Evaluation of Different Hybrid Distributed Generators in a Microgrid—A Metaheuristic Approach

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ABSTRACT

An economic estimation of an autonomous power delivery system constituting different types of non-conventional and renewable energy resources has been performed considering an Indian load demand scenario. The mathematical analysis was done by the application of a modified differential evolution (MDE). The MDE-evaluated total annual costs for the autonomous microgrid system utilizing three sets of distributed energy resources (DERs) have been compared. Solar module and fuel cells as DERs form the first set of DERs; solar module and bio-mass gasifier unit as DERs is considered as second set; and fuel cell along with Battery Energy Storage System (BESS) constitute the third set of DERs. Different types of consumers together form the microgrid with optimal supply of power from DERs. The optimal power generation conditions have been obtained pertaining to minimum cost of microgrid system. For the same load demand in microgrid operation, the results, using a hybrid solar-biomass system are found to be most cost effective. A reduction of 6.9 % in the annual cost is obtained using the combination of solar module and biomass gasifier unit from that obtained using a solar module fuel cell combination. The corresponding reduction is 10% from that utilizing only fuel cell.

Keywords: DERs, SPS, BMGU, Microgrid, Modified Differential Evolution.

INTRODUCTION

Modulation of electric power system is the most vital key in improving the social and economic living conditions. The role of electric power has grown up steadily in widening both its scope and importance over the last few decades. This has made a huge demand of electric power today. With the focus on delivering power effectively and efficiently, the centralized electricity supply services are shifting towards the newly developing technology of dispersed systems, known as distributed energy resources (DERs). DERs or distributed generators (DG) are usually located close to energy loads and efficiently distribute energy with minimum losses. The non-conventional DERs and renewable energy sources such as fuel cells, solar modules, wind power and biomass gasifier units also play a key role in reducing environmental pollution. A number of works [1-6] relating to the design and operation of DERs are available in the literature, but ample attention has not yet been paid to the economic issues associated with DERs. To overcome the power control, protection and distribution difficulties in a conventional power delivery system, the concept of microgrid has come up as a new electricity delivery system [1]. Possibilities of developing microgrid with DERs have been discussed in the literature [7-9]. Though the technical issues of microgrid have been dealt by several researchers [9-11], but the economic estimation of these newly built microgrids has not yet been sufficiently dealt and standardized. Zoka *et al.* [12] presented a technique of minimizing the total cost of a microgrid energy delivery system by optimal operation planning of DERs. Though their method provided a precise solution, it could not take into account issues such as imprecision, partial truth, uncertainty, and approximation which are essential to achieve tractability, robustness, ease of implementation and low solution cost. Moreover the conventional deterministic techniques often involve a repetitive and rigorous computation. In order to arrive at a solution that incorporates all these issues, it is apparent that soft computing techniques with their adaptive nature could be of more beneficial.

Applications of different evolutionary methods on economic load dispatch and load scheduling problems are available in the literature [13-17]. However, evolutionary approach in the analysis of energy economy for a micro grid system with different frame works of energy delivery resources can hardly be found in the literature. Differential Evolution (DE) technique is an evolutionary method which helps to achieve the true global optimum solution using few control parameters regardless of initial parameter values [18]. Moreover, DE is able to mitigate the drawback of long computational time, so this algorithm seems to be a promising approach for such engineering optimization. Modifications to the basic DE algorithm can also be made to overcome occasional problems of premature convergence and deterioration in the performance with the growth of dimensionality of the search space for exploring better results in such optimization problems. An improved performance can be predicted by tuning the control parameters of basic DE as shown in [19]. However, application of this technique to solve economic problems that include microgrid and DER is sparse in the literature.

The present work deals with the economic estimation of consumer based power delivery systems through optimal power operation planning of hybrid-DERs for different cases of Indian load demand scenario. Keeping in mind the huge gap in power demand and supply and lack of availability of data on the operation of microgrid systems, especially in an Indian power delivery scenario, an attempt has been made in this work to conduct different case studies in a small Indian locality, under two types of seasons. The variation or shortfall in load demand between winter and summer season has been taken into account to cover up the total power demand of every consumer over a whole year. To cope up with this shortfall in power generation, microgrids driven by diesel generator sets are often formed in small localities. These obviously have an adverse impact on the environment. Fuel cells operate without high temperature combustion. The losses associated with mechanical–to–electrical conversion processes, as found in all conventional electrical power producing systems are nil in the case of fuel cells. Renewable energy sources are found to improve the status of environment by eliminating the harmful gases emitted by diesel generators along with saving the running fuel costs for different non-renewable resources. Among the renewable resources, the wind energy is place-dependent and generally varies from season to season and sometimes becomes unpredictable. India being a tropical country with reliable daily solar radiations, production of consumable electricity from solar energy resources can also be highly effective. Moreover agriculture being an important sector of the Indian economy, biomass resources is abundantly available and therefore can be potentially exploited for electricity production. Hence, the present power delivery systems comprise fuel cells, solar modules and biomass gasifier units as Distributed energy resources or Distributed Generators (DGs) along with a battery system to supply power to a small locality. Moreover, a provision for purchasing electricity in contract with utility is also considered in both the types of power delivery system. Studies from literature relevant to the DERS considered in this work are referred to in subsequent sections.

The microgrid system considered for the economic analysis has been structured by connecting the DERs to the consumers' load through transformers, circuit breakers, distribution lines and a controller. This corresponds to five types of consumers, namely, hostel, bank & post-office, market, campus-quarters, and hospital with two types of seasonal load variations in an Indian small residential locality. Finally the paper depicts an economic comparison for two test cases of power delivery system utilizing two different hybrid-DERs. The mathematical analyses are performed by the application of a modified differential evolution (MDE).

PROBLEM FORMULATION

The cost evaluation of consumer based microgrid power delivery system, in an Indian scenario have been studied by considering two sets of DERs. The test cases are as follows;

1. Consumers operate as microgrid power system using solar module and biomass gasifier unit (BMGU) as the DERs along with BESS.
2. Consumers operate as microgrid power system using fuel cell and solar module as the DERs, beside BESS.
3. Consumers together form a microgrid power system using fuel cell as DER along with BESS.

These test cases has been chosen in anticipation of a future scenario where simultaneous operation of multiple non-conventional and/or renewable DERs and consumers organized into microgrids will be a presumably cheaper solution to the energy and environmental challenges being faced by mankind. The DERs comprise Phosphoric Acid Fuel Cells (PAFC), solar photovoltaic system (SPS), biomass gasifier unit (BMGU) and a lead acid battery energy storage system (BESS). PAFC is the most advanced one among the various types of fuel cells having capacity ranging from 50 kW to 11 MW [20, 21]. High efficiency, low chemical and thermal emissions, siting and fuel flexibility, reliability, low maintenance, excellent part-load performance, and modularity of PAFC prove to be more advantageous over conventional power generating equipment [21-23]. Nowadays, micropower systems consisting of solar modules have a better economical merit to serve a nearby load [24-26]. Biomass gasification energy generating units are an important decentralized power technology [27]. In order to utilize biomass energy, for electric power production, gasification process though less efficient than combustion, but it is more environmental friendly in compare to that of combustion [28]. Moreover, in the Indian context sustainable bio-energy is fast gaining in importance [30,31]. Among all batteries, lead acid battery is technologically the most mature, having high efficiency with lowest initial storage cost [29]. A provision of purchasing and selling of electricity in contract with utility has also been considered.

Economic assessment is made by minimizing total annual cost subject to the physical constraints of balanced power demand-supply, and ranges for the installed capacity of DERs.

Objective Function

The objective function is the total annual cost of the consumer based microgrid power system, which is given by:

$$R = R_O + R_I + R_M + R_U \quad (1)$$

where R_O, R_I, R_M, R_U are operating cost, initial cost, microgrid cost, and utility cost respectively.

As the operating cost R_O varies with different types of DERs or DGs for different operating periods, R_O is symbolized as R_O^{bios} for case 1, where bio-mass gasifier unit and solar module are the DERs, while R_O is represented as R_O^{fcs} and R_O^{fc} for case 2 (i.e. both solar module and fuel cell used as DERs), and case 3 (i.e. fuel cell is the only DERs) respectively. The operating Costs for Case 1 and Case 2, and case 3 are given in equations (2) and (3) and (4).

The first term on the right hand side of the above equations is the total operating cost for hybrid solar-biomass DER. P_{BM} and O_{BM} are power generation and running cost of BMGU respectively. The second term represents the operating cost of the BESS with P_{bt} and O_{bt} as power generation and operating cost of Battery respectively. The last term in gives us the total operating cost of solar module, where P_{SO} is the power generation from solar module; O_{SO} is the operating cost of solar module and is equal to zero. The number of days per season is represented by Nod_s. *Cons*, *hr*, and *ss* are the consumer, season and time index respectively.

$$R_O^{bios} = \sum_{cons=1}^{n} \sum_{ss=1}^{m} Nod_s \left[\sum_{\substack{hr=t_1 \\ hr \neq t_8:t_{16}}}^{t_{24}} \begin{matrix} P_{BM}(ss,hr,cons) O_{BM} + \sum_{hr=t_1}^{t_{24}} P_{bt}(ss,hr,cons) O_{bt} \\ + \sum_{hr=t_8}^{t_{16}} P_{SO}(ss,hr,cons) O_{SO} \end{matrix} \right] \quad (2)$$

$$R_O^{fcs} = \sum_{cons=1}^{n} \sum_{ss=1}^{m} Nod_s \left[\sum_{\substack{hr=t_1 \\ hr \neq t_8:t_{16}}}^{t_{24}} \begin{matrix} P_{FC}(ss,hr,cons) O_{FC} + \sum_{hr=t_1}^{t_{24}} P_{bt}(ss,hr,cons) O_{bt} \\ + \sum_{hr=t_8}^{t_{16}} P_{SO}(ss,hr,cons) O_{SO} \end{matrix} \right] \quad (3)$$

$$R_O^{fc} = \sum_{cons=1}^{n} \sum_{ss=1}^{m} Nod_s \left[\sum_{hr=t_1}^{t_{24}} \left\{ P_{FC}(ss, hr, cons) O_{FC} + P_{bt}(ss, hr, cons) O_{bt} \right\} \right] (4)$$

Here, R_O^{fcs} is the sum of the operating costs of DERs used for case 2, i.e. the operating cost of solar module plus operating cost of fuel cell plus operating cost of battery. $P_{FC}(ss,hr,cons)$,$P_{SO}(ss,hr,cons)$, and $P_{bt}(ss,hr,cons)$ are the power generated by fuel cell, solar module and battery respectively where the power generations depends on hour (*hr*), season(*ss*) and type of consumer(*cons*). In this case power generated from solar has been considered from 8 am to 4 pm, as during this period the solar irradiation is able to produce electric energy. While, on the other hand the fuel cell is used for generation during that period when solar power is absent, i.e. from 4 pm to 7 am. The running costs of fuel cell, solar module and battery are O_{FC}, O_{SO}, and O_{bt} respectively, which when multiplied with their respective power generations from fuel cell, solar module and battery.

The operating cost for case 3 (i.e. fuel cell acting as DERs along with battery energy storage system) is given, in equation 4 as the summation of operating cost of fuel cell and operating cost of battery energy storage system. The P_{FC} is the power generated by fuel cell which is a function of time, season and consumer, represented as *hr*, *ss,* and *cons* respectively.

The power generated from solar energy depends on certain geographical and environmental factors which are expressed [24] as shown below:

$$P_{SO} = \left[(Df)(RC_{PV}) \left(\frac{G_S}{S_S} \right) \right] \quad (5)$$

where, *Df* is the derating factor, RC_{PV} is the rated capacity of the solar array, G_S and S_S are global solar radiation incident on the surface of solar array and standard solar radiation for the rated capacity.

The bio-mass gasifier unit is based on fluid-bed gasification of bio-mass wastes like agricultural crops and wood wastes which produces useful electric energy. The transfer function is given in (6) as;

$$P_{BM} = \frac{M \times \eta_O \times LHV_b}{3600 \times hr} \quad (6)$$

Where *M* is the mass flow rate of bio-mass waste mixture, LHV_b is the low heating value of the mixture, and $–_O$ is the overall efficiency of the biomass production unit and *hr* is the operating hours.

Different DERs results in different initial costs for case 1, case 2 and case 3. The initial costs R_I is calculated as R_I^{bios} for case 1, R_I^{fcs} for case 2, and R_I^{fc} for case 3 from equations (7), (8) and (9)

$$R_I^{bios} = \sum_{cons=1}^{n} \left[\gamma ic_{BM}(cons) + \beta ic_{bt}(cons) + \mu ic_{SO}(cons) + I_{BM} ic_{BM} + I_{bt} ic_{bt} + I_{SO} ic_{SO}\right] \quad (7)$$

$$R_I^{fcs} = \sum_{cons=1}^{n} \left[\alpha ic_{FC}(cons) + \mu ic_{SO}(cons) + \beta ic_{bt}(cons) + I_{FC} ic_{FC} + I_{bt} ic_{bt} + I_{SO} ic_{SO}\right] \quad (8)$$

$$R_I^{fc} = \sum_{cons=1}^{n} \left[\alpha ic_{FC}(cons) + \beta ic_{bt}(cons) + I_{FC} ic_{FC} + I_{bt} ic_{bt}\right] \quad (9)$$

where, the initial costs of fuel cell, biomass gasifier unit, solar module and BESS are ic_{FC}, ic_{BM}, ic_{SO} and ic_{bt} respectively. For determining the total annual depreciation expenses of fuel cell, biomass gasifier unit, solar module and BESS, the initial capital costs are multiplied by factors α, γ, μ, and β respectively. I_{BM}, I_{FC}, I_{SO} and I_{bt} are the allowed interest rate of return on the initial investment by the funding agency.

Sinking fund method has been used to find α, γ, μ, and β with *dr* as the rate of depreciation and *Lft* as the life time of DERs. Hence α, β and γ can be found as:

$$\alpha, \gamma, \mu, \beta, = \frac{d_r^{Lft_{FC,BM,SO,bt}}}{(1+d_r)^{Lft_{FC,BM,SO,bt}} - 1} \quad (10)$$

The microgrid cost is expressed as:

$$R_M = \sigma ic_{sw} + n ic_{tfm} + \lambda ic_{cbl} + \sigma ic_c + I_{sw} ic_{sw} + I_{tfm} ic_{tfm} + I_{cbl} ic_{cbl} + I ic_{cc} \quad (11)$$

where the initial costs of the switching equipment, transformer, cable and controller are given as ic_{sw}, ic_{tfm}, ic_{cbl}, ic_c respectively. The interest rates on initial investment of switching equipment, transformer, cable and controller are considered as I_{sw}, I_{tfm}, I_{cbl}, and I_c respectively. The annual returns on the capital base for these equipments are given as the products of the interest rate and their initial cost, i.e. $I_{sw}\ ic_{sw}$, $I_{tfm}ic_{tfm}$, $I_{cbl}ic_{cbl}$, $I_c ic_c$ respectively. The multiplying factors for determining the annual depreciation values for switching equipment, transformer, cable and controller are δ, η, λ and σ respectively. These are also computed by the sinking fund method with the respective depreciation rates and life times.

$$R_U = \sum_{cons=1}^{n} \sum_{ss=1}^{m} Nod_s \sum_{hr=t_1}^{t_{24}} \left\{ \begin{matrix} e_p P_p(ss,hr,cons) - \\ e_s P_{sl}(ss,hr,cons) \end{matrix} \right\} + 12\, e_b \left\{ \max \left[P_p(cons) \right] \right\} \quad (12)$$

The first term of the above equation gives us the cost related to the electricity purchased from the utility. The second term corresponds to the income by selling electricity to the utility, and the last term is the base charge of electricity for contracting with the utility. The power purchasing and selling rates for purchased power (P_p) and of selling power (P_{sl}) are e_p and e_s respectively. The base charge of electricity for contracting with the utility is considered as e_b.

However these costs are subjected to many constraints that are needed to be considered for economic analysis.

Constraining Function

In order to minimize the total cost in Equation (1), the optimal power operation planning of DERs is considered as the main functional constraint. This constraint is expressed by

$$\sum_{cons=1}^{n} D_E(ss,hr,cons) = P_{BM}(ss,hr,cons) + P_{FC}(ss,hr,cons) + P_{SO}(ss,hr,cons) + P_{bt}(ss,hr,cons) + P_P(ss,hr,cons) - P_{sl}(ss,hr,cons) \quad (13)$$

where D_E is the load demand for *n* different consumers for different seasons (*ss*) and different hours (*hr*) over a day. The powers generated from fuel cell, BMGU, solar module, battery, purchased power and sold power are P_{FC}, P_{BMGU}, P_{SO}, P_{bt}, P_P, and P_{sl} respectively. As P_{sl} represents the excess power generation, so it is considered as negative part while calculating the operating cost.

In addition, the optimization procedure is also subject to following auxiliary constraints:

$$0 \le P_{BM}(hr, cons) \le IC_{BM}(cons) \quad (14)$$

$$0 \le P_{FC}(hr, cons) \le IC_{FC}(cons) \quad (15)$$

$$0 \le P_{SO}(hr, cons) \le IC_{SO}(cons) \quad (16)$$

$$0 \le P_{bt}(hr, cons) \le IC_{bt}(cons) \quad (17)$$

$$0 \le P_{BM}, P_{FC}, P_{bt}, P_P, P_{sl}, IC_{BM}, IC_{FC}, IC_{SO}, IC_{bt} \quad (18)$$

where (14), (15), (16) and (17) give us the upper and lower limits of power output from distributed energy resources and battery energy storage system to match the electric demand respectively, while (18) ensures that all the variables are positive. IC_{BM}, IC_{FC}, IC_{SO} and IC_{bt} are the installed capacities for biomass gasifier unit, fuel cell, solar photovoltaic system and BESS respectively.

With the objective function and constraining functions known *a priori*, a modified differential evolution (MDE) algorithm has been applied for economic analysis of these systems.

PROPOSED ALGORITHM

The proposed algorithm is basically a modification over conventional differential evolution. Differential algorithm is a vector based evolutionary stochastic search algorithm which was developed by R. Storn and K. Price during late 90s [32].

Differential Evolution:

The differential evolution algorithm (DE) is technically simple and highly efficient technique for constrained parameter optimization problems. The population of solution vectors is successively updated through probabilistic search method [33] which involves the following steps:

I. At first, a population size N_P of x encoded elements is chosen randomly as initial solution vector for j individual variables. For each x in $N_{P,}$ a mutant vector v_{ij} is formed by the formula[19] given as;

$$v_{ij}=x_{r1}+MF\left(x_{r2}-x_{r3}\right)$$

where r_1, r_2, and r_3 are three mutually distinct randomly drawn indices from (1,…i.,…N_P), and also distinct from i, and MF is the mutation factor.

II. Next, the crossover is performed [19] between individual elements of mutated v_{ij} variables. A trial vector u_{ij} is generated and then for each component of vector, a random number is drawn which lies between [0,1]. The crossover operation is given by

If r and j $< =$ CR,$u_{ij} = v_{ij}$, else $u_{ij} = x_{ij}$

III. Here, the crossover ratio (CR) serves as a cut off function, i denotes the population number, and j gives the number of variables involved in the objective function.

IV. In the selection step, the fitness value is calculated first by evaluating the objective function for both the initial and mutated solutions, provided the solutions lie within the constraining ranges of their respective variables. **[32]**Next, the selection is performed based on the logic that, if the fitness value corresponding to the mutated solutions is better than that corresponding to the initial solutions, then the initial matrix is replaced by the mutated one, otherwise the initial matrix remains same for the next generation.

The iteration procedure is continued until the termination condition is reached. This requires the difference between the best fitness values of consecutive iterations to become negligible in magnitude.

Modified Differential Evolution (MDE)

In the present problem, an attempt of using a modified DE (MDE) has been made for achieving an improved result. The modification involves each solution generating more than one offspring using different mutation operators by combining information of the best solution in the population and thereby increasing the probability of generating better offspring. A consideration of improved variants of DE [19] which utilizes the concept of neighborhood of each population member, balances the exploration and exploitation abilities of DE without imposing serious additional burden in terms of function evaluations. An increase in the probability of generating better offspring has been made by sampling the feasible region in a better way and reaching the global optimum solution. The mutation operation in MDE includes two mutant operands:

$$v_{i,j} = {}_{\alpha}x_{r3,jbest,j} + F\,(x_{r2,j} - x_{\beta})_{best,j}F(\,x_{r1,j} - x)$$

where, F_{α} and F_{β} indicate the influence of the best and parent solution respectively in search direction of off-spring. X_{best} is the best individual, while x_i is the i^{th} individual.

The flow chart of modified differential evolution (MDE) is shown in Figure 1.

Application of Modified Differential Evolution (MDE) to the Present Problem

In consideration of the objective and constraining functions as mentioned in section 3.3, the application of modified differential evolution algorithm is performed through the following steps:

Step I
Let

$$\begin{bmatrix} P^{ps}_{O_1DG} \\ P^{ps}_{O_2DG} \\ P^{ps}_{O_3DG} \\ \\ \\ P^{ps}_{O_{24}DG} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} P^{ps}_{O_1bt} \\ P^{ps}_{O_2bt} \\ P^{ps}_{O_3bt} \\ \\ \\ P^{ps}_{O_{24}bt} \end{bmatrix}$$

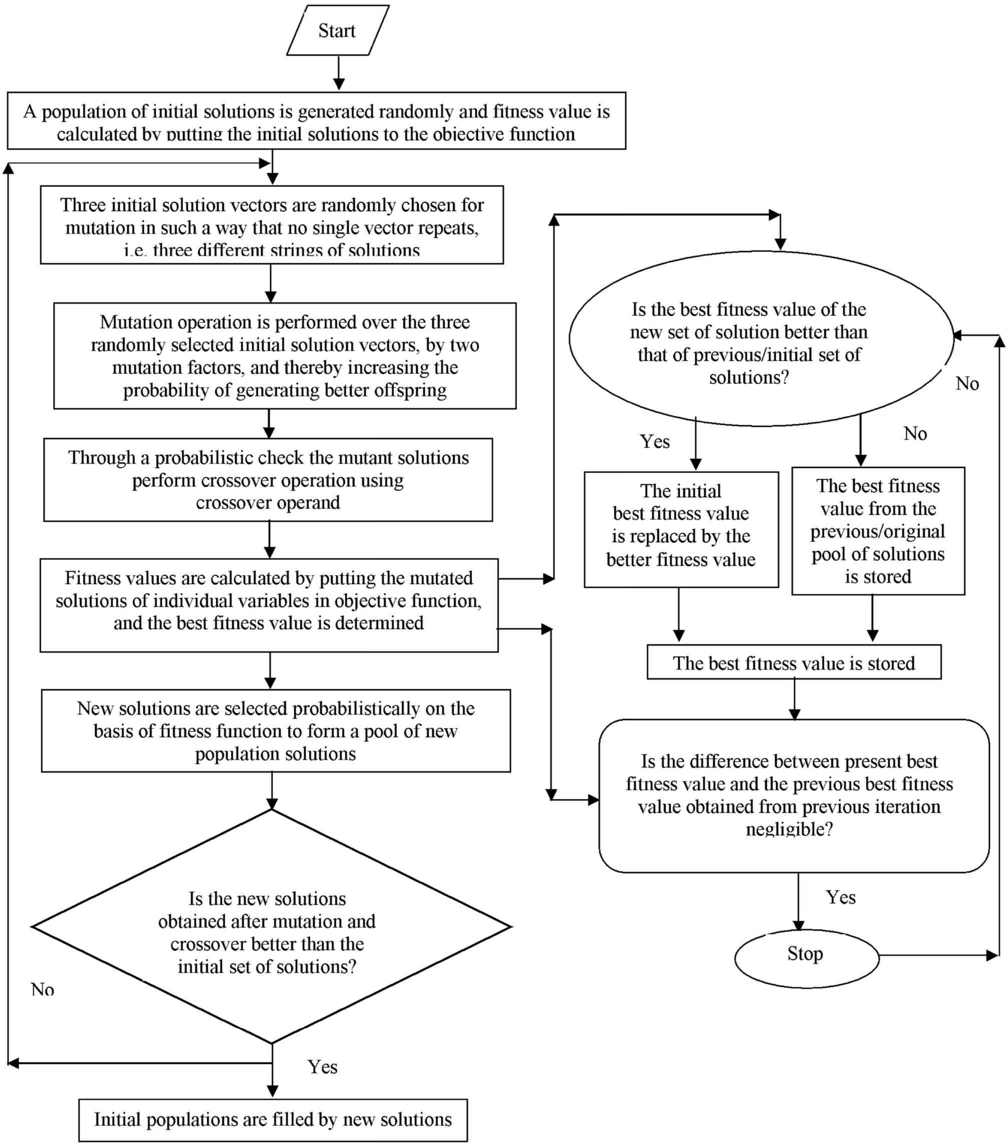

Figure 1. Flow Chart of Modified Differential Algorithm

be the initial solutions relating to power generation from DGs and BESS respectively. The solutions pertain to the 24 hours of a day. Moreover, the power generations are subjected to the constraining ranges which vary from consumer to consumer and season to season.

Step II

The solutions in Step I relating to the number of variables in the objective function (P_{DG}, P_{bt}, P_{SO} *etc.*) together form a matrix pool having a population size of *ps*. Moreover, the dimension of the initial matrix changes with the number of variables (Equation (2), (3) or (4)) that has being considered in the objective function (Equation (1)).

Step III

Three sets of the element matrix are chosen randomly from the pool of total population matrix [19]. Each encoded individuals form a mutant vector and new variables are found from the following equation

$$\mathbf{X = x_{r3a} + F_{best}(x_{r2} - x)_{\beta} + F_{best}(x_{rl} - x)} \qquad (22)$$

where, [x_1, x_2, x_3,………… x_{ps}] is the original set of elements in the trial vector, and [X_1, X_2, X_3,…. X_{ps}] is the mutated set of elements. F_α and F_α are the mutation factors and their dynamic ranges usually lie from 0.7 to 0.9 and 0.1 to 0.3, respectively [19]. These sets of encoded individuals are chosen through a defined rule, where three distinct rows r_1, r_2, and r_3 are randomly chosen provided $r_1 \neq r_2 \neq r_3$. Moreover, each random pick is done between all the rows of elements' vector, leaving one different row at every pick. Thus the number of picks exactly matches the population size, such that modified mutated set of elements are calculated for all the rows in the trial vector. Hence the mutated vector becomes as [X_1, $X_{2,}$ X_3 X_{ps}].

Step IV

Next, the crossover operation is performed by the application of crossover operator, as described below:

First, for each variable a random number is drawn which lies between [0, 1]. Then, those random numbers corresponding to their respective variables in X_1 element are compared by a certain probabilistic ratio, i.e. *CR*. It ranges from 0 to 1 [19]. If the random value corresponding to each variable is less than or equal to *CR*, the mutated set of variables are chosen, else the trial vector retains the original set of variables, *i.e.* x_1.

Step V

The selection is performed on the basis of fitness function [32], which is calculated with the values of trial solutions in the objective function. According to this fitness value a comparison is done between the mutated set of values with its respective original set of values. Finally, the whole initial trial matrix is replaced by the modified matrix, comprising of both original and mutated elements, as shown below:

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \\ \\ \\ X_{ps-1} \\ X_{ps} \end{bmatrix}$$

Step VI

Depending on the population size, all the above four steps are repeated until all the rows in the trial matrix go through the random selection, mutation and crossover processes. Thus all the four steps form a single iteration for the entire matrix, consisting of all the objective variables.

Step VII

At the end of each iteration, the individuals corresponding to the best fitness are checked through the given constraining ranges. The iteration procedure is continued until the termination criterion is satisfied. The termination criterion is based on the difference between the best fitness values of consecutive iterations becoming negligible.

INPUT PARAMETERS

Temporal variations of load during a day in a small residential locality of an academic institution in an Indian city are considered. Consumers in the form of hostel, market, bank & post office, hospital, and campus-quarters belonging to the specific locality together form a microgrid. The average load variations of consumers based microgrid for summer and winter season are given in Figure 2.

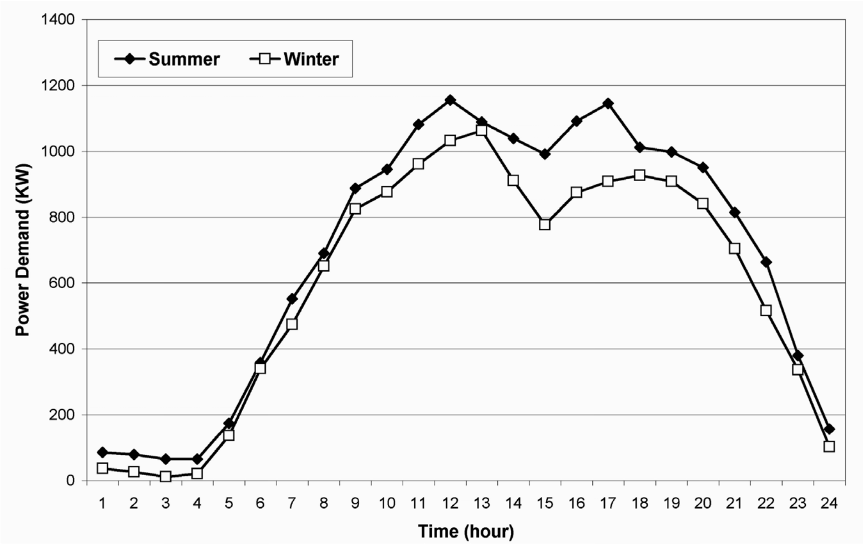

Figure 2. Load Demand Variation of all the Consumers forming a Microgrid for a day

The input parameters required for estimating the cost of a microgrid power delivering system include the initial and running cost of DERs, constructional cost of microgrid power system, and electricity charges from conventional power grid. The total cost of BMGU, PAFC and BESS comprises two major parts; net structure value cost and running cost, while Solar photovoltaic system (SPS) do not include any running cost. The initial and operating cost of DERs for three specific test cases 1, 2 and 3, as mentioned in section 2 are presented in Table 1 [34-35, 36-40].

The initial cost of solar module is given same for both the cases 1 and 2. This is because the installed capacity of solar module has been considered same in case 1 and case 2 during the day hours, which is dependent on the installed capacity. On the other hand, since the initial cost of BMGU is cheaper than PAFC for the same installed capacity, so the chosen installed capacity of BMGU in case 1, and that of PAFC in case 2 have been chosen differently. The installed capacity of BESS has

Table 1. Parameters Related to the Cost of DERs

Cost of DERs	Microgrid System (Case 1)	Microgrid System (Case 2)	Microgrid System (Case 3)
Initial Cost of PAFC [Rs $\times 10^6$]	-	82.5	121.5
Initial Cost of BMGU [Rs $\times 10^5$]	199.35	-	-
Initial Cost of SPS [Rs $\times 10^6$]	131.2	131.2	-
Initial Cost of BESS [Rs $\times 10^3$]	43,5000	362500	2,90,000
Running Cost of PAFC [Rs/kWh]	10	10	10
Running Cost of BMGU [Rs/kWh]	2.5	-	-
Running Cost of BESS [Rs/kWh]	6	6	6

been selected depending on the total installed capacities of other DERs, resulting to different initial costs for different cases.

The initial installation of DERs depends on the type and number of DERs. For kW range of load demand, an enormous amount of Joule heating resulting from the large current flow may occur. It is known [41] that the costs associated with the cables needed to avoid damage from Joule heating are much larger than the costs associated with setting up transformers. So, a step-up transformer at the generation site and a step-down transformer at the consumers' end have been installed for safe and reliable power transmission. Moreover, a controller, change over switches and circuit breakers are placed, at a common point of BMGU, PAFC, solar module, battery and grid. With the increments in number of DERs (i.e. in case 1 and case 2) the length of cable connecting all the consumers increases and as a result the cost also increases. Moreover, with only PAFC as DERs only one step-up and one step-down transformer was considered as a provision of purchasing and selling power from grid is considered; while in case 2 (PAFC and SPS as DERs) and case 1 (SPS and BMGU as DERs), as the number of DERs are two so two step-up transformer and one step-down transformers have been used for the same purpose.

The costs for constructing microgrid by considering SPS and BMGU as DER for case 1, using fuel cell and SPS as DERs in case 2, and utilizing only furl cell with BESS in case 3 are given in Table 2.

Table 2. Microgrid Constructional Cost

Equipments forming Microgrid	Case 1		Case 2		Case 3	
	Cost (Rs)	Life Time (years)	Cost (Rs)	Life Time (years)	Cost (Rs)	Life Time (years)
Switching equipments	474000	6	474000	6	437000	6
Transformers	3350000	15	3350000	15	3350000	15
Controller	20000	30	20000	30	20000	30
Cables	10900000	20	5,000,000	20	10900000	20

Contract charges are considered at rates representative of conventional power grids in the Indian scenario. The base rate is Rs. 200 per kVA, while the electricity rate is Rs. 6.30 per kWh during summer months and Rs 2.68 per kWh during winter months. MDE is applied to the present problem in consideration of these parameters for the three case studies as mentioned earlier.

RESULTS

In the present work, economic analysis of consumer based power delivery systems through optimal operation of DERs has been made through the application of MDE. A comparative study relating to the total cost of power delivery systems for three different cases of DERs *i.e.* case 1 (BMGU and SPS as DERs), case 2 (PAFC and SPS as DERs), and case 3 (PAFC as only DER along with BESS) has been conducted.

The optimal power generations as computed by MDE for microgrid power system of consumers utilizing BMGU and SPS as DERs (i.e. case 1) and PAFC and SPS (i.e. case 2) has been presented in Figure 3 and Figure 4 respectively.

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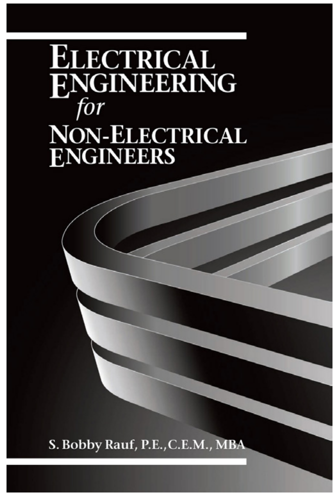

This book is designed to serve as a resource for exploring and understanding basic electrical engineering concepts and principles, as well as related analytical and mathematical strategies. The author has structured and cross-referenced the material to facilitate quick study and comprehension, and to aid the reader in progressing and extending their fundamental electrical engineering knowledge. Topics include critical electrical engineering components of energy projects, electrical-related energy cost factors, tips on improvement of electrical energy intensity in industrial and commercial settings, an update on generation of electricity from renewal sources, basic principles of illumination and efficient lighting, and an explanation of important energy engineering terms and concepts. Also included is a discussion of the skills and preparation necessary for succeeding in the electrical engineering portions of various certification and licensure exams. Practical examples and case studies of electrical applications in industrial and commercial settings are used to demonstrate the topics and procedures covered. Example problems, along with solutions are also included.

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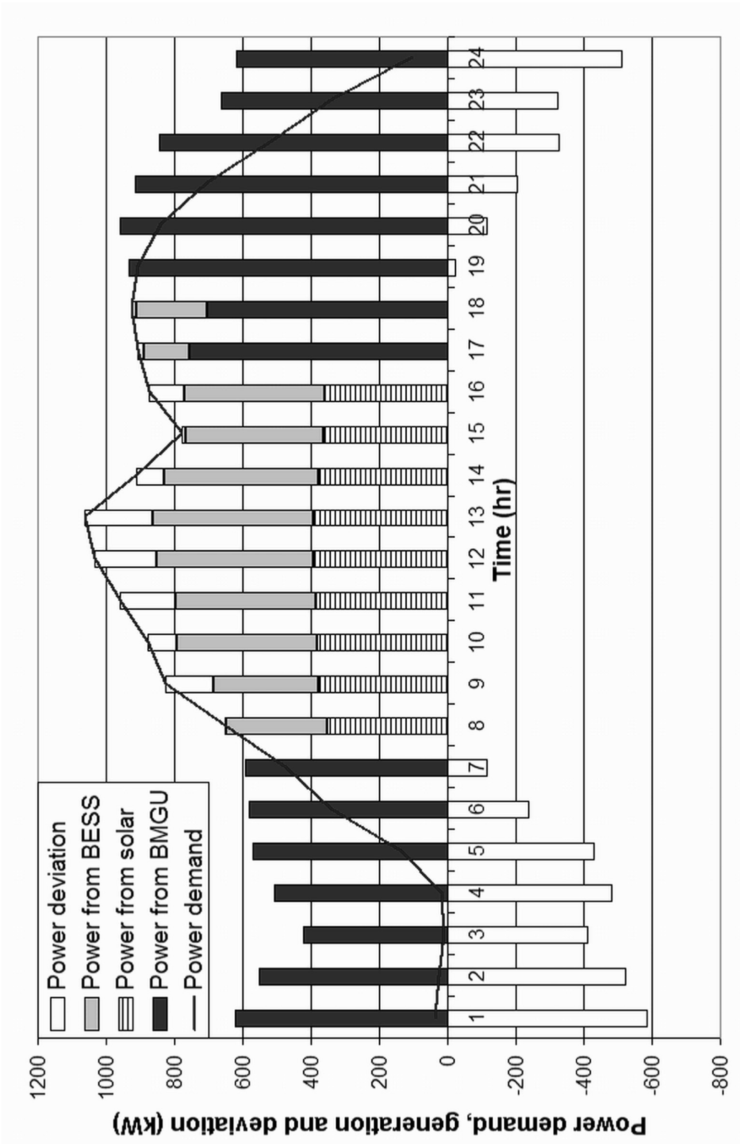

Figure 3. Optimal power operation pattern for the Microgrid for case 1 during winter loading condition, as computed by MDE

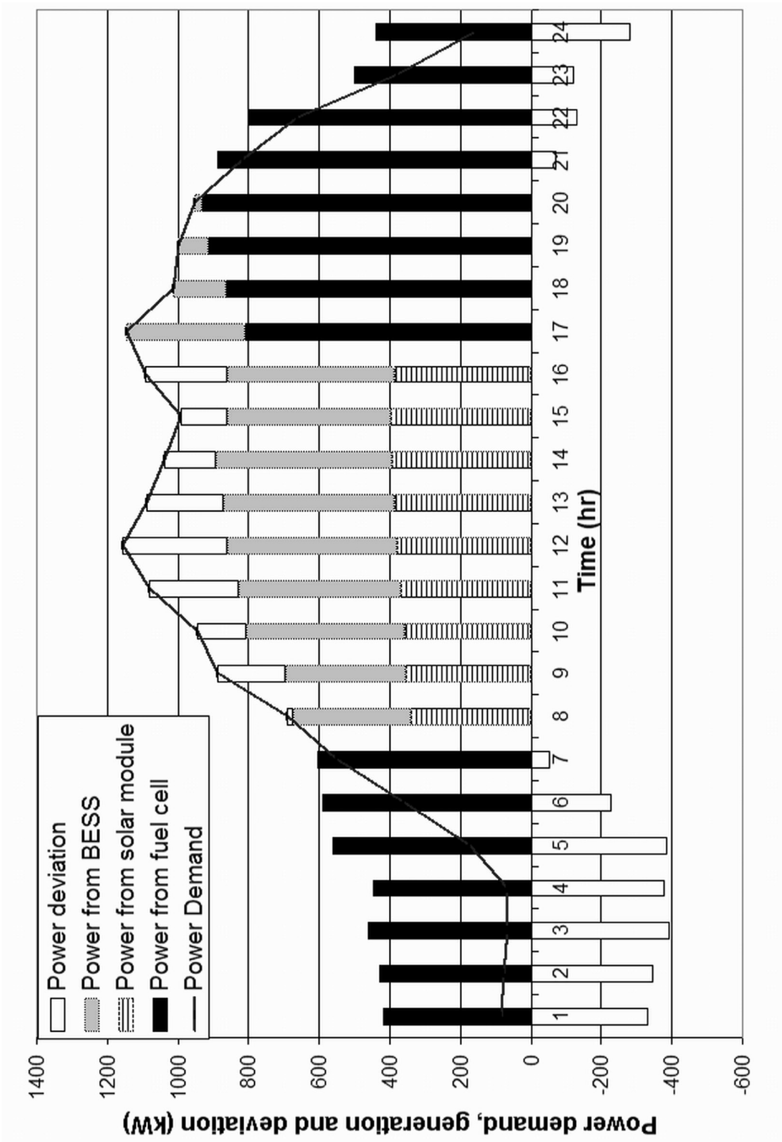

Figure 4. Optimal power operation pattern for the Microgrid for case 2 during summer load, as computed by MDE

Fgures 3 and 4 depict a typical picture of optimal power operation of different DERs for both case 1 and case 2. The difference between power demand and generation of power from the DERs defines the power deviation, symbolized by white bars in both the cases (case 1 and case 2). Positive power deviation indicates that less power is generated with respect to the load demand, while negative power deviation implies that more power is generated with respect to the load demand. The powers generated from BESS are decided on the basis of positive power deviations. It has been observed for both cases of DERs (Figure 3 and Figure 4) optimal powers generations from solar module are occurred during the same hours of a day, i.e. 8.00 am to 4.00 pm. As the installed capacity of solar modules are same for both the sets, so the powers generated from solar module are observed with respect to seasonal loading. The power generated from fuel cell as shown by black bars in Figure 4 and the powers generated from BMGU as shown by green bars in Figure 3 are noticed during the same duration of hours, i.e. from 5.00 pm to 7.00 am. During these periods the positive power deviations take places are mainly due to the shortage in power generation from fuel cell (in Figure 4) and BMGU (in Figure 5).For both the cases the power shortage are found to supply by BESS. Depending on the seasonal loads the power supply from BESS, as indicated by grey bars, observed to be same for both the sets of DERs. The positive power deviations occurring in spite of power supplied by BMGU along with BESS (case 1) and power supplied by PAFC along with BESS (case 2) is denoted by white bars in both the figures. This power shortage is mainly delivered by power purchased from conventional grid. Since for the same initial cost of more installed capacity of BMGU produces more power from that of PAFC, which has been noticed in Figure 3 during 5.00 pm to 7.00 am. During these hours DERs in case 1 produces more negative power generations with respect to that generated by DERs in case 1. As the negative or extra power generation is more for case 1(Figure 3), so apart form charging the BESS the extra powers are also used in selling to the grid.
The optimal power generations from PAFC and BESS for case 3 have been portrayed in Figure 5, as shown below;

The results of Figure 5 has been are noticed to have a similar optimal operation of PAFC and BESS in case 1. During 9.00 am to 8.00 pm the power shortage are noticed, which are mainly occurred due to the stoppage of fuel cell power with respect to the required demand. This was then supplied by BESS, as denoted by brown bars.

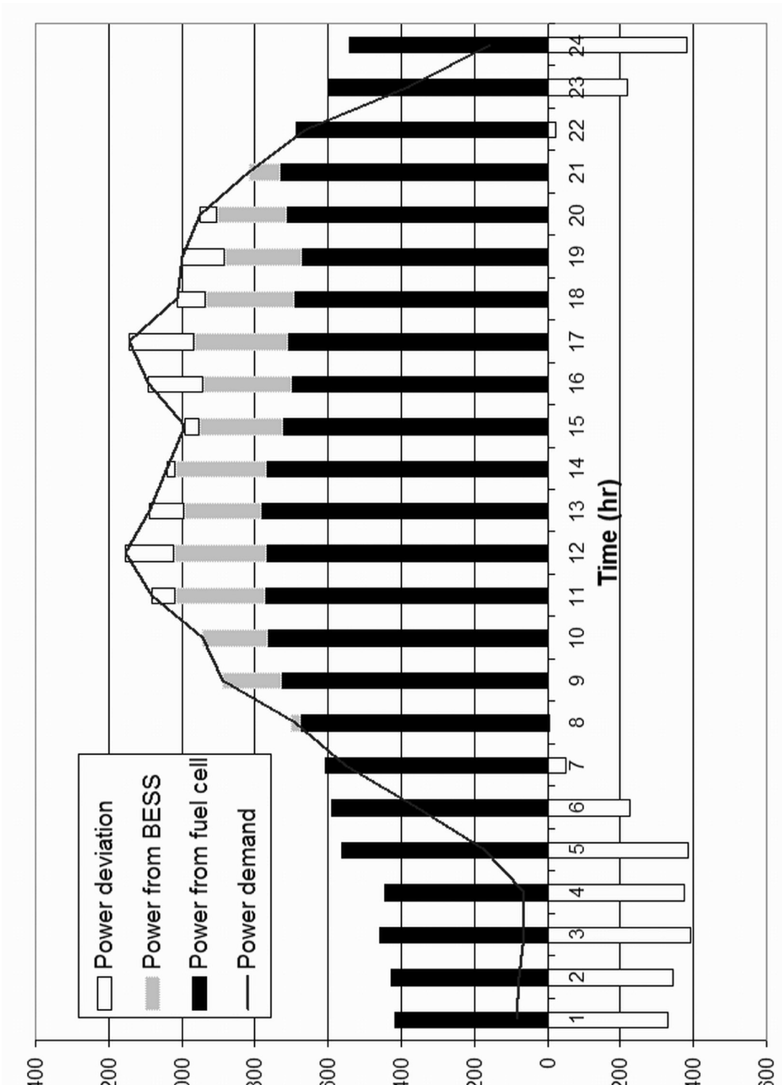

Figure 5. Optimal power operation pattern for the Microgrid for case 3 during summer load, as computed by MDE

It has been observed that the range of optimal power generation from DERs generally varies with consumers' seasonal load demands to limit unnecessary power generation, and thus provides a cost effective power delivery system. It can also be mentioned in this context, that beside the economic factor, the decentralized microgrid system also provides reliable power to the consumers because of the appropriate back-up supply from BESS and conventional power grid in case of positive power deviation including peak demand periods.

The computed total annual cost of consumer based microgrid power delivery system for case 1 (with BMGU and SPS as DERs), case 2 (with PAFC and SPS as DERs) and case 3(PAFC as only DER along with BESS) are shown in Table 3.

Table 3. Comparison of Total Cost between Case 1, Case 2 and Case 3

Microgrid Operation	Total Annual Cost *[Rs]*
Case 1	1.3201009×10^8
Case 2	1.4181307×10^8
Case 3	1.467734×10^8

The result, i.e. total annual cost was obtained by considering the duration of the seasons as weights (*i.e.* Summer Cost × 0.66 + Winter Cost × 0.33), where the summer cost obtained was for all the consumers operating as a microgrid under summer load; while the winter cost represents the same for winter microgrid load.

In spite case 1 involves an increased initial set-up cost from that of case 2 and 3 the running costs are found to be least for DERs in case 1. Thus the biomass gasifier unit along with solar module has been proved to be most cost effective in compare with other sets of DERs in case 2 and case 3.

The results of Table 3 portray that the total annual cost relating to microgrid operation using BMGU and SPS (i.e. case 1) is 6.9 % less than that using solar and fuel cell (i.e. case 2) for the same load demand, while is reduction is about 10 % with respect to case 3.

Table 4 illustrates the per unit energy cost calculated for each consumer operating as a microgrid power system for case 1, case 2 and case 3 respectively. The electricity price for each consumer, in a microgrid power operation has been calculated by dividing the total annual cost by the product of average load demand of all consumers forming microgrid in kW, the number of hours in a year (1 year=8760 hours) and the number of consumers. Here, the number of consumers is 5.

Table 4. Per Unit Costs for Consumers (Case 1, Case 2 and Case 3)

Microgrid Operation	Electric Price per unit *[Rs]*
Case 1	18.4
Case 2	20
Case 3	22

It is observed that per unit cost for every consumer obtained in case 1 is about 8 % less than that obtained in case 2, and 15 % from that of case 3. And it is observed that per unit cost obtained for consumer forming microgrid power delivery system with BMGU and SPS as DERs is less than that obtained for consumer forming microgrid power delivery system with that PAFC and SPS as DERs, and only PAFC as DERs. The maximum reduction is about 1. 6 % when calculated by MDE. The difference in per unit cost obtained due to the difference occurred in total cost as shown in table 4.

CONCLUSION

Different sets of DERs connected to a microgrid framework of an Indian power delivery system have been theoretically studied from an economic perspective using the method of Modified Differential Algorithm (MDE). MDE, as a soft computing technique can take into account imprecision, partial truth, uncertainty and approximation in the input data such as load profiles, unlike linear programming based approaches [3,12] to solve problems of a similar character. Moreover, it is realized MDE can be successfully and reliably implemented in this type of optimization problem instead of traditional method of linear programming [12]. In comparison to other conventional meta-heuristic techniques, differential evolution is a method which has self organizing tendency and also treats solutions as real number strings, so MDE didn't involve much encoding and decoding, consequently saving the computational time.

An economically favorable result has been obtained both for the microgrid power delivery system when both solar and BMGU act as DERs than when fuel cell and solar acts as DER; and only fuel cell with BESS acts as DER. This reduction in annual cost for microgrid power delivery system constituting BMGU and SPS is about 6.9% in comparison with SPS and PAFC as DERs and about 10% with respect to PAFC as DERs; under Indian load scenario. Microgrid power delivery systems consisting of economic and reliable distributed power sources such as BMGU coupled with SPS, in a small Indian locality may be a worthwhile option to be pursued in future power demand scenarios.

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