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Pinch Analysis Methodology for Trigeneration with Energy Storage System Design

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Rising energy prices, as well as environmental pollution and depletion of fossil fuel, have increased the need to find alternative energy sources and improve the efficiency of current energy systems. Conventional power plants only use an average thermal efficiency of 30 – 35 % to produce power while the remaining energy is dissipated to the environment. The thermal efficiency can be increased to 80 – 90 % by reusing the waste heat for other applications, such as heating and cooling. A trigeneration system is a technology that can produce power, heating and cooling from a single energy source. Pinch Analysis is a methodology that can help users optimise energy, water and other resources. This paper proposes a novel methodology for developing a Trigeneration Cascade Table (TriGenCT) with energy storage system based on the Pinch Analysis algebraic technique. There are five parts for developing TriGenCT which are data extraction, Single Utility Problem Table Algorithm, Multiple Utility Problem Table Algorithm, Total Site Problem Table Algorithm and TriGenCT with energy storage system. The usage of trigeneration system with storage can save energy up to 202 GWh/y. The development of a TriGenCT with energy storage system can be very useful for engineers and managers to optimize the design of trigeneration systems as well as energy storage systems.

1. Introduction

Rapid industrialisation, rising population and growing global concern on environmental pollution have put pressure on the need to find alternative energy sources and improved efficiency of the current energy systems. Trigeneration is a technology that promotes energy efficiency through a combination of electrical, cooling and heating from thermal energy. Usage of trigeneration systems can increase thermal efficiency from 30 – 35 % to 80 – 90 %, reduce the emission of pollutants, increase reliability and power quality and avoid distribution grid losses (Khamis et al., 2013). Diesel, natural gas, coal and nuclear can be used as fuel in a trigeneration system. Pinch Analysis is a well-established Process Integration methodology that has been used for designing optimal networks for recovery and conservation of resources for more than 40 y (Klemeš et al., 2017). Patole et al., (2016) introduced a Pinch Analysis method using the weighted composite quality index to allocate network of all sources which satisfy the demands based on several quantitative and qualitative indicators. Tibasiima and Okullo (2017) proposed a Pinch Analysis methodology to a typical Ugandan-based brewery process to reduce energy consumption in brewery operations. The methodology for trigeneration analysis based on Pinch Analysis still needs development. The objective of this work is to develop a systematic technique based on Pinch Analysis for optimising the sizing of the trigeneration system, integrated with an energy storage system to satisfy the variable demand requirements of power, cooling and heating in an industrial site. The development of this systematic technique can be a useful tool for engineers and power plant managers to determine the optimal design of trigeneration as well as the energy storage system and thus, improve the reliability of the power plant.

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2. TriGenCT with energy systems

Trigeneration system can generate a combination of electrical, heating and cooling from thermal energy. High-pressure steam (HPS) can be produced from the boiler. The HPS then create a motion by rotating fins in the steam turbine to generate power and produce low-pressure steam (LPS). LPS is then condensed in the condenser producing hot water (HW). Chilled water (CW) can be produced from absorption chiller which utilises the low-temperature waste heat from the HW. The development of a TriGenCT with energy systems can be divided into five parts. This includes data extraction, Single Utility Problem Table Algorithm for an individual plant at different time slices, Multiple Utility Problem Table Algorithm for an individual plant at different time slices, Total Site Problem Table Algorithm for all plants at different time slices and TriGenCT with energy storage systems. The procedure for Single Utility Problem Table Algorithm for an individual plant was introduced by Linnhoff and Flower (1978) and can be further seen e.g. in Klemeš et al. (2018). The procedures for Multiple Utility Problem Table Algorithm for an individual plant and Total Site Problem Table Algorithm for all plants, on the other hand, can be further seen in Liew et al. (2012).

2.1 Data Extraction

Illustrative Case Study for stream data of heating and cooling for Plants A, B, C and D are taken from Varbanov and Klemeš (2011). An illustrative Case Study data for power, on the other hand, are taken from Lam et al. (2003) for Plants A, B, C and D. An iteration method proposed by Ho et al. (2012) is used to determine the exact power capacity needed to supply energy to the demand. Firstly, the preliminary assumption is made where primary source produces 5,000 MWh of total thermal energy in a day. After that, energy sources and demands are cascaded from initial to final time periods in ascending order. The cumulative net energy is then calculated by considering charging and discharging energy of the storage systems. Calculation of the new size of power systems is obtained by using different values of initial and final cumulative energy cascaded. The percentage change between previous and the new size is obtained. Iteration was made until the percentage change is less than 0.05 %. As a result, the primary source then producing 5,570 MWh of total energy in a day, with production of (1) 33.3 % for power, (2) 47.3 % for heating in the form of HPS, LPS and HW (3) 2.7 % for CW and (4) remaining 16.7 % energy losses is being dissipated to the surrounding. A sodium sulphide (Na_2S) battery is assumed to be used as storage for power in this case study whereas zinc carbonate ($ZnCO_3$) is used for storing LPS and HPS. Iron(II) hydroxide ($Fe(OH)_2$) is used as storage for HW and CW. The charging and discharging efficiency for $ZnCO_3$ and $Fe(OH)_2$ are assumed at 80 % and 58 % (Abedin and Rosen, 2012). Charging and discharging efficiency of Na_2S, on the other hand, is assumed to be the same, which is 80 % (Bang, 2005). Inverter efficiency for converting AC to DC and DC to AC is assumed to be 90 % (Haidar et al., 2010).

2.2 TriGenCT with Energy Storage Systems

Construction of TriGenCT with energy storage systems is used to determine the minimum target for outsourced power, cooling and heating, amount of excess power, heating and cooling for storage during the first day and continuous 24 h operations and maximum storage capacity. Table 1 shows TriGenCT with energy storage systems. Development of TriGenCT with energy storage systems is as follows:

1. Column 1 lists the time that has been arranged in ascending order from the Illustrative Case Study and Column 2 lists the time interval based on two adjacent times.
2. A power source and demands for each time interval are listed in Columns 3 and 4 where the power, heating and cooling source are from the trigeneration system. The heating and cooling demands in Column 4, on the other hand, are obtained from the external utility requirement in the Total Site Problem Table Algorithm.
3. Power, heating and cooling generation and consumption in Columns 5 and 6 are obtained by multiplying the time interval by power, heating and cooling source and demand rating.
4. Net surplus/deficit of energies in Column 7 are determined by deducting the energy generation and consumption. A positive value means the energy is in surplus whereas a negative value means the energy is in deficit.
5. The net surplus/deficit of energy in Column 8 represents the surplus energy of higher utility in temperature is converted to deficit energy of lower utility in temperature. Energy losses efficiency for turbine, condenser and absorption chiller due to friction and leakage are also considered when high energy utility converted to lower energy utility. The efficiency of energy losses for turbine, condenser and absorption chiller is 12 %, 13 % (Haldkar et al., 2013) and 30 % (Srikhirin et al., 2001). For example, in this case, 367.18 MWh of HW is converted to CW at a time between 6 to 17 h and 179.09 MWh of energy has lost. The HPS can be converted to a lower steam level to produce power by rotating the turbine if there is a deficit of power at that time interval and excess of HPS. The lower steam level is assumed to increase by 5 % from the HPS supplied to produce power. For example, at a time between

6 to 17 h, 11.62 MWh out of 13.18 MWh of HPS is converted to reduce the negative value of power and at the same time, 0.66 MWh of LPS is also produced, however 1.58 MWh are losses due to friction and leakage.

6. Charging energy in Column 9 for power is obtained by multiplying the new net surplus power in Column 8 by the storage charging and inverter efficiencies which can be obtained from data extraction. Charging energy for heating is obtained by multiplying the new net surplus energy with storage charging efficiency and for cooling is obtained by dividing the new net surplus cooling energy by the charging efficiency.
7. Discharging energy in Column 10 for power is obtained by dividing the new net deficit power by discharging and inverter efficiencies. Discharging energy for heating is obtained by dividing the new net deficit energy by discharging efficiency and for cooling is obtained by multiplying the new deficit cooling energy by discharging efficiency.
8. Infeasible cascade for a start-up is conducted based on Eq(1).

$$E_i = E_{i-1} + E_c + E_{disc}, \tag{1}$$

where;
E_i = energy at the present time; E_{i-1} = energy at the previous time; E_c = Charging energy; E_{disc} = Discharging energy

9. Feasible cascade for start-up and continuous 24 h operations listed in Columns 12 and 13 uses the same equation as Eq(1). Initial energy in the feasible cascade is the absolute value of the most negative energy in the infeasible cascade. These columns can determine the minimum outsourced value of power, heating and cooling during start-up and continuous 24 h operations at the first row, amount of excess power, heating and cooling during start-up and continuous 24 h operations can be determined at the last row of columns and also maximum storage capacity at the maximum values of power, heating and cooling.

2.3 Total Energy Saving of Trigeneration Systems with or Without Storage

The rating for producing power is 77.18 MW as shown in Column 3 in Table 1. The small size of double extraction, condensing steam turbine is the most suitable turbine used because the turbine can generate electricity from 15 kW to 100 MW/h (Elliott Group, 2014). The double extraction, condensing steam turbine also contains two outlets which the first outlet extracts the steam for the feeding heating process whereas the second outlet extracts the remaining steam to the condenser which is suitable for trigeneration system (Turbines info, 2011). Taking coal as a fuel for the trigeneration system, 483 kt is required to generate 5,570 MWh for three applications in one system in a day. Total energy saving of a trigeneration system with or without storage is shown in Eq(2). Excess power, heating and cooling without storage will cause dissipation of energy to the environmental whereas deficit of power, heating and cooling need to be purchased from the grid and other plants.

$$E_s = \sum_{with\ storage}(S_E - M_E) + (S_{HPS} - M_{HPS}) + (S_{LPS} - M_{LPS}) + (S_{HW} - M_{HW}) + (S_{CW} - M_{CW}) - \sum_{without\ storage}(E_P + E_N + H_P + H_N + C_P + C_N), \tag{2}$$

Where;
E_s = Total energy saving; S_E = Excess power; M_E = minimum outsourced power; S_{HPS} = Excess HPS; M_{HPS} = Minimum outsourced HPS; S_{LPS} = Excess LPS; M_{LPS} = minimum outsourced LPS; S_{HW} = Excess HW; M_{HW} = minimum outsourced HW; S_{CW} = Excess CW; M_{CW} = minimum outsourced CW; E_P = Surplus power, E_N = Deficit power; H_P = Surplus heating; H_N = Deficit heating; C_P = Surplus cooling; C_N = Deficit cooling

As shown in Table 1, the minimum target for outsourced power, heating and cooling during the first day obtained at the first row of Column 12 are 0 MWh, 360.08 MWh and 0 MWh. The minimum target for outsourced power, heating and cooling during continuous 24 h operation, on the other hand, can be obtained at the first row in Column 13 as 0 MWh, 360.08 MWh and 0 MWh. The excess power, heating and cooling based on a case study for the first day are 11.35 MWh, 217.88 MWh and 0 MWh. Excess power, heating and cooling from the first day can be brought to the next day. The excess power, heating and cooling for continuous 24 h operations are 11.35 MWh, 1.23 MWh and 0 MWh. External HW of 143.43 MWh needs to be supplied to the demand. Surplus power, heating and cooling can be obtained from positive values in Column 8 whereas deficit power, heating and cooling are obtained from negatives values in the same column. Based on Eq (2), the total energy can be saved up to 553.23 MWh in a day, translating to 202 GWh of energy saved for a year. The maximum storage capacity for power, HPS, LPS, HW and cooling are 151.12 MWh, 0.72 MWh, 418.93 MWh, 544.48 MWh and 0 MWh, where it is based on the highest values in Columns 12 or 13. Power is the most important application that needs to be considered. In this case, because the power is a surplus, the company can sell the excess power to the grid. However, when power is a deficit, the company can buy power from the grid, preferably at off-peak tariff.

Table 1a: TriGenCT with energy storage systems

1	2	3					4				
Time (h)	Time interval (h)	Rating (MW) Source Power	Heating HPS	LPS	HW	Cooling	Demand Power	Heating HPS	LPS	HW	Cooling
0 6	6	77.18	1.30	82.91	25.65	6.32	42.20	1.15	57.98	-20.84	6.32
6 17	11	77.18	1.30	82.91	25.65	6.32	80.00	0.10	57.98	-28.62	39.70
17 20	3	77.18	1.30	82.91	25.65	6.32	96.80	1.15	163.90	130.90	6.32
20 24	4	77.18	1.30	82.91	25.65	6.32	85.60	1.15	57.98	-17.27	6.32

Table 1b: TriGenCT with energy storage systems

5					6				
Generation (MWh) Power	Heating HPS	LPS	HW	Cooling	Consumption (MWh) Power	Heating HPS	LPS	HW	Cooling
463.09	7.79	497.47	153.90	37.93	253.20	6.89	347.87	-125.00	37.92
848.99	14.28	912.03	282.15	69.53	880.00	1.10	637.76	-314.80	436.70
231.54	3.89	248.74	76.95	18.96	290.40	3.44	491.70	392.70	18.96
308.72	5.19	102.60	102.60	25.28	342.40	4.59	231.91	-69.08	25.28

Table 1c: TriGenCT with energy storage systems

7					8				
Net surplus/deficit (MWh) Power	Heating HPS	LPS	HW	Cooling	New net surplus/deficit (MWh) Power	Heating HPS	LPS	HW	Cooling
209.89	0.90	149.60	278.94	0.00	209.89	0.90	149.60	278.94	0.00
-31.01	13.18	274.23	596.97	-367.18	-19.40	0.00	274.93	50.70	0.00
-58.86	0.45	-242.97	-315.75	0.00	-58.81	0.00	-242.98	-315.80	0.00
-33.68	0.60	99.72	171.68	0.00	-33.61	0.00	99.77	171.68	0.00

Table 1d: TriGenCT with energy storage systems

9					10				
Charging energy (MWh)					Discharging energy (MWh)				
Power	Heating			Cooling	Power	Heating			Cooling
	HPS	LPS	HW			HPS	LPS	HW	
151.12	0.72	119.68	223.15	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	219.94	40.56	0.00	-24.25	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	-73.51	0.00	-418.93	-544.48	0.00
0.00	0.00	79.82	137.34	0.00	-42.01	0.00	0.00	0.00	0.00

Table 1e: TriGenCT with energy storage systems

11					12				
Start-up									
Infeasible Cascade (MWh)					Feasible Cascade (MWh)				
Power	Heating			Cooling	Power	Heating			Cooling
	HPS	LPS	HW			HPS	LPS	HW	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	79.31	280.77	0.00
151.12	0.72	119.68	223.15	0.00	151.12	0.72	198.99	503.92	0.00
126.87	0.72	339.62	263.71	0.00	126.87	0.72	418.93	544.48	0.00
53.36	0.72	-79.31	-280.77	0.00	53.36	0.72	0.00	0.00	0.00
11.35	0.72	0.51	-143.43	0.00	11.35	0.72	79.82	137.34	0.00

Available excess power, heating and cooling for first day

Minimum outsourced for first day

Maximum Storage

Table 1f: TriGenCT with energy storage systems

13				
Continuous 24 h operation				
Feasible Cascade (MWh)				
Power	Heating			Cooling
	HPS	LPS	HW	
0.00	0.00	79.31	280.77	0.00
151.12	0.72	198.99	503.92	0.00
126.87	0.72	418.93	544.48	0.00
53.36	0.72	0.00	0.00	0.00
11.35	0.72	79.82	137.34	0.00

Minimum outsourced for continuous 24 h operation

Available excess power, heating and cooling for continuous 24 h operation

3. Conclusion

A new numerical method based on Pinch Analysis called the TriGenCT has been developed to determine simultaneously the minimum target for outsourced power, heating and cooling, amount of excess power, heating and cooling during the first day and continuous 24 h operations, and the maximum storage capacity. The result shows the 11.35 MWh of surplus power can be sold to the grid, taking energy as the most important application that needs to be considered. Heating, on the other hand, in excess conditions for HPS and LPS in continuous

24 h operations which is 1.23 MWh. Excess heating will be sold to the district heating networks. 143.43 MWh of HW is in deficit conditions for 24 h operations which required to buy from the other company. The advantage of the TriGenCT is that this tool can cascade three applications simultaneously rather than only power application in Power Cascade Table developed by Mohammad Rozali et al. (2013). Heat energy losses due to charging and storage system discharging storage are also taken into consideration in this method. The results extracted from the TriGenCT can be used to design an optimum trigeneration system and operating cost can be reduced by using the trigeneration system. By comparing three separate systems producing power, heating and cooling and trigeneration system at the same value, the difference on coal as fuel needed to be burned is 232 kt. The cost that can be saved by using trigeneration system is up to RM 31.92 M/d.

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