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Expansion of a Diesel Plant into a Hybrid Power System Using Power Pinch Analysis

Nor Erniza Mohammad Rozali[*a], Sharifah Rafidah Wan Alwi[b,c],
Wai Shin Ho[b,d], Zainuddin Abdul Manan[b,c], Jiří Jaromír Klemeš[e]

[a]Department of Chemical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia.
[b]Process Systems Engineering Centre (PROSPECT), Research Institute on Sustainable Environment (RISE), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[c]Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[d]Faculty of Petroleum & Renewable Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[e]Centre for Process Integration and Intensification – CPI^2, Faculty of Information Technology, University of Pannonia, Egyetem u. 10, H-8200 Veszprém, Hungary
erniza.rozali@petronas.com.my

Diesel power system is one of the popular schemes for energy supply generation. It is, however, typically associated with high costs of emission control and maintenance on top of the diesel fuel cost. These limitations can be overcome by incorporating renewable energy technologies such as wind turbines and solar PV along with the existing diesel station. Hybrid systems provide cleaner and reliable power supply, and can be more cost-effective than sole diesel systems. This paper assesses the feasibility of expanding an existing diesel power plant into a hybrid power system (HPS) using Power Pinch Analysis (PoPA). An HPS configuration developed with PoPA methodology can provide optimal solar and wind electricity supplies while minimising the diesel runtime. Results show that an HPS that combines solar and wind system with diesel power generation can provide significant diesel fuel savings while satisfying the demands at a reasonable cost.

1. Introduction

Diesel power systems have been a popular means of electrification of remote villages, some commercial facilities and industrial sites. Though the capital cost of this technology is relatively inexpensive, it has to be maintained regularly. In addition, transportation of diesel fuel to remote locations can be costly. Diesel plant can also contribute to the emissions of greenhouse gases and other pollutants. These limitations can be overcome via the expansion of the existing diesel station into a hybrid power system (HPS) that includes renewable energy (RE) technologies such as wind turbines and solar PV (Drouilhet, 2001). An HPS provides cleaner and reliable power supply, and can be more cost-effective than sole diesel systems.

Extensive studies on supplementing diesel generation by RE sources have been conducted. Ajan et al. (2003) studied the technical and financial aspects of incorporating a PV system into an existing diesel plant. The load-sharing mechanism was simulated using MATLAB to yield a hybrid PV-diesel system with the lowest life cycle cost. The techno-economic feasibility of a diesel system supplemented by solar PV and wind energy has been studied by Shaahid et al. (2010). The optimal RE mix i.e. wind, solar and diesel capacity was explored using the HOMER software. Results show that the solar and wind inclusion into the existing diesel plant decreased diesel fuel consumption, reduced carbon emission and decreased operation time of diesel generators. HOMER has also been utilised by Khan et al. (2015) to propose the optimal combination of PV, wind and micro-hydro systems with the existing diesel generator in Tioman island, Malaysia. The proposed hybrid configuration showed promising results in reducing diesel fuel dependency and in achieving a relatively high RE utilisation. Yap and Karri (2015) recently incorporated both dynamic and artificial neural network modelling techniques to integrate PV-to-diesel system

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applications. The proposed model enables various PV and diesel generator types to be integrated, to aid the planning of future solar-diesel system deployments.

Expansion of a diesel plant with RE systems has been mostly implemented using software tools and mathematical modelling approaches. Application of insight-based method for this purpose has so far received less attention. This work aims to study the feasibility of an HPS expansion into existing diesel power plants using an insight-based technique known as the Power Pinch Analysis (PoPA). PoPA was developed by Wan Alwi et al. (2012) to establish electricity targets for an optimal HPS design. It has been extended for various applications, including power and storage allocations (Mohammad Rozali et al., 2013b), load shifting (Wan Alwi et al., 2013), storage optimisation (Mohammad Rozali et al., 2013a) and HPS sizing (Mohammad Rozali et al., 2014). This paper presents a methodology for the HPS design using PoPA that optimises the solar and wind electricity supplies while minimising the diesel runtime. Insights on the real time electricity flows provided by the PoPA allows designers to plan and control the operation time of the diesel generators, thereby resulting in additional savings in diesel fuel as well as maintenance costs.

2. Methodology

The feasibility of incorporating solar PV and wind energy systems into an existing diesel plant is examined by implementing the PoPA tool known as the Storage Cascade Table (SCT) ─ Mohammad Rozali et al. (2012). The SCT approach has been revised to adapt the load sharing mechanism of the generation sources, with the objective to minimise the operational time of the diesel generator while optimising the utilisation of the REs. In order to reduce the dependency on diesel, both the solar and wind energy were assigned as the main sources of RE to serve the loads and charge the battery storage. The diesel generator only runs when the RE generated and stored are insufficient.

2.1 Determine the power output and operational hours of diesel generator

Tables 1 and 2 show the average daily RE generation from solar and wind as well as the average daily load profile for an industrial site. An existing 200 kW diesel generator is used to meet the site energy demand. Prior to the integration of PV and wind energy with the existing diesel plant, the generation profile of the diesel generator is equivalent to the average load profile. The diesel fuel consumption is obtained using Eq(1). The generator runs for 24 h every day and consumes 1,065.78 L of diesel fuel daily.

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

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 (200 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 (Mohammed et al., 2015).

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			
Wind		2	10	8	70	560
	Solar	8	18	10	80	800

Table 2: Power demands for Illustrative Case Study

Power demand appliances		Time, h		Time interval, h	Power rating, kW	Electricity consumption, kWh
AC	DC	From	To			
	Appliance 1	0	24	24	30	720
Appliance 2		8	18	10	50	500
	Appliance 3	0	24	24	20	480
Appliance 4		8	18	10	50	500
Appliance 5		8	20	12	40	480

Tables 3a and 3b demonstrates the use of the SCT to allocate the electricity and the operational times for the diesel power generator after the supplementation of PV and wind systems. PV system provides DC electricity while wind turbine generates AC electricity. When the electricity load exceeded the generated RE quantity, the diesel generator would supply AC electricity to the system. The step-wise construction of Table 3a is described in (Mohammad Rozali et al., 2013b):

1) Column 1 lists the time for power sources and demands in ascending order, while the duration between two adjacent time intervals is listed in Column 2.
2) The sums of ratings for the power sources and power demands for each time-interval are given in Columns 3 and 4.
3) Columns 5 and 6 list the quantities of electricity sources and demands between time intervals which is calculated with Eq(2).

∑ Electricity Source/ Demand = ∑ Power Rating × Time interval duration (2)

4) The surpluses and deficits for each AC and DC electricity between time intervals are calculated by using Eq(3), and listed in Column 7. A positive value indicates electricity surplus while negative value represents electricity deficit.

Electricity surplus/ deficit = ∑ Electricity Source - ∑ Electricity Demand (3)

Table 3a: Storage Cascade Table for diesel plant expansion

1	2	3		4		5		6		7	
Time, h	Time interval duration, h	∑Power source rating, kW		∑Power demand rating, kW		∑Electricity source kWh		∑Electricity demand, kWh		Electricity surplus/deficit, kWh	
		AC	DC	AC	DC	AC	DC	AC	DC	AC	DC
0											
	2	0	0	0	50	0	0	0	100	0	-100
2											
	6	70	0	0	50	420	0	0	300	420	-300
8											
	2	70	80	140	50	140	160	280	100	-140	60
10											
	8	0	80	140	50	0	640	1,120	400	-1,120	240
18											
	2	0	0	40	50	0	0	80	100	-80	-100
20											
	4	0	0	0	50	0	0	0	200	0	-200
24											

Table 3b: Storage Cascade Table for diesel plant expansion (continued)

8		9	10	11	12		13
Converted surplus, kWh		Charging/ Discharging quantity (AC), kWh	Discharge for DC deficit, kWh	Storage capacity, kWh	Unmet load, kWh		Diesel rating, kW
AC	DC				AC	DC	
				0			
0	0	0	0	0	0	100 (105.26)	52.63
399	0	99	0	89.10	0	0 (0)	0
0	57	0	-76.18	0	6.82	0 (0)	3.411
0	228	0	0	0	892	0 (0)	111.50
0	0	0	0	0	80	100 (105.26)	92.63
0	0	0	0	0	0	200 (210.53)	52.63

Table 3b is constructed as follows;

1) Eq(4) is used to calculate the amount of converted electricity surplus and listed in Column 8. The AC (or DC) surplus is only converted if there is deficit in the DC (or AC) demand. Eq(3) is only applicable if the amount of surplus is less than the deficit quantity. However, if the surplus is higher, only the exact amount of the required electricity for the load is converted from the available surplus. In such a case, Eq(5) is used to calculate the amount of surplus to be converted. Converter is assumed to be 95% efficient.

$$\text{Amount of converted surplus} = \text{Electricity surplus} \times \text{converter efficiency} \tag{4}$$

$$\text{Amount of electricity surplus to be converted} = \frac{\text{Amount of deficit}}{\text{Converter efficiency}} \tag{5}$$

2) The amount of DC electricity available for storage after load utilisation is obtained using Eq(6) and listed in Column 9. The positive value indicates the charging quantity while the negative value represents the discharging quantity.

$$\text{Charging/Discharging quantity (DC)} = AC_{converted} + DC_{s/d} - DC_{converted} \tag{6}$$

Where
$AC_{converted}$ = amount of DC converted from AC surplus; $DC_{s/d}$ = DC surplus/deficit; $DC_{converted}$ = amount of DC surplus converted to AC to satisfy the AC load demand.

3) Step 2 only provides the discharging amount for DC deficit. The discharged quantity for AC deficit is determined using Eq(7) and listed in Column 10.

$$\text{Discharging quantity for DC deficit} = \frac{\text{Converted DC surplus + AC deficit}}{\text{Rectifier efficiency}} \tag{7}$$

If the storage capacity is less than the DC discharge requirement to meet the AC deficit, the battery is discharged to its depth of discharge (DoD). The DoD of the battery is typically about 80 % of its maximum capacity (Notton et al., 2011). In this scenario, Eq(8) is required to calculate the amount of the available DC electricity from storage to supply the deficit in AC demand.

$$\text{DC electricity available from storage [kWh]} = S_{t-1} \times \eta_I \times \eta_d \tag{8}$$

Where
S_{t-1} = storage capacity at previous time interval [kWh]; t = time [h]; η_I = inverter efficiency (0.95); η_d = discharging efficiency (0.9).

4) The cumulative storage capacity is listed in Column 11. Eq(9) is used in the calculation which is based on the charging and discharging amount in Columns 9 and 10.

$$S_t = S_{t-1}\,(1 - \sigma \times T) + (C_t \times \eta_c) + D_t / \eta_d \tag{9}$$

Where
S_t= storage capacity [kWh]; C_t = charging quantity [kWh]; D_t = discharging quantity [kWh]; σ = hourly self-discharge rate; t = time [h]; η_c = charging efficiency; η_d = discharging efficiency.
The electricity cascade for the following time interval resumes at zero if the battery has been discharged to its DoD.

5) The largest value in Column 9 is divided by the DoD to obtain the actual maximum battery storage capacity via Eq(10).

$$S_{(t)actual} = S_{(t)} / DoD \tag{10}$$

6) Column 12 provides the amount of electricity that needs to be compensated by the diesel generator because of the shortage in solar PV and wind power. The operational time of the diesel generator can be identified based on the allocations of the unsatisfied load. The diesel generator supplies AC electricity that has to be converted by the rectifier to DC electricity, suffering losses during the conversion. Eq(11) calculates the actual electricity amount that should be generated by the diesel generator to serve the shortage in DC demands (figures in bracket).

$$\text{Actual generation for unmet DC load} = \frac{\text{Unmet DC load}}{\text{Rectifier efficiency}} \tag{11}$$

7) Based on the total sum of the unmet AC and DC load, the output power of the diesel generator, P_D at each time interval is determined using Eq(12), as presented in Column 13.

$$P_D = \frac{\text{Total unmet load}}{\text{Time interval}} \tag{12}$$

The daily operational hours of the existing 200 kW diesel generator has decreased after supplementing it with PV and wind systems. Compared to the 24 h present operation, the diesel generator has to operate for 18 h only after the expansion. The lower operational duration reduced the daily consumption of the diesel fuel to 735.55 L. This corresponds to 31 % annual diesel savings as compared to the diesel-only situation.

2.2 Economic analysis

The economic assessment was performed using the net present cost (NPC) analysis. The NPC is represented as Eq(13), and includes the cost of installing and operating the system throughout its lifetime (Ngan and Tan, 2012):

$$NPC = TAC/\ CRF \tag{13}$$

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

The TAC is the sum of the annualised costs of each component of the power system including the capital investment, operation and maintenance (OM) and fuel cost. The technical and economic specifications for the components are given in Table 4.

Table 4: Economic specifications for the HPS components (Khan et al., 2015)

Specifications	PV module	Wind turbine	Diesel generator	Battery
Capital cost ($/kW)	3,000	1,400	0 (currently installed)	250
OM cost ($/kW.y)	10	28	210	10
Fuel consumption (L/y)	-	-	0.63	-
Fuel cost ($/L)	-	-	268,395	-

The CRF is a ratio used to calculate the present value of a series of equal annual cash flows. It is calculated according to Eq(14).

$$CRF = \frac{i\,(1+i)^N}{(1=i)^N - 1} \tag{14}$$

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

For a project lifetime of 25 years, the results of the NPC analysis show that the diesel-only system is cheaper than the PV-wind-diesel system (TAC = 580,808 $/y). After supplementing the diesel system with PV and wind technologies, the NPC has increased from $3,669,787 to $7,424,673. Although the post-expansion NPC is higher, it is accompanied by a significant annual diesel cost savings of 75,986 $/y. This shows that the HPS is more cost-effective with the increase in the diesel price. At a diesel price above $2.5/L, the diesel-only system would cost higher than the HPS. In addition, the HPS helps to significantly reduce the emissions of gaseous pollutants. .

3. Conclusions

Power Pinch Analysis has been successfully applied to determine the optimal power output and operational hours for a diesel generator supplemented with PV and wind systems. Due to the proposed load-sharing pattern between the diesel and RE sources, the total runtime of the diesel generator has been reduced. This has led to diesel fuel savings as well as reduction in environmental emissions. Despite the high NPC, the proposed HPS expansion can be economical for many stand-alone diesel systems for a projected increase in diesel price in the long run. The expected decrease in the investment costs of PV and wind energy technologies due to continuous R&D is also expected to lower the plant expansion cost. Apart from the presented hybrid PV-wind-diesel system, the cost-effectiveness of other hybrid configurations such as the PV-diesel and wind-diesel can also be investigated.

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