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Value-based operational strategy at the planning of CHP-based micro-grid

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Abstract
CHP-based micro-grid is stipulated to serve its customers with both electrical as well as thermal demand simultaneously, but from operational point of view, it is to opt either tracking of electrical demand profile or thermal. At the planning stage, owner of the micro-grid could evaluate which mode would be most economically beneficial to his system for investment. Maximization of net present value (NPV) of the 6-bus meshed and 14-bus radial micro-grid have been used in the present paper as an important decision making tool, along with internal rate of return (IRR) and payback period (PP) as supporting tools. As per the above tool, higher the benefits accrued from the system at lower investment, better is the choice of the mode of operation. As both higher benefits and lower investment are related with proper locations, capacity-sizes and types of DERs, Loss sensitivity index (LSI) method has been used, here, to take care of optimal locations, whereas optimal sizes and its separation into micro-turbines and diesel generators have been done using particle swarm optimization (PSO) technique with an object to maximization of NPV under certain power quality and reliability (PQR) constraints.

Keywords: Particle swarm optimisation, Loss sensitivity index, Micro-grid, Energy storage.

1. Introduction

Major shortcomings of large central power plants using coal, oil, and gas are alteration of global climate due to emission of huge amount of greenhouse gases, possibilities of blackouts of August 2003 in North America and November 2006 in Pan-Europe, loss of generation due to natural disaster like Hurricane Katrina in 2005. Besides, there is depletion of reserves of fossil fuels. Lastly, deregulation and restructuring of present electricity market encourage participation of large number of Independent Power Producers (IPP) to unleash competition in the market. So, there is a shift of one's reliance from central system to many more smaller-scale and local sources. When penetration levels of these micro-source units become high, excessive voltages, unacceptable increase in fault levels, voltage unbalance and overloading may occur. Ultimate solution, therefore, is the coordinate operation of these units to form a micro-grid, which enhances local reliability, reduce feeder losses, support local voltages, provide increased efficiency through using waste heat combined heat and power (CHP), voltage sag correction or provide uninterruptible power [1-6]

Investment in micro-grid, like other projects, is a complex decision and no single criterion provides a unique solution to arrive at the decision. Pay back period as an investment criterion would give a ranking of project on the basis of how quickly investment cost can be recovered. On the other hand, net present value (NPV) criterion is an absolute figure to decide whether investment in a particular project should be made. If NPV is higher than zero, then investment in the project is worthwhile. NPV, being an absolute figure, does not provide us with the information on the rate of return on investment. Internal rate of return (IRR) is another tool of using discounted cash flow for arriving at the worth of the project and this rate of return is obtained at NPV =0 or BCR=1. IRR itself is a discount rate and a ceiling limit of our preference for present over the future. A higher IRR expresses the higher capacity of the project to generate benefits over a period of time. It is a common practice for a decision maker to translate future cash flows into their present values. Discounting is the process of determining present value of a series of future cash flows. Interest rate (*ir*), inflation rate (*if*) are the two discount rates being used, here. This paper uses diesel generators and micro-turbines as two CHP-based DERs. Micro-turbines have low emission, higher thermal output at 400^0F or above and quiet operation. In contrast with the micro-turbines, diesel exhaust is nearly stoichiometric, exhaust heat is typically used to generate hot water at about 230^0F or lower pressure (15 psig) emission is comparatively high but can be reduced with selective catalytic reduction (SCR). [7-10]

Many researchers had worked on the economic analysis of optimal deployment of distributed energy resources (DER) using genetic algorithm, tabu search, evolutionary programming, GAMS, DER-CAM etc. J. Teng et. al.[9] proposed a economic analysis for distributed generation planning using genetic algorithms. Authors did not consider micro-grid concept and took power loss reduction and customer interruption cost (CIC) into account as benefit of distributed generators placement. Zoka et. al.[10] evaluated, for six types of consumers, economic feasibility of micro-grid on the basis of minimization of total annual customer cost which consisted of optimal operation cost of distributed generators, micro-grid construction cost and power interruption cost (PIC). Mitra et. al. [11] presented a dynamic programming based optimal size, site and mix of DERs to meet electrical and thermal loads under reliability constraint. Dugan et. al. [12] presented a discussion on economic viability of distributed generator investment option and compared with its traditional counterpart, like up-gradation by feeder and/or substation. Costa et. al. [13] identified all relevant costs and benefits of micro-grid relating to consumers, distribution operators etc. and built a decision model within regulatory framework considering reliability model of uncertainty, global economic benefit for consumers and micro-generators. Asano and Bando [14] presented a decisive methodology to design three CHP-based micro-grid with an object to minimize annual cost. Siddiqui et. al. [15] uses DER-CAM technique to minimize the cost of meeting the known electrical and thermal loads of micro-grids and for given utility tariffs, fuel cost and equipments performance data, this paper proposes a model of location and optimal selection of DER system, which could work parallel to macro-grid.

The present paper conducts two separate studies for decision of investment planning of 6-bus meshed and 14-bus radial micro-grid based on operational strategies of whether tracking of electrical demand or thermal is most economically feasible. Investment decision is influenced by the optimal deployment of DERs in micro-grid where locations of DERs are determined by loss sensitivity indices (LSI). Optimal size and its separation into micro-turbines and diesel generators are determined using particle swarm optimization (PSO) technique with maximization of NPV of the micro-grid. IRR and PP are the two additional tools being used, here, in support of investment decision. PSO was developed through simulation of a simplified social system and has been found to be robust in solving continuous, non-linear as well as discrete optimization problems. The PSO technique can generate high quality solution within shorter calculation time and has more stable convergence characteristics than other stochastic methods. [16]. The contents of this paper are organized into nine sections. Following the section on introduction, section 2 provides detailed formulations of the problem. Section 3 gives a brief overview of PSO technique. Section 4 details the PSO algorithms in the context of present problem. Section 5 includes necessary figures, results and discussions of two study cases. The conclusion is drawn in section 6. References are appended last.

2. Problem formulations

As per the analysis of the system, problem formulations are divided into following subsections.

2.1 Optimal location of DERs

Optimal locations of the DERs are determined on the basis of loss sensitivity indices and its equation (1) is based on Newton-Raphson load flow method.[26]

$$\frac{\partial \mathrm{P}_l}{\partial \mathrm{P}_i} = \left[J_{L1}\right] * \left[\frac{\partial \mathrm{P}_l}{\partial \delta_i}\right] \tag{1}$$

where $\left[J_{L1}\right]$ is Jacobian sub-matrix of $[J^T]^{-1}$ i.e., containing all $[\partial\delta_i / \partial P_i]$ terms.

2.2 Optimal size and type of DERs

In the context of determination of optimal size and type of DERs, the objective function is framed as

$$Max(NPV) \tag{2}$$

2.2.1 PQR constraints

- Bus voltage tolerance limit

$U_{i\min} \le U_i \le U_{i\max}$

- Limit on the active and reactive power generation of the DER

$P_{i\ \min} \le P_i \le P_{i\ \max}$

$Q_{i\ \min} \le Q_i \le Q_{i\ \max}$

- Line flow limits (e.g. must be below thermal limits) and takes care of internal congestion of the micro-grid

$S_{ij} \le S_{ij\ \max}$

- Limit on active and reactive power injection to slack bus:

P_1 and Q_1 are made as small as possible (nearly zero). This reduces the power drawl from utility to zero.

2.2.2 Separation of capacity into types

Separation of DER capacities into diesel generators (DE) and micro-turbines (MT) are done using equations (3) to (5),

$$MT(i) + DE(i) = Pg(i) \tag{3}$$

$$MT(i) = Pg(i) * \frac{Cost2}{Cost1 + Cost2} \tag{4}$$

$$DE(i) = Pg(i) - MT(i) \tag{5}$$

where $MT(i)$ is Micro-turbine capacity at i^{th} bus; $DE(i)$ is the diesel engine capacity at i^{th} bus, *Pg(i)* is the total generating capacity at i^{th} bus. *Cost1*and *Cost2* are respectively per unit DER capacity cost of micro-turbines and diesel generators. Linear relation between cost and DER capacity has been considered.

2.2.3 Equations for economic feasibility

Payback Periods (*PP*): For a project with equal annual receipt,

$$PP = \frac{I_0}{C_t} \tag{6}$$

NPV formulation is as follows: Present value factor (*PVF*) is given by

$$PVF = \frac{(1 + if)}{(1 + ir)} \tag{7}$$

$$NPV = -I_0 + \sum_{t=1}^{EL} C_t \times (PVF)^t \tag{8}$$

$$C_t = \sum annual(Benefit - (O\ \&\ M)Cost) \tag{9}$$

$$Benefit = [C_e \times (\Delta E_{loss} + E_{excess}) + C_{etv} \times \sum E_{load}(h,d,s) + C_{etf} + C_{etd} \times D_p + C_{ht} \times \Delta H_w(h,d,s) \times \eta_{hex}] \tag{10}$$

where C_t is uniform annual receipt. I_0 is initial investment as well as installation costs and includes the cost of DERs, heat exchangers, both thermal and electric storages and micro-grid construction cost. Installation cost consists of cost of site, cost of construction, survey fees, project and process contingencies, etc., to name a few. Operation and maintenance (O&M) cost consists of fuel cost, labor cost, periodic inspection cost, repair and parts replacement costs. C_e is the price in \$/kWh at which energy transaction takes place between micro-grid and utility. ΔE_{loss} is the reduction of average annual system energy loss in KWh due to DER deployment and micro-grid owner charges to the utility, for this energy, at a price of C_e. E_{excess} is the annual generated energy of micro-grid sold to utility through 'Net Metering', in kWh. $\sum E_{load}(h,d,s)$ is the sum of annual demands supplied by all generators, h, d, s represent time, day, and season respectively on which load depends. C_{ht} is the cost of heat energy in \$/kWh. C_e and C_{ht} are amortized cost. ΔH_w is the total annual waste heat recovered from all DERs in kWh. η_{hex} is the efficiency of heat exchanger. C_{etv}, C_{etf}, and C_{etd} are respectively tariff components due to volumetric (\$/kWh),fixed (\$/month) and demand (\$/kW) and they are charged on consumers. D_p is the monthly peak demand in kW. Benefit and O&M costs are the future annual costs. Therefore, to calculate *NPV*, it is required to discount the value of future costs. *PVF* is the present value factor and used to bring the future cost to present value. *ir*, *if*, and *EL* are respectively the per unit interest rate, p.u. inflation rate, and economic life of equipments

IRR is found out by trial - error and is the break-even discount rate. It is *PVF* at which *NPV* is zero.

3. PSO technique

PSO technique conducts search for optimal solution using particle swarm intelligence system. This method simulates the social behaviour of flocking of birds in search of food on a square grid of land, which is termed as the solution space. Each particle represents a potential solution, which is a point in the solution space, or as a position in the square area of land, in case of the birds analogy. The birds fly in search of food. The location of food is analogous to the optimum solution to the problem. Each bird, given its present position, has a sense of distance from the food. This is analogous to the "objective value" of the corresponding optimisation problem. The aim of the birds is to converge or narrow down on that location where the food is, or in other words minimize the distance from the location of the food. The final location where the birds settle down is the optimal solution identified by the solution process. It becomes necessary to choose optimum values for the parameters for the best performance of PSO. Selection of learning factors pulls each particle towards its best location (pbest) and its neighborhood best location (nbest). They represent the weighting of the stochastic acceleration terms. Inertia weight is very important for the convergence behavior of PSO. The concept of inertia weight has been developed to have a better control over exploration and exploitation. Constriction factor controls the magnitude of the velocities, but in a different way from inertia weight. [16]

Particle Dynamic Equations:

$$V_{t+1} = \Psi*((W)*(V_t) + (C_1)*(rand())*(P^l - X_t) + (C_2)*(rand())*(P^g - X_t) \tag{11}$$

$$X_{t+1} = X_t + V_{t+1} \tag{12}$$

where V_t is the particle velocity at the t-th iteration, X_t is the particle position at the t-th iteration, P^l is the local best position or particle Best position thus far, P^g is the best global position or the Best solution among all particles, W is the inertia weight factor, C_1 & C_2 are the learning factors and ψ is the constriction factor.

4. PSO algorithms for maximisation of NPV

The proposed algorithm is implemented with MATLAB 6.5 language on a Pentium-IV PC. Gauss-Siedel load flow method has been embedded into PSO algorithms for finding out the optimal solution. The computational steps in respect to case of 6-bus system are as follows, other cases are similar:

- Read the input data:- Bus data, Line data , no. of buses (n), no. of lines (n) and all other data under section 5.
- Initialize the swarm position at PQ-bus nos.2, 4, and 5. These Bus positions are obtained from loss sensitivity analysis. Swarm-size is taken 20 at each bus and swarm values are generated randomly within the stipulated capacity limits of DERs. Swarm, in the present case, is the DER capacity-size.
- Run the program for each of the 20 sets and obtain for each set separation of swarm into micro-turbine and diesel generators, as per Eqs. (3), (4), and (5). Finally, obtain the 20 NPV values using Eqs. (7) to (10). Find out the maximum NPV and corresponding swarm combinations. Program is run under the given PQR constraints.
- Update the 20 sets of swarms as per the equations (11) and (12). Repeat the step third above for each of 20 sets and 1000 iterations. Find out the highest of 1000 maximum NPV and corresponding swarm combination.
- Compare the present maximum value of NPV with its previous maximum and if found higher, replace the previous one.
- Run steps 2nd to 5th for 50 trials and find the maximum NPV.
- After getting the DERs' capacity at maximum NPV, separation of capacity into MT and DE is done as per Eqs. (3), (4) and (5). Other parameters are also noted.

5. Case study

This paper uses 6-bus meshed and 14-bus radial micro-grids as study cases. For electrical demand tracking mode of operation, thermal storages and for thermal demand tracking mode, electrical storages are used as need arises. Net metering is used to register both ways of power flow and mainly, for selling of surplus electricity to utility. The purpose of the paper is to compare economic feasibility, from owner-side of micro-grid, between electric demand tracking and thermal demand tracking modes of operations and to plan the investment accordingly. PSO algorithms are used for finding optimally deployed capacity of DERs based on maximization of NPV of micro-grid. For present economic analysis based on NPV, focus is, mainly, given on major benefits of micro-grid owner, like self-generation, system loss reduction, waste heat utilization. Following points are considered in the study: -

- DERs operate at full load i.e. no part loading operation
- Loads as per profiles and 365 days of operation of CHP-based DERs;
- All customers are Commercial and tariff structure is at constant rate,
- Centralized heat exchanger per bus, instead of unit wise;
- Zero slack bus injection constraint helps to know, at the planning stage, what exact DER capacity of micro-grid required to meet the internal demand.
- LSI at the terminal buses are usually found higher values, but due to line outage probability, there is a chance of islanding of DERs. At terminal buses these DERs are under utilized. So they are shifted from terminal buses to next higher values.
- No spare capacity of DER and other equipments

The data used in two case studies are as follows:

- Interest rate (*ir*) is 10%., inflation rate(*if*) is 3%, economic life cycle (EL) of all equipments are 20 years.[8-9]
- Cost of electricity (C_e) is $ 0.11 /kWh, cost of Heat (C_h) is $ 0.05 /kWh, selling price of electricity to utility is $0.12 /kWh. [18, 24].
- The data for Micro-turbine (in $/kW/yr): - Investment cost is 1000.00/kW, maintenance cost plus operation cost plus fuel cost are 779.64/kW; Annual recoverable waste heat is 14826.04 kWh/yr and calculated from heat rate 12,186 kJ/kWh and thermal efficiency of 50%.. All the above data have been taken with reference to 30 kW micro-turbine. [9, 17, 18, 20-22, 25].
- Data for Diesel Engines (in $/kW/yr.):- Investment cost is $ 300.00/kW ($ 850.00/kW); maintenance cost plus operation cost plus fuel cost are $ 814.00/kW ($ 831.5/kW); Annual recoverable waste heat is 9331.58 (7509.5) kWh/yr./p.u. capacity and calculated from heat rate 12,783 (10,287) kj/kWh and

thermal efficiency of 30%. For all the above data, 20 kW and bracketed terms for 300 kW diesel engines have been taken as reference. [18] [23] [25]

- Data of heat exchanger (all are in p.u.): -Turnkey cost is \$190/kW. (O&M) fixed and Variable costs are assumed zero. Efficiency (η_{hex}) is 0.9. [25]
- Micro-grid cost data (as a fixed cost):- Cost of central controller (C_{CC}) is \$21,264.00,cost of DER controller (C_{GC}) is \$11,057.00, cost of load controllers (C_{LC}) is \$18,713.00, Cost of interfacing equipments (C_{INF}) is \$14,176.00, cost of LV circuit breaker (C_{CB}) is \$2,835.00. [10] [13]
- Data for Tariff: - Constant rate tariff – fixed rate is \$20/month, volumetric rate is \$0.11/kWh, demand rate is \$7/kW/month. [10] [19]
- Cost data of thermal storage: - Fixed cost is \$10,000, variable cost is \$100/kWh. [15][25]
- Cost data of electrical storage: - Fixed cost is \$ 295; Variable cost is \$ 193 per kWh. [15][25]
- PSO data: - Population size: 20; Acceleration Constants: C_1, C2 = 2; Generation or iteration = 1000; Inertia weight factor: w_{max}=0.95 and w_{min}=0.2. Constriction Factor = 1.[26]

System is studied under four stages – 1) without DER and at peak demand, 2) with optimal deployment of DERs at peak demand, 3) with optimal deployment of DERs under electrical load profile tracking and 4) with optimal deployment of DERs under thermal load profile tracking. Only 6-bus system is shown in Figure 1, where dotted lines indicate co-ordination among central controller (CC), loads controller (LC) and DERs controller (GC). 30kW micro-turbines and 20 kW diesel generators have are used as DERs in 6-bus system, but for 14-bus system, these are 30 kW micro-turbines and 300 kW diesel generators.

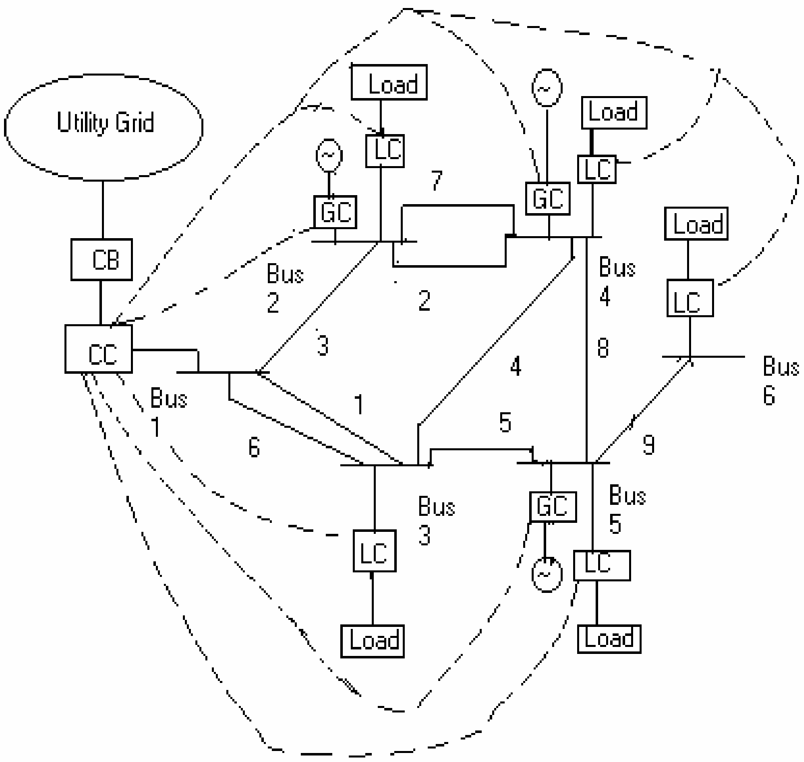

Figure 1. 6-Bus meshed micro-grid

5.1 Base case i.e. without DER

5.1.1 6-bus system

Line data and bus data are shown in Table 1 and Table 2 respectively. Load flow results are shown in Table 4. System loss at peak demand of 185 kW is obtained as 7.1 kW, which is 3.8% of peak demand. Monetary value of system loss is calculated using the utility's energy price of \$0.12/kwh.

Table 1. Line data – with base 100 kVA

Line No.	Start Bus	End Bus	R [p.u.]	X [p.u.]	B [p.u.]
1	1	3	0.0342	0.18	0.0106
2	3	4	0.114	0.60	0.0352
3	1	2	0.0912	0.48	0.0282
4	3	4	0.0228	0.12	0.0071
5	3	5	0.0228	0.12	0.0071
6	1	3	0.0342	0.18	0.0106
7	2	4	0.114	0.60	0.0352
8	4	5	0.0228	0.12	0.0071
9	5	6	0.0228	0.12	0.0071

Table 2. Bus data

Bus No.	6-Bus System		14- Bus system	
	Real load demand, [kW]	Reactive load demand, [kvar]	Real load demand, [kW]	Reactive load demand, [kvar]
1	0.0	0.0	0.0	0.0
2	20.0	6.5	200.0	65.0
3	85.0	27.9	850.0	279
4	40.0	13.12	400.0	131.2
5	20.0	6.5	200.0	65.0
6	20.0	6.5	200.0	65.0
7	-	-	76.0	16.0
8	-	-	100.0	30.0
9	-	-	61.0	16.0
10	-	-	112.0	75.0
11	-	-	610.0	90.0
12	-	-	16.0	61.0
13	-	-	90.0	59.0
14	-	-	135.0	61.0

5.1.2 14-bus system

Bus data and line data are shown in Table 2 and Table 3 respectively. Load flow results are shown in Table 4. System annual loss at peak demand of 3.05 MW is obtained as 27.72×10^5 kWh. Loss is 10.4% of peak demand. Monetary value of annual system loss is found as $ 3.33×10^5 p.a. using the utility's energy price of $0.12/kwh.

5.2 At Peak demand, without load profile

Important to simulation is that results are obtained at almost zero slack bus injection. DERs capacity, obtained by simulation, would be capable of supplying the total demand of the micro-grid. Payback periods, NPV and IRR are obtained at peak demand and with an assumption of concurrency of both electric and thermal demand. Only constant rate tariff has been used. This case is an ideal one as concurrency is hardly possible and is being studied for economic interest.

5.2.1 6-bus system

As per LSI data (Figure 2), terminal bus-6 has highest index value of –0.093, but buses 2, 4, and 5 are selected for DERs locations, as they possess next higher values in order. In Figure 2, abscissa is shifted downward to accommodate both positive and negative LSI values. Results of simulation are shown in Table 5. O&M cost is 53.67% of yearly benefit. Selling of heat is 31.93% and selling of electricity is 66.1 % of yearly benefit.

Table 3. Line data – with base 1000 kVA

Line no.	Start Bus	End Bus	R [p.u.]	X [p.u.]	B [p.u.]
1	1	2	0.0119	0.0414	0.0045
2	2	3	0.0119	0.0414	0.0042
3	3	4	0.0135	0.04211	0.0064
4	4	5	0.0167	0.0845	0.0
5	5	6	0.01938	0.05917	0.0
6	6	7	0.0224	0.12	0.0
7	6	8	0.03181	0.0845	0.0
8	7	9	0.0342	0.17038	0.0
9	2	10	0.0167	0.042	0.0085
10	10	11	0.01938	0.05917	0.0264
11	11	12	0.06701	0.17103	0.0173
12	12	13	0.09498	0.1989	0.0
13	11	14	0.08135	0.15581	0.0

Table 4. Base case (5.1)

System Loss		Line Flow, [kW]	Bus Voltage, [p.u.]	Slack Bus Injection,	
Annual, [kWh]	[$/annum]	Max^{m}	Min^{m}	[kW]	System
62,266.00	7,471.93	80.02	0.88792	192.1	6-bus
27.72×10^5	3.3×10^5	3366.4	0.6852	3366.4	14-bus

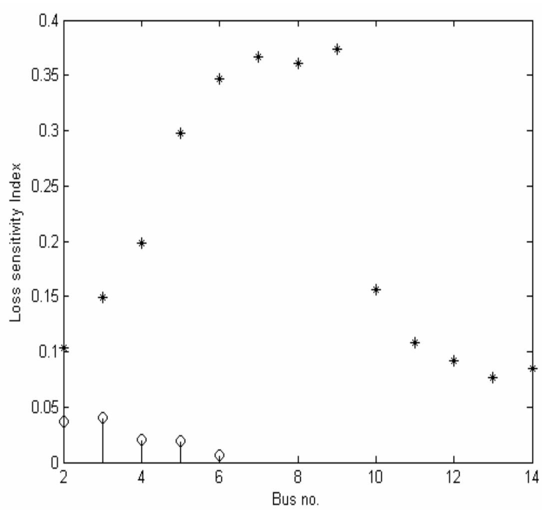

Figure 2. LSI plot (‘O’ for 6-bus, ‘*’ for 14-bus)

5.2.2 14-bus system

On considerations of both LSI values (Figure 2) and reliability, junction bus numbers 2, 6,and 11 are selected as locations of DERs. Simulation results (Table 5) are obtained at zero slack bus injection. Annual O&M cost is 51.8% of yearly benefit. Yearly selling of heat is 32.85% and selling of electricity is 63.72 % of yearly benefit.

Table 5. Results – case (5.2)

	Slack Bus Injection,	System Loss		Line Flow, [kW]	Bus Voltage, [p.u.]
System	[kW].	Annual, [kWh]	[$/annum]	Max^{m}	Min^{m}
6-Bus	0.00	14,016.00	1682.00	35.3	0.987
14-Bus	0.00	13,37,650.0	1,60,520.0	25.5	0.951

5.3 Tracking of electrical load profile

Both thermal and electrical load profiles (Figure 3) are included in the study along with constant rate tariff. In Figure 3, bracketed terms in the ordinate indicate the load values in MW for 14-bus system, whereas non-bracketed terms are in kW for 6-bus. Payback period (PP), NPV and IRR are evaluated under previous assumptions Load profiles (both electricity and heat), Figure 3, are daily average of all the four seasons. DERs' operation schedule is as per the tracking of electricity demand. Heat is stored during the time span from 22:00 to 07:00 and sold during 07:00 to 22:00 hrs.

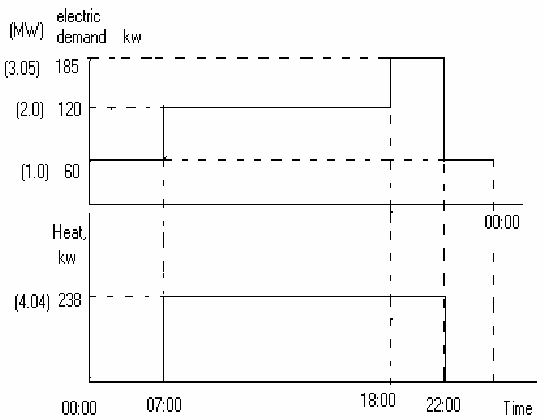

Figure 3. Load profiles- both electric and thermal (bracketed terms are in MW)

5.3.1 6-bus system

Simulation results are shown in Table 6. At various time spans, capacities-in-operation of micro-turbines (MT) and diesel generators (DE) are shown in Table 6. Investment costs of DERs are 46% of total investment, whereas thermal storage cost is only 14.46%. Rest is for micro-grid construction cost and cost of heat exchanger, which are same as thermal demand tracking operation. Yearly O&M cost is 49.54% of annual benefits accrued. Benefit from selling of heat is 28.16% of total annual benefit, but benefit from selling of electricity to self-demand is 70.57% of benefit. Benefit from selling of excess generation to utility through 'Net Metering' is 2.97% of total annual benefit.

5.3.2 14-bus system

Simulation results are shown in Table 6. Investment for DERs is 66.42% of total investment cost, but thermal storage cost is 19.65%. Yearly O&M cost is 46.92% of total annual benefit accrued. Benefit from selling of heat is 30.64% of benefit, but yearly benefit from selling of electricity to self-demand is 62.97% of total benefits. Benefit from selling of excess generation to utility through 'Net Metering' is 1.35% of annual benefits.

Table 6. Results – case (5.3)

System	DER Type	DER Capacity [kW] during Time Span of the day, [hr.]			Annual Loss Reduction	
		22:00 to 07:00	07:00 to 18:00	18:00 to 22:00	[kWh]	Saving, [$/p.a]
6-Bus	MT	2× 30	3×30	3×30	22002.2	2640.26
	DE	-	2×20	5×20		
14-Bus	MT	34× 30	52× 30	52× 30	1.0462×10^6	1.25×10^5
	DE	-	2× 300	6× 300		

5.4 Tracking of thermal demand

Payback period, NPV and IRR are calculated using constant rate electricity tariff and load profiles. Assumptions, here, are same as of study case (5.3) above, only changes are DERs' operation schedule is as per the tracking of thermal demand and Electricity is stored during the time span from 07:00 to 18:00 and sold during 22:00 to 07:00 hrs.

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5.4.1 6-bus system

Results are shown in Table 7. Electrical storage cost is 38.43% of total investments, which is higher than thermal storage cost. Per unit (kWh) electrical storage cost is about three times higher than that of thermal storage. Yearly O&M cost is 52.75% of yearly benefits. Benefit per annum from selling of heat is 32.63%, direct selling of electricity to self-demand is 49%, selling of electricity to self-demand through storage is 12.07% and selling of electricity to utility is 4.4% of annual benefit.

Table 7. Results – case (5.4)

System	DER Type	DER Capacity [kW] during Time Span of the day,[hr.] 07:00 to 22:00	Annual Loss Reduction, [kWh]	Saving, [$/ p.a.]
6-Bus	MT	3×30		
	DE	5×20	30156.3	3317.19
14-Bus	MT	52×30		
	DE	6×300	1.43×10^{6}	1.72×10^{5}

5.4.2 14-bus system

Results are shown in Table 7. Electrical storage cost is as high as 37.76% of total investments, which is higher than thermal storage cost. Yearly O&M cost is 54.8% of total annual benefits. Benefit per annum from selling of heat is 23%, direct selling of electricity to self-demand is 55.6%, selling of electricity to self-demand through storage is 12.42% and selling of electricity to utility is 3% of net yearly benefit.

5.5 Comparison

Comparative studies are shown in the following sections. Table 8 summarizes and compares the economic parameters for the cases studies.

- Comparison between (5.1) and (5.2)

Results (Table 4 and Table 5) of 6-bus and 14-bus cases reveal that optimal deployment of DERs reduces maximum line flow and system loss. As slack bus injection is made zero, utility's congestion is abated to a large extent. There is a reasonable increase of minimum bus voltage and this indicates enhancement of power quality and reliability (PQR) of the system due to optimal deployment of DERs.

- Comparison between (5.2) and (5.3) / (5.4)

Case (5.2) is an ideal case without load profiles and there is no investment for storage equipments – both thermal as well as electrical, so investment cost is lower compared to case (5.3) or (5.4). Again, annual saving is higher, so payback is faster in case (5.2), NPV is higher as well as IRR is high (Table 8). Hence, case (5.2) is economically preferred, but in reality, system without load profile has no existence.

- Comparison between (5.3) and (5.4)

In (5.3), there is no investment for electrical storage, whereas in (5.4) there is no investment for thermal storage. Electrical storage cost per kWh is higher than thermal storage cost. Investment cost in (5.3) is, respectively, 28.02% (for 6-bus) and 22.03% (for 14-bus) lower with respect to corresponding values in (5.4). Again, annual savings in 6-bus case (5.3) is 13.9% higher than that in6-bus case (5.4) and in 14-bus case (5.3), 3% higher from its counterpart case (5.4). So, payback periods in both cases of (5.3) are lower than in (5.4); again, NPV and IRR both are higher (Table 8). Thus, case (5.3), electrical load tracking operation is more economically lucrative. Both 14-bus and 6-bus systems are giving, almost, same economic results.

Table 8. Results – economic parameters

System	Case	Payback Periods, [Yr.]	NPV, [$]	IRR, [%]
6-Bus	5.2.1	1.643	1455160.1	65.68
	5.3.1	2.7	778880.00	41.02
	5.4.1	3.8	662640.00	29.77
14-Bus	5.2.2	1.546	2.2122×10^{7}	69.61
	5.3.2	2.699	1.3784×10^{7}	41.08
	5.4.2	3.44	1.2548×10^{7}	32.69

6. Conclusion

If investment planning is concerned, the paper focuses on selection of mode of operation, whether electrical demand profile or thermal demand profile is to be tracked for achieving better economic results. Though results are obtained for a particular load profiles, thermal as well as electrical, it sends a message to the owner of micro-grid about the relevance of analysis. Reasons behind lower payback periods, and higher NPV as well as IRR for electric demand tracking mode of operation, in both 14-bus and 6-bus systems, are lower price of heat compared to price of electricity and higher cost of electrical storage equipments compared to thermal storage equipments. There are number of factors, such as type of manufacturer and technology of DERs, policies of local utility, government policies, etc., on which analysis is affected. Besides, seasonal effect on demand, load growth rate, fuel price - all these uncertainty factors influences the results. Zero slack bus injection takes care of reduction of utility's congestion. Again, reduction of maximum line flow lowers the internal congestion of the micro-grid system. System's internal congestion creates voltage sag, which, in its severity, is accompanied by interruption of supply to the customers. Micro-grid hedges against this loss and becomes beneficial on power quality and reliability ground. Future study can be extended considering other benefits, like reduction of customers interruption cost (CIC), reduction of emission, deferral of investment, of DERs deployment.

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References

[1] Ackerman, T. Anderson, G. Soder L. Distributed generation: a definition. Electric Power Systems Rsearch, 57, 195-204, 2001.
[2] Miranda, G. J. Be prepared! An overview of process industry options in the deregulated power era. IEEE Industry Applications Magazines, Mar/Apr 2003.
[3] Hatziargyriou, N. Asano, H. Iravani, R. Marnay, C. Microgrids. IEEE Power & Energy Magazine, July / august 2007.
[4] Kirschen, D. Strbac, G. Why investments do not prevent blackouts. UMIST, Manchester, UK, 27 Aug. 2003
[5] Jiayi H. Chuanwen J. Rong X. A review on distributed energy resources and MicroGrid. Renewable & Sustainable Energy Reviews 12, 2472-2483, 2008.
[6] Marnay, C. Bailey, O. The CERT's microgrid and the future of the macrogrid. CERTS Aug. 2004.
[7] Kueck, J. D. et. al., Micro grid energy management. CERTS, Jan. 2003.
[8] Willis, H. L. Scott, W. G. Distributed power generation planning and evaluation. Marcel Dekker, New York, 2000.
[9] Teng,J. Liu, Y. Chen, C. Chen, Chi-Fa Value-based distributed generator placements for service quality improvements. Int. Journal of Electrical Power & Energy Systems, vol. 29, Issue 3, pp 268-274, Mar. 2007.
[10] Zoka, Y. et.al. An economic evaluation for an autonomous independent network of distributed energy resources. Electric Power Systems Research, vol. 77, Issue 7, pp 831-838, May 2007.
[11] Mitra, J. Vallem, M.R. S. B. Patra, S. B. A probabilistic search method for optimal resource deployment in a microgrid. 9th International Conference on Probabilistic Methods Applied to Power Systems KTH, Stockholm, Sweden, June 11-15,2006.
[12] Dugan, R. McDermott, T. E. Ball, G. J. Planning for distributed generation. IEEE Industry Application Magazine, March/April 2001.
[13] Costa, P. M. Matos, M. A. Economic analysis of microgrids including reliability aspect. 9th IAEE Int. Conf. on Probabilistic Methods Applied to Power Systems, KTH, Stockholm, Sweden, June 11-15, 2006.
[14] Asano, H. Bando, S. Operational planning method and economic analysis of microgrid with intermittent renewable energy and battery storage. 29th IAEE International Conference, Potsdam, Germany, June 7-10, 2006.

[15] Siddiqui, A. S. Marnay, C.Bailey, O. and LaCommare, K. H. Optimal selection of on-site generation with combined heat and power applications. International Journal of Distributed Energy Resources, vol. 1, No. 1, pp 33-62., 2005.
[16] Kenedy, J. Eberhart, R. C. Particle Swarm Optimisation. Proceeding of IEEE International Conference on Neural Network (ICNN 1995), vol. 4, Perth, Australia, 1995.
[17] http://www.ee.washington.edu/research/pstca/
[18] http://www.energy.ca.gov/distgen/
[19] Firestone, R. Marnay, C. Maribu, K. M. The value of distributed generation under different tariff structures. In the Proceedings of 2006 ACEEE Sumer Study on Energy Efficiency in Buildings, May 2006.
[20] http://www.eren.doe.gov/femp/
[21] http://www.epa.gov/chp_support_tools.htm
[22] http://www.mydocs.epri.com/docs/public/TR-114182
[23] http://www.dieselserviceandsupply.com
[24] http://www.energia.fi/en/districtheating/
[25] Marnay, C. et.al. Modelling of customer adoption of distributed energy resources. CERTS, Aug. 2001.
[26] Basu, A.K. Chowdhury, S. Chowdhury, S.P. Strategic deployment of CHP-based distributed energy resources in microgrids. Power and Energy Society General Meeting 2009, PES'09 IEEE, pp. 1-6, 26-30 July 2009.

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