Optimal Operation of Parallel-connected Diesel Generators for Remote Electrification through Energy Management Approach

Kanzumba Kusakana
Department of Electrical, Electronic and Computer Engineering
Central University of Technology, Free State
Bloemfontein, South Africa
Email: kkusakana@cut.ac.za

***Abstract*— In this paper, optimal scheduling and energy management concepts are used to demonstrate the operational cost saving achievable using multiple paralleled diesel generators over a "Single" diesel generator unit for supplying small loads not connected to the grid. These two supply options are modelled and simulated using Matlab. From the two case studies undertaken, the simulation results show that using multiple connected small diesel generators instead on a single large one is a better option be considered for standalone power generation.**

***Index Terms*-- Cost effectiveness, Diesel generator, Operation scheduling, Paralleled operation.**

1. Introduction

In 2016, as many as 1.5 billion people on the planet do not have access to reliable sources of electricity [1]. Many of these people are located in remote or rural areas where grid extensions from the main generating stations are impractical or often not cost-effective [2-3]. This lack energy is considered to be on of humanity's top ten problems for the next 50 years. It has resulted in poor economic developments and is widely considered to be a major factor contributing to the continued poverty in rural areas [4]. Although there has been significant advancement in the deployment of some contemporary technologies, such as mobile telephones, the electrical energy required to operate these equipment is still a serious challenge [5].

Luckily, innovative means of supplying these areas in electricity such as do currently exist. The most common ones are:

- "Microgrids" for relatively high consumption, from household equipment to even commercial and industrial appliances. However, these are capital intensive and require specialized operation and maintenance [6].
- "Distributed generations" such as Micro/pico-hydro, Solar, Wind or Diesel Generators (DGs) for relatively small scale energy consumption. These technologies provide enough power to respond to basic needs such as lighting or battery charging. Their capital costs are low and they require little and they can be inexpensive to operate [7].

Compared to the other distributed generation options, DG is the most popular supply option due to its low specific capital cost per kW produced, its high power-to-weight ratio and its reliability. The modern DGs have proven to be a remarkably versatile and robust mean of generating reasonable amounts of electricity. The fuel used is quite common and has high volumetric and weight energy density. The other advantage of DGs is that the power produced is not dependent on variable and exogenous resources such as solar irradiance, water resource or wind speed; it is available on demand [8].

There are, however, some important disadvantages to DGs for rural, standalone electrification. Fuel can be very expensive, or completely inaccessible. DGs are often noisy, polluting the environment and have low overall efficiency [9].

Knowing the advantages, disadvantages and reasons why consumers select DGs over other supply options, it is therefore imperative to use means of minimizing the fuel consumed by DGs during operation. This can be realised by allowing DGs to always run close to their full load ratings resulting in an increase in the performance efficiency and a decrease in specific fuel consumption. In practice, this can be achieved by:

- Using a dump load that can waste the excess power into heat while keeping the load factor high. However, this technique is not energy efficient [10].
- Using battery-integrated DGs operating in a charging-cycle dispatch strategy. However, the capital cost is increased by also considering the cost of the battery storage system [11-13].

978-1-5090-4746-8/17/$31.00 ©2017 IEEE

- Using Multiple paralleled DGs which can adequately provide energy the load even during peak time [14].

However, in a number of standalone applications, there are substantial benefits in distributing the total load demand among different smaller DGs, connected in parallel to increase the supply reliability, availability, fuel efficiency and operational flexibility. This paper will explore the potential benefits of using small DGs in parallel in standalone and isolated applications. In this paper, optimal scheduling and energy management concepts are used to demonstrate the operational cost saving achievable using multiple paralleled diesel generators over a "Single" diesel generator unit for supplying small loads not connected to the grid. These two supply options are modelled and simulated using Matlab. From the two case studies undertaken, the simulation results show that using multiple connected small diesel generators instead on a single large one is a better option be considered for standalone power generation.

2. PROPOSED SUPPLY OPTIONS DESCRIPTION

DGs are selected based on their low initial capital cost as well as the fact that they are currently well deployed and used in isolated areas. As stated in the introduction, the main objective of this paper is to develop a model that will minimize the operation cost while optimally scheduling the power supplied to an isolated load by using multiple paralleled DGs.

A. Load description

The proposed daily load profile is given on Fig. 1. From this figure, it can be seen that the demand is very low the night and then increases during the day to reach a first peak at 10:00 noon and a second one around 18:00.

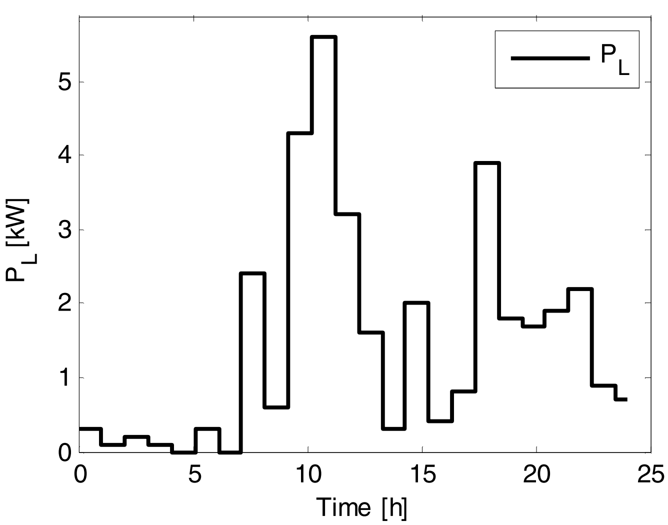

Figure 1: Proposed domestic load profile [15]

Therefore, any adequate supply option must be able to meet the demand throughout the day. This load profile will be will be used for comparison purposed between the case where a larger DG is used and the one where multiple paralleled DGs are used.

B. Supply options selection

The focus of this research is only on the DGs based on the fact that they are widely used in rural areas. The power flows of two selected options namely the single DG and the multiple paralleled DGs are presented in the subsections below.

1) Single DG

Fig. 2 explains the power flow in the single DG option. In this case, the load is directly and continuously supplied by the DG running under the following dispatch strategy. The output of the DG is continuously adjusted to follow and meet the variable demand. The major disadvantage of this supply option is that the specific fuel consumption is very high when the load is lower compared to the DG nominal rating.

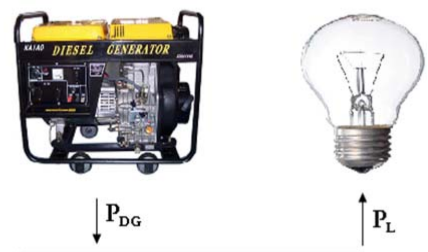

Figure 2: Single DG

2) Multiple paralleled DGs

Fig. 3 explains the power flow in the multiple paralleled DGs option where the total demand can be shared among several smaller DGs. In this case, two DGs are considered where one operates as main supply while the second is used to balance the deficit of power in peak demand periods when the power from the first DG is not enough to satisfy the demand.

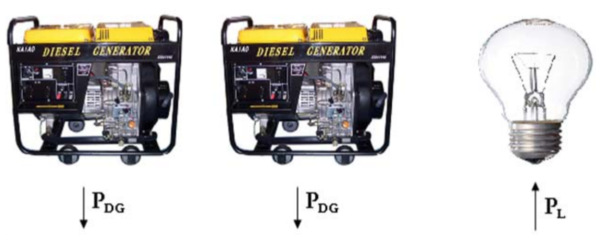

Figure 3: Multiple paralleled DGs

3. MODEL DEVELOPMENT

A. Objective function

In this case the one DG is used as main supply while the second DG is used only when the load demand is higher than the first DG power rating. Because of the short simulation horizon time, only the fuel expenses will be considered as operation cost. Therefore, the developed model has the following main objectives:

- Maximizing the use of the first DG_1,
- Minimizing the operation cost and running time of the second DG_2 during the operation time.

These can be mathematically modeled as:

$$\max C_f \times \sum_{j=1}^{N} (aP_{DG1(j)}^2 + bP_{DG1(j)} + c) + \quad (1)$$
$$\min C_f \times \sum_{j=1}^{N} (aP_{DG2(j)}^2 + bP_{DG2(j)} + c)$$

Where:

- N is the number of sampling intervals within the operation range or period of the system;
- a, b, c are the fuel cost coefficients depending on the size and DG manufacturer;
- j is the j^{th} sampling interval;
- $P_{DG(j)}$ is the output power from the DG at j^{th} sampling interval;
- C_f is the price of one liter of fuel.

B. Constraints

The developed objective function is subjected to the following constraints:

3.2.1 Power balance:

At any sampling interval j, the sum of the supplied powers from the $DG_1$and DG_2 must be equal to the demand. This can be expressed as:

$$P_{DG1(j)} + P_{DG2(j)} = P_{L(j)} \quad (2)$$

3.2.2 Variable limits:

These constraints depend on the characteristics of each power source and can be expressed as:

$$0 \le P_{DG1(j)} \le P_{DG}^{\max} \quad (1 \le j \le N) \quad (3)$$

$$0 \le P_{DG2(j)} \le P_{PV(j)}^{\max} \quad (1 \le j \le N) \quad (4)$$

3.1. Proposed algorithm

The objective function has been modeled as a sum of the quadratic (non-linear) functions of the two DGs output powers. This non-linear optimisation problem can be solved using "fmincon" function in MATLAB [16]. The modified which canonical form of fmincon suited to the specific developed model can be expresses as:

$$\min_x f(x) \text{ Subject to: } \begin{cases} A_{eq}.x = b_{eq} \\ l_b \le x \le u_b \end{cases} \quad (5)$$

Where:

- x, b_{eq}, l_b, and u_b are vectors;
- A_{eq} is a matrice;
- and $f(x)$ is a non-linear function that returns a scalar.

4. Main simulation input parameters

4.1. Single DG case

In this case, one single DG is used to continuously supply the variable load demand. The DG's rating is 5.6 kW, with the ability of supplying the load even during the peak demand periods. The simulation data are given in Table 1.

Table 1 [11]:
Simulation parameters (Single DG)

Item	**Figure**
Simulation horizon time	24 hrs
Sampling time	30 min
DG rated power	5.6kW
Diesel fuel price	1.1 $/L
A	-0.0113 L/kWh^2
B	0.3527 L/kWh
C	0.2433 L

4.2. Multiple paralleled DGs case

In this case, two small generators of the same rating are connected in parallel to supply the load demand. Each DG is 2.8 kW, half of the rating of the single DG considered in the case above. The simulation data are given in Table 2.

Table 2 [11]:
Simulation parameters (Multiple paralleled DGs)

Item	**Figure**
Simulation horizon time	24 hrs
Sampling time	30 min
DG_1 rated power	2.8 kW
DG_2 rated power	2.8 kW
Diesel fuel price	1.1 $/L
a	0.246 L/kWh^2
b	0.0815 L/kWh
c	0.4333 L

5. Results and discussion

In this section, the single DG, and the multiple paralleled DGs options are simulated using Matlab when subjected to the same load requirement. The simulation results of the two supply options are performed for each of the 24 hours within the proposed time horizon.

5.1. Single DG case

From Fig.4, it can be seen that the DG operates in a load following dispatch strategy, continuously matching the load demand. This results in high specific fuel consumption when the load is lower than the DG rating.

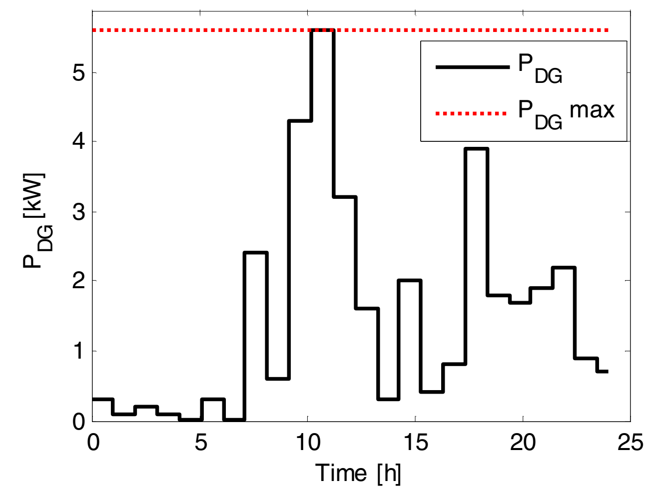

Figure 4: DG (paralleled operation) output power profile

5.2. Multiple paralleled DGs case

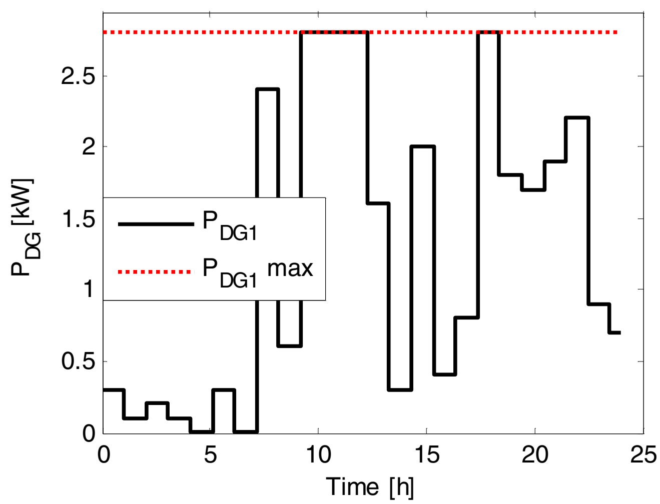

Figure 5: Main DG_1 output power profile

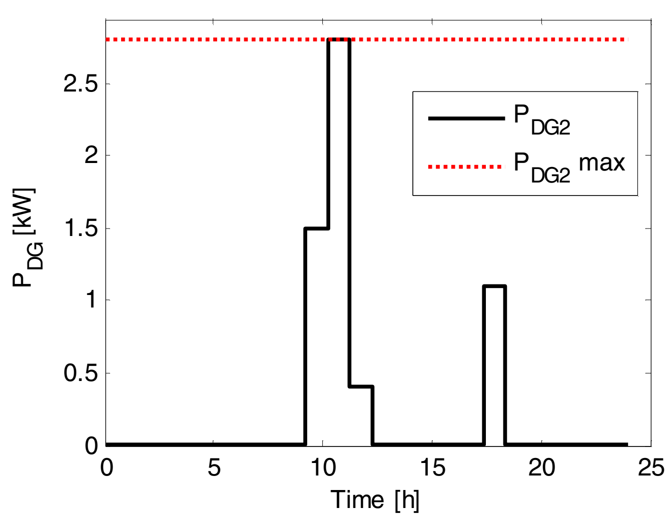

Figure 6: DG_2 output power profile

Fig. 5 shows the power flow of the main 2.8 kW DG1 used to supply the load, therefore it is running at a better load factor compared to the single 5.6 kW DG which results in lower specific fuel consumption. However, during peak demand periods, the main DG1 is not able to supply the demand by itself, the second 2.8 kW DG2 is switched ON to balance the deficit of power needed as shown in Fig. 6.

5.3. Comparison of the three proposed supply options

It has to be highlighted that the resultant daily fuel expenses (operation cost) are highly dependent on the dimensions, brand as well as on the DG's fuel cost curve used in the simulation.

Table 3 shows how much daily cost can be saved using the several paralleled DGs instead of one larger for the selected daily load profile. From this table it can be seen that for this specific case, 30.7 % fuel saving for the selected day using two small paralleled operated DGs instead of one larger. This is due to the fact that DG_1 is operating at high load factor while DG_2 operating time is significantly low.

Table 3:
Daily fuel cost savings

Supply option	*Consumption (L)*	*Cost ($)*
Single DG	22.52 L	24.77 $
Multiple paralleled DGs	15.59 L	17.15 $
Savings	6.93 L	7.62$

6. Conclusions

In this work, the potential techno-economic advantages of multiple paralleled diesel generators instead of a single large unit for rural energy supply is investigated using mathematical modelling and simulation. A typical household daily power demand has been selected as case study to analyse and assess the savings achieved using a single DG compared to multiple paralleled DGs.

Matlab software has been used for modelling and simulation the case where two DGs are used in parallel. The results have shown that 30.7 % fuel saving for the selected day using two small paralleled operated DGs instead of one larger.

The results from this study can be used to promote the use of multiple paralleled diesel generators in micro isolated rural applications.

References

[1] United Nations. "The Sustainable Development Goals Report 2016". Available from: http://unstats.un.org/sdgs/report/2016/The%20Sustainable%20Development%20Goals%20Report%202016.pdf Accessed on 20th January 2017.

[2] K. Kusakana. "Optimal scheduling for distributed hybrid system with pumped hydro storage". Energy Conversion and Management 111 (2016), 253-260.

[3] K. Kusakana. "Energy management of a grid-connected hydrokinetic system under Time of Use tariff". Renewable Energy 101 (2017), 1325-1333.
[4] V. Kamat. "Energy Challenge and Nanotechnology". Available from: http://www3.nd.edu/~pkamat/pdf/energy.pdf Accessed on 20th January 2017.
[5] K. Kusakana, H.J. Vermaak. "Hybrid renewable power systems for mobile telephony base stations in developing countries". Renewable Energy 51 (2013), 419-425.
[6] K. Kusakana. "Optimal operation control of a grid-connected photovoltaic-battery hybrid system". 2016 IEEE PES Power Africa Conference, 239-244.
[7] K. Kusakana. "Optimal scheduling for distributed hybrid system with pumped hydro storage". Energy Conversion and Management 111, 253-260.
[8] H. Tazvinga, X. Xia, J. Zhang. "Minimum cost solution of photovoltaic-diesel-battery hybrid power systems for remote consumers". Solar Energy, 96 (2013), 292-299.
[9] K. Kusakana, H.J. Vermaak. "Hybrid Diesel Generator - battery systems for off-grid rural applications". International Conference on Industrial Technology (ICIT 2013), 839-844.
[10] P. Arun, R. Banerjee, S. Bandyopadhyay. "Optimum sizing of battery-integrated diesel generator for remote electrification through design-space approach". Energy 33 (2008), 1155-1168.
[11] K. Kusakana. "Minimum cost solution of isolated battery-integrated diesel generator hybrid systems". South African University Power and Energy conference (SAUPEC 2015), 141-147.
[12] K. Kusakana. "Energy dispatching of an isolated Diesel-Battery Hybrid Power System". International Conference on Industrial Technology (ICIT 2016), 499-504.
[13] K Kusakana. "Optimisation of battery-integrated diesel generator hybrid systems using an ON/OFF operating strategy". International Conference on Domestic Use of Energy (DUE 2015) 187-192.
[14] K. Kusakana. "Benefits of multiple paralleled diesel generators in traditional single-generator for micro isolated applications". World Renewable Energy Congress XVI (WREC 2017), unpublished.
[15] K. Kusakana. "Optimal scheduling for distributed hybrid system with pumped hydro storage". Energy Conversion and Management 111, 253-260.
[16] B.P. Numbi, S.J. Malinga. "Optimal energy cost and economic analysis of a residential grid-interactive solar PV system-case of eThekwini municipality in South Africa". Applied Energy 186 (2017), 28-45.