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Research Paper

Integration of diesel plant into a hybrid power system using power pinch analysis

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HIGHLIGHTS

- Integration of diesel system with renewable energy technologies.
- Optimising renewable electricity supplies while minimising diesel generation.
- Reduction in diesel fuel consumption to achieve cost savings.

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ABSTRACT

Diesel power systems are one of the schemes for energy supply generation. However, they are mostly associated with difficulties of emission control and cost of the maintenance on top of the diesel fuel cost. Some of these problems can be reduced by incorporating renewable energy such as wind turbines and solar PV along with the existing diesel station. Hybrid systems provide clean 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). A HPS configuration developed using PoPA methodology can provide close-to-optimal solar and wind electricity supplies while minimising the diesel generation. Results show that a 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 commonly used for electrification of remote villages, commercial facilities and industrial sites. Distributed power generation system with diesel-engine-generator has been proven to be handy and reliable in meeting the dynamic household electricity demand as reported by Wang et al. [1]. Though the capital cost of this diesel power technology is relatively inexpensive, it has to be maintained regularly. In addition, transportation of diesel fuel to remote locations can be costly. Diesel plants 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 [2]. Photovoltaic or PV system has been a growing solar energy technology that can directly convert the sun radiation into electricity. Combination of wind and solar PV with diesel power in a HPS provides cleaner and reliable power supply, and can be more cost-effective than sole diesel systems.

Extensive studies on supplementing diesel generation with RE sources have been conducted elsewhere. The techno-economic feasibility of a diesel system supplemented by solar PV and wind energy has been studied by Shaahid et al. [3]. The optimal RE mix i.e. wind, solar and diesel capacity was explored using HOMER software. Results show that the inclusion of solar and wind into the existing diesel plant decreased diesel fuel consumption, reduced

Abbreviations: CRF, capital recovery factor; HPS, hybrid power systems; NPC, net present cost; PoPA, Power Pinch Analysis; RE, renewable energy; SCT, Storage Cascade Table; TAC, total annualised cost.

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GHG emission and decreased operation time of diesel generators. Another notable study that compares the performance of hybrid system with pure diesel system was done by Maleki and Askarzadeh [4]. These authors employed a discrete version of harmony search to analyse different generation systems including PV–wind–diesel, wind–diesel, PV–diesel and diesel alone in terms of the total annual cost and environmental emissions.

Shin et al. [5] combined diesel and renewable energy generators to electrify isolated islands, using a linear-programming based optimisation algorithm. Optimal HPS capacities and operation planning established from the optimisation recommend a hybrid generation system rather than a conventional stand-alone diesel system due to high fuel cost. Yap and Karri [6] incorporated both dynamic and artificial neural network modelling techniques to integrate PV-to-diesel system applications. The proposed model enables various PV and diesel generator types to be integrated, to aid the planning of future-diesel system deployments. A bi-objective design model for the integrated traditional diesel generators with PV plant and battery storage was recently presented by Bortolini et al. [7]. The authors developed the analytical technical, economic and environmental models for the hybrid system, in order to obtain the optimal system capacity with matching financial and environmental targets. There has been a trade-off between the two assessed objectives, but relevant savings in fuel cost and reduction of emissions still had been able to be achieved.

Expansion of diesel plants with RE systems has been mostly implemented using mathematical modelling tools. Application of insight-based method for this purpose has so far received less attention. The recent study conducted by Dimitrova and Maréchal [8] has applied the Process Integration methodology, however, focusing only on the hybrid electric vehicle energy system. A diesel engine was integrated in their study to a hybrid electric powertrain, where the diesel system operating zone was restricted to the low speeds and low load zone.

The work presented in this paper 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) [9]. PoPA is an extension of the heat Pinch Analysis (PA), which was initially established for the design of optimal heat exchanger networks [10]. Following the developments of PA for various resource conservation networks, the focus of PoPA had been on the optimal HPS supply planning and demand management. Analogous to the heat pinch, time difference is taken as the driving force for electricity transfer in PoPA, instead of the temperature gradient. The Pinch in PoPA gives the limits for power recovery, as no power exchange is allowed between the sources and the demands at the Pinch Point.

Graphical PoPA tools were initially developed by Wan Alwi et al. [9] to establish electricity targets for an optimal HPS design during the start-up and continuous 24 h operations. Algebraic PoPA tools were presented by Mohammad Rozali et al. [11] to provide a more rapid and precise electricity targeting. PoPA development has covered a wide range of applications including power and storage allocations considering energy losses [12], optimal HPS sizing [13], peak-off-peak load shifting [14] and storage optimisation [15]. However the PoPA is yet to be applied in integrating existing diesel plants with RE systems in HPS. This paper presents a methodology that employs the concept of PoPA to optimise the RE electricity supplies in HPS while minimising the diesel generation. Insights on the real time electricity flows provided by the PoPA allow designers to plan and control the operational time of the diesel generators, thereby resulting in additional savings in diesel fuel as well as maintenance cost.

2. Methodology

The feasibility of incorporating renewable energy systems into an existing diesel plant has been examined by implementing the PoPA tool known as the Storage Cascade Table (SCT) [12]. The SCT approach was 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, the REs were assigned as the main sources to serve the loads and to charge the storage. The diesel generator needs to be run only at times when the renewable electricity harvested and storage fails to satisfy the load demand. Power conditioning unit is the main player in the energy management, which decides on the mode of operation: the connection and disconnection of the diesel generator [16].

Tables 1 and 2 show the limiting power data to demonstrate the application of SCT, considering the incorporation of renewable energy technologies into a diesel plant. The additional power producers involved in the

Illustrative Case Study are solar PV and wind energy systems. Both can supplement the available 200 kW diesel generator used to meet the site energy demand. Prior to the integration of the systems, the generation profile of the diesel generator was equivalent to the average load profile. The diesel fuel consumption is obtained using Eq. (1).

$$F_D = A_D \times P_D + B_D \times P_R \tag{1}$$

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 for existing case); A_D and B_D = coefficients of the fuel consumption curve. The typical value for A_D is 0.246 L/kW h and B_D, 0.08145 L/kW h [17].

The diesel generator initially ran for 24 h/d and consumed 1365.78 L/d of diesel fuel. The procedure to supplement diesel system with RE has been set as follows;

Step 1: Determine the new power output and operational hours of diesel generator

Solar PV system provides DC (direct current) electricity while wind turbine generates AC (alternating current) electricity. Lead-acid battery functions as the storage system, which is charged during excess renewable electricity generation, and discharged at deficit times. When the load demand exceeded both the generated RE electricity and the storage supply, the diesel generator would be connected to supply AC electricity to the system. Table 3 shows the SCT adapted from [12]. The key difference between the two methods is that the previous SCT gives the amount of electricity that should be purchased from the power grid. The SCT for diesel plant expansion on the other hand provides the allocations of electricity and the operational times for the diesel power generator,

Table 1
Power sources for illustrative case study.

Power source		Time (h)		Time interval (h)	Power source rating (kW)	Electricity generation (kW h)
AC	DC	From	To			
Wind		2	10	8	70	560
	Solar	8	18	10	80	800