MINIMUM COST SOLUTION OF ISOLATED BATTERY-INTEGRATED DIESEL GENERATOR HYBRID SYSTEMS

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Abstract: The present paper develops a mathematical programming model to optimize the operation of a battery-integrated diesel generator hybrid system. The optimization approach is aimed at minimizing the cost function subject to the load energy requirements as well as to the diesel generator and the battery operational constraints. The main purpose of the developed control algorithm is to minimize the diesel generator operation cost in the electricity generation process. The non-linearity of the load demand, the non-linearity of the diesel generator fuel consumption curve as well as the battery operation limits have been considered in the developed model. The simulations have been performed using fmincon interior point in MATLAB, and the results obtained represent a helpful tool for energy planners and also justify the consideration of battery-integrated hybrid system in rural and isolated electricity generation.

Keywords: Battery-integrated, Diesel generator, Optimal operation control, Cost minimization.

1. INTRODUCTION

The lack of reliable electrical power supply, the high cost of AC grid extension and rough topography are some of the severe challenges faced in the rural electrification of a good number of developing countries. In most of the cases, loads in those rural areas are powered by small Diesel Generators (DGs) running continuously.

Compared to other supply option such as renewable energy sources, DGs have low initial capital costs and generate electricity on demand. They are easily transportable, modular, and have a high power-to-weight ratio. DGs can also be integrated with other sources and energy storage in hybrid system configurations making it an ideal option for standalone power generation.

However, due to the long running times and the highly non-linearity in the daily load demand profiles, DGs are usually operated inefficiently resulting in higher cost of energy produced. This overall cost includes the following:

- Operating cost which comes mainly from the direct fuel cost;
- Cost of the transportation of the fuel. This can be high depending on how the area to supply is remote or isolated;
- The maintenance and replacement cost of the generator.

In isolated power generation, battery storage systems are often used as back-up when the DG runs out of fuel, also during the DG start up or also to cover up the load when the generator is shut-down for maintenance.

By using battery integrated diesel generator hybrid systems in isolated power generation, significant savings can be archived in the overall DG running costs. In this configuration, the DG is used to recharge the battery when the load demand is low, and to balance the deficit of the power supply from the battery when the load demand is high. This combination enhances the efficiency and the maximum output capability of the entire hybrid system.

Few research works have been conducted on the subject of optimal operation control of battery-integrated hybrid system in isolated electrification. In ref. [1] the authors have used the Hybrid Optimization Model for Electric Renewables (HOMER) for the feasibility study of a battery-integrated DG hybrid system for rural electricity supply. It has been noticed that even though adding batteries means increasing the initial cost of the system, the resulting cost of energy produced as well as the total net present costs are sensibly being reduced while using the hybrid system instead of the DG alone. However, for the optimal operation, some kind of rule-based (heuristic) algorithm is used by HOMER to solve the system's optimal operation control problem. Since no performance index is optimized, the solution provided by this method may lead to a very high running cost of the system.

In ref. [2] an optimization algorithm based upon the simulated annealing technique for a battery-integrated DG hybrid system have been presented. The developed algorithm provides optimal generator setting and battery charge/discharge schedules for a given daily load cycle. However, the developed model does not consider the non-linearity of the DG fuel consumption at different loading which was assumed to be linear.

Based on the shortfalls revealed in the papers above; the present paper reports on the development of a mathematical programming model to optimize the operation of a battery-integrated hybrid system. The optimization approach is aimed at minimizing the operation cost function subject to the load energy requirements as well as to the DG and the battery operational constraints. The main purpose of the developed control algorithm is to minimize the DG's operation cost in the electricity generation process. The non-linearity in the fluctuation of the load demand, the non-linearity of the DG fuel consumption curve as well as the battery operation limits have been considered in the developed model. The simulations of two different load types have been performed using fmincon interior point implemented in MATLAB; the results have been compared with the case where the DG is used alone to supply the load.

2. HYBRID SYSTEM COMPONENTS AND OPERARTION DESCRIPTION

2.1. Diesel generator

A DG is normal diesel engine coupled to an electrical generator. DGs are usually designed in such a way that they always operate close to their power rating to achieve high efficiency; this condition can be used later as an operation constraint. With this operation strategy as well as operation constraint, the DG is expected to run at high load factors, which will result a decrease of the fuel consumption, of the Carbon footprint and increase of the DG lifespan [3].

The fuel cost (FC) is calculated for a day is given by the quadratic non-linear function below:

$$C_f \sum_{j=1}^{N} (aP_{DG(j)}^2 + bP_{DG(j)} + c) \qquad (1)$$

Where: a, b, c are the parameters of the DG fuel consumption curve;

$P_{DG(j)}$ is the output power or control variable from the DG at any time t.

2.2. Battery storage system

The output power from the DG and the load demand at any given sampling interval *j*, determine whether the battery is charging or discharging. The dynamics of the battery state of charge (SOC) can be expressed in discrete-time domain by a first order difference equation as follows [4]:

$$SOC_{(j+1)} = SOC_{(j)} - \frac{\eta_{Bat}}{E_{nom}} \times P_{Bat(j)} \qquad (2)$$

Where: SOC is the state of charge of the battery; η_{Bat} is the battery charging or discharging efficiency; E_{nom} is the battery system nominal energy, P_{Bat} is the power flowing from the battery system.

2.3. battery-integrated DG hybrid system

The schematic of a battery-integrated DG hybrid system's power flow is shown in Fig. 1. The system main components are the DG operating and the battery bank used through a bi-directional converter. In this configuration, the battery is used to supply the load; and is allowed to be discharged within the preset operating limit. If the load demand is cannot be met by the battery, the then DG comes into operation either to supply the deficit of power from the battery needed by the load, or to supply the load and recharge the battery simultaneously.

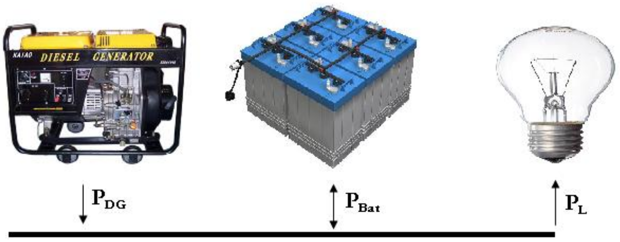

Figure 1: Hybrid system layout (power flow)

3. OPTIMIZATION MODEL AND PROPOSED ALGORITHM

The optimization problem addressed in this work aims at finding the daily optimal scheduling of energy production at any given time that minimizes the DG fuel expenses while totally responding to the load energy requirements within the system's operating limits and constraints. As stated in the introduction, the control of the hybrid system is implemented using the continuous operation control strategy.

3.1. Continuous operation control modeling

In this case the DG is always ON and its output power continuously controlled, depending on the demand, to minimize the fuel usage resulting in operation cost.

3.1.1. Objective function

The objective is to minimize the fuel consumption cost from the DG during the operation time. This can be expressed as:

$$\min C_f \times \sum_{j=1}^{N} (aP_{DG(j)}^2 + bP_{DG(j)} + c) \qquad (5)$$

Where:

N = the number of sampling intervals within the operation range or period of the system;

a ,b, c = the fuel cost coefficients;

j = the j^{th} sampling interval;

$P_{DG(j)}$ = the output power from the DG at j^{th} sampling interval;

C_f = the price of 1litre of fuel.

3.1.2. Constraints

The different constraints on the operation are as follows:

- Power balance:

At any sampling interval *j*, the sum of the supplied powers from the DG and from the battery must be equal to the demand. This can be expressed as:

$$P_{DG(j)} + P_{Bat(j)} = P_{L(j)} \qquad (6)$$

- Variable limits:

The DG and battery modules are modelled as variable power sources controllable in the range of zero to their rated power for the 24 hour period. Therefore the variable limits are the output limits of these different power sources as well as of the battery storage system at any time t. These constraints depend on the characteristics of each power source and can be expressed as:

$$0 \le P_{DG(j)} \le P_{DG}^{\max} \quad (1 \le j \le N) \qquad (7)$$

$$-P_{Bat}^{rated} \le P_{Bat(j)} \le P_{Bat}^{rated} \quad (1 \le j \le N) \qquad (8)$$

- Battery state of charge:

The available battery bank state of charge n any sampling internal must not be less than the minimum allowable and must not be higher than the maximum allowable state of charge. This can be expressed as:

$$SOC^{\min} \le SOC_{(j)} \le SOC^{\max} \qquad (9)$$

3.2. Proposed algorithm

The objective functions have been modeled as a non-linear function of the DG output power. The non-linear optimisation problem can be solved using the “fmincon” function in MATLAB [5]. This function solves problems in the form:

$$\min_{x} \; f(x) \text{ Subject to: } \begin{cases} c(x) \le 0 \\ c_{eq}(x) = 0 \\ A.x \le b \\ A_{eq}.x = b_{eq} \\ l_b \le x \le u_b \end{cases} \qquad (10)$$

Where:
x, b, b_{eq}, l_b, and u_b = vectors;
A and A_{eq} = matrices;
$c(x)$ and $c_{eq}(x)$ = functions that return vectors;
$f(x)$ = function that returns a scalar.

$f(x)$, $c(x)$, and $c_{eq}(x)$ can be nonlinear functions.

4. CASE STUDIES

4.1. 24 hours load demand

A typical South African rural household and a BTS load demands are selected as two case studies to analyze the benefit of battery-integrated hybrid system compared to the DG alone. The 24h demand for both cases are shown in Fig 2 and Fig 3. These data are used as input to the energy optimization model developed in section 3 above.

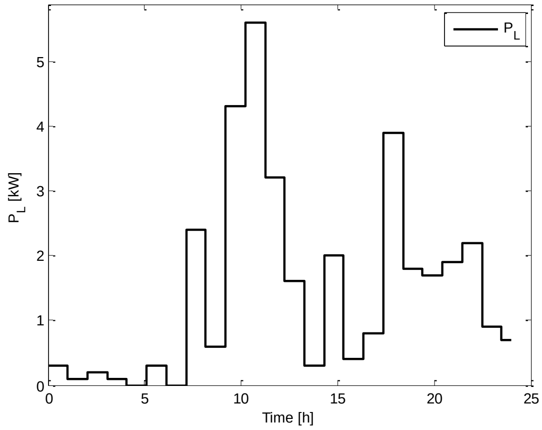

Figure 2: Household load profile

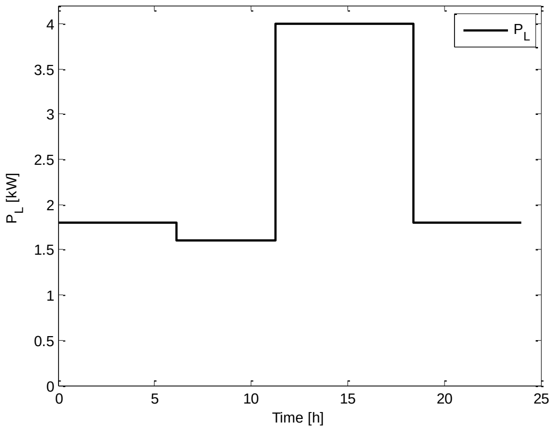

Figure 3: BTS load profile

4.2. Component size and model parameters

Table 1: Simulation parameters

Item	Household	BTS
Sampling time	15 min	15 min
Battery nominal capacity	5.6kWh	5.6kWh
Battery maximum SOC	95%	95%
Battery minimum SOC	40%	40%
Battery charging efficiency	85%	85%
DG rated power	5.6kW	2.6kW
Diesel fuel price	1.4$/l	1.4$/l
a	0.246	-0.0113
b	0.0815	0.3527
c	0.4333	1.1531

The sizes of the components as well as the different parameters used in the simulations are given on the table 1.

5. SIMULATION RESULTS AND DISCUSSION

5.1. Case 1: Rural household

Fig.4 shows the load demand, the DG output power, the battery power flow as well as the battery SOC during a 24h period. It can be noticed that during the night and early morning the load demand is low; therefore it is successfully met only by the DG which is at the same time charging the battery to its maximum SOC.

The load demand starts increasing, and the first peak demand occurs from 7h00 to 8h00, therefore the battery and DG output powers increase. After this first peak demand, the DG output power is kept constant to recharge battery system; this can be noticed on the top-left figure where the negative part of the battery power flow (P_B) represents the charging process.

From 9h00, the demand rises again, to reach a peak of 5.6kW, in this case the battery is extensively used and its SOC is reduces to the minimum operating limit at around 12h00 (40%). Therefore, after the peak, the DG produces more power than the load requirement to recharge the battery. This situation is also repeated during the evening peak.

Form the figure, it can be seen that neither the DG nor the battery reached their maximum operating power limits. The continuous operation control can allow a considerable reduction on the size or ratings of the DG and battery which can be lower than the peak demand. This can considerably increases the load factor as well as the initial cost compared to the case where the DG is used alone.

5.2. Case 2: BTS Load

From figure 5, it can be noticed that the BTS load profile is generally flat, except during the daytime when the air-conditioning system is switched on giving a 4kW peak demand for six hour (from 12h00 to 18h00). During that peak demand, the battery system is operated first at its maximum limit to supply the load while the DG is kept low. The DG output power increases later, when the battery energy is depleted, to balance the deficit of energy needed by the load.

After the peak, the SOC of the battery is at its minimum operation limit (40%); therefore the DG produces more than the load requirement. This surplus is used to recharge the battery bank for future use as shown in Figure 5.

5.3. Daily operation costs summary

Table 2 shows how much fuel (cost) can be saved by using the hybrid system instead of the selected DG (only) in both the household and BTS cases. The results obtained from the simulation demonstrate the importance of considering the non-linearity of the DG fuel consumption curve as well as the one of the load when operating the hybrid system in order to minimize the daily operation costs.

It has to be highlighted that the amount of fuel saved is highly dependent of the type of DG (fuel consumption parameters) as well as on the battery operation settings (initial, maximum and minimum SOC).

Table 3: Daily fuel cost savings

	Household		BTS Load	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	19.06L	26.7$	24.06L	33.7$
Hybrid system	12.96L	17.8$	18.47L	25.8$
Savings	6.1L	8.9$	5.59L	7.9$

6. CONCLUSION

A mathematical model to minimize the daily operation of a battery-integrated DG hybrid system has been developed. This model aims to minimize the use of the diesel generator while optimizing the use of the battery storage system. As already mentioned, this work considers the non-linearity of the load demand as well as diesel fuel consumption resulting in uniform daily operational costs. The hourly load demand as well as the diesel generator fuel consumption curve parameters data has been used as input data for simulation purposes. The simulation results shows that by using the battery-integrated DG hybrid system and taking into account the non-linearity in daily load demand, more accurate operation costs (fuel consumption) can be obtained.

In this work, only the continuous control of the DG used in the hybrid system has been studied, therefore for future work, the ON/OFF operation control of the DG should also be studied and the results compared with the continuous control.

7. REFERENCES

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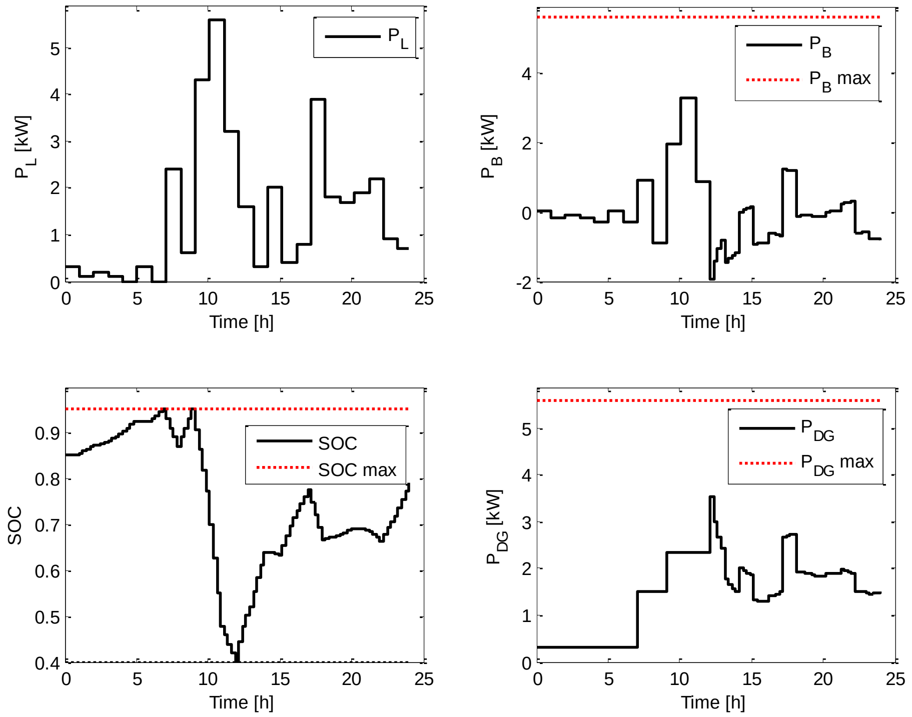

Figure 4: Daily load, DG, battery power flow and battery SOC (Household case)

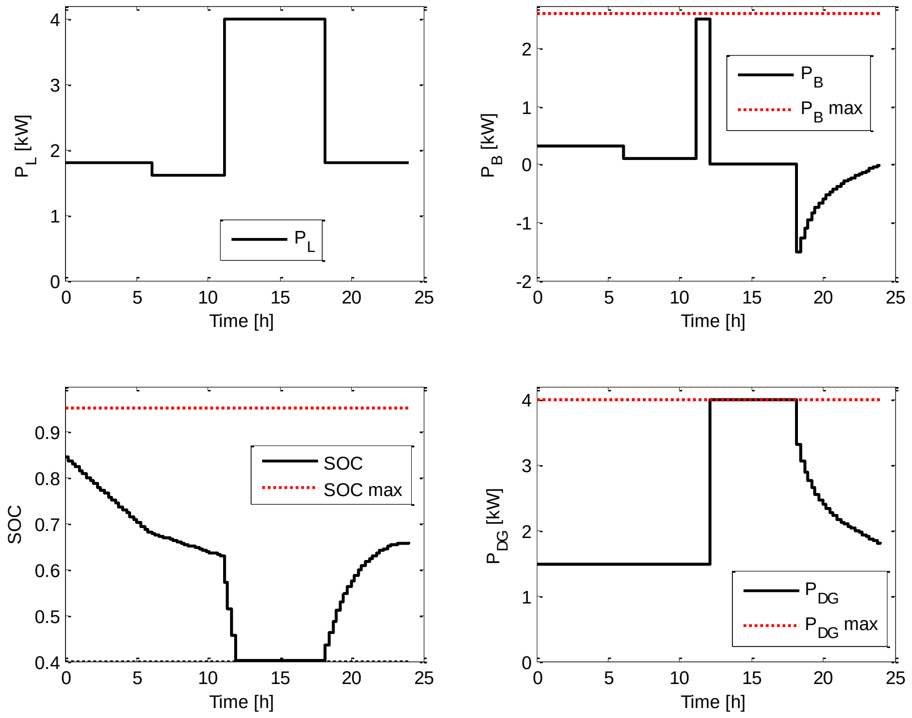

Figure 5: Daily load, DG, battery power flow and battery SOC (BTS case)