2006

Evaluation of configuration plans for DGs in developing countries using advanced planning techniques

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Publication Details

Agalgaonkar, A. P., Kulkarni, S. V. & Khaparde, S. A. (2006). Evaluation of configuration plans for DGs in developing countries using advanced planning techniques. IEEE Transactions on Power Systems, 21 (2), 973-981.

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Abstract

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Disciplines

Physical Sciences and Mathematics

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Evaluation of Configuration Plans for DGs in Developing Countries Using Advanced Planning Techniques

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***Abstract*—Many developing countries have emphasis on distributed generation (DG) technology for their generation expansion planning. The planning considerations and judicious choice of attributes are dictated by prevailing conditions. The attributes considered are capital costs, energy not served per annum, and profits from injecting power into the grid at peak load, all of which are important for a developing country. The uncertain futures considered are three possible loading conditions, which can be low, medium and high. Different scenarios (plans) are generated by various combinations of configurations. DGs can be configured as stand-alone mode, hybrid operation, or micro-grid formation with or without grid connection. With the increased complexities in DG planning options along with the multiple attributes to be accounted, more sophisticated techniques other than conventional economic analysis are needed to arrive at correct decisions by decision makers. The analytical hierarchy process (AHP) is used for obtaining relative weights in an objective way. Further, the statistical method like interval-based multi-attribute decision making with tradeoff analysis is used for shortlisting the feasible plans and identifying the most appropriate plan. It is proposed to use the weights obtained from AHP for finding the performance efficiencies in data envelopment analysis (DEA) for evaluating the plans. A new composite utility function is proposed to resolve cases where performance efficiency is insufficient for evaluation in DEA application. The sample system is derived with reference to a rural electrification scheme in India. The assessment of plans is presented and discussed. The comparative strengths and weaknesses of the methods are reported on the basis of the results obtained.**

***Index Terms*—Data envelopment analysis (DEA), decision support system, distributed generation (DG), hybrid operation, micro-grid, tradeoff/frontier analysis.**

I. Introduction

The developing countries are adopting distributed generation (DG) technologies for their generation expansion planning. Until recently, the viability of DG in a power system was generally justified by cost-benefit analysis, possibility of T&D deferment, reduction in T&D losses, minimizing emissions, etc. [1]–[3]. Some of the technical issues of concern are discussed in [4]. The detailed comparison between distributed resource power system and conventional central station generation with T&D system, on the basis of various performance characteristics such as efficiency and losses, reliability and power quality, investment, fuel, O&M, emissions, etc., is given in [5] and [6]. These, although being important issues, need not be the only deciding factors. It is very likely that without fulfilling all these requirements, DG may become attractive so as to protect sensitive loads.

Studies have predicted that DG may account for up to 20% of the all-new generation going online by the year 2010 [7]. However, the technologies should be candidly assessed on a common platform. The decision maker is confronted with the strategic planning studies with various options for DGs, such as grid connection, hybrid systems, and now a new option of micro-grid. The micro-grid option has attracted considerable attention from researchers, and though there are many positive points that can be listed in its favor, these have to be substantiated with the analytical methods that can quantify the benefits.

The multi-attribute decision making (MADM) approach is one of the most suitable technical aids for strategic planning. It selects the best resource strategy with regard to chosen attributes [8], [9]. This analysis is very much useful for a decision maker/DG owner to find out the best solution under uncertainties and with the consideration of conflicting attributes. Various MADM techniques the from management perspective are collectively published in [10].

The operational performance statistics of different generating units can be evaluated using data envelopment analysis (DEA) for various performance indicators [11]. It is observed that DEA can be widely used as a tool for multi-criterion decision making with the help of preference information.

In this paper, planning of a typical medium-voltage rural distribution system in the State of Maharashtra, India, is considered for different loading conditions. The different attributes, viz. capital costs, energy not served per annum, and profits from injecting power into grid at peak load, representing the typical characteristics of a developing country, are considered. A novel approach of DEA based on analytical hierarchy process (AHP) is proposed and compared with the interval-based MADM technique for finding the preferential ranking of various configuration plans, such as single source DG, hybrid DG, micro-grid, etc. A new concept of composite utility function is also proposed for getting information about infeasible values of different attributes. A comparative assessment of various DG tech-

Manuscript received June 20, 2005; revised October 13, 2005. This work was supported by Central Power Research Institute (CPRI), Bangalore, India under the project titled “Study of infrastructure and issues involved in implementation of Distributed Generation in rural India” (as per sanction order no. CPRI/R&D/RSOP/IITB/2004). Paper no. TPWRS-00370-2005.

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Digital Object Identifier 10.1109/TPWRS.2006.873420

nologies using the proposed methodologies can provide an executive summary to decision makers.

This paper is organized as follows: Section II illustrates the problem formulation. Section III describes the evaluation techniques for DG configuration plans. Then, Section IV provides the algorithm for the proposed approach. The sample system and results are presented in Sections V and VI, respectively. Section VII concludes the findings.

II. Problem Formulation

The ever-increasing electricity demands, 100% rural electrification, and scarcity of the conventional generation resources are the major concerns for most of the developing countries in the world. This paper addresses a typical problem of rural electrification from the State of Maharashtra, India.

A. Background and Motivation

Maharashtra is ranked second in the country in terms of power generation from renewables. The installed capacity for wind as well as for bagasse/biomass is expected to be around 1000 and 500 MW, respectively, at the end of year 2007 [12]. Bagasse is fibrous residue left after the extraction of juice from sugarcane. Biomass is abundantly available in the form of husk, straw, shell of coconut, wild bushes, crop/agro residues, etc. According to Indian Electricity Act 2003 and the guidelines from the Ministry of Power (MoP), Government of India, the Maharashtra Electricity Regulatory Commission (MERC) has proposed a comprehensive plan for implementation and facilitation of rural electrification and supply initiatives in the State [13], [14]. In Maharashtra, grid-connected wind generation and hybrid wind + solar systems are already in place. It is also observed that there is a possibility to interconnect two or more renewable sources located in the close vicinity of each other, thereby forming a micro-grid. National Renewable Energy Laboratory (NREL), in the U.S., has identified India as one of the key countries for exploring the possibility of the micro-grid to electrify remote rural areas [15]. The well-known advantages of interconnection in a grid, viz. improvements in reliability and security, can be realized on a mini scale by the micro-grid. Some of the salient features of the micro-grid are discussed in [16].

B. Challenge Faced by Decision Maker

Prima-facie, it seems that finding a reliable and cost-effective solution for rural electrification is a trivial problem. However, few intricate issues complicate the decision-making process. In India, every State has got a state nodal agency, which as a preliminary requirement evaluates the practical feasibility of all the renewables. Later on, in order to find the solution for rural electrification, the policy maker/stakeholder/decision maker has to evaluate all the possible plans. These plans can have various combinations of stand-alone, hybrid, and micro-grid applications, including renewables and other DG technologies. In addition, there is also a need to account for various conflicting attributes as seen by the stakeholders. Thus, the problem posed is simply to evaluate the DG configuration plans, and further, the plans can be ranked based on some normalized common platform using advanced planning techniques. These advanced planning techniques are described in the next section.

The proposed formulation allows the consideration of all the concerned issues, thereby presenting a novel approach of decision making.

III. Evaluation Techniques

A. Cost-Benefit Analysis

Cost-benefit analysis is a prerequisite for justifying viability of any planning option. In [17], the benefit-to-cost ratio (BCR) criteria is used for minimizing DISCO's investment and operating costs, i.e., maximization of its profit with and without DG. The DG will be economically attractive, and it will be the most preferred option for congested systems [18]. NREL has used the electricity asset evaluation model (EAEM) for justifying DG technology rather than upgrading T&D systems in congested areas [19].

The simulation package, HOMER, has been developed by NREL [20]. It compares the cost of energy (CoE) and net present cost (NPC) of various expansion plans, such as independent grid, stand-alone DG, hybrid DG, etc. However, it is not possible to model the micro-grid with all its capabilities in this software. Moreover, additional attributes other than cost and emissions cannot be incorporated. Since the evaluation of DG configuration plans is a typical MADM problem, it requires sophisticated planning methodologies. Accordingly, interval-based MADM and DEA-based MADM techniques are discussed in this section. Both these methodologies are based on AHP, which is used for the optimal selection of weights of independent attributes in this paper.

B. Analytical Hierarchy Process

AHP is the simplistic way to decide the relative importance of all the attributes objectively. The preliminary requirement for AHP is to decide the hierarchy of the planning process. The members constituting the hierarchy are allowed to rate each other, and finally the relative grading of attributes (weights) is determined [21]–[23]. The proposed hierarchical structure for evaluating the relative importance of various attributes is as shown in the Section VI-A. A software package supporting AHP, *Expert Choice* [24], is used to make these calculations so as to guide the decision maker.

C. Interval-Based MADM Using Tradeoff Analysis [25]

The tradeoff analysis is commonly used for finding the best possible solution to the problems with multiple conflicting objectives and uncertainties. This approach is very much useful in electric utility strategic planning for dealing with a wide range of resource options. It is a very organized way of evaluating relationships between attributes and uncertainties and eliminating many plans that are inferior [26]. Typical tradeoff curves can be obtained using normalized values of attributes for all the configuration plans under the various uncertain futures. With no uncertainty, results are conditional on one particular future. The tradeoff region forms the boundary between the sets of possible and unattainable attributes. Since minimization of all the attributes gives the most viable solution, it can be easily inferred that plans near the origin of the tradeoff region are more attractive. In tradeoff analysis [27], tolerance limit needs to be specified for each attribute as "much worse," "significantly better," etc., by the decision maker. Thus, although tradeoff analysis is useful for shortlisting the impressive plans, the use of an interval-based MADM technique with a strong statistical base is proposed for finding a superior alternative. The concept can be briefly described as follows.

1) Additive Utility Function: Usually most of the MADM problems can be tackled by transforming n-dimensional vector performance into a scalar performance through use of multi-attribute utility function (MAUF). The MAUF model is comprised of a single utility function and the weighting parameters associated with the chosen attributes. MAUF can be decomposed into a series of single-attribute assessments and represented in a special form known as linear additive form. It assumes that the contribution of an individual attribute to the composite utility is independent of other attribute values. A general expression of linear additive utility function model can be expressed as

$$Ut(x) = \sum_{i=1}^{n} w_i \cdot Ut_i(x_i) \tag{1}$$

where

$Ut(x)$ composite utility characterized by the vector of attributes $x = [x_i, \ldots, x_n]$;

$Ut_i(x_i)$ single-utility function with respect to the ith attribute;

w_i appropriate weighting parameter for the ith attribute, representing its relative importance in comparison to other attributes and satisfying $\sum w_i = 1$.

2) Variance of Composite Distance: There are two important terms that are of concern in the construction of the linear additive utility model: one is individual utility function and other is the corresponding weighting parameter. However, in many MADM applications, a single-utility function $Ut_i(x_i)$ can be represented by the normalized attribute value r_i. If x_i and r_i are the measured and normalized values of the ith attribute, respectively, x_i^r is the range of variation of measured attribute values, and x_i^* is the minimal value of the ith attribute, then the composite distance $Ut_d\ (x)$ can be represented as

$$Ut_d(x) = \sum_{i=1}^{n} w_i \cdot \left| \frac{x_i - x_i^*}{x_i^r} \right| = \sum_{i=1}^{n} w_i \cdot r_i. \tag{2}$$

For (1), the best alternative is the one for which the value of composite utility is maximum. On the contrary, the most favorite alternative determined by (2) represents the minimal distance from an ideal point on the direction preferred by the decision maker, and hence, the term composite utility is replaced by composite distance.

The influence of inaccurate data on various planning alternatives can be examined by using the technique of *Propagation of Errors* [8], [28]. Accordingly, the variance of composite distance for linear additive utility function is

$$\sigma_d^2 = \sum_{i=1}^{n} \left(r_i^2 \sigma_{wi}^2 + w_i^2 \sigma_{ri}^2 \right) \tag{3}$$

where σ_d is the standard deviation of composite distance values, σ_{ri} and σ_{wi} are the standard deviations, i.e., the error parameters of the normalized ith attribute and its weighting parameter, respectively.

The utility function for a single attribute can be approximated by taking the normalization of attribute ratings. Since each attribute possesses various units of measurement, normalization is necessary to obtain a comparable scale that further allows the additivity in (1) [8].

D. DEA-Based MADM

DEA is a linear programming (LP)-based technique for measuring performance efficiency (ratio of total outputs to total inputs) of organizational units which are termed as decision-making units (DMUs) [29], [30]. The DMUs should be homogeneous entities in the sense that they use the same resources to obtain the same outcomes, even though in varying amounts [31]. The DMUs can be also represented in the form of various configuration plans with multiple attributes. DEA can be used for MADM if the attributes are represented in the form of inputs and outputs. The attributes to be maximized are considered as outputs, while the attributes to be minimized are considered as inputs. Especially in the case of single-output two-input case, one can generate the efficient frontier by plotting two ratios, i.e., (input 1/output) versus (input 2/output). It is observed that this efficient frontier is the same as the tradeoff region as explained earlier, i.e., plans near the origin are the most viable plans. Thus, the determination of the efficient frontier is a preliminary screening process so as to identify the feasible sets.

The performance efficiency for a multi-input, multi-output DMU can be defined as the weighted sum of its outputs divided by the weighted sum of its inputs [29]. Initially, the best set of weights is chosen for a particular DMU, and then the same set is further used to weigh the inputs and outputs for each of the other DMUs. Thus, the cross efficiency of each of the other DMUs is calculated. The procedure is then repeated for all DMUs, which leads to the matrix of cross efficiencies [32].

1) Simple Efficiency and Cross Efficiency [32]: Suppose, DMU i selects its own weights w_{ij} (for i's jth output) and x_{ik} (for i's kth input), then the cross efficiency of DMU m, using the weights chosen by i is

$$E_{im} = \frac{\sum_j O_{mj} \cdot w_{ij}}{\sum_k I_{mk} \cdot x_{ik}} \tag{4}$$

where O_{mj} is the normalized value of m's jth output, and I_{mk} is the normalized value of m's kth input.

Accordingly, the DEA formulation for MADM is:

$$\text{Maximize} \quad E_{ii} = \frac{\sum_j O_{ij} \cdot w_{ij}}{\sum_k I_{ik} \cdot x_{ik}} \tag{5}$$

subject to :

$$1)\ x_{ik}\ and\ w_{ij} \geq 0 \tag{6}$$

$$2)\ E_{im} \leq 1 \text{ for all DMUs, including } i. \tag{7}$$

Equations (5)–(7) represent LP formulation for selecting appropriate weights by maximizing the objective function, which is commonly called as i's "efficiency" or "simple efficiency" (E_{ii}). The process of obtaining the simple efficiency is known as self-appraisal (i.e., i rates itself) for a DMU. It may be noted that (5) can also be written as numerator minus denominator and could achieve the same objective. This concept is used to define composite utility function (CUF) later. For n number of DMUs, there results an $n \times n$ matrix, representing cross efficiencies as off-diagonal elements and the simple efficiency terms as the diagonal elements. Finally, the average of the ith column entries of the matrix excluding the diagonal term can be interpreted as an averaged peer appraisal (e_i) of DMU i. The averaging may be done with or without self-efficiency. Thus, the averaged peer appraisal (without self-appraisal) for n DMUs is

$$e_i = \frac{1}{(n-1)} \cdot \sum_{m=1, m \neq i}^{n} E_{mi}. \tag{8}$$

The DMU with the highest value of the averaged peer appraisal is the most favorable option. However, the weights w_{ij} and x_{ik}, which maximize DMU i's simple efficiency, may not be unique. One possibility suggested in [32] to address this issue is to introduce a secondary objective function that either minimizes/maximizes the other DMUs' cross efficiencies (aggressive/benevolent formulation). In all, the main issue of concern in this formulation is "weight selection."

2) Proposed Approach: The use of DEA is already proposed in [33] to generate local weights in AHP, wherein some important characteristics of DEAHP are also highlighted. In this paper, we have proposed the use of optimal weights obtained from AHP for calculating two new indexes: one is performance efficiency, and the other is CUF. The basic motivation for calculating these indexes is to simplify the complex MADM formulation using DEA.

a) Performance efficiency: A novel approach based on AHP is used to get rid of LP formulation for obtaining the weights. Initially with the help of AHP, the relative importance (optimal weights) for all the attributes is calculated. These weights are then directly used for evaluating the performance efficiency of each configuration plan. A plan with the maximum efficiency is the best plan. The performance efficiency can be given by

$$\text{Performance efficiency} = \frac{\sum_j O_{mj} \cdot w_{ho}}{\sum_k I_{mk} \cdot w_{hi}} \tag{9}$$

where w_{ho} and w_{hi} are the optimal weights obtained by AHP. It minimizes the computational burden of evaluating the simple and cross efficiencies.

The interval-based MADM and the proposed DEA-based MADM techniques are compared for a realistic distribution system with different loading patterns. It is observed that for some configuration plans with a certain loading condition, the absolute values for a particular attribute are infeasible in the case of an interval-based MADM, while they are zero for the proposed DEA-based MADM approach. Hence, the information related to these particular values is lost. Such a case can be better analyzed with the help of CUF.

b) Composite utility function: The function described by (9) evaluates performance efficiency considering input in the denominator. A lower value of weighted input implies higher efficiency. The other way of expressing higher efficiency would be to add the weighted input with a negative sign to the weighted output. The CUF can be represented as

$$CUF = \sum_j O_{mj} \cdot w_{ho} - \sum_k I_{mk} \cdot w_{hi}. \tag{10}$$

IV. Algorithm

The proposed methodology can be described in steps as follows.

1) Initially, various planning options/scenarios are generated, and different attributes (independent of each other) along with uncertain futures are defined.
2) By using AHP, the relative significance of each attribute is evaluated.
3) The tradeoff region/frontier is formed with the help of normalized values of attributes by eliminating inferior plans. This step is repeated for all the futures. Hence, at the end of this step, the feasible space of configuration plans for all the futures is generated.
4) The interval-based MADM technique using additive utility function is used for computing the variance of composite distance for each feasible plan. A plan with minimum variance of composite distance is the best plan. The preferential ranking of all other plans can be done by using the values of variance.
5) The DEA-based MADM is also applied for the set of feasible plans (obtained from frontier curve), and the plan with maximum performance efficiency is taken as the best plan. If some plans become indeterminate, then CUF is used [as per (10)] as an additional tool for finding the most suitable plan.

V. Sample System

In this paper, a sample 11-kV distribution feeder of a typical medium-voltage rural distribution system in the State of Maharshtra, India, is considered. Three independent attributes and three uncertain futures are considered, and the value of each attribute is calculated for various possible configuration plans under consideration. AHP is used for deciding the priorities among all attributes. By using a tradeoff/frontier analysis, the viable sets of plans are shortlisted for all the uncertain futures. The interval-based MADM approach is used for shortlisting favorable plans and for finding best plan. These results are verified using the DEA-based MADM technique.

A. Sample System

A small portion of the sample system under consideration is as shown in Fig. 1.

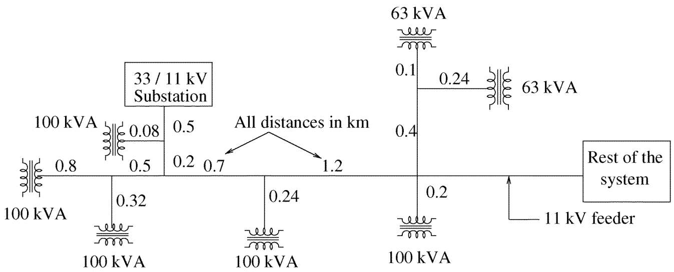

Fig. 1. Sample system under study.

TABLE I
DIFFERENT LOADING PATTERNS

Future	Residential (kW) (14%)	Commercial (kW) (3.5%)	Industrial (kW) (13%)	Agricultural (kW) (69.5%)	Total (kW) (100%)
F1	247	62	224	1212	1745
F2	353	88	328	1751	2520
F3	122	31	114	607	874

It covers around 25 circuit kilometers of an 11-kV feeder as a small part of the MV distribution system to be electrified. This is a typical radial feeder serving a mix of consumers, viz. residential, commercial, industrial, and agricultural. Usually, such a system has only one source, and hence, redundancy is very poor. Nevertheless, it can be improved with the help of a meshed network instead of a radial network at some strategic locations.

Three uncertain futures are considered with different loading conditions for residential, commercial, industrial, and agricultural sectors, as shown in Table I. Future 1 (F1) represents the medium loading condition. In addition, two separate loading conditions, viz. high load (F2) and low load (F3), are considered.

It is assumed that the expansion strategies for electrification of this particular feeder include the conventional grid as well as DG configuration plans with stand-alone, hybrid, and micro-grid operations.

Typical overhead distribution system requirements include 11-kV feeder, double pole structures with distribution transformer (100- or 63-kVA capacity) centers, three-phase distribution boxes, etc. These details are obtained from the Maharashtra State Electricity Board (MSEB), India. The DG technologies considered for this particular study are gas turbine, wind-solar hybrid, biomass, and bagasse. Micro-grid formation is considered by integrating biomass, bagasse, and wind-solar technology. All these DGs may or may not be connected with the grid. For grid-connected DG options, it is assumed that the grid supplies around 30% of the total load. DG capacities are flexible, depending upon the loading conditions. For the hybrid wind-solar system, it is assumed that the capacity factor is around 45%. Three totally independent attributes, i.e., energy not served in an annum (MWh), capital cost (billion INR), and profits for injecting power at peak loads (INR), are evaluated as follows.

1) Energy Not Served in an Annum (Attribute 1): With typical problems of a developing country, the vertically integrated State Electricity Boards are unable to supply reliable and quality power to consumers. Currently, in the State of Maharashtra, there is a routine load shedding of 6 h for rural feeders and 3 h for cities on daily basis. Hence, it is assumed that the grid power is not be available for 6 h in a day. For single-source DG options, it is assumed that there is requirement of routine maintenance for 24 h in each quarter of a year. On the contrary, in the case of micro-grid and hybrid DGs, it is expected that the continuity of supply will be maintained all throughout the year. Thus, the product of total outage hours and the total unmet load gives the energy not served in an annum for each plan. Finally, the attribute values for all the futures (F1, F2, and F3) are normalized and represented in Table II.

2) Capital Cost (Attribute 2): For promoting private participation in rural electrification, the DG technologies are awarded a subsidy to the extent of up to 40% of the capital cost. Since our sample system is a typical representation of a rural feeder, the capital cost for the DG technologies is calculated by considering 40% subsidy for the overall capital investment. This includes the per MW cost for various types of generating resources under consideration [34] and the total expenditure for distribution system infrastructure, i.e., the cost of a feeder, double pole structures, transformers, etc. The normalized values of this attribute are as shown in Table II.

3) Profits for Injecting Power at Peak Load (Attribute 3): The new concept of availability based tariff (ABT) [35] has been implemented in India since the middle of 2002, wherein all the central sector generators and beneficiaries (i.e., various States) must declare a schedule for generation and drawal for every 15 min, one day in advance. Any deviation from the schedule is charged at the rates that are frequency dependent. The intra-state ABT mechanism is currently under consideration to encourage schemes consisting of local additional generation near the load centers. The single-source DGs may benefit by injecting some additional amount of unscheduled power into the grid (in the peak periods) under the intra-state ABT mechanism [36]. It is assumed that micro-grids, being self-sufficient in nature, schedule their different generating resources according to the nature of load diversity in the proposed system. Since the preliminary aim for each DG option is to serve local loads in its close vicinity, the third attribute, i.e., profits for injecting power at peak loads, is evaluated by injecting fractional power at average frequency in the peak periods. Here, the typical peak period can be divided into morning peak and evening peak. The typical frequency pattern for both the time slots is obtained from the Western Regional Load Dispatch Centre (WRLDC), India. The average frequency for these two time slots is considered for the profit calculations, i.e., initially, the frequency-based per unit unscheduled interchange (UI) charges (in INR) can be calculated as

$$\begin{aligned}
\text{UI Charges} & \\
&= 5.7 && \text{for frequency} < 49 \text{ Hz} \\
&= 5.7 - [4.5 * (f - 49)] && \text{for } 49 < \text{f} < 49.8 \text{ Hz} \\
&= 2.1 - [3.0 * (f - 49.8)] && \text{for } 49.8 < \text{f} < 50.5 \text{ Hz} \\
&= 0.00 && \text{for frequency} > 50.5 \text{ Hz.}
\end{aligned}$$

Subsequently, with the help of excess power availability for each plan under all the futures, the total profits can be calculated as the product of UI charges and excess electricity throughout

TABLE II
NORMALIZED VALUES OF ATTRIBUTES FOR DIFFERENT CONFIGURATION PLANS

Plan no.	Configuration plans	Energy not served in an annum (attribute 1)			Capital cost (attribute 2)			Reciprocal of profit (attribute 3)		
		F1	F2	F3	F1	F2	F3	F1	F2	F3
1	Conventional grid	Inferior plan								
2	Gas turbine	0.044	0.044	0.044	0.048	0.043	0.057	1.000	0.250	0.960
3	Gas turbine + grid	0.340	0.360	0.340	0.058	0.052	0.073	1.000	INF	0.960
4	Wind + solar	0.019	0.020	0.013	1.000	1.000	1.000	1.000	0.250	0.960
5	Wind + solar + grid	0.310	0.340	0.320	0.580	0.550	0.670	0.850	INF	0.960
6	Micro-grid with biomass + wind + solar	0.000	0.000	0.000	0.350	0.370	0.480	1.000	INF	1.000
7	Micro-grid with bagasse + biomass	0.000	0.000	0.000	0.075	0.064	0.089	1.000	INF	0.960
8	Micro-grid with biomass + wind + solar + bagasse	0.000	0.000	0.000	0.350	0.370	0.530	1.000	1.000	1.000
9	Biomass + grid	0.340	0.360	0.340	0.058	0.048	0.069	1.000	INF	0.960
10	Micro-grid with biomass + wind + solar + grid	0.000	0.000	0.000	0.350	0.370	0.480	1.000	INF	1.000
11	Micro-grid with bagasse + biomass + grid	0.000	0.000	0.000	0.075	0.064	0.089	1.000	INF	0.960
12	Micro-grid with biomass + wind + solar + bagasse + grid	0.000	0.000	0.000	0.350	0.370	0.530	1.000	1.000	1.000

year. This attribute (profit for injecting power at peak load) has been identified as the output of the DEA approach.

For the sake of tradeoff analysis, it is envisaged that all the three attributes should be minimized for arriving at the most preferred solution. Hence, the last attribute is converted into reciprocal of profit. The normalized values of this modified attribute are as shown in Table II. The term INF for some plans corresponding to future 2 represents the indeterminate value of the attribute due to nonavailability of any power for export, i.e., there is zero profit resulting from the "divide by zero" term.

As per the tradeoff/frontier analysis, the planning option with a conventional grid is considered as an inferior plan.

VI. RESULTS

The evaluation techniques described in Section III are applied to the sample system using the algorithm in Section IV, and the results of all the techniques are presented in the following sub-sections.

A. *Use of AHP for the Proposed Approach*

Initially, the decision maker identifies the list of stakeholders. Every stakeholder has to give feedback regarding the relative importance of all the attributes. With this information, the decision maker is ready to find the best possible weights using AHP in an objective way. Thus, to begin with, the hierarchy of the proposed planning process is decided as shown in Fig. 2. The values of different weights for all the attributes are then calculated by using the software package *Expert Choice*. In this particular software, the decision maker has to decide the priority of one attribute over the other. Suppose that the attributes (discussed earlier) are to be compared from the customer point of view; then the preference of each attribute has to be decided from the customer's perspective. Intuitively, in this case, the energy not served per annum should have the highest priority among all the three attributes. From the utility point of view, the energy not served per annum and the profits for injecting peak power have the same importance. For the hybrid DG/micro-grid, the capital cost investment has the top priority.

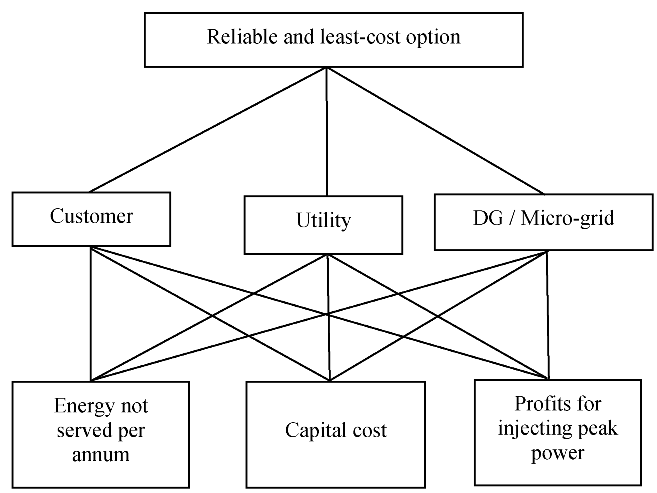

Fig. 2. Hierarchy of the proposed planning process.

For the proposed hierarchy as shown in Fig. 2, the results obtained from *Expert Choice* indicate that the energy not served per annum gets the highest priority $(w_1 = 0.539)$ as compared to capital cost $(w_2 = 0.302)$ and peak load payments $(w_3 = 0.159)$.

B. *Tradeoff Analysis*

Initially, with the help of normalized values of various attributes for different futures as shown in Table II, the tradeoff region is generated among all the attributes for all the futures. Since the plans with feasible values of attributes in all the three futures can only be considered, plans 3, 5, 6, 7, 9, 10 and 11 are summarily rejected. Thus, for three attributes, three futures, and four feasible plans, a total of 12 tradeoff surfaces can be plotted. One representative tradeoff plot between attribute 1 and attribute 2 for future 1 is as shown in Fig. 3. It is observed that some plans are overlapping. Hence, with a careful observation of the tradeoff region, the decision maker is able to locate the

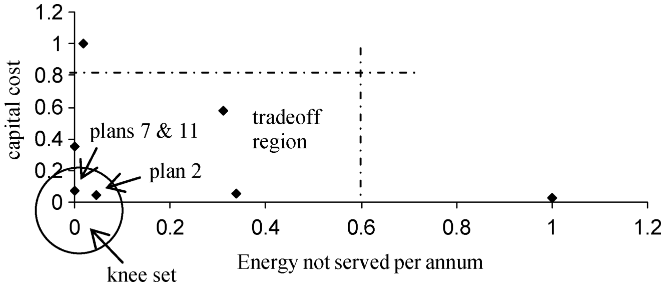

Fig. 3. Tradeoff region for future 1.

TABLE III
VARIANCE OF COMPOSITE DISTANCE

Plan no.	Variance of composite distance (preferential ranking is shown in the bracket)		
	F1	F2	F3
2	0.0711 (3)	0.3215 (12)	0.0506 (1)
3	0.3837 (17)	--	0.3625 (15)
4	0.1663 (11)	0.1214 (8)	0.1243 (9)
5	0.3365 (14)	--	0.3266 (13)
6	0.0854 (4)	--	0.117 (6)
7	0.0883 (5)	--	0.0668 (2)
8	0.0854 (4)	0.1304 (10)	0.1199 (7)
9	0.3837 (17)	--	0.3628 (16)
10	0.0854 (4)	--	0.117 (6)
11	0.0883 (5)	--	0.0668 (2)
12	0.0854 (4)	0.1304 (10)	0.1199 (7)

robust plans. In this particular case, plans 2, 7, and 11 are the most viable plans (knee set) for future 1. This process has to be repeated for all the uncertain futures.

C. Implementation of Interval-Based MADM for Evaluating Variance of Composite Distance

The variance of the composite distance is calculated for each plan contained in the tradeoff region. The implementation of MADM helps the decision maker for preferential ranking of various configuration plans.

According to the MADM analysis, plans 2, 4, 8, and 12 are the robust plans. They appear in the feasible set of all the futures. Plan 2, i.e., stand-alone gas turbine system, plan 8, i.e., micro-grid (bagasse plus biomass plus wind-solar) without any grid connection, and plan 12, i.e., micro-grid (bagasse plus biomass plus wind-solar) connected with the conventional grid, are some of the plans with high preferential ranking in supporting futures, as shown in Table III.

The effect of operation and maintenance (O&M) costs on the evaluation of plans can be considered in many ways. First, the costs can be rolled in the total costs. This approach would not display explicitly the effect of O&M costs. The second approach is to consider O&M costs as a separate attribute. However, the attributes need to be independent, and since the O&M costs are coupled to capital costs, it cannot be considered as a separate attribute. The third approach that is followed is to apply O&M cost after the initial screening is over. This approach is just to fine-tune the evaluation process after the consideration of O&M costs. The consideration of O&M costs has significant impact on ranking of plans if the O&M costs vary over wide band for different generation technologies.

TABLE IV
VARIANCE OF COMPOSITE DISTANCE BY CONSIDERING OPERATING COST

Plan no.	Variance of composite distance (preferential ranking is shown in the bracket)		
	F1	F2	F3
2	0.3109 (7)	0.3211 (8)	0.3653 (9)
4	0.1091 (3)	0.1219 (5)	0.0893 (2)
8	0.0854 (1)	0.1304 (6)	0.1149 (4)
12	0.0854 (1)	0.1304 (6)	0.1149 (4)

Accordingly, we have incorporated the operating cost in addition to the capital cost as one of our attributes, and the interval-based MADM technique is applied to all the robust plans, i.e., plans 2, 4, 8, and 12. It is assumed that the operating costs for a typical gas turbine are 25.5% of the capital cost on an annual basis. For renewables, the average operating costs are in the range of 11% of the capital cost [1]. The values for the variance of composite distance for three uncertain futures are as shown in Table IV.

The conventional DG technologies can be compared with renewable energy technology with a proper consideration of the operating cost along with the capital investments. It is observed that with the inclusion of the operating cost parameter in the attribute of capital cost, the wind-plus-solar option and micro-grid option become more viable.

D. Use of DEA Based on AHP

In the DEA-based approach, the attributes to be maximized are considered as outputs, while the attributes to be minimized are considered as inputs. Accordingly, the three attributes (as discussed earlier) can be interpreted as a two-input single-output case. The efficient frontier is generated for determining the feasible set of configuration plans.

We have applied DEA based on AHP for calculating the performance efficiency of all the DG configuration plans. It is observed that only four expansion options, i.e., plans 2, 4, 8, and 12 are the most feasible plans in all the futures. These plans include gas turbine, wind-solar, and micro-grid as some of the feasible technologies. The normalized values of performance efficiency along with the preferential rankings for all the plans are shown in Table V. It is also observed that with the consideration of the operating cost as an additional parameter, the renewable technologies become more viable (see Table VI). After careful observation of the results obtained using DEA, it is quite clear that the feasible set of configuration plans remains the same for interval-based and DEA-based MADM techniques.

E. Composite Utility Function Approach

In both the MADM techniques, it is observed that some configuration plans, such as 6, 7, 10, and 11, are comparable with the shortlisted plans 2, 4, 8, and 12, under future 1 and future 3. However, these plans are getting omitted due to the lack of information under future 2. Thus, it is quite likely that these methodologies may give some ambiguous results under such special situations. The new CUF approach proposed in this paper is the simplest approach for gathering information in such typical situations. This is applied for all the plans by considering the operating cost in addition to the capital cost. The results obtained

TABLE V
NORMALIZED VALUES OF PERFORMANCE EFFICIENCY

Plan no.	Performance efficiency (preferential ranking is shown in the bracket)		
	F1	F2	F3
2	0.59 (5)	0.73 (3)	0.65 (4)
3	0.11 (10)	0.00	0.13 (9)
4	0.075 (14)	0.085 (12)	0.086 (11)
5	0.078 (13)	0.00	0.071 (15)
6	0.21 (6)	0.00	0.18 (7)
7	1.00 (1)	0.00	0.99 (2)
8	0.21 (6)	0.06 (10)	0.16 (8)
9	0.11 (10)	0.00	0.13 (9)
10	0.21 (6)	0.00	0.18 (7)
11	1.00 (1)	0.00	0.99 (2)
12	0.21 (6)	0.06 (10)	0.16 (8)

TABLE VI
NORMALIZED VALUES OF PERFORMANCE EFFICIENCY BY CONSIDERING OPERATING COST

Plan no.	Performance efficiency (preferential ranking is shown in the bracket)		
	F1	F2	F3
2	0.19 (6)	0.19 (6)	0.19 (6)
4	0.20 (5)	0.19 (6)	0.22 (4)
8	1.00 (1)	0.24 (3)	0.63 (2)
12	1.00 (1)	0.24 (3)	0.63 (2)

TABLE VII
COMPOSITE UTILITY FUNCTION BY CONSIDERING OPERATING COST

Plan no.	Composite utility function (preferential ranking is shown in the bracket)		
	F1	F2	F3
2	0.048 (5)	0.079 (3)	0.069 (4)
3	-0.424 (18)	-0.557 (22)	-0.405 (16)
4	-0.198 (14)	-0.173 (13)	-0.163 (12)
5	-0.508 (19)	-0.675 (23)	-0.552 (20)
6	0.028 (6)	-0.114 (11)	0.006 (7)
7	0.112 (2)	-0.019 (9)	0.132 (1)
8	0.028 (6)	-0.074 (10)	-0.009 (8)
9	-0.422 (17)	-0.553 (21)	-0.400 (15)
10	0.028 (6)	-0.114 (11)	0.006 (7)
11	0.112 (2)	-0.019 (9)	0.132 (1)
12	0.028 (6)	-0.074 (10)	-0.009 (8)

using CUF [as per (10)] are shown in Table VII. It is observed and confirmed that almost all the plans with micro-grid perform well under all the futures. The negative values of CUF are not of particular significance since only relative performance is evaluated.

Thus, the results are quite indicative of the fact that the AHP can be used as a common thread for finding the relative importance among the various attributes in the proposed MADM techniques.

VII. CONCLUSIONS

1) Advanced planning techniques are proposed for the evaluation of many combinations of the DG plans, with different attributes and possible variation in loads. The proposed method is applied to the practical system from the State of Maharashtra, India.
2) To begin with, various stake holders and attributes are identified, and the relative significance of all the attributes is found using AHP.
3) Tradeoff analysis is used for short-listing the feasible set of DG configuration plans.
4) The preferential ranking of all the feasible plans has been done by comparing the variance of composite distance, which is obtained using the interval-based MADM technique and weights from AHP.
5) The proposed DEA approach using AHP validates the above results by evaluating the performance efficiency of each plan.
6) It is observed that in typical conditions, some information related to the values of different attributes under certain futures is lost. To overcome this problem, the new composite utility function is proposed. The proposed CUF is based on the algebraic sum of weighted input and output values of an attribute and does not involve divisions. Thus, CUF is able to identify the omitted plans that have very good performance.
7) It can be observed that the proposed method is able to rank all the plans in an objective way.

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