# Energy Dispatching of an isolated Diesel-Battery Hybrid Power System

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***Abstract*—In this paper, two control strategies involving "continuous" and "ON/OFF" operation of the diesel generator in the battery-integrated hybrid system are developed, implemented and compared. The main purpose of these modeled controlled strategies is to minimize the diesel generator operation cost in standalone electricity generation processes. The simulations have been performed using "fmincon" for the continuous operation and "intlinprog" for the ON/OFF operation strategy implemented in Matlab. A rural household and a base transceiver station have been used as case studies; and the daily operation cost obtained are compared to the scenario where the diesel generator is used alone to supply the same load demand. Sensitivity analyses have been conducted on the battery control settings as key parameters to find how changes in these parameters do impact the daily operation cost of the hybrid system. The results show that using the developed optimal energy dispatch models, significant fuel saving can be achieved compared to the case where the diesel is used alone to supply the same load requirements.**

***Keywords*— Battery, Diesel generator, Operation scheduling, Operation cost minimization.***

## I. INTRODUCTION

The lack of reliable electricity supply, the high cost of electrical grid extensions and the rough topography are some of the severe challenges faced in the rural electrification of a good number of developing countries. In most cases, loads in such rural areas are powered using standalone options such as small scale renewable energy (RE) sources or diesel-engine driven alternators (DGs) running continuously [1-3].

Compared to small scale (RE) sources, DGs have low investment costs and can generate electricity on demand. They are easily transportable, modular, and have a high power-to-weight ratio. DG can also be integrated with other RE and energy storage devices in hybrid system configurations to provide highly reliable electricity, making it an ideal solution for standalone rural electricity supply [4-6].

However, due to the long running times and the highly variable load demand; DGs are usually having high operation and maintenance costs when associated to low operation efficiency in higher cost of energy production [7].

It is well known that for DGs to perform efficiently, they have to be loaded close to their rated capacity. One way to implement this operating condition is to supply the useful demand together with a dummy load that can dissipate the excess power while keeping the load factor high. However, this technique is not energy efficient [8].

Storage systems, such as battery can be used to recover and store the excess of energy generated when the DG is running at high load factor. In this configuration, the DG is used to recharge the battery when the load demand is low; it can also be used as a back-up to balance the deficit of the power supply from the battery when the load demand is high. This combination can decrease the DG fuel consumption while increasing the reliability of power supply.

Few research works have been conducted on the subject of optimal operation control of battery-integrated hybrid system in isolated electrification [9-13]. However, while analyzing those works, it can be noticed that none of them looked at the optimization of the system's daily operation cost from an energy efficiency point of view. Energy efficiency can be defined as the ratio of the output to the input energy and is characterized by the performance efficiency, the operation efficiency, the equipment efficiency, and the technology efficiency as main components [14]. Operation efficiency is a system-wide measure, which is assessed by taking into consideration the optimal sizing and matching of all system components, time control and human coordination [15]. Operation efficiency can be enhanced using mathematical optimization and optimal control techniques as investigated in [14] and [15].

Therefore this paper reports on the development of mathematical programming models to optimize the operation efficiency of a battery-integrated hybrid system measured in monetary. 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 algorithms is to minimize the diesel generator operation cost in the electricity generation process. The non-linearity in the fluctuation 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 models. The simulations of two control strategies, namely continuous operation and ON/OFF control have been performed using MATLAB 2014a; the results have been compared with the case where the DG is used alone to supply the load.

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## II. Hybrid system components description and operartion

### A. Diesel generator

Standalone diesel generators are usually in such a way that high efficiency is achieved when they operate close to their rated powers. With this operation constraint, the DGs are expected to run at high load factors, which will result in a decrease of the fuel consumption and of carbon footprint and increase of the DG lifespan [16]. The fuel cost of a power system can be expressed mainly as a function of its real power output and can be modeled by a quadratic polynomial. The daily fuel cost can be expressed as follows:

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

Where: $C_f$ is the price of one liter; a, b, c are the parameters of the DG fuel consumption curve; $P_{DG(j)}$ is the output power from the DG at any time sampling time *j*.

### B. Battery storage system

The output power from the DG and the load demand at any given sampling interval *j*, determines 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 [17]:

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

Where: SOC is the state of charge of the battery; $\eta_{Bat}$ 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. By induction reasoning, the dynamics of the battery state of charge at $j^{th}$ sampling interval can be expressed in terms of its initial value $SOC_{(0)}$ as follows:

$$SOC_{(j)} = SOC_{(0)} - t_s \frac{\eta_{Bat}}{E_{nom}} \sum_{i=1}^{j} P_{Bat(j)} \quad (3)$$

### C. Battery-integrated DG hybrid system

The schematic of a battery-integrated DG hybrid system's power flow is shown in Figure 1. The system main components are the operating DG 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 cannot be met by the battery, then the 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.

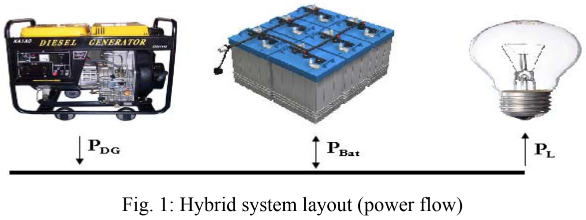


Fig. 1: Hybrid system layout (power flow)

## III. Optimization models and proposed algorithm

The optimization problem addressed in this work aims at finding the 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 can be implemented using two different strategies, namely "*continuous operation"* and "*on/off*" control.

### A. 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 [18].

#### 1) Objective function

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

$$\min C_f \times \sum_{j=1}^{N} (aP_{DG(j)}^2 + bP_{DG(j)} + c) \quad (4)$$

#### 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:

$$P_{DG(j)} + P_{Bat(j)} = P_{L(j)} \quad (5)$$

- Variable limits:

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:

$$0 \le P_{DG(j)} \le P_{DG}^{\max} \quad (1 \le j \le N) \quad (6)$$

$$-P_{Bat}^{rated} \le P_{Bat(j)} \le P_{Bat}^{rated} \quad (1 \le j \le N) \quad (7)$$

- Battery state of charge:

The available battery bank state of charge in 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:

$$SOC^{\min} \le SOC_{(j)} \le SOC^{\max} \quad (8)$$

#### 3) 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 [19]. This function solves problems in this form:

$$\min_x f(x) \text{ Subject to: } \begin{cases} c(x) \le 0 \\ c_{eq}(x) = 0 \\ A.x \le b \\ A_{eq}.x = b_{eq} \\ l_b \le x \le u_b \end{cases} \quad (9)$$

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

### B. DG on/off operational model

In this case, the philosophy is to obtain an optimal ON/OFF schedule of the DG that minimizes its operation cost [20]. The battery bank is expected to act as the main supply of energy with the DG considered as a back-up energy source. When the DG is on, it is forced to run at its rated output power which is a constant. Since the DG is switched ON/OFF and the battery bank is smoothly controlled to meet the demand, the problem is therefore formulated as a mixed-integer programming one. The mathematical model is given in the sections below:

#### 1) Objective function

The binary switching variables may be introduced in the objective function as:

$$\min C_f \times \sum_{j=1}^{N} (aP_{DG-rated}^2 + bP_{DG-rated} + c) \times S_{(j)} \quad (10)$$

Where: $S_{(j)}$ is a discrete-switching function that takes the value of either 0 or 1. $S_{(j)}=0$ means that the DG is switched off during the $j^{th}$ sampling interval, while $S_{(j)}=1$ means that the DG is switched on. The output power of the DG is therefore a constant.

#### 2) Constraints

- Power balance:

In this case, the power balance can be expressed as:

$$P_{DG-rated} S_{(j)} + P_{Bat(j)} = P_{L(j)} \qquad (1 \le j \le N) \quad (11)$$

- Control variable limits:

As explained above the switch can only take two values [0 or 1] which are its lower and upper limits.

The battery module is modeled as a variable power source controllable in the range of minus rated power, when charging, to its rated power for the 24 hour period. The equations (6) and (7) linked to the battery power output and state of charge developed in section III are also used in the present case.

#### 3) Proposed algorithm

The objective function has been modeled as a function of the switch controlling the DG and the variable battery output power. This mixed-integer optimization problem can be solved using "*Intlinprog*" function from MATLAB Optimization toolbox [21]. This function solves problems in the form:

$$\min_x f^T x \text{ Subject to: } \begin{cases} x(\text{int}\, con) \\ A.x \le b \\ A_{eq}.x = b_{eq} \\ l_b \le x \le u_b \end{cases} \quad (12)$$

Where: *f, x, intcon, b,* $b_{eq}$, $l_b$, and $u_b$ are vectors; *A* and $A_{eq}$ are matrices.

## IV. APPLICATION EXAMPLE

### A. Daily load demand

A typical South African rural household and a base transceiver system (BTS) daily load demands are selected as two case studies to analyze the benefit of battery-integrated hybrid system compared to the DG alone. The daily demands for both cases are shown in Figure 2 and Figure 3 [22]. These data are used as input to the energy optimization model developed in section III above.

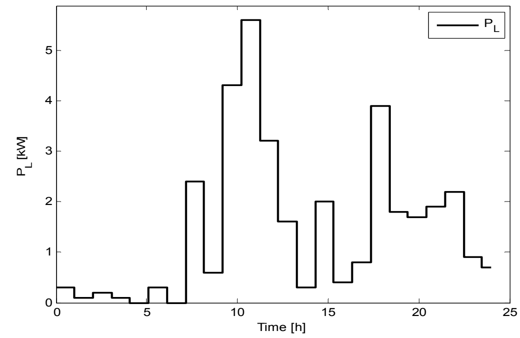


Fig. 2: Household load profile

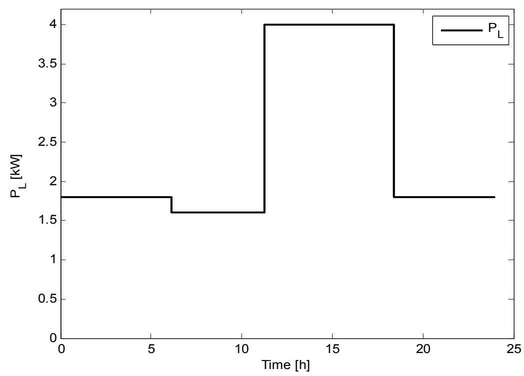


Fig. 3: BTS load profile

### B. Component size and model parameters

The sizes of the components as well as the different parameters used in the simulations are given in the Table I [23].

TABLE I. 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 |

## V. SIMULATION RESULTS AND DISCUSSION

In this section, the simulations of the two control strategies, namely continuous operation and on/off control are presented and compared to the case where the DG is used alone to supply the load.

### *A. Continuous operation*

#### *1) Case 1: Rural household*

Figure 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.

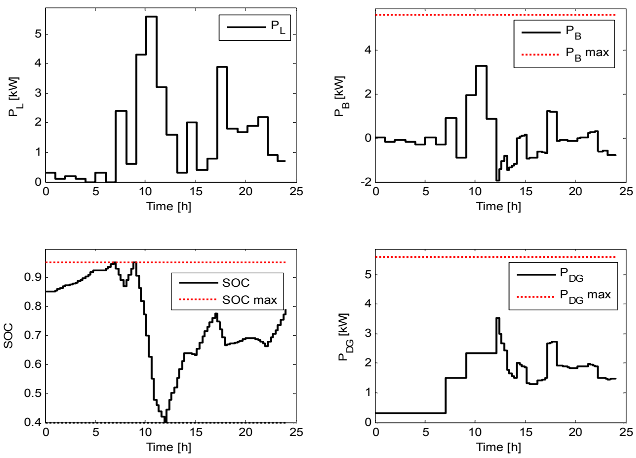


Fig. 4: Daily load, battery power flow, battery SOC and DG (Household case)

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-right 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 reduced 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 same 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 one required during the peak demand. This can considerably increases the load factor as well as decrease the initial cost compared to the case where the DG is used alone.

#### *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 below.

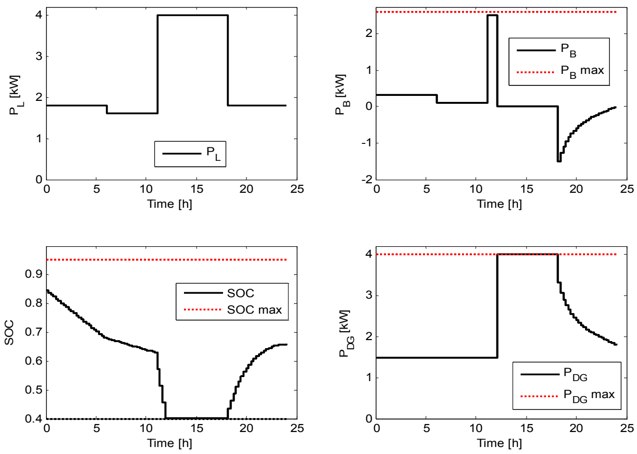


Fig. 5: Daily load, battery power flow, battery SOC and DG (BTS case)

#### *3) Daily operation costs summary*

Table II 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.

TABLE II. DAILY FUEL COST SAVINGS (CONTINUOUS OPERATION)

| | Household | | BTS Load | |
|---|---|---|---|---|
| | Consumption (L) | Cost ($) | Consumption (L) | Cost ($) |
| DG only | 19.13L | 26.8$ | 28.00L | 39.20$ |
| Hybrid system | 12.96L | 17.8$ | 18.47L | 25.8$ |
| Savings | 6.17L | 9$ | 9.53L | 13.4$ |

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).

## *B. ON/OFF operation*

### *1) Case 1: Rural household*

Figure 6 shows the load demand, the state of the switch controlling the DG, the battery power flow as well as the battery SOC during a 24 hour period.
It can be noticed that during the night and early morning the load demand is low; therefore it is successfully met by the battery system while the DG is kept OFF.

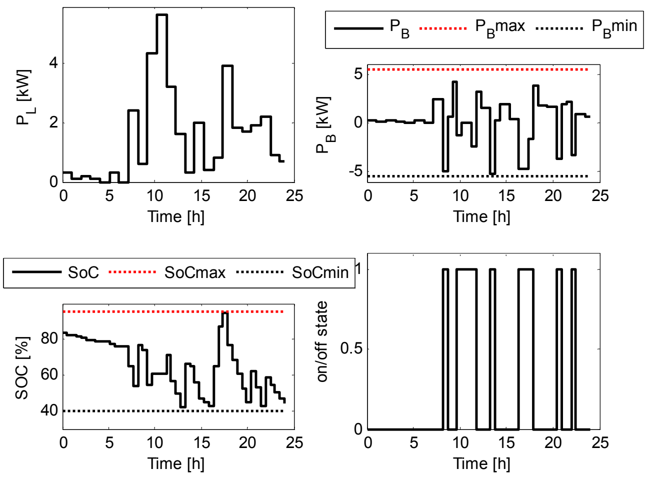


Fig. 6: Daily load, battery power flow, battery SOC and DG (Household case)

When the load demand increases during the day and the battery power cannot meet the demand, the DG is switched on, giving its rated power of 5.6 kW. The load demand is therefore satisfied and the surplus of power from the DG, which is not used by the load, is used to recharge the battery. This can be noticed on the top-right figure where the negative part of the battery power flow ($P_B$) represents the charging process. Depending on the variation of the demand when the DG is ON, the battery can be recharged up to its maximum SOC.

While analyzing Figure 6, it can be noticed that for this specific case, the DG operates for a total of 6 hours and is OFF for the rest of the day. This can help the DG to have a long calendar lifespan; however the impact of excessive ON and OFF cycles on the DG lifespan should be studied.

### *2) Case 2: BTS Load*

From Figure 7, 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). Throughout the day, the battery system is operated first to supply the load while the DG is kept OFF. The DG is turned ON, as soon as the load demand cannot be met by the battery operating within its limits, to supply the deficit of power and the excess is used at the same time to recharge the battery. It can also be noticed that the length of the DG's ON-time is longer when the load demand is high compared to the night time when the demand is low.

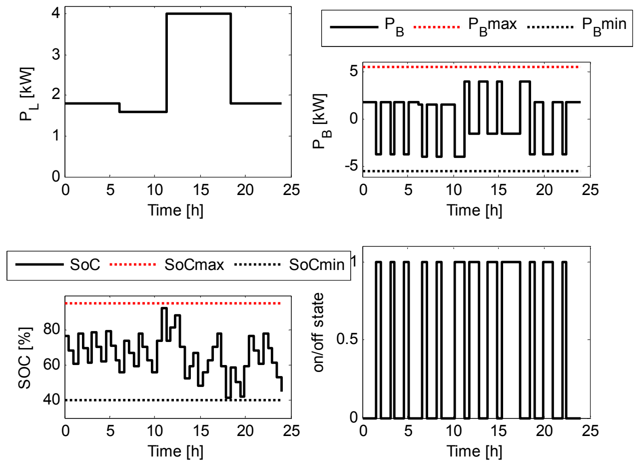


Fig. 7: Daily load, battery power flow, battery SOC and DG (BTS case)

The number of ON/OFF cycles as well as the duration of the DG's ON-time is highly dependent on the size of the storage capacity available. A large battery bank capacity might reduce the number of DG's ON/OFF cycles; however, it might also increase both the length of the DG's ON-time needed to recharge the battery and the amount of fuel consumed. Therefore the optimal size of the battery storage system, that minimizes both the number and length of the DG's ON/OFF cycles, should also be studies.

### *3) Daily operation costs summary*

Table III 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.

TABLE III. DAILY OPERATION COSTS SUMMARY

| | **Household** | | **BTS Load** | |
|---|---|---|---|---|
| | Consumption (L) | Cost ($) | Consumption (L) | Cost ($) |
| DG only | 19.13L | 26.8$ | 28.00L | 39.20$ |
| Hybrid system | 17.83L | 25.0$ | 25.80L | 36.12$ |
| Savings | 1.30L | 2.52$ | 2.20L | 3.08$ |

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

### C. Sensitivity analysis

In this section, sensitivity analyses have been conducted on the battery control settings as key parameters. The main aim of these analyses is to find how do changes in these parameter impact the daily operation cost of the hybrid system.

#### 1) Impact of the battery's depth of discharge

Here, the impact of the battery's depth of discharge (DOD) on the hybrid system's daily operation cost is studied for both "continuous" and "ON/OFF" operation strategies.

Table 4 considers three depths of discharges (100%, 80% and 60%) related to different types of batteries currently available on the market such as Lithium-ion, Nickel-cadmium and lead-acid. For all the considered cases, the battery has been considered to be fully charged at the beginning of the day. After analysis of the results in Table IV, it can be concluded that the continuous operation mode of the DG in the hybrid system achieves better fuel saving than the ON/OFF (at different DOD). It can also be seen from this table that the larger battery's DOD reduces the DG's daily fuel consumed resulting in reduction in the daily operation cost. However it has to be noted that battery with large DOD are expensive, therefore they cost will have a negative impact on the hybrid system's initial cost.

TABLE IV. IMPACT OF THE BATTERY'S DEPTH OF DISCHARGE

| Operation strategy | DoD = 100% | DoD = 80% | DoD = 60% |
|---|---|---|---|
| *Continuous* | 9.01 L | 10.98 L | 12.96 L |
| *ON/OFF* | 11.87 L | 14.86 L | 17.83 L |

#### 2) Impact of the battery initial's state of charge

In this section, the impact of the initial state of charge ($SOC_0$) on the hybrid system's daily operation cost is studied for both "continuous" and "ON/OFF" operation strategies. The $SOC_0$ is a key factor because the battery can only be recharged by the DG; this would increase the DG running time and operation cost in both "continuous" and "ON/OFF" operation strategies. Table 5 summarizes the simulation results obtained when varying $SOC_0$. In the three selected cases, the DOD has been considered as 100%.

TABLE V. IMPACT OF THE BATTERY INITIAL'S STATE OF CHARGE

| Operation strategy | $SOC_0 = 0\%$ | $SOC_0 = 50\%$ | $SOC_0 = 100\%$ |
|---|---|---|---|
| *Continuous* | 14.37 L | 9.7 L | 9.01 L |
| *ON/OFF* | 17.83 L | 14.52 L | 11.87 L |

## VI. CONCLUSION

Two control strategies to minimize the daily fuel consumption of a DG in a battery integrated hybrid systems have been modelled and simulated. As already mentioned, this work considers the non-linearity of the load demand as well as the non-linearity of the diesel fuel consumption curve resulting in uniform daily operational costs. The hourly load demands as well as the diesel generator fuel consumption curve parameters have been used as input data for simulation purposes. The simulation results show that by using the battery-integrated DG hybrid system under the continuous or ON/OFF operation control strategy, significant fuel (operation cost) can be saved compared to the case where the DG is used alone. When comparing the two control strategies, it has been demonstrated that more fuel saving is achieved using the continuous control than using the ON/OFF control strategy.

When comparing the two control strategies through sensitivity analyses using the battery's initial state of charge or the battery depth of discharge as control parameters, it has been demonstrated that more fuel saving is achieved using the continuous control than using the ON/OFF control strategy. However the ON/OFF control achieves more DG daily operating time reduction compared to the case where the continuous control is implemented.

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