infty (z^T Q z + W_{\mathrm{ba}}^2) dt \tag{11}$$

The elements of matrix Q are adjusted systematically to design the feedback gains $k_{1\mathrm{b}}$ and $k_{2\mathrm{b}}$. The block diagram of the BESS system power controller is shown in Fig. 3.

III. Results and Discussion

A. Simulation Results

The performance of the proposed controllers for the PV and BESS system is validated by simulating the study MG when

TABLE I: Microgrid system parameters

Parameters	Symbol	Value
PV array voltage	v_{pv}	300 V
PV filter inductance	L_{pv}	10 mH
PV filter resistance	R_{pv}	10 mΩ
PV filter capacitance	C_{pv}	100×10^{-6} F
PV line resistance	R_{line}	1.5 Ω
PV line inductance	L_{line}	200 mH
Battery voltage	v_{ba}	500 V
Battery filter inductance	L_{ba}	10 mH
Battery filter resistance	R_{ba}	10 mΩ

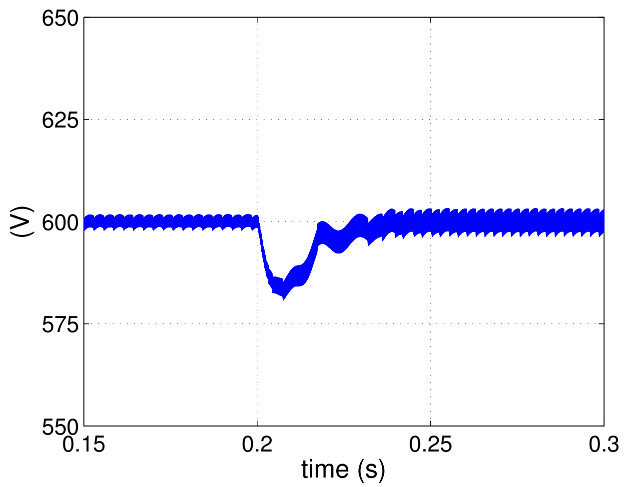

Fig. 4: PV output voltage

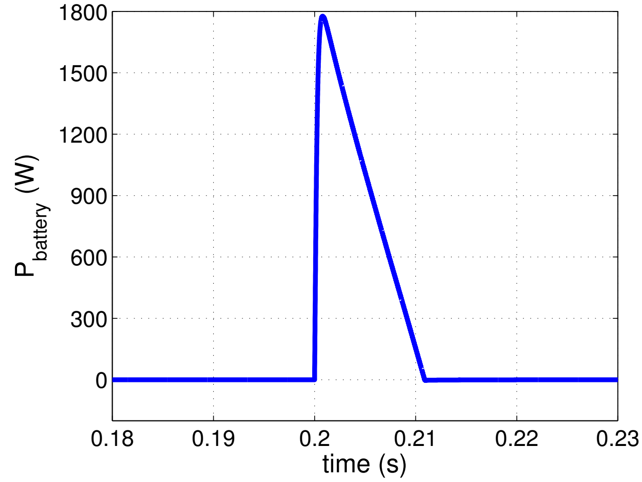

Fig. 5: Battery output power

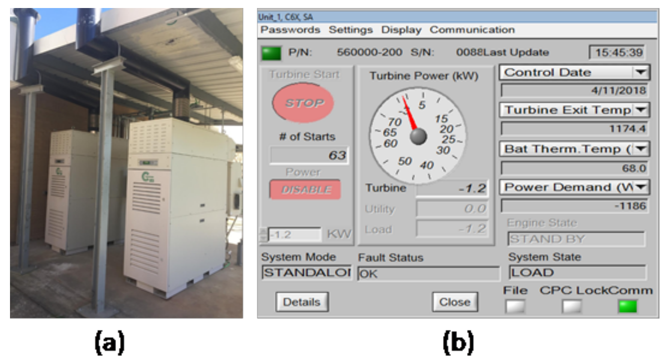

Fig. 6: (a) Inverter based generator in a prototype campus MG and (b) CRM Control window for Generator control and data acquisition

the load is increased from 3.6 kW to 7.2 kW. The PV reference voltage $v_{\mathrm{opv}}^{\mathrm{ref}}$ is 600 V, and the BESS power reference $P_{\mathrm{oba}}^{\mathrm{ref}}$ is set to zero. Therefore, the battery only injects/absorbs power only when a disturbance occurs. Parameters of system under study are given in table I. The PV output voltage and the battery output power when the load increases at t=0.2 s are shown in Figs. 4 and 5, respectively. It can be seen that the PV output voltage is maintained at the desired value following the load change, and the BESS responds quickly to the disturbance and injects some power to support the voltage.

B. A Prototype MG Act as a Test-Bed

At McNeese State University in Lake Charles Louisiana, a campus MG has been installed and currently used as a prototype test bed for research. It has two 65 kW of combined heat and power (CHP) generators from Capstone Inc. and a 15 kW of photovoltaic (PV) inverter as an internal energy sources. The PV simulator with battery storage units from Chroma Inc. USA feeding a smart inverter (Trio from ABB Inc.) [4]–[7]. Several resistive and rotating loads are connected either to the internal energy sources or to the grid power via machine control center (MCC). Operation of this 480 V MG is controlled by a distributed control system (DCS) 800XA [4]–[8], [10]. Two 5 kW motors are connected as rotating loads and a variable 0-130 kW resistive load was employed to load the turbine.

We used the Capstone Remote Monitoring (CRM) to acquire necessary status data from the sensor placed at different location at the generator and control the microturbine based on those information. A list of about 100 sensor data have been made available for the user in real time with archiving facility. Fig. 6 shows the two inverter based generator in McNeese MG and CRM control windows for generator control and data acquisition. Generator has a battery pack that charges during turbine operation and made this charge available when there is sudden change of load occurs such as during load change or any mechanical/thermal perturbation. Also during starting, it provides energy to the electric machine to run as a motor and pick up a certain speed before turbine pick up the machine load and operate the permanent magnet machine as a generator [7].

In an effort to investigate energy contribution of battery pack, we conduct an experiment using CRM to record battery voltage. We start and run the two turbine in a multipack

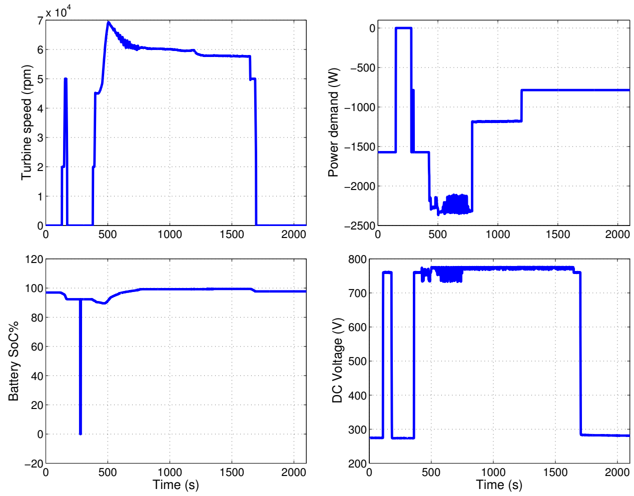

Fig. 7: Stand-by generator's battery condition at no electrical demand (a) turbine speed in (rpm) (b) power demand at no external load connected in (W) (c) battery state of charge and (d) DC voltage available at the inverter input bus in (V).

configuration at no load and monitor the engine speed, power demand and DC voltage supplied by the battery to the inverter. Fig. 7 shows the effect of change of battery voltage when mechanical or thermal demand changes at no electrical load. As seen in the figure, engine speed increases as the mechanical demand increases. However, battery feeds the inverter with almost constant voltage (having a permissible ripple) to achieve stable high quality output ac voltage. Internal charge controller provides battery required charges to maintain this DC output voltage.

IV. Conclusion

A voltage control algorithm for a PV array and a power controller for a battery storage are proposed to control energy delivery in an isolated MG to supply electrical loads in rural areas. The voltage controller is used to maintain the output voltage of the PV at the desired voltage level, while the power control strategy of the BESS ensures that the battery responds quickly only when a disturbance occurs. The BESS injects or absorbs power to support the standalone MG. Additionally, experimental results from a prototype MG shows that storage battery's charge control is vital to ensure quality power delivery.

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