PLACEMENT AND SIZING OF COMBINED HEAT AND POWER SYSTEMS CONSIDERING COST/BENEFIT ANALYSIS

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ABSTRACT

This paper presents a cost/worth analysis approach for optimal placement and sizing of Combined Heat and Power (CHP) systems. Particle Swarm Optimization (PSO) as a powerful optimization technique, is employed for optimization. Different benefits brought up by CHP systems are taken into account as a multi-objective decision making. Economic factors such as power and heat selling, reliability improvement, loss reduction, deferred upgrading investment and CHP costs are considered in this study.

This paper conducts two separate case studies, 6-bus meshed test system and 14-bus radial test system to demonstrate economic feasibility for investment planning when cost and CHP benefits are taken into account. The impacts of considering different parameters such as the rate of load growth and interest are studied. Results indicate that the proposed methodology is capable of finding the best location and the optimal size of CHP that can cause improvement in network operation along with financial benefits.

INTRODUCTION

Restructuring of power systems have created an increased interest in Distributed Energy Resources (DERs), which is expected to play an increasingly essential role in electric power systems operation and planning. Most important economic benefits bring about by DER technologies to the power systems are modelled and quantified in economic terms in [1]. A cost/worth analysis is used in [2] which studies economic consideration of using DG by considering load point reliability indices and loss reduction in the power system. Currently, application of DER and specially Combined Heat and Power (CHP) systems in factories, buildings and houses has an essential role in providing improved energy efficiency and demand-side growth management [3]. A CHP system simultaneously produces electrical and thermal energy from a single fuel [4]. While a common gas-powered generation system typically has a heat efficiency of about 30–37% along with an energy loss of almost 40–50% as waste heat [5-6] cogeneration systems are able to mitigate this huge loss of energy effectively.

In [7] the impact of deployment of CHP-based DERs on microgrid reliability has been discussed. The loss sensitivity index of each bus has been taken into account for the selection of optimal locations of CHPs. Maximum benefit-to-cost ratio of the microgrid owner has been considered to achieve the optimal size of the CHP.

Reliability and availability modelling of combined heat and power (CHP) systems has been addressed in [3]. A mixed integer nonlinear programming model has been developed in [8] for optimal sizing for residential CHP systems. Particle Swarm Optimization (PSO) is a heuristic optimization algorithm that has been widely used in different problems especially the locating problems in power system. It is a heuristic global optimization approach and its main strength is in its simplicity and fast convergence [9].

This paper presents a new methodology to solve the complicated problem of finding the optimal location and size of the CHP. PSO is employed as an optimization tool to find the proper location and size of CHPs. The costs associated with generation of electricity and heat from CHP can be categorized into capital investment cost, operation and maintenance (O&M) costs. On the other hand, benefits include earnings on selling of the generated electricity and recovered waste heat, energy loss reduction, reliability improvement, and deferral or elimination of upgrade investment. All of these costs and earnings have been calculated in terms of the Present Value Factor (PVF), compounded over the study period. It is a common practice for a decision maker to translate future cash flows into their present values [7]. The interest rate is being used here for the calculation of the PVF.

PARTICLE SWARM OPTIMIZATION

Heuristic methods may be used to solve some combinatorial multi-object optimization problems. These methods are called "intelligent," because the move from one solution to another is done using rules based upon human reasoning. The most important advantage of heuristic methods lies in the fact that they are not limited by restrictive assumptions about the search space like continuity, existence of derivative of the objective function, etc. Several heuristic methods can be addressed such as: Tabu Search (TS), Simulated Annealing (SA), Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) [10]-[12]. Each one has its own pros and cons which make them possible to apply to the appropriate problems, where in this paper PSO method is selected as an intelligent optimization method. Kennedy and Eberhart first introduced PSO method, which is also an evolutionary computation technique [9],[13]. Similar to GA, PSO is a population-based optimization tool. The system is initialized with a population of random solutions and searches for the optimal by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation.

PROPOSED METHOD

Optimal CHP placement and sizing is aimed to find the optimal CHP location and size in order to maximize or minimize a specific objective function with respects to considered variables and constraints. An important approach is to incorporate the cost and benefit of CHP application in the objective function.

Proposed Approach

Fig. 1 shows proposed optimization procedure. In the proposed procedure after initializing the PSO parameters, first population is randomly initiated. Then for the t^{th} year of the years in the study time horizon (N_{Year}) the load, electricity and heat are determined considering the interest rate. The benefits of the CHP are calculated in the year *t* in the next step. Then cost associated with application of CHPs in the t^{th} year is calculated. This process is repeated until all the years in the time horizon are considered. Then the overall BCR of the solution (particle) created by the PSO algorithm is calculated. The position and velocity of the particles as well as *p_best* and *g_best* are updated in the next step.
This process is repeated until the termination criterion is satisfied. The largest value of BCR that was found and its corresponding design will be selected as the optimal solution. Considering the load growth rate of α, the load associated with *m*-th design and *t*-th year can be calculated using:

$$Pd_t = Pd_1 \times (1+\alpha)^{t-1} \tag{1}$$

where, Pd_1 and Pd_t are load at the first and the *t*th years, respectively.
Here, a cost/worth approach is explained for placement and sizing of a CHP. The objective function is the benefit to cost ratio of CHP application. CHP cost is composed of the Investment Cost (IC), Operation Cost (OC) and Maintenance Cost (MC). CHP benefit is composed of Reliability Improvement (RI), Upgrade Investment Deferral (UID), Power Purchase Saving (PPS), Heat Purchase Saving (HPS), and Loss Reduction (LR) of the system due to application of CHP. The objective function is defined as follows:

$$Max\ BCR = \frac{Benefit_{CHP}}{Cost_{CHP}} \tag{2}$$

where, *BCR* refers to Benefit to Cost Ratio, $Benefit_{CHP}$ and $Cost_{CHP}$ refer to the total benefits and total costs of CHP application, respectively.

$$Benefit_{CHP} = \sum_{k=1}^{N_{CHP}} \sum_{t=1}^{N_{year}} [PPS_{k,t}^{CHP} + HS_{k,t}^{CHP} + \Delta CIC_{k,t}^{CHP} + UID_{k,t}^{CHP} + \Delta CLoss_{k,t}^{CHP}] \tag{6}$$

$$Cost_{CHP} = \sum_{k=1}^{N_{CHP}} IC_k^{CHP} + \sum_{t=1}^{N_{year}} (OC_{kt}^{CHP} + MC_{kt}^{CHP}) \tag{7}$$

where, N_{CHP} and N_{year} are the number of CHPs and number of years in study period, respectively.

1. DR Benefits Calculation

All of the benefits of CHP systems cannot be modelled on economic values such as environment benefits and voltage improvement which are quantified in non-economic values in [14]. In this study, economic factors such as RI, LR, UID, PPS and HPS are quantified in economic terms to study benefits of CHP.

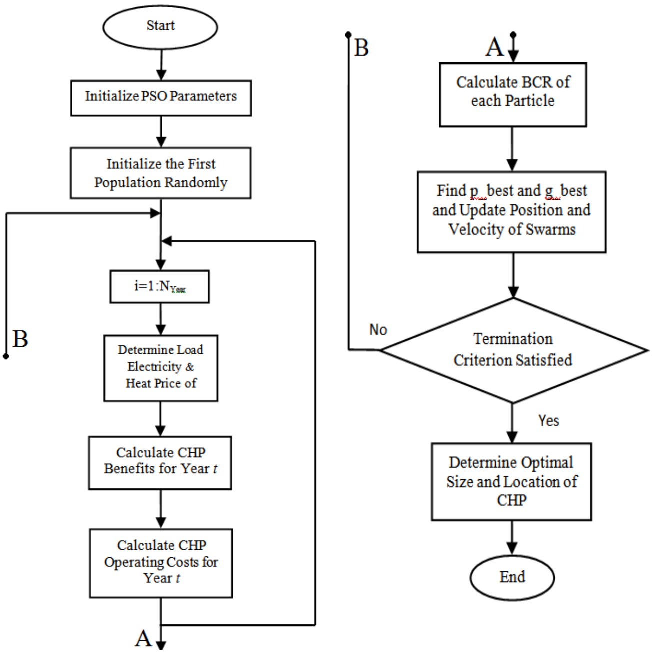

Fig1. Flowchart of the proposed deterministic approach.

•Upgrade Investment Deferral (UID)

As electricity is produced near the loads especially during peak load hours, power flows are essentially reduced (as long as the total DR capacity does not exceed the local load), thus deferring the need to upgrade some overloaded feeders [1].
The value of this benefit of CHP depends mainly on the power system cost-structure, network configuration and planning strategies, the type of feeder and the area that CHP will be located at and also load growth rate. An annual value of 120 $/kVA for the deferral benefit is considered in this study based upon [1],[15].

•Power Purchase Saving (PPS)

PPS represents the saving due to reduction in electric power that must be purchased from electricity market to supply the customers.

$$PPS = \sum_{t=1}^{N_{year}} \sum_{k=1}^{N_{CHP}} P_{k,t}^{CHP} \times EP_t \tag{3}$$

where, $P_{k,t}^{CHP}$ is the output power of the *k*-th CHP unit at the *t*-th year and EP_t is the energy price at the *t*-th year. Considering interest rate (IR), the value of EP for the *t*-th year can be calculated using

$$EP_t = EP_1 \times (1+IR)^{t-1} \tag{4}$$

•Heat Purchase Saving (HPS)

HPS represents the saving due to purchased heat to supply the customers.

$$HPS = \sum_{t=1}^{N_{year}} \sum_{k=1}^{N_{DG}} H_{k,t}^{CHP} \times HP_t \tag{5}$$

where, $H_{k,t}^{CHP}$ is the heat output of the *k*-th CHP unit at the

t-th year and HP_t is the heat price at the t-th year. Considering interest rate (IR), the value of HP for the t-th year can be calculated using

$$HP_t = HP_1 \times (1+IR)^{t-1} \quad (6)$$

•*Loss Reduction*

Power losses in distribution systems are very important for the utilities. Losses of the system reduce the efficiency of transmitting energy to customers. The total reduction of real power losses in a distribution system can be calculated by (20).

$$LRR = \sum_{t=1}^{N_{year}} (P_{Loss,t} - P_{Loss,t}^{CHP}) \times EP_t \quad (7)$$

where, $P_{Loss,t}$ is the active power loss before installing CHP units in the distribution system at the t-th year and $P_{Loss,t}^{DR}$ is the total active power loss after installation of CHP units in the network at the t-th year.

•*Reliability Improvement (RI)*

CHP units can have a positive influence on distribution system reliability if they are located properly. It is considered that the CHP can still supply loads in the case of main source unavailability. Therefore, there will be a reduction of the duration related indices since part of the load can be attended by the CHP while the main supply interruption cause is being repaired. Reliability improvement of the system after installation of the CHP is modeled as follows:

$$RI = \sum_{t=1}^{N_{year}} CIC_t - CIC_t^{CHP} \quad (8)$$

where, CIC_t is the Annual Customer interruption cost, without CHP application ($), at the t-th year and CIC_t^{CHP} is the Annual Customer interruption cost, when CHP is applied in the network at the t-th year. The value of loss load is considered to be 1000$/MVA [16].

2. DR Costs Calculation

Cost of DR is composed of three components as follows:

IC_k : Initial cost of the k-th DR

OC_{kt} : Operating cost of the k-th DR at the t-th year

MC_{kt} : Maintenance cost of the k-th DR at the t-th year

Initial cost (IC) includes procurement, installation costs and costs of required equipments for connection of CHP to transmission system. Operating cost (OC) is the fuel cost that will be calculated for each year using IR. Maintenance cost (MC) consists of maintenance and repair costs.

SIMULATION RESULTS

The proposed method is applied to two different case studies. Among the two, the first one is studied on six-bus meshed network; case 2 is on radial 14-bus test system. Load profiles (thermal and electric), of these test system are borrowed from [7]. The cases are studied at peak demand with the cost benefit of CHPs and heat recovery equipment. PSO parameters are presented in Table I.

TABLE I
PSO PARAMETERS

SWARM SIZE	C1	C2	W1	W2	ITERMAX
30	1.70	1.70	0.90	0.40	200

For the cost-benefit analyses, the focuses are mainly given to benefits, such as electricity and heat selling, system-loss reduction, reliability improvement and upgrade investment deferral. The interest rate is 0.1 p.u.; average utilization (u): 40%; and the economic life cycle is considered to be 5 years [7]. The price of utility electricity is U.S.$0.12/kWh and the cost of heat is U.S.$0.05/kWh [7]. The data for microturbine as prime mover of CHP (U.S.$/kW/yr): the investment cost is U.S. $1000/kW. The maintenance cost plus operation cost plus fuel cost are 779.64/kW/Yr. Data of heat exchanger (in per unit) are: The turnkey cost is U.S.$190/kW. The (O&M) fixed and variable costs are assumed zero. The efficiency is 0.8 [7]. The heat/electricity ratio is considered to be 1.5 based on [10]. The following assumptions are made based on [3] to model the reliability and the impact of CHP on it. In 98.39999% of the cases, the CHP system generates hot water, and in 94.2074% of the cases, the CHP generates electricity. When the generator is in parallel with the distribution network, the total reliability of the system will be 99.9994%, considering the reliability of the distribution network to be 99.9897%. The customer interruption cost is considered to be 1 $/kWh [16].

6-Bus Meshed Test System

Table II shows the result of deterministic optimal locating and sizing problem for six-bus meshed test system. The best solution is a CHP with power capacity of 14.478kW at bus 6. The maximum heat capacity of this unit will be 21.717 based upon aforementioned assumptions. The results show that BCR is very high for this placement problem, and thus it can be concluded that application of CHP in distribution system is economically feasible.

14-Bus Radial Test System

Table III shows the result of deterministic problem of optimal locating and sizing of 14-bus radial test system. Seven solutions that have the maximum of BCR are ranked in this table. It is interesting that all solutions have the same BCR and the ranking is made based on the solution that has the lower number of CHP units. The best solution is a CHP with power capacity of 30.5kW at bus 6 and a 41.175KW CHP unit at bus 14. The maximum heat capacity of these units will be 45.75KW and 61.763KW respectively. The results show that BCR is still high for this placement problem in this case, and the investment costs will be returned in less than 3 years.

TABLE II
OPTIMAL LOCATION AND SIZE OF ELECTRIC POWER OF CHP UNITS
(SIX-BUS CASE)

Rank \ Bus	1	2	3	4	5	6	BCR
1	0	0	0	0	0	14.478	2.046805
2	0	0	0	0	0	14.9498	2.046793
3	0	0	0	0	0	14.949	2.046793
4	0	0	0	0	0	14.949	2.046793
5	0	0	0	0	2.621	12.541	2.046316
6	0	0	0	0	3.5788	9.062	2.045554
7	0	0	0	0	4.3246	8.047	2.045159
8	0	1.4266	6.5753	2.3016	4.1518	7.1828	2.039663
9	0	1.7219	22.664	5.5904	4.1685	5.4389	2.036416
10	0	1.7219	22.664	5.5904	4.1685	5.4389	2.036416

TABLE III
OPTIMAL LOCATION AND SIZE OF ELECTRIC POWER OF CHP UNITS
(14-BUS CASE)

Bus #	Solutions Priority						
	1	2	3	4	5	6	7
1-4	0	0	0	0	0	0	0
5	0	0	11.586	11.510	0	0	25.797
6	0	61	0	61	0	5.106	0
7	0	0	0	0	0	0	6.101
8	30.500	0	30.500	0	25.765	26.530	22.954
9	0	10.592	0	16.375	18.605	18.605	0
10	0	0	0	0	15.756	17.727	22.588
11-12	0	0	0	0	0	0	0
13	0	0	0	0	27.450	27.450	12.858
14	41.175	27.157	41.175	28.505	41.175	41.175	28.934
BCR	1.9851	1.9851	1.9851	1.9851	1.9851	1.9851	1.9851

CONCLUSION

This paper has proposed an efficient method for optimal locating and sizing of CHP units. A cost/benefit analysis is applied to find optimal size and location of CHP units. This method considers economic factors such as reliability improvement, loss reduction, upgrade investment deferral and CHP costs. The results of applying proposed method on two different distribution test systems show that the proposed method is effective in finding optimal location and proper size of CHP units that reduce total cost of the system operation effectively and increase social welfare.

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