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A new framework for optimisation of Pressurised Water Reactor design as a trigeneration system

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Abstract. Conventional nuclear power reactors convert between 30 – 35 % only of the total energy input into electricity while the remaining was wasted. The waste heat is sometimes used for desalination processes while the remaining heat is transferred to a cooling media or lost to the surrounding. Therefore, heat from nuclear reactor can be used to produce heat and power, as well as for cooling in a trigeneration system. This paper presents the Trigeneration System Cascade Analysis (TriGenSCA) for an optimal Pressurised Water Reactor (PWR) design. The TriGenSCA framework allows engineers to determine an optimum utility generation system size and estimate the required amount of external utilities. The analysis includes data extraction, cascade analysis for size estimation and calculation of the new trigeneration system size. The technique also enables users to determine accurate results for energy minimisation based on demand fluctuations. Application of the framework on a case study presented on this paper demonstrates the trigeneration PWR system successfully saved energy of 328GWh/y (97 %).

1. Introduction

Trigeneration is a system of technology that produces power, heating and cooling from a single source of fuel. Trigeneration has been one of the most effective use of energy available with a history of more than 100 years [1]. The trigeneration was mainly utilized in a large-scale centralized power plants and industrial applications. Conventionally, production of electricity and heat are by purchasing electricity from the local grid and heat is generated through burning fuel in a boiler. Trigeneration system, however, reuse by-product heat which can be as much as 60 – 80 % of total primary energy for different applications. Most nuclear power plants are almost entirely comprised of PWR [2]. Khamis *et al.* [3] stated installing a trigeneration system within a nuclear power plant ecosystem allows investors to achieve return on investment within five to six years. Pinch Analysis (PA) is a well-established methodology for designing an efficient resource utilization system. Manan *et al.* [4] first introduced the cascade analysis technique to determine the minimum water targets for water networks.



The techniques have been extended to determine the minimum targets for CO₂ [5], resource supply chain and biomass energy generation and storage capacity [6] as well as energy production in integrated energy system such as trigeneration system [7]. Jamaluddin *et al.* [7] developed a novel systematic methodology based on Pinch Analysis for trigeneration system to determine the minimum target for outsourced power, heating and cooling during the first and continuous 24 h operations, and the maximum storage capacity, simultaneously. Varbanov *et al.* [8] introduced Time Slice (TSL) as set of time intervals in integrated energy system to minimize heat waste and carbon footprint of the considered sites. The development of trigeneration system based on Pinch Analysis, however, still open for further development. The objective of this paper is to design an optimum PWR with a trigeneration system and to estimate the amount of external utilities required. The work presented in this paper can help engineers to determine the appropriate size of PWR with a trigeneration system for the load demand, thereby reducing operation cost of the power plant.

2. Methodology

Initially, PWR as a trigeneration system includes a steam generator to generate very high-pressure steam (VHPS) at varying pressures: from high-pressure steam (HPS) to low-pressure steam (LPS). A condenser is used to produce hot water (HW) whereas an absorption chiller is used to produce chilled water (ChW). Figure 1 shows the conceptual design of a trigeneration PWR system. The usage of electricity, heating and cooling as upstream and downstream of the systems is provided. All parameters for simulation are based on PWR NPP in Three Miles Islands [9]. The demand for heating and cooling are taken from [10] for heating and cooling and [11] for electricity. The minimum temperature difference between utility and process as an energy trade-off is set for both sides. As stated by [9], the minimum temperature difference of PWR NPP in Three Miles Island is 27.8 °C. The minimum temperature difference of Plants A, B, C and D are 12 °C [10]. Methodology of designing an optimal design trigeneration PWR system is shown in Figure 2.

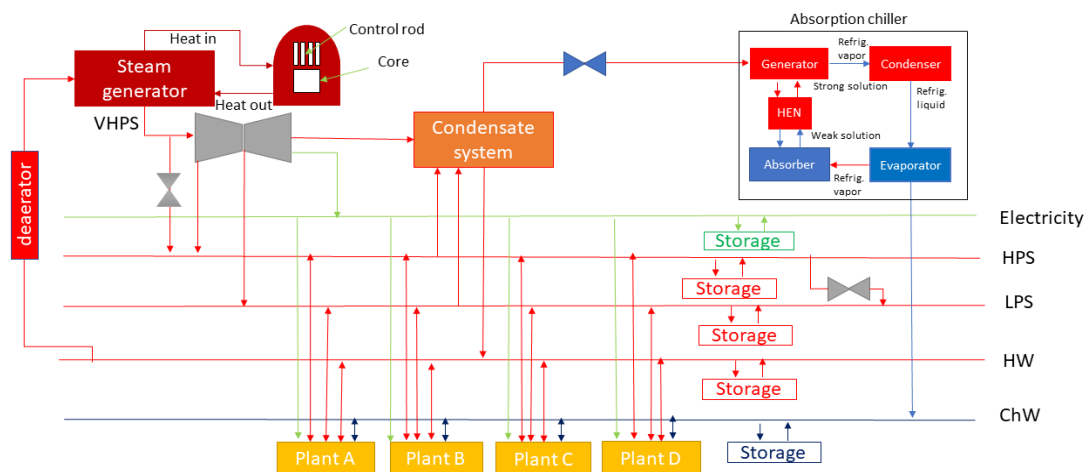


Figure 1. Conceptual design of trigeneration PWR system

2.1. Data Extraction

In the first step, data need to be extracted at demand side are the power rating and time for electricity demand requirement, and flow rate, heat capacity, temperature and time for heating and cooling demand requirements from each industrial sites served by the centralized PWR power supply system. In this paper, the methodology is illustrated using an illustrative case study. PWR as a source side for power, heating and cooling can be obtained from [9]. Energy storage systems for power, heating and cooling are also taken into consideration in the total utility sites system. The energy losses due to charging and discharging of power, heating and cooling are considered in the energy storage systems. Energy losses due to the conversion of the power of AC-DC and DC-AC is also considered. Sodium

sulphide (NaS) is used for the power storage system. NaS battery is highly efficient and can accommodate a large storage capacity of up to 245 MWh. Meanwhile, zinc carbonate (ZnCO_3) is used for HPS and LPS storage systems. HW and ChW use Iron (II) hydroxide ($\text{Fe}(\text{OH})_2$) as energy storage systems. ZnCO_3 and $\text{Fe}(\text{OH})_2$ are phase change materials (PCM) which enables them to store important quantities of heat over narrow temperature ranges, without a large volume changes.

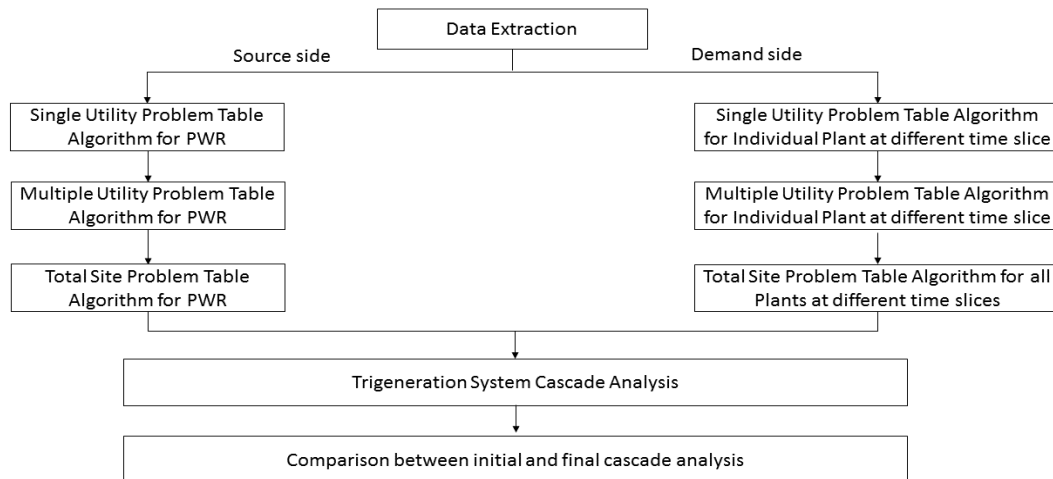


Figure 2. Methodology for determining the optimal trigeneration system

2.2. Single Site Utility Problem Table Algorithm

Single Site Utility Problem Table Algorithm (PTA) is proposed by [12] as the second step to determine the Pinch Temperature as well as to conclude values of minimum external heat and cooling needed in the systems. There are four-time slices for industrial Plants A, B, C and D can be determined which are 0 to 6 h, 6 to 17 h, 17 and 20 h and 20 to 24 h, and every time slice is performed through Single Site Utility PTA. On the other hand, the source side of PWR only has one-time slice which is 0 to 24 h since the PWR generates constant power, heating and cooling for 24 h of operation. The methodology of Single Site Utility PTA can be referred to [12].

2.3. Multiple Site Utility Problem Table Algorithm

Liew *et al.* [13] have extended the PTA to identify pockets and target the exact amounts of utilities needed at specific utility temperature interval. Pinch Temperature from Single Site Utility PTA is needed in this method to determine heating and cooling regions. The method is called the Multiple Utility Problem Table Algorithm. The method is conducted as a third step for all four-time slices for industrial Plants A, B, C and D and one time slice for PWR. Further detail of the methodology can be referred in [13].

2.4. Total Site Utility Problem Table Algorithm

Total Site Utility Problem Table Algorithm (TS PTA) proposed by [13] is used as the fourth step to summarize the different utilities from the highest to the lowest temperature. The TS PTA is conducted at different time slices and total external utility requirements can be obtained on different temperatures at every time slices. The construction of TS PTA can be followed as presented by [13].

2.5. Trigeneration System Cascade Analysis

Trigeneration System Cascade Analysis (TriGenSCA) is a numerical technique of Pinch Analysis methodology to determine the optimal storage size and amount of energy needed from the PWR power plant with trigeneration to supply the energy needed in terms of electricity, heating and cooling by the industrial plants. This methodology is modified from the work of [6] which proposed Electric System Cascade Analysis (ESCA) which only cascade power as the utility to the load demand. There are four main steps that can be used in the TriGenSCA which are data extraction, cascade analysis for sizing

estimation, calculation of the new size of trigeneration system, calculation of new sizing of trigeneration system and percentage change of the new and previous sizing of trigeneration system. Iteration method is involved in this method and will be stopped when the percentage change of new and previous sizing of trigeneration system is equal to or less than 0.05%.

In the first step, results from TS PTA for source and demand sides for heating and cooling is used as data in TriGenSCA. Power data for demands side can be obtained directly from [11]. Power data for source side is obtained from [9]. The second step for constructing TriGenSCA is the construction of cascading analysis for sizing estimation is modified from ESCA in [6] work. The detail construction of TriGenSCA can be referred to [7] and can be shown in Table 1. Time interval of 1 h is used to obtain the initial and final energy of the trigeneration system. The initial and final energy of the trigeneration system is used to calculate the new size of the trigeneration system. The calculation of the new size of the trigeneration system is in the third step to determine the optimal energy generation. Equation (1) shows the calculation of the new size of trigeneration system. The calculation of the new size of trigeneration system is iterated until differences between the new and previous size of trigeneration system equal to or less than 0.05%. As stated by [6], a value of 0.05% is set as a tolerance to make sure the accuracy of the results. Percentage change between the previous and new size of trigeneration system need to be iterated until the value is equal to or less than 0.05%. Equation (2) shows that the percentage change between the new and previous sizing of trigeneration system.

$$S_{B(new)} = \frac{E_{t(final)} - E_{t(initial)}}{T} \quad (1)$$

where;

$S_{B(new)}$ = New size of trigeneration system;

S_B = Previous size of trigeneration system;

$E_{t(final)}$ = Final energy content at t = 24 h;

$E_{t(initial)}$ = Initial energy content at t = 0 h;

T = Total time duration

$$P = \frac{S_{B(new)} - S_B}{S_B} \times 100 \quad (2)$$

where;

P = Percentage change;

$S_{B(new)}$ = New size of the trigeneration system;

S_B = Previous size of the trigeneration system

Table 1a. Construction of TriGenSCA before iteration

| Time (h) | Demand (MW) | | | | | Energy generation (MW) | | | | |
|----------|-------------|-------|-------|----|-------|------------------------|-------|-------|-------|-----|
| | Power | HPS | LPS | HW | ChW | Power | HPS | LPS | HW | ChW |
| 1 | 52.25 | 1.148 | 78.61 | 24 | 44.24 | 60 | 0.012 | 64.89 | 97.39 | 0 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 24 | 52.25 | 1.148 | 78.61 | 24 | 44.24 | 60 | 0.012 | 64.89 | 97.39 | 0 |

Table 1b. Construction of TriGenSCA before iteration.

| Time (h) | Net energy requirement (MW) | | | | | New net energy requirement (MWh) | | | | |
|----------|-----------------------------|-------|--------|-------|--------|----------------------------------|-----|--------|-------|-----|
| | Power | HPS | LPS | HW | ChW | Power | HPS | LPS | HW | ChW |
| 1 | 7.75 | -1.14 | -13.72 | 73.39 | -44.24 | 7.75 | 0 | -14.86 | 15.88 | 0 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 24 | -35.67 | -1.14 | -17.72 | 73.39 | -44.24 | -35.67 | 0 | -18.86 | 15.88 | 0 |

Table 1c. Construction of TriGenSCA before iteration.

| Time (h) | Charging energy (MWh) | | | | | Discharging energy (MWh) | | | | |
|----------|-----------------------|-----|-----|-------|-----|--------------------------|-----|--------|----|-----|
| | Power | HPS | LPS | HW | ChW | Power | HPS | LPS | HW | ChW |
| 1 | 5.58 | 0 | 0 | 12.70 | 0 | 0 | 0 | -25.61 | 0 | 0 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 24 | 0 | 0 | 0 | 12.70 | 0 | -49.54 | 0 | -32.51 | 0 | 0 |

Table 1d. Construction of TriGenSCA before iteration.

| Time (h) | Cumulative energy (MWh) | | | | | New cumulative energy (MWh) | | | | |
|----------|-------------------------|------|--------|--------|-----|-----------------------------|------|--------|--------|-----|
| | Power | HPS | LPS | HW | ChW | Power | HPS | LPS | HW | ChW |
| 1 | 0 | 0 | 0 | 0 | 0 | 811.94 | 0 | 153.69 | 0 | 0 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 24 | -811.94 | 0.13 | -91.82 | 114.32 | 0 | 0 | 0.13 | 61.87 | 114.32 | 0 |

Initial energy content

Final energy content

2.6. Comparison between Initial and Final Cascade Analysis

The results of initial and final energy contents using TriGenSCA can be compared to determine the total energy that is deficit/excess. A positive value of total energy represents energy in excess whereas a negative value of total energy represents energy in deficit. Figure 3 shows the comparison between the initial and final cascade of PWR as trigeneration system using TriGenSCA. Equation (3) shows the total energy that is required/excess using TriGenSCA. Based on the calculation, the energy that is required from external at initial cascade analysis is 922.15 MWh whereas 22.62 MWh of energy are in excess at final analysis.

$$E_T = \sum_{i=1}^n \dots - \sum_{i=1}^n \dots \tag{3}$$

where;

E_T = Total energy required (-)/excess (+);

$\sum_{i=1}^n$ Summation of final energy content;

$\sum_{i=1}^n$ Summation of initial energy content

3. Conclusions

A new methodology based on the optimisation technique to obtain the optimal size of trigeneration system called the Trigenation System Cascade Analysis (TriGenSCA) has been developed. The work is an extension of the methodology by [6] which only considered power whereas this method considers power, heating and cooling optimal energy, simultaneously. The development of TriGenSCA can save energy up to 899.53 MWh/d (922.15 MWh - 22.62 MWh = 899.53 MWh) or 328 GWh/y. Work is in progress to extend the methodology to consider cost and maximum energy storage capacity. Development of this methodology can help designers, engineers and energy manager to minimise the total energy usage and operation cost.

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