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Study of the Effects of Peak/Off-Peak Load Shifting on Hybrid Power System Storage Using Power Pinch Analysis

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The difference in electricity pricing based on the time of power use has led to load shifting from peak to off-peak hours in hybrid power systems (HPS). Apart from optimising electricity cost, shifting of load may also change the capacity of storage in the system. Power Pinch Analysis has been recently applied to guide load shifting aiming to minimise the cost of electricity, considering the peak and off-peak electricity pricing. This work extends the study by scrutinising the effects of peak/off-peak load shifting on the capacity of storage in HPS. Shifting heuristics are developed to ensure optimal storage size is achieved. Results show that the proposed load shifting strategy from peak to off-peak hours has successfully minimised the costs of both the storage system and the electricity bill.

1. Introduction

Hybrid power systems (HPS) generally comprises of two or more generation sources to provide electricity supply to load demands. Load demand distribution however is not constant throughout a day or year and varies dependent on time and ambient temperature. The significant difference of the load profiles over time has led to the inspiration to shift part of the peak hours' load to off-peak hours. Load shifting from peak to off-peak hours changes the electricity load profile and allows users to control the peak electricity demand and optimise the electricity cost. Apart from adjusting the peak demand, it should be noted that shifting of load may also change the capacity of storage system.

Numerous studies on load shifting in power systems considering the optimal storage design have been conducted. Mohamed et al. (2012) proposed a real-time energy management algorithm to manage the energy storage in hybrid microgrids. The total cost of energy for the system was reduced by peak/off-peak shifting. Hashim et al. (2014) developed a mixed integer linear programming (MILP) model to design an integrated biomas solar town, with the incorporation of load shifting and energy storage. The MILP model has optimally shifted the loads to interval with low demands, while utilising the energy storage to minimise the capacity of the operating units.

El Motaleb et al. (2016) examined the effects of various load shifting levels on the optimal sizing of HPS storage using stochastic modelling. The one-time investment and annual operational costs of the energy storage were successfully minimised while setting the expected energy not served (EENS) as the constraint. Desired levelised cost of energy storage (LCOES) values for battery systems were achieved via demand load shifting by Parra et al. (2016). The authors applied simulation-based optimisation to quantify the demand load shifting based on two different retail tariffs, namely time-of-use tariff and real-time-pricing tariff. Prinsloo et al. (2016) scrutinised the operational plans and cost performances of energy management for different storage scenarios at isolated rural

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villages in Africa. The experimental results show that incremental optimisation of the storage capacity enhances the efficiency of energy management, while reducing operational and customer billing costs.

The concept of Pinch Analysis for load shifting process in HPS has been presented by Wan Alwi et al. (2013). Power Pinch Analysis (PoPA) method was applied to identify the power allocations of the system, before load shifting strategies were executed to reduce the storage capacity and maximum demand. The drawback of this study is that, the effects of electricity tariff variation with time towards electricity cost were not taken into account. Mohammad Rozali et al. (2015) later proposed peak/off-peak load shifting using the earlier PoPA concept, with the aim to minimise the cost of electricity. The effects of load shifting considering the peak and off-peak electricity pricing towards the systems' storage capacity however has not been explored using PoPA. Optimisation of storage capacity in HPS is vital because storage unit is the dominant factor for hybrid system cost (El Motaleb et al., 2016). Therefore, correct shifting strategy that considers the capacity and allocation of storage should be formulated, in order to ensure the cost of storage in the HPS is optimal.

In this paper, PoPA is applied to provide insights in order to formulate peak/off-peak load shifting strategy to achieve optimal storage capacity in HPS. Two new heuristics are proposed to guide the load shifting, with the aim to minimise the capacity of storage. The savings in investment due to the reduced storage capacity is calculated after each shifting strategy.

2. Methodology

This section describes the step-wise procedure to analyse the effects of peak/off-peak load shifting on the HPS storage. The methodology is implemented as follows;

2.1 Step 1: Determine the optimal allocations of storage and outsourced electricity

PoPA graphical tool called the Outsourced and Storage Electricity Curves (OSEC) was utilised to establish the allocations of storage and outsourced electricity at each time interval. The OSEC was constructed using the procedure as described by Wan Alwi et al. (2013). For each time interval, the Source Composite Curve (SCC) was directly positioned to the Demand Composite Curve (DCC) until it pinches the DCC at a point. If the amount of electricity for the SCC is more than that of the DCC (SCC slope is less steep than the DCC slope), excess electricity is available for storage. On the other hand, outsourced electricity is required if the amount of electricity for the DCC is more than that of the SCC (SCC slope is higher than the DCC slope).

The positioning step was repeated for every time interval to give the complete OSEC for the day. Given the complete OSEC plot, the allocations of storage capacity (S) and outsourced electricity (O) can be extracted. Note that the amount of electricity stores at t = 24 h for the first day operation is also called as the available excess electricity for the next day (AEEND). The AEEND can be utilised for the subsequent day operation, to reduce the outsourced requirement for the continuous 24 h operation (Wan Alwi et al., 2012).

2.2 Step 2: Shift demand from peak to off peak hours

The allocation of the highest energy storage (maximum storage capacity), is essential in order to plan the shifting strategies. The off-peak hours having the maximum storage capacity should be targeted as the destination for the shifting of demand from the peak hours. The peak hours is where the demand is high, which is between 8 to 22 h (Tenaga Nasional Berhad, 2017). Note that it is possible to reduce the maximum storage capacity only if it occurs between the off-peak hours. No size reduction can be achieved if the maximum storage occurs during the peak hours. This is because load would never be shifted to peak hours due to the high peak electricity tariff. Two heuristics were developed to guide the load shifting, with the aim to minimise the maximum storage capacity.

Heuristic 1: The maximum storage capacity can be reduced by shifting electricity demand during peak hours to the time intervals with the maximum electricity surpluses, occurring during off-peak hours.

Heuristic 2: The maximum storage capacity can be reduced by shifting electricity demand during peak hours to the time intervals with high available AEEND. The time intervals of where the demand is shifted to can be straddling the peak and off-peak hours, provided that it is preceded by the time interval with large electricity storage.

After the shifting of load has been performed, the reduced capacity of storage and outsourced electricity requirement were recorded to be used in the following step.

2.3 Step 3: Economic analysis

Economic evaluation was done to verify the effectiveness of the shifting heuristics, towards minimising the capacity of the storage system. The analysis focused only on the storage cost, since the costs for the generators and other auxiliary components in the HPS were assumed to be unaffected by the shifting. The effects of the shifting heuristics towards the investment of the storage system was represented using the payback period analysis, as in Eq(1).

$$\textit{Payback period} = \frac{\textit{Net capital investment}}{\textit{Net annual savings}} \tag{1}$$

The net capital investment is the capital cost of the storage for a given capacity. The difference in the electricity cost for both pre- and post-implementation of HPS was considered in the net annual savings computation. Taking into account the operating cost of the storage, the net annual savings was calculated via Eq(2).

$$\textit{Net annual savings} = C_O - C_{O,HPS} - (S \times OM) \tag{2}$$

Where C_O is the annual electricity cost without HPS [RM/y]; $C_{O,HPS}$ is the annual electricity (outsourced) cost with HPS [RM/y]; S is the actual storage size [kW]; OM is the annualized operating and maintenance cost of the storage [RM/kWy].

The peak/off-peak tariffs and the maximum demand cost were considered in the calculation of annual electricity cost, as given in Eq(3).

$$C_O \text{ or } C_{O,HPS} = \sum\left(O_{on} \times T_{E,on}\right) + \left(O_{off} \times T_{E,off}\right) + \left(MD_{on} \times T_{MD}\right) \tag{3}$$

Where O_{on} and O_{off} are the annual outsourced electricity requirement during the peak and off-peak hours [kWh]; $T_{E,on}$ and $T_{E,off}$ are the electricity tariff charged during peak and off-peak hours [RM/kWh]; MD_{on} is the annual maximum demand per month during peak hours [kW]; T_{MD} is the maximum demand charged per month during peak hours = 37.00 RM/kW.

3. Results and discussion

A HPS with three renewable sources, i.e. biomass, wind and solar was studied in the Illustrative Case Study. The system serves five appliances, which were assumed to be flexible loads. Flexible loads can be shifted to any time interval without affecting the service that these appliances provide, because they can be operated at any time throughout the day (Göransson et al., 2014). Tables 1 and 2 show the limiting power sources and demands for the Illustrative Case Study. Sodium Sulfur (NaS) battery was used as the storage system for the HPS.

Table 1: Limiting power sources for illustrative case study (Wan Alwi et al., 2013)

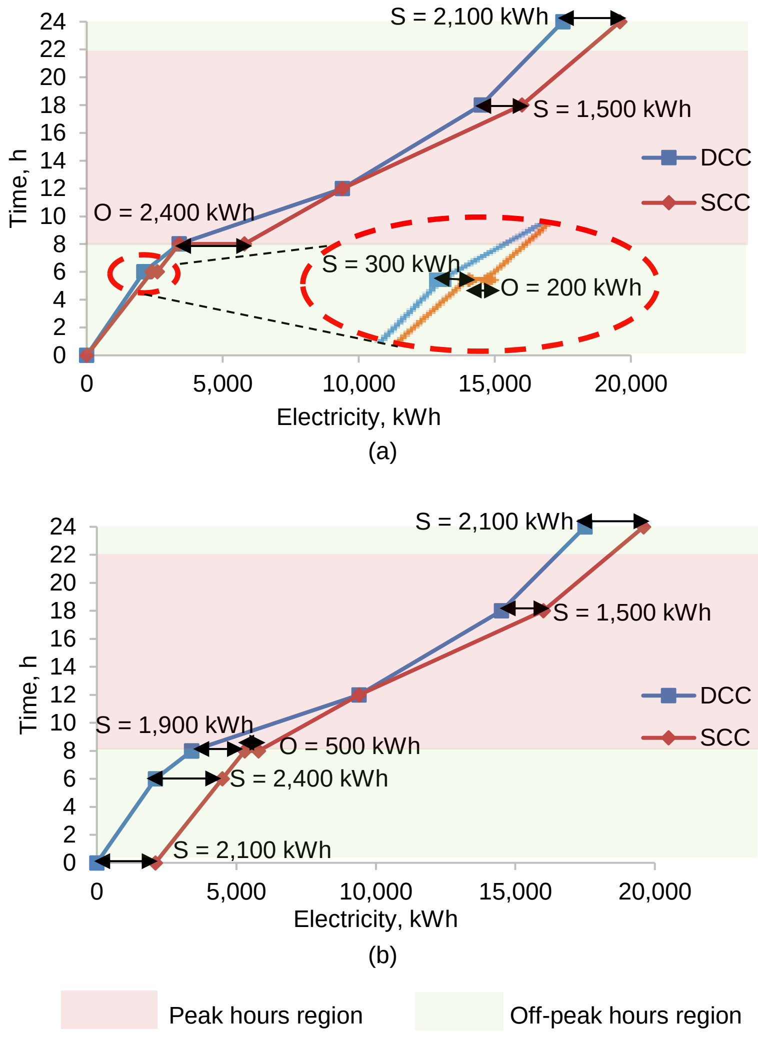
No.	Description	Time, h		Power rating, kW
		From	To	
S1	Biomass	12	24	600
S2	Wind	0	12	400
S3	Solar	8	18	500

Table 2: Limiting power demands for illustrative case study (Wan Alwi et al., 2013)

No.	Description	Time, h		Power rating, kW
		From	To	
D1	Appliance 1	6	12	300
D2	Appliance 2	8	18	350
D3	Appliance 3	8	12	500
D4	Appliance 4	0	12	350
D5	Appliance 5	12	24	500

Figure 1 shows the completed OSEC for the Illustrative Case Study. OSEC for the first day operation and continuous 24 h operation are given in Figure 1(a) and Figure 1(b).

It can be observed from Figure 1(a) that maximum energy of 2,100 kWh was stored between time intervals 18 and 24 h. This is the amount of the AEEND that can be utilised for the subsequent day operation, as shown in Figure 1(b). This consequently increase the storage capacity between 0 and 6 h to 2,400 kWh, which is within the off-peak periods during the continuous 24 h operation. Figure 1(b) also shows that the highest outsourced electricity (O = 500 kWh) occurred within the peak hours i.e. between time intervals 8 and 12 h. Storage and outsourced allocations at the other time intervals can be referred to Figure 1.



(a)

(b)

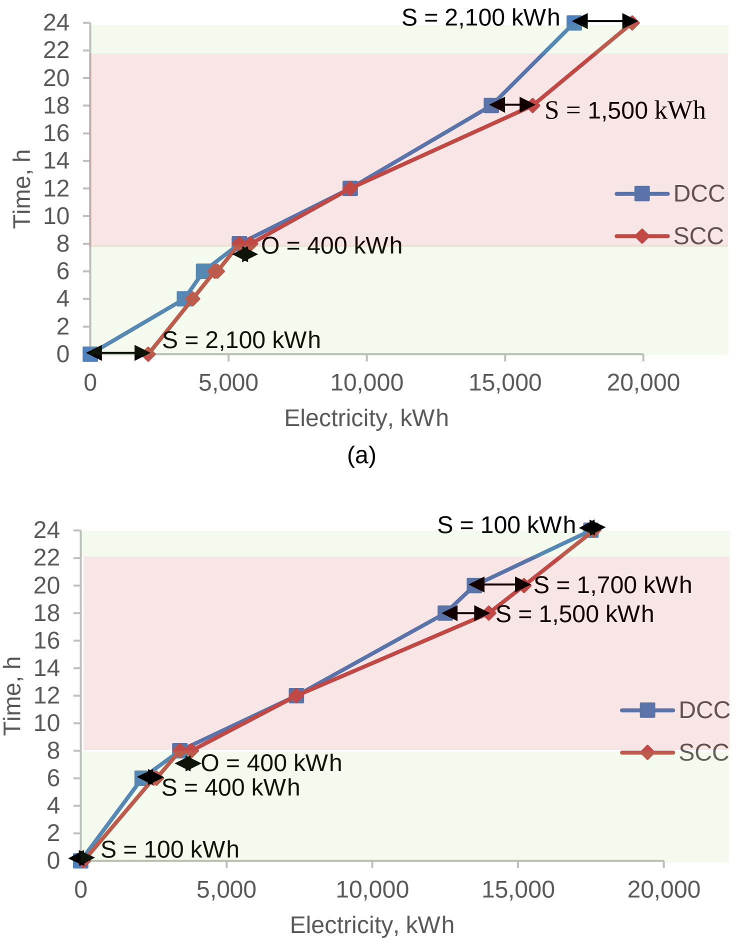
Figure 1: OSEC for Illustrative Case Study (a) first day operation; (b) continuous 24 h operation

Shifting Heuristic 1 was considered for the load shifting. To proceed with the load shifting using this heuristic, one must identify the demand appliance operating during the peak hours. This demand would be shifted to the off-peak time interval, where the maximum storage capacity occurs, i.e. between 0 and 6 h (see Figure 1(b)). Appliance 3 (D3) was selected for the load shifting since it consumes electricity within the time intervals with the highest deficits occurrence (between 8 and 12 h). The effect of shifting D3 to time ‘0 to 4 h’ is given in Figure 2(a). As observed, the size of the maximum storage has been reduced from 2,400 kWh to 2,100 kWh (12.5 % reduction). The outsourced electricity requirement during the peak hours has also been reduced to 400 kWh.

As mentioned previously, the high AEEND (2,100 kWh) in the first day operation is the cause of the high maximum storage capacity during the continuous 24 h operation. Therefore, instead of directly shifting the demand to where the maximum storage is allocated, the time interval of where the AEEND is can be aimed as the destination for the load shifting, as stated in the shifting Heuristic 2. Figure 2(b) visualise the effect of shifting D3 to time ’20 to 24 h’. This shifting obeys the heuristic since the ’20 to 24 h’ intervals are preceded with storage capacity of 1,500 kWh (see Figure 1(b)). As observed from Figure 2(b), the maximum storage capacity has now reduced to 1,700 kWh. This translates to 29.2 % reduction from the initial capacity. Reduction in the total outsourced electricity requirement during the peak hours has also been achieved. Note that due to this shifting heuristic, the amount of AEEND decreases to 100 kWh.

The final procedure is to carry out the economic analysis. The capital and operating expenditures for the NaS battery are 560 RM/kW and 67 RM/kWy (Komor and Glassmire, 2012). Prior to the load shifting, the maximum capacity of the storage for the HPS is 2,400 kWh (see Figure 1(b)). The maximum storage capacity was reduced to 2,100 kWh and 1,700 kWh after shifting Heuristic 1 and shifting Heuristic 2 (see Figure 2). The actual size for

the battery storage was obtained assuming that the depth of discharge (DoD) for the NaS battery to be 80 % of the maximum storage capacity (Komor and Glassmire, 2012).
The current Malaysia's industrial pricing and tariff applies peak usage tariff rate of 0.355 RM/kWh. The cost of the grid electricity during the off-peak period on the other hand is 0.219 RM/kWh (Tenaga Nasional Berhad, 2017). Table 2 summarises the results from the economic assessment.



(a)

(b)

Figure 2: OSEC for continuous 24 h operation after (a) shifting Heuristic 1; (b) shifting Heuristic 2

Table 4: Economic evaluation results

	Before shifting	After shifting *Heuristic 1*	After shifting *Heuristic 2*
Net capital investment, RM	1,680,000	1,470,000	1,190,000
Peak electricity cost, RM/y	65,462	51,830	51,830
Off-peak electricity cost, RM/y	44	8,453	8,015
Maximum demand cost, RM/y	73,075	40,700	44,400
Neat annual savings, RM/y	4,026,046	4,063,644	4,060,382
Payback period, y	0.62	0.35	0.30

Overall, shifting Heuristic 2 provides the lowest payback period for the investment on the battery storage. Though the payback period reduction compared to before shifting is very small for both shifting heuristics (< 4 months), the total electricity cost savings achieved was lucrative. Up to RM 35,000 can be saved annually if the HPS operates with the shifted load profiles instead of the original load profiles. It can be observed that higher annual cost savings was achieved from the shifting Heuristic 1, since the maximum demand cost is lower. However, smaller battery storage size obtained due to the shifting Heuristic 2 contributes to cheaper storage investment, thus yielding lower payback period. It is expected that given a larger HPS scale (e.g. >50 MW), the effects of load shifting on the storage cost and payback would be more significant.

4. Conclusions

Two shifting heuristics have been proposed in order to minimise the storage capacity in HPS, while shifting the loads from peak to off-peak hours. Given the essential insights established from PoPA tool called the OSEC, effective shifting strategies have been done to successfully provide savings in the storage investment, as well as in the electricity billing. Results show that the savings in electricity cost is more substantial compared to the storage cost savings. This cost however contributes to the overall economics of the HPS. In addition, no investment is required to carry out the load shifting, and the designers are highly encouraged to carry out the shifting heuristics to economically optimise their HPS.

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