Optimal dispatching of a photovoltaic-biogas hybrid system

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Abstract: This paper presents an optimal dispatching strategy for a photovoltaic-biogas hybrid system for an off-grid institution. The aim is to prioritise use of the PV system to meet demand whenever available. If the demand is less than the PV output, the remaining power generated is dumped. If the demand is larger than the PV output, the imbalance is met by the biogas system. Since biogas production is continuous, the biogas system can supply power directly to the load and/or store energy during times when PV is meeting demand. During times when PV cannot meet the load the biogas storage system discharges to ensure that all generators run to meet the load. The results show opportunities for implementation of such autonomous systems in most developing countries where electrification rates are low. The outcome of this study is expected to inform micro-grid controller designers of the envisaged operation strategies. In cases where such a system is connected to the grid and feed-in tariffs and net metering are allowed, any excess electricity can be exported to the grid hence generating revenue or credits for the institution.

Key Words: net metering, optimal dispatching, controller designers, configurations

1 Introduction

Distributed generation options such as biogas and solar photovoltaic (PV) are promising options for energy supply in rural off-grid locations and for institutions such as hospitals, clinics, hotels and schools, especially in areas where grid connection is impossible or not economic. Biogas systems feedstock is readily available in most rural areas and also at schools, hospitals, hotels and other isolated institutions while the solar resource is abundant in most developing countries of the world including Africa. Biogas systems have the advantage that they can meet both electrical and thermal energy requirements of the consumer. The biogas system also includes gas storage and hence demand can be met at all times. When the storage is full and demand for biogas is low, the biogas can be flared to avoid the harmful effects of the gas to the environment. Typically, a turbine or engine running on biogas is utilized to generate power. In a hybrid sytem such as the one proposed in this paper, power generated by the biogas engine is used to meet the load during periods of low PV production and at night times.

Various hybrid system configurations have been proposed by various researchers to solve the energy access problem faced by most developing countries [8, 9]. An economic optimization model of a micro-combined heat and power(CHP) system for a multi-apartment housing consisting of a natural gas fed prime mover, a thermal energy storage system and an auxiliary boiler is presented in [10]. Two different operational strategies are explored to meet the load with and without heat dumping. [11] examined the feasiblilty and constraints of biogas use in Tanzania by randomly selecting two hundred households with and without biogas facilities from four villages.

Research and development efforts in renewable energy technologies such as PV/biogas CHP systems for institutional and community energy generation applications are crucial in order to ensure universal access to energy for people living in marginalised and remote areas where it is difficult or uneconomic to extend the grid. In order to ensure supply reliability of such systems, more research effort is required in areas such as performance improvements, optimal sizing and dispatching strategies, among others. This paper presents an off-grid PV and biogas hybrid system and the focus is on optimal dispatching of PV and biogas systems in order to meet the load demand at all times. The outcome of such a study will inform controller designers on the expected system operational strategies to be considered when designing micro-grid systems of this nature.

2 Description of PV-biogas system

The hybrid system evaluated consists of a photovoltaic array and a biogas plant. Priority is given to the PV system to meet demand. If the demand is less than the PV's output, the remaining power generated will be dumped or sent to the grid. If the demand is larger than the PV's output, the imbalance will be met by the biogas system. Since biogas production is continuous, the biogas system can supply energy directly to the load or store it during times when demand is being met by PV. During times when PV cannot meet the load the biogas storage system also discharges to meet the load. Fig. 1 shows the schematic of this hybrid system, in which the direction of arrows represent the power flow in the system. where $P_B(t)$ is the power produced by the biogas

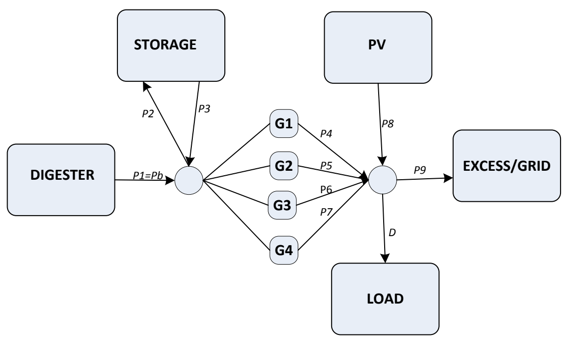

Fig. 1: Schematic of the hybrid system

system; $P_2(t)$ power supplied to the storage system; $P_3(t)$ is the power from the storage system; $P_4(t)$ - $P_7(t)$ represent the power from generators G_1 - G_4 respectively;$P_8(t)$ the PV power and $P_9(t)$ is the excess power all at hour t. Controllers and converters have been left out for simplicity purposes.

2.1 PV array

Each solar array consists of several solar cells to convert sunlight into direct current (DC) power. The hourly power output of a given area can be simply formulated as:

$$P_{pv} = \eta_{pv} I_{pv} A_c, \tag{1}$$

where P_{pv} is the hourly power output from the PV array; A_c is the size of PV array; η_{pv} is the efficiency of power generation; I_{pv} is the hourly solar irradiation on the PV array (kWh/m^2).

The hourly solar irradiation on the PV array is closely related to time of a day, season of a year, tilt, location, global irradiation, diffuse fraction and so on. In this study, the simplified isotropic diffuse formula [1, 2] is used as

$$I_{pv} = (I_B - I_D)R_B + I_D, \tag{2}$$

where I_B and I_D are the hourly global and diffuse irradiation respectively. R_B is a geometric ratio of the actual irradiation on tilted plane to the standard irradiation on horizontal plane for north facing collectors is given by:

$$R_B = \frac{cos\theta}{cos\theta_z} = \frac{sin\delta sin(\phi+\beta) + cos\delta cos\omega cos(\phi+\beta)}{sin\delta sin\phi + cos\delta cos\phi cos\omega} \tag{3}$$

where: θ is the angle of incidence i.e angle between the sun's direct rays(beam radiation) on a surface and the normal to that surface; θ_z is the Zenith angle i.e angle between the vertical and the line joining the sun and the observer or simply angle of incidence of beam radiation on a horizontal surface; δ is the declination angle i.e angular position of the sun at solar noon w.r.t the plane of the equator (+ve in NH and -ve in SH) expressed as:

$$\delta = 23.45 sin\left[\frac{360(284+n)}{365}\right]; \tag{4}$$

n is the day of year number; ϕ is the latitude i.e angular location N or S of the equator (+ve in NH and -ve in SH); β is the tilt angle i.e angle between the plane of the surface in question and the horizontal; ω is the hour angle i.e the angular displacement of the sun E or W of the local meridian due to the rotation of the earth on its axis at $15°$C per hour (morning -ve and afternoon +ve;) The efficiency of power generation has a complicated model. It can be expressed as a function of the hourly irradiation I_{pv} and the ambient temperature T_A as

$$\eta_{pv} = \eta_R\left[1 - \frac{0.9\beta I_{pv}(T_{C0} - T_{A0})}{I_{pv0}} - \beta(T_A - T_R)\right], \tag{5}$$

where η_R is the referenced efficiency that measured under standard test conditions (STC); T_R is the referenced cell temperature at STC (25°C); β is the temperature coefficient for cell efficiency (typically 0.004-0.005); T_{C0} (typically 45°C) and T_{A0} (typically 20°C) are the cell and ambient temperatures at Nominal Operating Cell Temperature (NOCT) test conditions; I_{pv0} is the average solar irradiation on the array at NOCT conditions [12].

A PV module will be typically rated at 25°C under $1kW/m^2$. However, when operating in the field, they typically operate at higher temperatures and at somewhat lower insolation conditions. In order to determine the power output of the solar cell, it is important to determine the expected operating temperature of the PV module. The Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the following conditions: irradiance velocity = 1 m/s, and mounting = open back side.

2.2 Biogas system with storage system

The schematic of biogas process chain considered is as shown in Fig. 2. Storage tanks have been conveniently omitted and any excess gas from the production process is flared. Constrained in the capacity of the storage, the state of charge

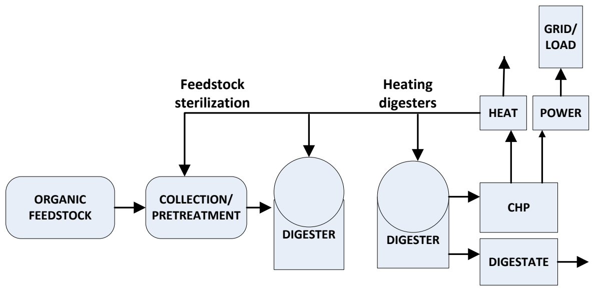

Fig. 2: Schematic of the biogas system

(SOC) is dynamically changing due to possible charge by the biogas system and possible discharge for the customer usage. Let $S(t)$ denote the SOC of the storage at the tth hour. Based on the SOC at the previous hour, the dynamic change of SOC can be formulated as

$$S(t) = S(t-1) + \alpha P_2(t) - \alpha P_3(t), \tag{6}$$

where $\alpha = \frac{\Delta t}{C_b}$ with Δt as the time-step and C_b the storage capacity); $P_2(t)$ is the charging power for the storage; $P_3(t)$ is the discharging power from the storage system; $S(t)$ is the SOC at the tth hour; $S(t-1)$ is the SOC at the previous hour. According to dynamic Eq. (6), the SOC of storage system $S(t)$ can be expressed by the initial SOC $S(0)$ of a day as

$$S(t) = S(0) + \alpha\sum_{\tau=1}^{t} P_2(\tau) - \alpha\sum_{\tau=1}^{t} P_3(\tau). \tag{7}$$

3 Hybrid system model

Optimal control of the target hybrid system aims to minimize use of energy from the biogas system and excess energy, and maximize energy from PV. Detailed calculations related to the biogas and generator systems have been omitted but will be subjects of future works of this on-going research. The production is assumed to be constant based on a preliminary study out of the scope of this paper. The maximum PV capacity is also based on the same preliminary study.

The objective function can be formulated as,

$$\min\sum_{t=1}^{24}(w_1(P_4(t) + P_5(t) + P_6(t) + P_7(t)) \\ - w_2 P_8(t) + w_3 P_9(t)). \tag{8}$$

For the objective function, control variables $P_2(t)$,$P_3(t)$,$P_4(t)$,$P_5(t)$,$P_6(t)$,$P_7(t)$,$P_8(t)$,$P_9(t)$ $(0 < t \leq 24)$ have to satisfy several constraints:

(1) Biogas system output constraint: The biogas system is responsible for charging the storage and for immediate customer usage.

$$P_2(t)-P_3(t)+P_4(t)+P_5(t)+P_6(t)+P_7(t) = P_B(t). \quad (9)$$

(2) Power balance constraint: The load demand of customers must be satisfied by the combined power of the PV array and the biogas system with storage.

$$P_4(t)+P_5(t)+P_6(t)+P_7(t)+P_7(t)-P_9(t) = D(t), \quad (10)$$

where $D(t)$ is the load demand at hour t.

(3) SOC boundary constraint: The SOC of storage system must be less than or equal to the storage capacity S^{max} and larger than the minimal allowable value S^{min}

$$S^{min} \leq S(t) \leq S^{max} \quad (11)$$

(4) Power flow constraint: For safety and other physical reasons, power flow from each source must be non-negative, and less than or equal to the minimum and maximum allowable values

$$P_i^{min} \leq P_i(t) \leq P_i^{max}, \quad (12)$$

where P_i^{max} is the defined maximum power delivered per hour.

Optimal control will be utilized to dispatch the hourly power $P_i(i = 2, ..., 9)$ over a day.

4 Parameters

Table 1: Parameters of PV-biogas system

Nominal storage capacity	30000 kWh
Biogas system production	2500 kW
Capacity G1	1000 kW
Capacity G2	1000 kW
Capacity G3	1200 kW
Capacity G4	2000 kW
PV array's capacity	6000 kW

Because the linear objective function has linear constraints, the linear programming optimization tool in MATLAB is used to solve the problem. The function "*linprog*" is used which usually solves problems in such a form:

$$\min f^T x, s.t. \begin{cases} Ax \leq b \\ A_{eq}x = b_{eq} \\ lb \leq x \leq ub \end{cases}, \quad (13)$$

where $f^T x$ represents the objective function, and f, x, b, beq, lb, and ub are vectors, and A and Aeq are matrices.

5 Results

The results show that demand is met at all times and there is maximum utilization of PV output resulting in excess energy of $4184kWh$ (sum of $P9$ over the 24 hr period).

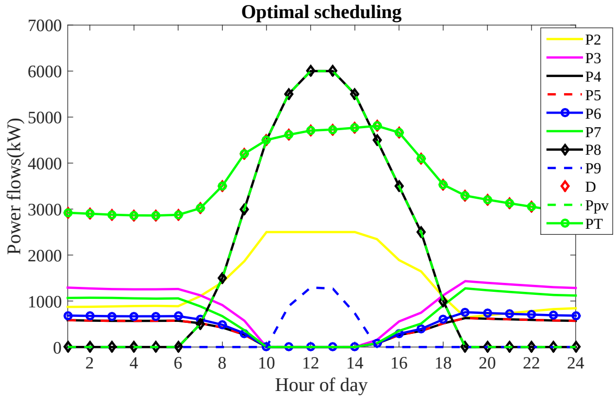

Fig. 3: Optimal dispatching

Fig. 4 shows the charging and discharging of the storage system, which is within the specified limits. The storage system is shown to discharge in the early hours of the morning and at night with all the generators supplying the load.The generators are shown to be off during the day when PV output can fully meet the load from about 10:00-15:00Hrs

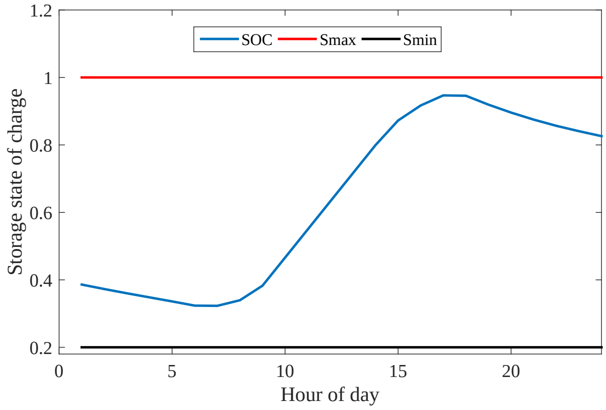

Fig. 4: Charging and discharging states of storage system

In Fig. 5, the PV output is reduced and consequently the generators are operating throughout the day to meet the load. Such a condition may be expected during periods of bad weather.

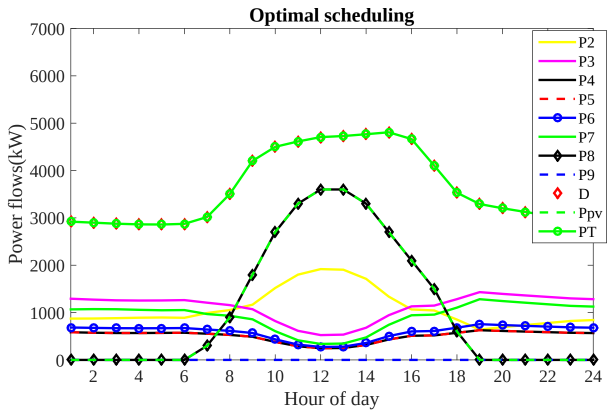

Fig. 5: Optimal dispatching with reduced PV output

In Fig.6 the storage dynamics show that there is less charging owing to the fact that the biogas system is utilizing most the produced energy to met the load.

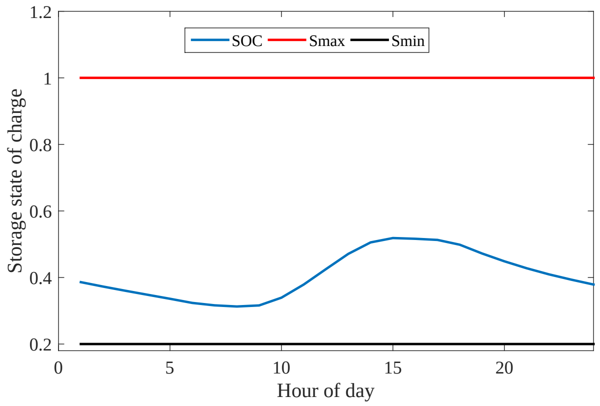

Fig. 6: Charging and discharging states of storage system

6 Conclusion

An optimal dispatching strategy of a stand alone PV-biogas system has been presented showing how the load is met completely by such a system. It has been shown that during periods of high production from PV the biogas system generators can be switched off and all gas produced can be stored for later use. The biogas system will mainly be deployed during night time. In unfavourable weather it has been shown that he gerators can run throughout the day to compliment PV production. Future work will investigate grid connected PV-biogas systems in order to quantify the benefits of such a system in reducing both energy bills and peak demand charges. Detailed analyses of the various components of the system will also be subjects of future works.

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