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Design of Hybrid Power Systems with Energy Losses

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Pinch Analysis has been recently extended into the design of hybrid power systems to determine the maximum power recovery and battery storage capacity. Graphical and numerical Power Pinch Analysis (PoPA) tools are systematic and simple to implement in the optimisation of power systems. The losses incurred in the systems however are not taken into consideration in the previous works. This paper extends the PoPA method by considering the energy losses that occur in the power system conversion, transfer and storage. These losses on the minimum outsourced electrical energy targets and storage capacity are evaluated and the Storage Cascade Table (SCT) of PoPA is developed to include the effect of energy losses in the system design. The developed method is demonstrated on an illustrative case study and reflects the actual power targets for off-grid hybrid power systems.

1. Introduction

A Hybrid Power System (HPS) consists of renewable energy (RE) sources as electricity producer and a battery bank as power backup. RE sources provide cleaner and sustainable energy systems and also eliminate the need for long distance transmission cables as they can be installed close to the load. HPS has therefore been widely implemented as a promising solution to boost energy supply security and address the environmental impact associated with energy usage. Use of HPS incurs certain amount of power losses even though these losses are much less than those incurred by conventional power systems. The conversion and transfer of power are the significant processes that contribute to the power losses. The conversion between alternating current (AC) and direct current (DC) in HPS involves rectifier (AC to DC) and inverter (DC to AC) which contribute to approximately 5 % of total losses each (Burger and Ruther, 2005). Transfer process involves battery with charging and discharging efficiencies of 90 % (Zhou et al., 2008) as well as self-discharge losses of 0.01 %/h during storage (Ai et al., 2003). Losses in a system are the key element to the system's efficiency and a critical consideration when designing the system. This is because the total electricity delivered to the load is greatly influenced by the losses.

Extensive studies have been conducted to optimise the Distributed Generation (DG) systems that are based on RE with power losses minimisation as the main objective. Methods applicable for this purpose are the artificial intelligence techniques, numerical programming and analytical approaches.

One of the most established artificial intelligence tools is the Genetic Algorithm (GA). GA is proposed by Singh and Goswami (2010) to determine the optimal location and size of DGs that will yield the minimum total losses. Combination of different artificial intelligence techniques for optimal DG allocation is presented by Gandomkar et al. (2005) and Moradi and Abedini (2012). The proposed

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techniques have proven more advantageous compared to the Simple Genetic Algorithm (SGA) in terms of accuracy and convergence process.

Augugliaro et al. (1990) developed a mathematical model to minimise the cost of power losses on radial DG system. A nonlinear programming package is used for the nonlinear objective function and constraints. Iterative search technique was applied by Ghosh et al. (2010) along with Newton Raphson method to effectively reduce the cost and loss. Khalesi et al. (2011) minimised the system power loss and increased the reliability improvement and voltage profile with dynamic programming. It was used to solve the multi-objective problems derived based on the cost/benefit form.

Design and optimisation of power system using Pinch Analysis has been proposed recently. The graphical and numerical approaches presented offer simple and systematic procedure for electricity targeting and HPS designing. Bandyopadhyay (2011) developed a graphical representation, which is analogous to the Grand Composite Curve (GCC) in Heat Exchanger Networks - HENs (Townsend and Linnhoff 1983) and recent overview by Klemeš et al. (2010) where the quality (time) was drawn as the x- axis. However, this method can only set targets for start-up operations. Graphical tools by (Wan Alwi et al., 2012) called the Power Composite Curve (PCC) and Continuous PCC (CPCC) map the time against electricity plot for power sources and demands composites. These tools can determine the electricity targets for start up and also for daily operations. Numerical tools were presented by Mohammad Rozali et al. (2012). They constructed the Power Cascade Table (PCT) and Storage Cascade Table (SCT) for electricity targeting during start up and daily operations as well as to determine the storage capacity. The graphical tools give good visualisation insight while the numerical techniques provide better accuracy and faster algorithmic calculations. The Pinch tools are proven to be more helpful for designers because complex mathematical programming, simulation and modelling steps are avoided.

However, the proposed Pinch Analysis tools still have limitations. (Bandyopadhyay, 2011) considered the charging and discharging process efficiencies, but the self-discharge loss is assumed to be negligible. (Wan Alwi et al., 2012) assumed 100 % power transfer and battery efficiency. Presented work is therefore an improvement of the Power Pinch Analysis (PoPA) by including battery (charging/discharging and self discharge), inverter and rectifier efficiency in the methodology. The electricity targets for start up and daily operations are determined by constructing the Storage Cascade Table (Mohammad Rozali et al., 2012) without neglecting the losses to reflect the actual performance of the HPS and avoid under sizing systems design.

2. Methodology

This section describes the methodology for PoPA including the electricity losses from conversion (inverter and rectifier), transfer (charging and discharging) and storage (self-discharge). The efficiencies of the components are usually provided by manufacturers, and for this study are assumed as 95 % for inverter and rectifier and 90 % for battery charging and discharging. The self discharge rate of battery is dependent on the battery type and is assumed as 0.01 %/h. The final aims of the methodology described in this section are identical with the objectives of SCT method (Mohammad Rozali et al., 2012) with difference only in the procedure. The generated electricity from RE as well as the appliances loads are classified into two groups which are the AC and DC electricity. When DC electricity sources are insufficient to satisfy the DC load, three options are available for solutions (Hocaoğlu et al., 2009):

i. The AC electricity surplus at the time interval will be converted to DC, or
ii. The battery will be discharged, or
iii. The outsourced DC electricity will be purchased from grid.

In the event of insufficient AC sources, three options can be applied for solutions include (Hocaoğlu et al., 2009):

i. The DC electricity surplus at the time interval will be converted to AC, or
ii. The battery will be discharged and converted to AC, or
iii. The external AC electricity will be imported from grid.

The developed tool is performed in two key steps i.e. (1) Specify the limiting power data, and (2) Determine the outsourced electricity supply required at each time interval, amount of electricity available for storage at real time and storage capacity

Step 1: Specify the limiting power data

The uncontrolled and unpredictable characteristics of the data which consists of REs power generation and power consumption should be considered in deriving the limiting power data. Based on the time-series meteorological data for a location, limiting power data should be assigned to the minimum available power sources and maximum load demand for every time intervals. Limiting power sources and demands data for Illustrative Case Study 1 is tabulated in Table 1 and Table 2.

Table 1: Limiting power sources for Illustrative Case Study 1

Power sources		Time, h		Time interval, h	Power generated, kW	Electricity generation, kWh
AC	DC	From	To			
Wind		2	10	8	5	40
Biomass		0	24	24	7	168
	Solar	8	18	10	5	50

Table 2: Limiting power demands for Illustrative Case Study 1

Power demand appliances		Time, h		Time interval, h	Power demands, kW	Electricity consumption, kWh
AC	DC	From	To			
	Appliance 1	0	24	24	3	72
Appliance 2		8	18	10	5	50
	Appliance 3	0	24	24	2	48
Appliance 4		8	18	10	5	50
Appliance 5		8	20	12	4	48

Step 2: Determine the outsourced electricity supply required at each time interval, amount of electricity available for storage at real time and storage capacity

This is determined by constructing the modified SCT. Its step wise construction (Table 3a) is:

1) The time intervals for power sources and power demands are listed in Column 1 in ascending order while Column 2 gives the duration between two adjacent time-intervals.
2) The total ∑ of ratings for power sources and power demands for each time interval are given in column 3 and 4. These values can be obtained from the Power Cascade Table (PCT) (Mohammad Rozali et al., 2012). The sources and demands for AC and DC electricity are listed separately
3) The quantities of electricity sources and demands between time intervals are obtained via Eq. 1 and listed in Columns 5 and 6.

$$\sum \textit{Electricity Source/ Demand} = \sum \textit{Power Rating} \times \textit{Time interval duration} \quad (1)$$

4) The sources are sent directly to the demands accordingly for AC and DC. The surplus and deficit of each AC and DC electricity between time intervals is calculated by using Eq. 2 and listed in Column 7 and 8.

$$\textit{Electricity surplus/ deficit} = \sum \textit{Electricity Source} - \sum \textit{Electricity Demand} \quad (2)$$

A positive value indicates electricity surplus while negative value represents electricity deficit.

Table 3b is constructed with following steps;

1) The electricity deficit would be satisfied with the first option as stated earlier. Column 9 and 10 gives the converted AC and DC electricity surplus, which is obtained from Eq. 3 and 4. Note that only the exact amount required for AC load is converted from DC. This is because converting all DC electricity surpluses to AC would lead to bigger losses because it has to be converted back to DC before it can be stored. A controller is installed mainly to manage the interaction among

various system components. Real time data of the system including the battery capacity, load levels and source levels are to be monitored by the controller before producing the control signals to match with the set point values (Boonbumroong et al., 2011). AC electricity surplus is converted completely to DC because it can directly be sent to storage system if excess.

$$\textit{Amount of converted AC electricity} = \textit{AC electricity surplus} \times \textit{Rectifier efficiency} \quad (3)$$

$$\textit{Amount of DC electricity surplus to be converted} = \frac{\textit{Amount of AC deficit}}{\textit{Inverter efficiency}} \quad (4)$$

2) Column 11 shows the available DC electricity for storing after load utilisation, which is obtained by using Eq. 5.

$$\textit{DC electricity surplus} + \textit{Amount of DC converted from AC electricity surplus} - \textit{Amount of DC electricity surplus converted to AC} \quad (5)$$

The positive value represents the charging quantity while the negative value indicates discharging quantity for DC deficit.

3) The quantity of discharged electricity from battery to satisfy AC deficit is calculated with Eq. 6 and listed in Column 12.

$$\textit{DC Electricity to be discharged} = \frac{\textit{AC deficit}}{\textit{Inverter efficiency}} - \underset{\textit{(Column 8)}}{\textit{Converted DC surplus}} \quad (6)$$

If the storage capacity is less than the AC deficit, the whole storage will be discharged. Column 10 shows that the battery has to be discharged for AC demand between time intervals 8 to 18 h.

4) Based on value in Column 11 and 12, the cumulative storage capacity (Column 13) is calculated by including the battery efficiency (self-discharge rate, charging and discharging) via Eq. 7. The electricity cascade resumes at zero when the storage has been completely discharged at time interval 10 to 18 h. The largest value in Column 13 gives the upper limit for storage capacity of 37.528 kWh occurring at time interval 2 to 8 h.

$$B_{(t)} = B_{(t-1)}\,(1- \sigma \times T) + (C_t \times \eta_c) + \frac{D_t}{\eta_d} \quad (7)$$

where

B_t= battery capacity [kWh]; C_t = charging quantity [kWh]; D_t = discharging quantity [kWh]; σ= hourly self-discharge rate; t = time [h]; T = time interval; η_c = charging efficiency; η_d = discharging efficiency

Steps 2 to 4 demonstrated the application of the second option in the event of electricity deficit, where the battery storage is discharged and converted to AC for AC deficit.

5) When the amount of storage is still insufficient for the load, the last option for external electricity to be purchased from the grid is applied. Column 14 and 15 list the outsourced electricity required for AC and DC. Eq. 8 is derived to obtain the kW instantaneous external power demand.

$$\textit{Outsourced power rating} = \frac{\textit{Outsourced electricity}}{\textit{Time interval}} \quad (8)$$

For this illustrative case study, external AC electricity of 3.1 kW is needed to be imported at time interval 10 to 18 h while between the time intervals 18 to 20 h, 2.15 kW external DC electricity is required.

6) For next day (daily) operation, the battery capacity at t = 0 is taken from the previous day stored electricity (5.94 kWh). Eq. 7 is used to calculate the battery capacity and listed in Column 16. The largest value of 43.46 kWh gives the upper limit of storage capacity.

7) The amount of instantaneous external power demand in kW is calculated via Eq. 8 for AC and DC. The AC power demand required for this case study is 2.4 kW occurring between time intervals 10 – 18 h while DC power demand occurs at 18 – 20 h with 2.15 kW.

Table 3a: Modified Storage Cascade Table for Illustrative Case Study 1

1	2	3		4		5		6		7	8
Time h	Time interval h	∑ Power source rating kW		∑ Power demand rating kW		∑ Electricity source kWh		∑ Electricity demand kWh		AC surplus/ deficit kWh	DC surplus/ deficit kWh
		AC	DC	AC	DC	AC	DC	AC	DC		
0											
	2	7	0	0	5	14	0	0	10	14	-10
2											
	6	12	0	0	5	72	0	0	30	72	-30
8											
	2	12	5	14	5	24	10	28	10	-4	0
10											
	8	7	5	14	5	56	40	112	40	-56	0
18											
	2	7	0	4	5	14	0	8	10	6	-10
20											
	4	7	0	5	5	28	0	0	20	28	-20
24											

Table 3b: Modified Storage Cascade Table for Illustrative Case Study 1

9	10	11	12	13	14	15	16	17	18
Converted AC surplus, kWh	Converted DC surplus, kWh	Charging/ Discharging quantity (DC), kWh	Discharge for AC deficit kWh	Start up			Operation		
				Battery capacity kWh	Outsourced electricity, kWh		Battery capacity kWh	Outsourced electricity kWh	
					AC	DC		AC	DC
				0			5.94		
13.3	0	3.3	0	2.97	0	0	8.91	0	0
68.4	0	38.4	0	37.53	0	0	43.56	0	0
0	0	0	-4.21	32.84	0	0	38.77	0	0
0	0	0	-31.20	0	24.80	0	0	19.16	0
5.7	0	-4.3	0	0	0	4.3	0	0	4.3
26.6	0	6.6	0	5.94	0	0	5.94	0	0

The Case study shows significant difference in results with the original SCT (Mohammad Rozali et al., 2012) and the GCC technique (Bandyopadhyay, 2011). Compared to the SCT, the maximum storage capacity for start up operation obtained in the proposed tool is reduced to 37.53 kWh from 46 kWh, while the maximum storage for normal operation is reduced from 54 kWh to 43.56 kWh. The GCC method gives closer maximum storage capacity to the SCT with 41.4 kWh. This is because only the charging and discharging efficiencies are considered in the methodology, but not the self discharge rate as well as inverter and rectifier efficiencies. The maximum demand in this tool is characterised into

AC and DC power separately, and instead of 2 kW of maximum power demand for start up as obtained from SCT, this work yield maximum demand of 3.1 kW and 2.15 kW for AC and DC power

3. Conclusion

New numerical methods for optimal power allocation in HPS taking into consideration the losses in the systems have been presented. This tool can determine maximum battery storage capacity, outsourced electricity supply needed at each time interval as well as the maximum power demand. The illustrative Case study shows that consideration of power losses in power allocation reduce the storage capacity, but gives larger outsourced electricity supply required as well as maximum power demand. The results obtained match closely with the actual performance and avoid under-sized system designs.

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