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Design of Grid-tied Hybrid Diesel-Renewable Energy Systems Using Power Pinch Analysis

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Diesel power systems have been widely applied for energy supply generation. This power scheme however requires periodical maintenance and contributes to the emissions of greenhouse gases. These challenges may be mitigated by integrating existing diesel station with renewable energy (RE) technologies into a hybrid system. Integration of diesel plants with RE systems has been mostly implemented using software and mathematical programming approaches, where the focus of the study is mainly on grid-independent hybrid system. Grid-connected hybrid systems have the potential to supply electricity at a lower cost in comparison to the standalone hybrid power systems. This work aims to design a system that integrates diesel plant with RE technologies into grid-tied hybrid system using insight-based Power Pinch Analysis (PoPA) method. The interactions between diesel generator, RE sources and the grid in meeting the load demands were considered in the methodology development. Various load sharing scenarios between the multiple generation sources were assessed to establish the optimal system operation. Economic assessment was performed to ensure the trade-off between the costs of generation sources and grid electricity cost can be maximized. Based on the demonstrated Illustrative Case Study, load sharing based on peak/off peak period contributes to the lowest net present cost of MYR 32,813,708, hence is deduced as the optimal on-grid hybrid diesel RE system.

1. Introduction

Worldwide energy consumption is increasing steadily and many developing countries experience extreme growth in energy demand. Diesel power system has been one of the most popular methods for electrification. Though the capital cost of diesel power technology is relatively inexpensive, it requires periodical maintenance. Emission control is also one of the critical concerns in running diesel plant operation. According to Jamaludin et al. (2019), diesel fuel consumption is among the highest contributor for carbon emissions. These challenges may be overcome by integrating the existing diesel station with renewable energy (RE) sources into a hybrid power system (HPS). A HPS that combines multiple RE sources to supplement the diesel power system may provide cleaner and reliable power supply to the load demands.

The potential of an off-grid hybrid diesel-PV-battery system to electrify an isolated Saharan community was studied by Fodhil et al. (2019). The total system cost, carbon emissions and unmet load were simultaneously minimised using Particle Swarm Optimisation and ε-constraint method. The established optimal hybrid system allows PV penetration of 93 % to support the diesel system at a minimum cost of energy of 1.59 MYR/kWh. Powell et al. (2019) combined solar PV and diesel generator in an off-grid hybrid irrigation pumping system. The hybrid installation contributes to almost one million litres of diesel fuel saving on top of 26 % reduction in the CO_2 emission. Arceo et al. (2019) examined the eco-efficiency performance of a remote hybrid wind-diesel system in Western Australia using eco-efficiency analysis (EEA) framework. Both life cycle cost and life cycle carbon emissions were successfully achieved after load restriction on the diesel engines was applied in the hybrid system.

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The aforementioned studies focused only on grid-independent HPS. Grid-connected HPS however has the potential to produce electricity at a lower system cost in comparison to the off-grid system (Türkay and Telli, 2011). Halabi et al. (2017) scrutinized the technical, economical and environmental aspects affecting the performance of a hybrid system comprising of diesel generators, PV system and grid connection. The authors recommended grid connection over battery storage application because the excess energy in the system was totally consumed while providing additional income to the local network. Rajbongshi et al. (2017) presented a grid-connected hybrid PV-biomass-diesel system to improve the access as well as the quality of grid power for remote villages. The authors employed HOMER software to establish the optimal system configuration considering various load profiles. For daily energy demand of 178 kWh, grid purchase and sales of 9 % and 23 % were obtained where the economics is better than the off-grid system. Bi-objective optimisation of a grid-connected hybrid PV-diesel-fuel cell system was performed by Gharibi and Askarzadeh (2019). Grid factor was set as the continuous decision variable while the costs of diesel fuel, electricity and storage system were minimised. Results from the simulation study verify the importance of the grid in supporting the hybrid system.

Integration of diesel plants with RE sources has been mostly realised via software and mathematical modelling tools. Application of insight-based method for this purpose has so far received minor attention. The feasibility of expanding diesel power plant into an off-grid HPS using insight-based Power Pinch Analysis (PoPA) method has been assessed by Mohammad Rozali et al. (2015). The total generation and working duration of diesel generator have been minimised, which consequently contributes to diesel fuel savings and environmental emissions reduction. Mohammad Rozali et al. (2019) later presented an extended PoPA tool called the Probability-Power Pinch Analysis (P-PoPA) that utilise probability theory to integrate diesel system with RE within a shorter time of analysis. Both studies however do not explore the potential of incorporating diesel system with RE technologies in a grid-connected HPS. An on-grid HPS may operate without storage system thus contributes to savings in the installation and operational costs. The sole PoPA study dedicated for the design of on-grid HPS was given by Mohammad Rozali et al. (2016). The authors introduced the On-Grid Problem Table that can provide the maximum RE electricity targets for the Feed-in Tariff (FiT) purchase agreement. Integration of diesel system was not included in the analysis. The presented On-Grid Problem Table can be potentially utilised to examine the feasibility of incorporating diesel system with RE sources into on-grid HPS if reduction in the diesel fuel cost and carbon emissions is desired for any existing diesel stations.

This study aims to design a system that integrates diesel plant with RE technologies into grid-tied HPS using PoPA. The interactions between the diesel generator, RE sources and the grid in meeting the load demands were considered in the methodology development. The economic trade-offs associated with the interactions between the multiple power sources were assessed in order to achieve the best load sharing considering the peak/off-peak electricity tariffs.

2. Methodology

The main objective to integrate existing diesel plant with RE sources and grid electricity is to minimise diesel fuel consumption and cost of grid electricity by maximising RE sources role in the HPS. Though the on-grid hybrid diesel-RE system does not require storage system, purchasing of electricity from the grid to fulfil the demands at different time of the day could lead to diverse economic performance. The methodology was performed by adapting the On-Grid Problem Table technique from Mohammad Rozali et al. (2016). It consists of two key steps as follows:

2.1 Determine the minimum diesel output and grid electricity

This is done by adapting the On-Grid Problem Table technique from Mohammad Rozali et al. (2016). Tables 1 and 2 tabulate the average renewable power potential from biomass and solar, and the load profile of an industrial site for Illustrative Case Study.

Table 1: Power sources for Illustrative Case Study

Power sources		Time, h		Time interval, h	Power rating, kW	Electricity generation, kWh
AC	DC	From	To			
Biomass		2	24	24	90	2,160
	Solar	8	18	10	70	700

The load demand is currently powered by a 150 kW diesel generator. Every day, the generator steadily operates for 24 h with daily fuel consumption of 967.38 L as computed using Eq(1).

$$F_D = A_D \times P_D + B_D \times P_R \quad (1)$$

Where F_D= fuel consumption of the diesel generator; P_D = output power of the diesel generator; P_R = rated power of the diesel generator (150 kW); A_D and B_D = coefficients of the fuel consumption curve. The typical value for A_D is 0.246 L/kWh and B_D, 0.08145 L/kWh (Wu et al., 2018).

Table 2: Power demands for Illustrative Case Study

Power demand appliances		Time, h		Time	Power rating,	Electricity consumption,
AC	DC	From	To	interval, h	kW	kWh
	Appliance 1	0	24	24	30	720
Appliance 2		0	10	10	50	500
	Appliance 3	0	24	24	20	480
Appliance 4		0	18	10	50	500
Appliance 5		18	20	2	40	80

It is desired to minimise the diesel runtime by supplementing the system with the available onsite renewable biomass and solar, as well as the grid electricity. The load is first fulfilled by the RE sources, before the diesel power and grid electricity are supplied. The amount of the minimum diesel output and grid electricity can be determined from the constructed On-Grid Problem Table as shown in Table 3.

The step-wise construction of the method is as follows (Mohammad Rozali et al., 2016):

1) Column 1 lists the time for power sources and power demands in ascending order, while Column 2 outlines the corresponding duration between two adjacent time intervals.
2) Columns 3 and 4 show the power rating of sources and demands with arrows demonstrating the time interval of when the generation and consumption occur.
3) Columns 5 and 6 provide the sum of power ratings within each time interval. The sum was calculated independently and listed is separate columns for AC and DC power sources and demands.
4) Amount of electricity sources and demands can be determined via Eq(2) as shown in Columns 7 and 8.

$$\sum \textit{Electricity Source/ Demand} = \sum \textit{Power Rating} \times \textit{Time interval duration} \quad (2)$$

5) The quantity of electricity surpluses or deficits after electricity transfer from the sources to the demands for both AC and DC electricity is given in Column 9. Eq(3) was used to obtain the value, which can be either positive (surpluses) or negative (deficits).

$$\textit{Electricity surplus/ deficit} = \sum \textit{Electricity Source} - \sum \textit{Electricity Demand} \quad (3)$$

6) Column 10 lists the amount of converted electricity surpluses. Eq(4) can be used to calculate the converted amount for DC electricity, regardless of the amount of surplus. For AC surplus, the equation is applicable only if the surplus amount is lower than the DC deficit. When the AC surplus is more than the DC requirement, Eq(5) should be used to convert only the exact amount of AC surplus to satisfy the DC deficit. This is to avoid unnecessary power losses to convert the excess amount back to AC electricity, which is the form of electricity used for electricity export to the grid. It was assumed that 5 % of the energy is lost during the conversion, therefore the converter efficiency is 95 %.

$$\textit{Amount of converted surplus(AC/DC)} = \textit{Electricity surplus} \times \textit{converter efficiency} \quad (4)$$

$$\textit{Amount of electricity AC surplus to be converted} = \frac{\textit{Amount of deficit}}{\textit{Converter efficiency}} \quad (5)$$

7) Column 11 shows the excess RE electricity available after load consumption in each time interval, which can be exported to the grid to gain additional income.
8) Despite the fact that there are excess of RE electricity in certain time intervals, the system might have some load demands which are still not fully satisfied by the RE sources on different time intervals of the day because of the absence of storage system. The amount of unmet load is listed in Column 12. The unmet load can be supplied by either the diesel power or the grid electricity, or both. Since diesel power and grid electricity are in AC, conversion loss should be included in the computation of the unmet DC load. The actual requirement for the unmet DC load is shown in bracket. The minimum requirement from diesel system or from the grid is given in the last row of the column, which is the total unmet load by the RE.
9) The allocations of diesel power and grid electricity are given in Columns 13 and 14. Assuming no electricity is outsourced from the grid, the values in Column 12 were used to give the diesel generator output in Column 13, which were obtained via Eq(6).

$$P_D = \frac{\textit{Total unmet load}}{\textit{Time interval}} \qquad (6)$$

Table 3a: On-Grid Problem Table for the Illustrative Case Study

1	2	3		4					5		6		7		8	
Time, h	Time interval duration, h	∑Power rating, kW							∑Power source rating kWh		∑Power demand rating, kWh		∑Electricity source kWh		∑Electricity demand, kWh	
		Source		Demand					AC	DC	AC	DC	AC	DC	AC	DC
		90	70	30	50	20	50	40								
0																
	2								90	0	100	50	180	0	200	100
2																
	6								90	0	100	50	540	0	600	300
8																
	2								90	70	100	50	180	140	200	100
10																
	8								90	70	0	50	720	560	0	400
18																
	2								90	0	40	50	180	0	80	100
20																
	4								90	0	0	50	360	0	0	200
24																

→ AC source → DC source - - - → AC demand - - - → DC demand

Table 3b: On-Grid Problem Table for the Illustrative Case Study (continued)

9		10		11		12		13	14
Electricity surplus/ deficit, kWh		Converted surplus, kWh		RE electricity, kWh		Unmet load, kWh		Diesel output, kW	Grid electricity, kW
AC	DC	AC	DC	AC	DC	AC	DC		
-20	-100	0	0	0	0	20	100 (105.26)	62.63	0
-60	-300	0	0	0	0	60	300 (315.79)	62.63	0
-20	40	0	21.05	0	18.95	20	0	0	0
720	160	0	0	720	160	0	0	0	0
100	-100	95.00	0	0	0	0	100 (105.26)	52.63	0
360	-200	210.53	0	149.47	0	0	0	0	0
						100	526.32		

It can be observed from Column 13 of the On-grid Problem Table that after the supplementation of the RE sources, the diesel generator runtime has been reduced from 24 h to only 10 h. The diesel generator only requires 312.05 L fuel for the hybrid diesel-RE system. Further savings in the diesel fuel can be achieved if the grid electricity is used to supply parts of the unmet load. The various load sharing scenarios between the diesel generator and the grid electricity need to be evaluated.

2.2 Evaluations of load sharing scenarios based on economic trade-offs

Different load sharing scenarios between the diesel generator and the grid electricity may have diverse impacts on the overall HPS cost. The shares of supply from both the diesel system and the grid across all time intervals were varied in Scenarios 1, 2 and 3.

In Scenario 4, instead of supplying the unmet load together, the diesel power and grid electricity were allocated to the unmet load based on the peak and off-peak hours. Since the tariff of electricity is higher during peak hours (between 8 to 22 h), the unmet load occurring within these hours is fulfilled by the diesel generator. The grid electricity is purchased only within the off-peak hours accordingly for the unmet load that takes place outside of the peak periods.

The different economic performances can then be analysed based on the total diesel output and grid electricity of each scenario. The net present cost (NPC) for the scenarios were calculated using Eq(7) (Rezzouk and Mellit, 2015).

$$NPC = TAC/CRF \tag{7}$$

Where TAC = total annualised cost; CRF = capital recovery factor.

The TAC is the sum of costs for each component in the on-grid hybrid diesel-RE system as listed in Table 4.

Table 4: Economic specifications for the on-grid hybrid diesel-RE system (Khan et al., 2015)

Specifications	Biomass generator	PV module	Diesel generator	Grid electricity
Capital cost (MYR/kW)	4,494	12,720	0 (currently installed)	-
OM cost (MYR/kW.y)	18,571	42.4	890	-
Replacement cost (MYR/kW)	3,646	12,720	1,327	-
Fuel cost (MYR/L)	-	-	2.1	-
Peak electricity tariff rate (MYR/kWh)	-	-	-	0.337
Off-peak electricity tariff rate (MYR/kWh)	-	-	-	0.202

Eq(8) was utilised to give the CRF, which is the present value of a series of equal annual cash flows (Rezzouk and Mellit, 2015).

$$CRF = \frac{i(1+i)^N}{(1+i)^{N-1}} \tag{8}$$

Where N = project lifetime; i = annual real interest rate = 6 % (Rezzouk and Mellit, 2015).

The NPC results for project with 25 y lifetime is given in Table 5. The cost of fuel is the product of the annual diesel fuel requirement with the fuel cost per litre. To calculate the grid electricity cost, the peak and off-peak tariffs were multiplied with the amount of grid electricity as targeted in Column 14 of the constructed On-Grid Problem Table for each scenario. The grid electricity purchased between 8 to 22 h was multiplied with peak tariff rate (0.337 MYR/kWh), while the amount that is outsourced outside of the peak hours were multiplied with the lower off-peak tariff (0.202 MYR/kWh). The total of both represents the annual grid electricity cost as listed in Table 5.

Table 5: Results of all load sharing scenarios

Load sharing scenarios	Fuel cost (MYR/y)	Grid electricity cost, (MYR/y)	NPC (MYR)
1 (40 % diesel, 60 % grid)	170,593	29,934	33,110,467
2 (50 % diesel, 50 % grid)	182,026	24,945	33,211,781
3 (60 % diesel, 40 % grid)	193,459	19,956	33,313,095
4 (peak/off-peak hours based)	144,711	36,943	32,813,708

As observed from Table 5, Scenario 4 offers the lowest NPC as compared to the other load sharing scenarios. The three other scenarios with varying percentages of diesel power and grid electricity across all time intervals have higher NPC, with an increasing trend in the NPC as the portion of diesel power increases. This is because the tariff of electricity is significantly lower than the diesel fuel cost.

If Scenario 4 is to be implemented by this on-grid hybrid system, the operation of the diesel generator is limited to supply the unmet load only during the peak periods. This leads to approximately 80 % savings in the diesel fuel from to the total fuel requirement in the stand-alone diesel system without the support of RE sources and the grid.

3. Conclusions

The feasibility of combining diesel plant with RE sources in a grid-tied hybrid diesel-RE system has been presented. An algebraic PoPA tool called the On-grid Problem Table was used to establish the allocations of diesel output and the grid electricity for various load sharing scenarios. Illustrative Case Study's results demonstrate that the advantage of peak and of-peak electricity tariff should be taken into account in allocating the diesel power and grid electricity to the load, as it gives the lowest NPC of MYR 32,813,708. This on-grid HPS operation also contributes to diesel fuel saving of 80 % which can significantly reduce the environmental emissions. Different RE sources and load profiles, as well as diesel fuel cost and electricity tariff may yield different results. Nevertheless, the feasibility of incorporating diesel system with RE sources without the needs of installing storage system can be efficiently obtained using the proposed methodology framework, especially if the load in the system is located near to the utility grid.

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