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Integration of Diesel Plant into Hybrid Power System Using Numerical Probabilistic Approach

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Integrating existing diesel station with renewable energy (RE) technologies into a hybrid system has been an attractive solution towards mitigating greenhouse gases emissions problem of diesel power system. Apart from offering cleaner power supply, hybrid systems could also contribute towards reduction of diesel fuel cost. Application of insight-based Power Pinch Analysis (PoPA) method to integrate diesel plants and RE systems with the aim to minimise total generation and runtime of diesel generator has been proposed. This work utilises an extended PoPA tool called the Probability-Power Pinch Analysis (P-PoPA) to achieve the supplementation of RE technologies with existing diesel system. P-PoPA can provide accurate results as those established from the PoPA approach within a shorter time of analysis as it eliminates the manual matching of power sources and demands step. Correction factors based on all possible routes from the RE sources and the diesel generator to the demands are computed to determine the minimum diesel power target for the integrated system. Result of an illustrative case study shows that 31 % saving in the diesel fuel requirement can be achieved after the integration of the existing diesel plant with RE systems. The result of the P-PoPA method is accurate with an only 0.61 % difference to the result targeted using the conventional PoPA technique.

1. Introduction

Hybrid power system that combines diesel power and renewable energy (RE) resources has become popular due to its advantages over the sole diesel or RE system. Despite being widely applied for electrifying remote applications, stand-alone diesel system can contribute in atmospheric degradation. It also requires regular maintenance and the supply of diesel fuel to remote locations can be expensive. RE sources such as solar and wind on the other hand are non-polluting energy supply and may be installed near to the load demands, thereby eliminates the need for the cost of fuel transportation. The intermittent nature of these sources however may be a drawback towards the implementation. Integration of diesel power and RE technologies into hybrid system is therefore recommended to overcome the aforementioned shortcomings.

A number of hybrid diesel-RE system installations exist around the world, with most projects involve the supplementation of existing diesel plants with solar PV and wind turbines to reduce the fuel and running costs of diesel generator. Ogunjuyigbe et al. (2016) adopted renewable solar and wind energies as the primary power supply for a typical residential building, while diesel system operates based on the load requirements that could not be met by the primary sources. Simultaneous minimisation of the Life Cycle Cost, pollutant emission and dump energy were achieved using genetic algorithm method. The hybrid PV-wind-diesel system demonstrated the highest reduction in all the three design objectives as compared to the single diesel generator system. Hossain et al. (2017) proposed to incorporate solar PV and wind system along the existing diesel generators in a large resort centre in Malaysia to reduce the complete dependency of the system on the diesel power. Economic and technical analyses of the proposed hybrid system were done using HOMER software. Apart from

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achieving significant reduction in CO_2 and other greenhouse gases emissions, the proposed hybrid system also offers lower net present cost and cost of energy compared to the diesel-only system. Ferrari et al. (2018) optimised the energy mix of a hybrid PV-wind-diesel system based on the long-term energy production cost with respect to the conventional stand-alone diesel system configuration. The authors performed the system modelling and optimisation in MATLAB, in which the results show that notable cost and pollution savings for the studied consumer were successfully achieved.

Wu et al. (2018) utilised meta heuristic technique based on tabu search to size PV-diesel-battery hybrid energy system for reverse osmosis desalination process. The area of the PV panels, fuel consumption of the diesel generator, as well as the capacity of the battery were optimised in order to obtain the minimum life cycle cost of the system. The authors concluded that driving the high-pressure pumps in reverse osmosis plants by PV plant with diesel generator as the backup power supply can be more economically and environmentally advantageous over a single PV or diesel system. Forough and Roshandel (2018) addressed the demand fluctuations in a hybrid renewable energy system by optimising the backup diesel generator using mixed integer convex programming method. An increase of 13% in the RE share was achieved, which consequently reduces the diesel fuel consumption of the studied hybrid system from 31% to 19%.

Application of insight-based method to integrate diesel plants and RE systems into a hybrid system has been presented by Mohammad Rozali et al. (2015). Power Pinch Analysis (PoPA) technique called the Modified Storage Cascade Table (SCT) was applied to establish the optimal allocations for RE generation while minimising the total power output and the runtime of diesel generator. Energy losses during power conversion, transfer and storage were incorporated into the Modified SCT construction. While the proposed method is useful for insight-based decision making, it may not be effective to solve complex systems with many input and output variables if it is desired to consider the energy losses occurring in the systems during the method construction. This is because the matching between supply and demand for each time interval would need to be done manually, and errors might occur during the analysis. To address this limitation, Liu et al. (2016) utilised probability theory to simplify the PoPA technique. Probability-Power Pinch Analysis (P-PoPA) method was proposed in which correction factors based on all possible power routes from different power sources to different power demands in the system were determined to modify the results of earlier PoPA technique that assumes ideal operation with 100 % system efficiency. Results from the study demonstrates that the new P-PoPA method can provide accurate results as those established from the PoPA technique, within a shorter time of analysis. The presented P-PoPA method however is limited only for the targeting and design of hybrid power systems.

Utilisation of P-PoPA to integrate diesel plants and RE technologies into hybrid system has yet to be presented. Due to the integration of diesel system, additional power routes involving diesel generator need to be taken into account in the computation of correction factors. In this work, the supplementation of diesel systems with RE sources for hybrid system operation is carried out by using P-PoPA. Optimal load sharing between the diesel generator and RE sources are established based on correction factors, with the aim to maximise diesel fuel savings and environmental emission reduction.

2. Methodology

The integration of diesel system with RE technologies is carried out to minimise the operational time of the diesel generator by prioritising the RE power to serve the load demands. The diesel generator on the other hand is operated only when the RE generation is insufficient to satisfy the load. The system studied consists of an existing 200 kW diesel plant that supply AC electricity to industrial demands (Mohammad Rozali et al., 2015). The daily load profile for the system is tabulated in Table 1.

Table 1: Power demands for Illustrative Case Study

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

To cover the load demands, the diesel generator needs to operate for 24 h every day. The daily diesel fuel requirement is 1,065.78 L as calculated using Eq(1).

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

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).

The RE sources available on the site are solar and wind energy, and the potential generation from the RE is as shown in Table 2. Solar PV system generates DC electricity while wind power system supplies AC electricity. A battery storage is available in the hybrid system to store electricity in DC form when the RE generation is higher than the load requirement.

Table 2: Power sources for Illustrative Case Study

Power type	Power type	Time, h		Time interval, h	Power rating, kW	Electricity generation, kWh
		From	To			
Wind	AC	2	10	8	70	560
Solar	DC	8	18	10	80	800

The methodology to integrate diesel plant with RE technologies into a hybrid system using the P-PoPA tool is adapted from Liu et al. (2016) and Mohammad Rozali et al. (2013). It consists of three key steps as follows:

2.1 Construct Storage Cascade Table to determine the ideal power output and operational hours of diesel generator

The allocations of ideal diesel power output without considering any energy losses occurring in the system were established using an algebraic PoPA method called the Storage Cascade Table (SCT). The original SCT was amended to take into account the load sharing interactions between the RE generators, diesel system and battery storage. Based on the RE sources and load demands data in Tables 1 and 2, the SCT was constructed following the procedures as described in Mohammad Rozali et al. (2013) and is shown in Table 3.

1) Columns 1 and 2 listed the time for the power sources and demands, and the respective duration between two adjacent time intervals.
2) Columns 3 and 4 show the total power sources generation and demands consumption in each time interval.
3) The amount of electricity sources and demands in Columns 5 and 6 was computed for every time interval using Eq(2).

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

4) The lower figure between the values in Column 5 and Column 6 at each time interval indicates the amount of electricity that can be directly transferred from sources to demands, and is listed in Column 7. Summing up all the values in Column 7 gives the total electricity transfer, T_{ideal} of 1240 kWh.
5) Column 8 provides the amount of electricity surplus (+) and deficit (–) which was obtained via Eq(3). The sum of all positive values in Column 8 denotes the amount of energy that can be charged to the battery storage, C_{ideal} which is 120 kWh in this case.

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

6) To determine the amount of energy that can be stored in the battery at each time interval, the values in Column 8 were cumulatively cascaded down the time interval. It was assumed that, initially, there is no energy content in the battery storage. Thus, the cascading starts with zero at t = 0 h. Positive values in the electricity cascade indicates the stored capacity and were listed in Column 9. On the other hand, negative values from the electricity cascade represent the amount of unmet load that cannot be satisfied by the RE sources, and need to be supplied by the diesel power system. Column 10 listed the allocations of the unmet load, which also signify the diesel power requirement with the respective operational time for the diesel generators.
7) Column 11 gives the output power of the diesel generator, P_D which was calculated using Eq(4).

$$P_D = \frac{\textit{Total unmet load}}{\textit{Time interval}} \qquad (4)$$

It can be observed from Column 10 of the SCT that a total of 1320 kWh power (100+840+180+200 = 1,320 kWh) need to be supplied by the diesel plant (D_{ideal}). Supplementing the existing diesel system with solar PV and wind system has reduced the duration of the diesel generator daily operation from 24 h to only 16 h. The generation from the REs can cover all the demands between time 2 and 10 h, and thereby the diesel generator does not have to run within this time interval.

Table 3: Storage Cascade Table for hybrid diesel-RE system

1	2	3	4	5	6	7	8	9	10	11
Time, h	Time interval duration, h	∑Power source rating, kW	∑Power demand rating, kW	∑Electricity source kWh	∑Electricity demand, kWh	Amount of electricity transfer, kWh	Electricity surplus/ deficit, kWh	Battery capacity, kWh	Unmet load, kWh	Diesel rating, kW
								0		
0										
	2	0	50	0	100	0	-100	0	100	50
2										
	6	70	50	420	300	300	120	120	0	0
8										
	2	150	190	300	380	300	-80	40	0	0
10										
	8	80	190	640	1,520	640	-880	0	840	105
18										
	2	0	90	0	180	0	-180	0	180	90
20										
	4	0	50	0	200	0	-200	0	200	50
24										

2.2 Determine correction factors

The results in the previous step was established without taking into account the energy losses occur in the system, and thereby might be inaccurate. In order to incorporate the losses associated with power conversion and transfer, the results from the SCT should be multiplied with correction factors. The correction factors need to be computed accordingly based on the possible routes for power flow from one starting point (e.g. AC source, S_{AC}) to one destination point (e.g. AC demand, D_{AC}). Figure 1 illustrates the possible routes in a hybrid system involving AC/DC power sources and demands, AC diesel power and DC battery storage.

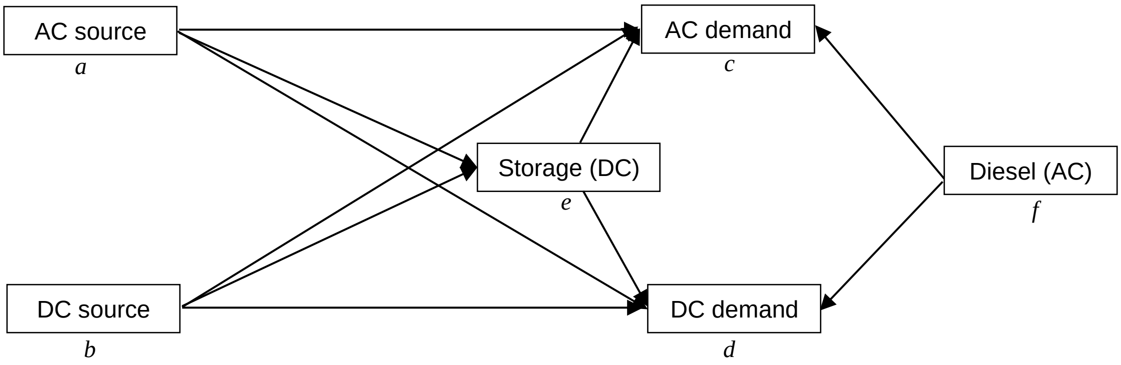

Figure 1: Possible routes of power flow in hybrid system

There are ten possible routes for the flows of electricity from RE sources, storage and diesel generator to satisfy the demands. The fraction values of each component in the system are denoted with a, b, c, d, e and f in the figure. Before the correction factors can be calculated, these fraction values need to be determined. For example, the fraction of AC source, a was obtained by dividing the electricity generation from wind generator (see Table 2) with the total generation from both wind and solar PV systems (560 kWh/ (560+800) kWh = 0.4118). To obtain the fraction for AC demand, c, the load consumption by AC appliances was divided by the total consumption in the system (1,480 kWh/ (1,480 + 1,200) kWh = 0.5522). Since there is only one type of storage system (DC), the fraction of the battery storage, e is 1. The same fraction for diesel system, f applies since only AC power is supplied by the diesel generator. Note that if other backup generators supplying DC power are installed in the system, the value of f will not be equal to 1. The fraction for diesel system would have to be computed accordingly. The fraction values for the other sources and demands are tabulated in Table 4.

Table 4: Fraction values for components in the hybrid system

Components	Power type	Fraction values
Source	AC	$a = S_{AC}/(S_{AC} + S_{DC}) = 0.4118$
	DC	$b = S_{DC}/(S_{AC} + S_{DC}) = 0.5882$
Demand	AC	$c = D_{AC}/(D_{AC} + D_{DC}) = 0.5522$
	DC	$d = D_{DC}/(D_{AC} + D_{DC}) = 0.4478$
Energy storage	DC	$e = 1$
Diesel system	AC	$f = 1$

Based on the fraction values, the probability of any power sources to be matched with any power demands can be determined. As for example, the probability of AC source (S_{AC}) to supply power to AC demand (D_{AC}) is the product of the fraction values of the two, i.e. $a \times c$. If the power flow involves different types of electricity (e.g. from AC source, S_{AC} to DC demand, D_{DC}), power conversion is required. Therefore, the product of the fraction values need to be multiplied by the converter efficiency, i which was assumed as 95 %. For routes involving storage system (e.g. from S_{AC} to battery storage, B_{DC} or from B_{DC} to D_{AC}), efficiency of battery charging or discharging should also be included in the correction factor calculation. The charging/discharging efficiency of the battery, η was assumed to be 90 %. When the generation from the RE sources is insufficient, diesel generator will supply the deficit amount to the loads. No losses occur if the power route is from the diesel generator (P_{AC}) to the AC demand, but supply of power from the diesel generator to DC demand will involve conversion loss. The correction factor is therefore equal to $f \times d \times i$. Table 5 summarises the correction factors for the routes in the hybrid system. F_{sd}, F_{sb}, F_{bd} and F_{pd} are the total correction factors for power routes from source to demand, from source to energy storage, from storage to demand, and from diesel generator to demand.

Table 5: Correction factors

Routes	Correction factors	Total correction factors
$S_{AC} \rightarrow D_{AC}$	$f1 = a \times c = 0.2274$	$F_{sd} = f1 + f2 + f3 + f4 = 0.9746$
$S_{DC} \rightarrow D_{DC}$	$f2 = b \times d = 0.2634$	
$S_{AC} \rightarrow D_{DC}$	$f3 = a \times d \times i = 0.1752$	
$S_{DC} \rightarrow D_{AC}$	$f4 = b \times c \times i = 0.3086$	
$S_{AC} \rightarrow B_{DC}$	$f5 = a \times e \times i \times \eta = 0.3521$	$F_{sb} = f5 + f6 = 0.8815$
$S_{DC} \rightarrow B_{DC}$	$f6 = b \times e \times \eta = 0.5294$	
$B_{DC} \rightarrow D_{AC}$	$f7 = e \times c \times i \times \eta = 0.4721$	$F_{bd} = f7 + f8 = 0.8751$
$B_{DC} \rightarrow D_{DC}$	$f8 = e \times d \times \eta = 0.4030$	
$P_{AC} \rightarrow D_{AC}$	$f9 = f \times c = 0.5522$	$F_{pd} = f9 + f10 = 0.9776$
$P_{AC} \rightarrow D_{DC}$	$f10 = f \times d \times i = 0.4254$	

2.3 Determine the actual diesel power output

The actual power that need to be supplied by the diesel plant, D_{actual} to cover the unmet load by the RE systems is expected to be larger than the D_{ideal} obtained from the SCT (1,320 kWh). This is because parts of the power are lost due to the inefficiencies during power conversion and transfer, which were assumed to be negligible in SCT construction. Based on the ideal values and correction factors determined earlier, the D_{actual} was calculated using Eq(5).

$$D_{actual} = D_{ideal} + T_{ideal}\,(1 - F_{sd}) + C_{ideal}\,(1 - F_{sb}F_{bd}) + D_{ideal}\,(1 - F_{pd}) \tag{5}$$

Besides D_{ideal}, the total diesel power required should cover the energy losses occurred during the transfer of power from sources to demands. The energy losses were calculated by multiplying the total electricity transfer, T_{ideal} with the probability of electricity not transferred from the sources to demands, '$1 - F_{sd}$'. Probability of energy losses during battery charging and discharging was also considered in computing the D_{actual}. It was assumed that the electricity charged to the battery will eventually be discharged from the battery at a later time. Therefore, the charging quantity, C_{ideal} was multiplied with '$1 - F_{sb}F_{bd}$' to consider the charging and discharging losses. Finally, the losses that occur when the power is supplied from the diesel generator to the demands were included in the calculation by multiplying the D_{ideal} with '$1 - F_{pd}$'. The actual diesel power, D_{actual} after the incorporation of all the energy losses was calculated to be 1,408.50 kWh.

Based on the actual diesel power output, the diesel fuel consumption by the generator can be calculated with Eq(1). As mentioned earlier, the daily runtime of the diesel generator for the integrated RE-diesel system is 16h.

Due to the shorter working hours, the diesel fuel consumption by the generator has decreased to 737.45 L. This translates to a 31 % lower diesel supply annually compared to the fuel supply requirement in the diesel-only system.

To validate the applicability of the presented P-PoPA method, the result was compared with the diesel power output obtained from the algebraic PoPA method, i.e. Modified SCT technique (Mohammad Rozali et al., 2015), which involves manual source and demand matching instead of using correction factors. The Modified SCT method targeted that a total of 1399.88 kWh need to be supplied by the diesel plant. This proves that the estimation using P-PoPA is acceptable with a very small error of 0.61 % as compared to the Modified SCT's result. This error might be due to the overall losses probability consideration in the P-PoPA method. This is not the case in the Modified SCT technique because all losses of energy are calculated while matching the source to the demand within each time interval.

3. Conclusions

Integration of an existing diesel plant with RE sources into a hybrid system using probabilistic theory method called the P-PoPA has been presented. The proposed hybrid system has successfully reduced the daily runtime of the diesel generator by 8 h. Due to the shorter operational hours, the annual diesel requirement has been significantly reduced by 31 % as compared to requirement in the conventional stand-alone diesel system. This may consequently contribute to the reduction in environmental emissions. The utilisation of P-PoPA for the integration has also been proven to be very handy as it eliminates the need to match the supply and demand in the system manually, hence may avoid error occurrences in the analysis. P-PoPA can be an alternative approach for engineers and energy planners to estimate the feasibility of integrating diesel plant with RE technologies before a more in-depth design procedure is carried out. Further studies should consider cases when the fraction of diesel system is not equal to 1, in which other backup power supply is available in the system to further reduce the diesel fuel consumption and cost.

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