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Electric System Cascade Analysis (ESCA): Cost and Efficiency Trade-Off and Optimization

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Electric System Cascade Analysis (ESCA), an optimisation technique for the design and scheduling of a distributed energy generation (DEG) system based on Pinch Analysis concept is developed with the basis to ensure maximal thermal efficiency of the power generators. By assuming that the power generator will operate at full load at all time, the optimal capacity of the power generator and the energy storage (ES) device including the optimal schedule of the system is revealed. While the generator operates at maximum thermal efficiency, it may results in higher energy losses due to extensive inversion of current, and storage of energy. It also may lead to the needs of larger ES which could be expensive. In this article, the trade-of between generator thermal efficiency and ES-related losses is studied upon. A new set of heuristic is also introduced to discuss on the flexibility of operating the power generator. It is revealed that indeed by increasing the capacity of the generator and allowing flexibility to its operation, the overall efficiency of the DEG system will be higher. As for the economics, the cost of the system increases with increasing capacity of the power generator despite decreasing capacity of ES.

1. Introduction

Increasing greenhouse gas emissions and its impact on enhanced global warming have increased the role and need of alternative (to fossil fuel) and clean energy resources namely, renewable energy (RE). In correspond to efficient generation and utilisation of energy resources, the distributed energy generation (DEG) system is now widely introduced. The system which is envisaged to increase the efficiency of RE and potentially reduce the operating cost of RE is also variably known as decentralised generation, embedded generation, or small-scale generation (Pepermans et al., 2005).
In order to further optimise and improve the operation of the DEG, various optimisation methods have been proposed for the design of the DEG systems. These models includes mathematical programming, see Kaldellis and Vlachos (2005); genetic algorithms - Koutroulis et al. (2006); Monte Carlo simulation - Karki and Billinton (2001); and Pinch Analysis - Nemet et al. (2012). The presented paper focuses on Pinch Analysis-based approaches for DEG system design, in specifics, on Electric System Cascade Analysis - ESCA (Ho et al., 2012).

2. Literature Review

Pinch Analysis for power system planning and scheduling was introduced by Bandyopadhyay (2011). In his work, Pinch Analysis and space design approach were both applied to design an isolated energy system, where Pinch Analysis is used to determine the optimal capacity of the energy storage. Ho et al. (2012) and Wan Alwi et al. (2012) presented new approaches for Power Pinch Analysis (PoPA). Wan Alwi et al. (2012) presented the Power Composite Curve (PCC), which can be used to determine the minimum outsourced electricity supply to be purchased and the excess generation of electricity available for next

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day operations. Ho et al. (2012) on the other hand, introduced a stepwise numerical approach known as ESCA, for designing a stand-alone distributed energy generation (DEG) and energy storage systems. The technique by Ho et al. (2012) can determine the optimal power generator capacity and the energy storage capacity.

As an extension to ESCA, Ho et al. (2014) further explore and applied ESCA methodology to optimise intermittent energy system, the solar photovoltaic (PV) system. This is followed by another study to incorporate load shifting to the general methodology of ESCA (Ho et al., 2013). By including load shifting the Power Demand Curve is manipulated in such to improve the overall efficiency of the system. Wan Alwi et al. (2013) on the other hand extends the PCC technique to also include load shifting in the graphical tool which is known as the Outsourced and Storage Electricity Curves (OSEC). Mohammad Rozali et al. (2013a) then developed a new numerical targeting tool utilising the concept of cascade analysis. Consideration efficiency losses during conversion, transfer, and storage are presented in another work by Mohammad Rozali et al. (2013b).

While these techniques did manage to design DEG, which is technically and economically feasible, it also revealed that losses mainly due to conversion and storage can be relatively high. Especially in ESCA, where it is assumed that the power generator is to be operated at full load at all time to increase its thermal efficiency, it could lead to the needs of more extensive charging and discharging of energy in and out of the energy storage (ES) device. The increased of charging and discharging activities could lead to lower overall efficiency of the system, in additional to increasing capacity of ES. In this paper, the impact of the assumed assumption on the power generator capacity and operation is explored. The power generator is designed at a larger capacity and is allowed to operate more flexible (lower thermal efficiency of the generator).

3. Methodology

The full methodology of ESCA can be referred to the paper by Ho et al. (2012) while the Grand Composite Curve is shown in Figure 1. The set of assumptions corresponded to the technique is as follows; Power is supplied to load before considered for storage. Power generators should be maintained at constant generation and fully distributed to increase its capacity factor and thermal efficiency; Energy storage stored energy at the beginning of the analysis when time, t = 0 h has to be equal to the stored energy at the end of analysis, t = 24 h) to prevent accumulation of power in the battery system. In Figure 1 the energy at the beginning of the analysis is shown as the Initial Energy Content (IEC) and the energy at the end of the analysis is shown as the Final Energy Content (FEC); The energy storage profile is assumed to repeat daily; Excess energy is stored in the energy storage; and the energy storage supply additional energy during high demand.

In this paper, the assumption where the power generator is specified to operate at full load at an optimal capacity is studied upon. The capacity of the power generator is increased and flexibility on the operating load is allowed. A new set of heuristic to decide on the operation is as follows: i) Power generator should fully meet the load demand, however if the power of the load is larger than the power generable by the power generator, ES will supply the additional power. ii) If the power of the load demand is less than the minimal power generable by the power generator due to its turndown ratio, the excess power will either be loss or stored in the ES. iii) Additional energy will have to be stored in the ES to sufficiently provide for the power demand in (i).

As for the energy efficiency analysis and economic analysis, the following three equations is used to calculate the overall system efficiency, *E* (total demand, *D* /total generation, *G*), total energy consumed and the total cost. The total energy consumed, *EC* is calculated based on the total generation, *G* multiply by the heat rate of the power generator, H_o. Where *o* is the operating load of the power generator. Note that the heat rate increases at lower operating load.

For the total cost calculation, *C*, the capacity of the power generator, *P* is multiplied by its cost, *PC*, the power-related capacity of the ES, *ESP* is multiplied by its cost, *ESPC*, and the energy-related capacity of the ES, *ESE* is multiplied by its cost, *ESEC*.

$$E = \frac{D}{G} \quad (1)$$

$$C = P \cdot PC + ESP \cdot ESPC + ESE \cdot ESEC \quad (2)$$

$$EC = G \cdot H_o \quad (3)$$

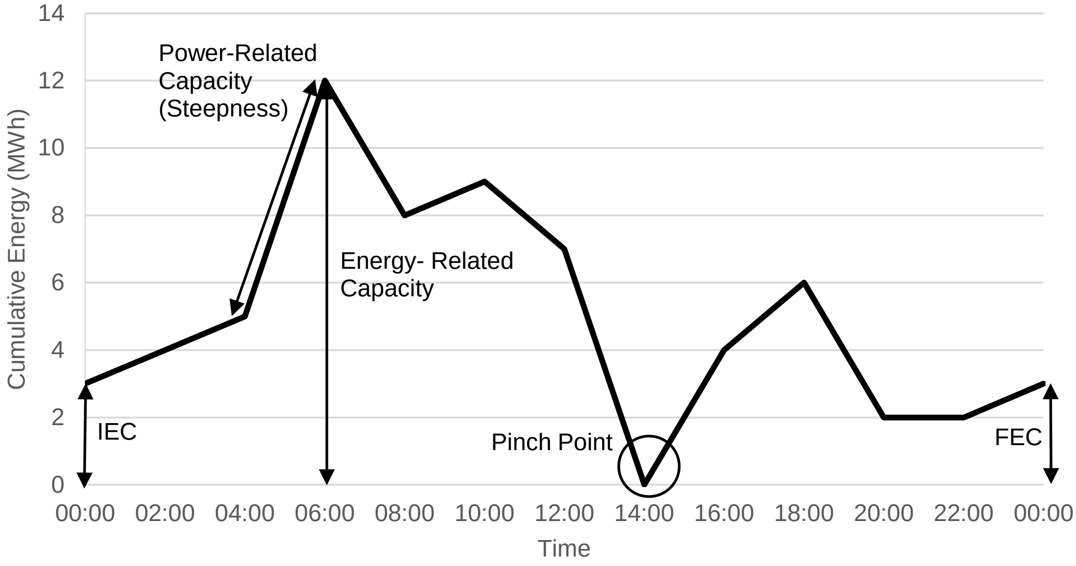

Figure 1: Grand Composite Curve of Power Pinch Analysis

4. Case Study

The demand load used in this analysis is as shown in Figure 2. The total energy demand is 84.5 MWh. The cost for the generator and ES is shown in Table 1. The power generator used in this case study is a biomass bubbling fluidised bed (BBFB) system. The ES is a sodium sulphate (NaS) battery. The turndown ratio of the power generator is taken as 30 % in this study. The charging and discharging efficiency of the NaS battery is 88.3 % with inverter efficiency of 90 %. The heat rate of the power generator is 14.24 GJ/MWh. The correlation between the heat rate and operating load is shown in Figure 3.

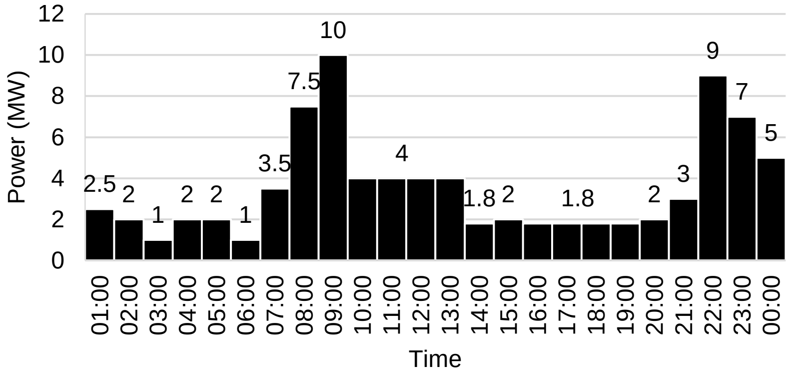

Figure 2: Power demand load profile with a total energy demand of 84.5 MWh

Table 1: Cost of power generator and ES

Operating Units	Cost
BBFB cost, *PC* (US Energy Information Administration, 2010)	3,860 $/kW
Power-related capacity of NaS cost, *ESPC* (Steward et al., 2009)	173 $/kW
Energy-related capacity of NaS cost, *ESEC*(Steward et al., 2009)	288 $/kWh

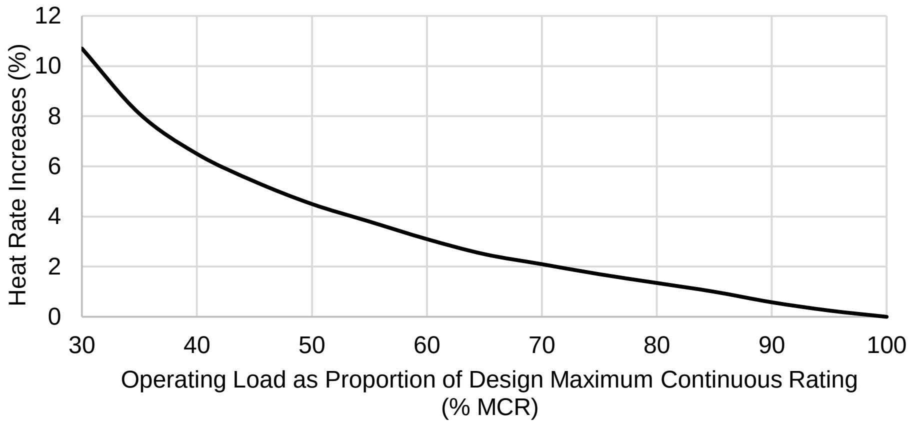

Figure 3: Impact of operating load on heat rate (International Energy Agency, 2010)

5. Results and Discussion

Based on ESCA and the new heuristic discussed in Section 3.0, the analysis is performed and the results of the capacities, overall efficiency of the system, total energy consumed and the total cost is tabulated in Table 2. The energy generation of the generator on the other hand is shown in Figure 4, where a) is the optimal capacity of the power plant based on the original ESCA, which is identified as 4MW; b) the capacity of the generator is increased to 6 MW; c) the capacity of the generator is increase to 8 MW; and lastly d) the capacity of the generator is increased to 10 MW.

Table 2: Capacities, overall efficiency, total energy consumed and total cost

Generator Capacity (MW)	ES Power-Related Capacity (MW)	ES Energy- Related Capacity (MWh) (After considering the depth of discharge of 20%)	Overall Efficiency (%)	Total Energy Consumed (GJ)	Total Cost (M$)
4	7.58	15.70	88.56	1,358.78	21.27
6	5.03	6.29	93.84	1,317.29	26.52
8	2.52	3.15	94.62	1,340.12	32.22
10	0	0	84.50	1,516.81	38.60

Base on the results shown in Table 2, it can be clearly seen that there is a trade-off between the capacity of the power generator and the ES, with increasing capacity of power generator, the capacity of ES reduces, and due to that the overall efficiency increases as there is less losses due to inversion, charging, and discharging of electricity. However the overall efficiency reduces at power generator capacity of 10 MW, this is mainly due to the turndown ratio of the system. At 30 % turndown ratio, the minimal generation of the plant is 3 MWh, however at most time the power demand is less than 3 MW, resulting in energy losses.

As for the total energy consumed, the result is almost similar to that for the overall efficiency, however comparing the case where the power generator capacity is 6 MW and 8 MW, although the system with 8 MW has a higher overall efficiency, the total energy consumed is higher. This is mainly due to the case where at most time, the 8 MW power generator will have to operate at a lower load thus resulting in higher heat rate (lower thermal efficiency). This can be justified in Figure 4 where the operation of the power generator has a higher fluctuation for the case of 8 MW power generator capacity. Base on this result, it can be concluded that the case of 6 MW power generator capacity is in fact more energy efficient than the case of 8 MW power generator capacity. The results of the total energy consumed are plotted and it is revealed that the optimal configuration of the system is when the capacity of the power generator is set as approximately 7 MW. The plot of the analysis is shown in Figure 5.

As for the total cost, the total cost increases with increasing capacity of the power generator despite the ES capacity reduces. This is mainly due to the much higher capital cost of BBFB compared to NaS batteries energy-related cost and power-related cost. As the capacity of the power generator and the power-related capacity of the ES is closely related, the cost of reducing a unit of the power-related capacity of the ES could not overcome the increasing cost of increasing a unit of the power generator capacity. The correlation between the capacity of the power generator and the power-related capacity of the ES can be defined as shown in Eq(4). Symbol *d* is the discharging efficiency and *f* is the inverter efficiency.

$$D = P + \frac{ESP}{d \cdot i} \tag{4}$$

At power generator capacity of 7 MW, the ES storage capacity is revealed to be 3.78 MW (power-related) and 6.95 MWh (energy-related).

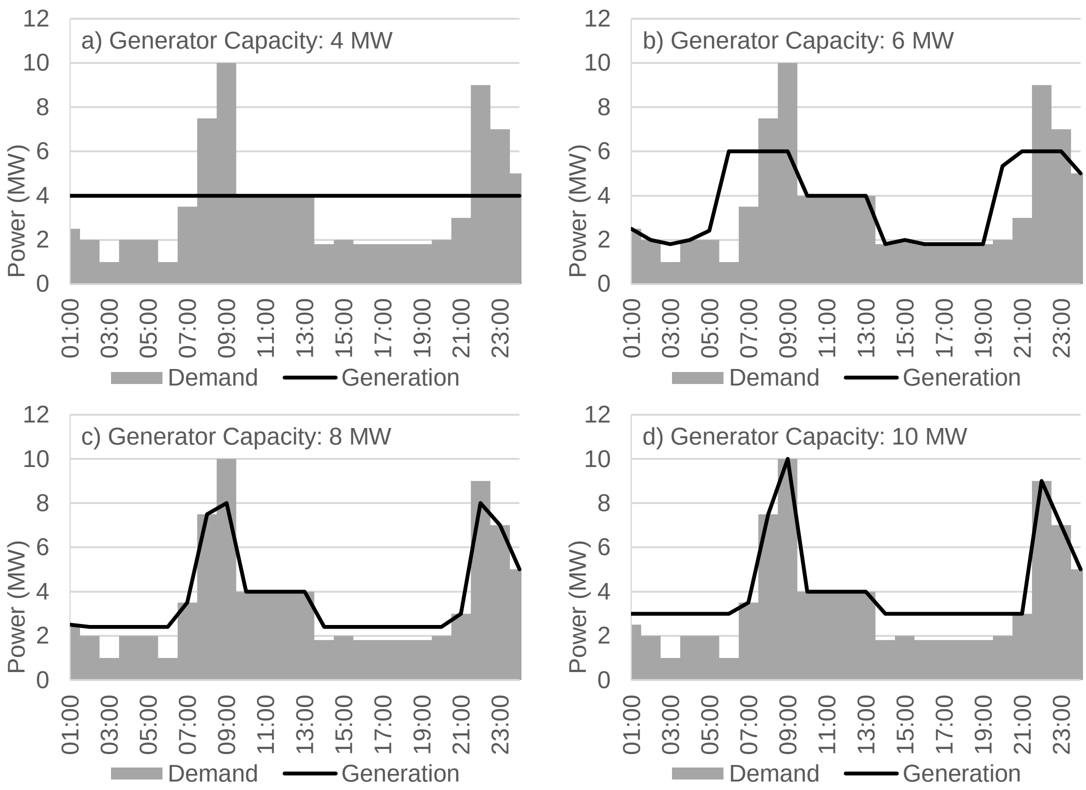

Figure 4: Power generation trend at different generator capacity: a) 4 MW, b) 6 MW, c) 8 MW, d) 10 MW

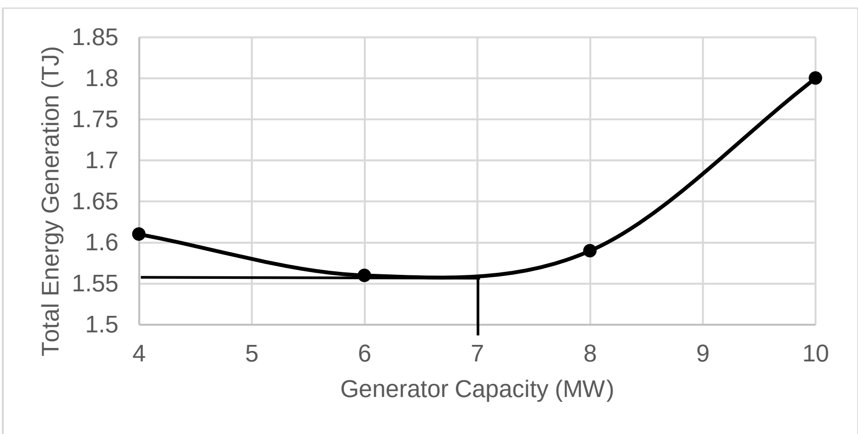

Figure 5: Correlation between total energy generation and generator capacity

6. Conclusion

ESCA was developed in 2012 with the goal to maintain the efficiency of the power generator at 100 % while the mismatch between supply and demand is balanced using energy storage. Based on the proposed operation, the minimal capacity of both the energy storage and generator can be identified. However, in the previously presented work, one major consideration was not taken into account, the fact that increasing usage of energy storage will increase the amount of energy losses by the energy system. In this paper, the correlation between the capacity of the generator and its total energy generation was studied. It shows that at minimal generator capacity (4 MW), the total energy generation by the energy system is higher than when the generator is at a moderate capacity (6 MW/8 MW) but lower than when the generator is at maximal capacity (10 MW). This work manages to capture the trade-off between the capacity and energy generation. The trade-off shown in this work is an important factor to consider especially when other decision variable is included during the design stage such as cost and emission. In cases where energy is cheap while power technology is expensive, the initial procedure of ESCA (minimizing generator capacity) may be preferred, otherwise it may be a better option to slightly increase the capacity of the power generator to reduce wastage of energy resources. This work shows the importance of adjusting the power generator capacity to obtain the optimal design and operation of the system. A set of heuristic to incorporate the factor into the existing ESCA will be discussed in future work.

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