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The distributed energy sources technology has progressed from isolated operation to hybrid and now to microgrid operation. The planning strategies initially considered cost-benefit analysis of distributed generation (DG). Later supporting advantages of the hybrid system including improvement of the efficiency were also considered for decision making. With increased complexities in DGs planning options along with multiple attributes to be accounted, more sophisticated techniques are needed to arrive at the correct decisions by decision makers. The analytical hierarchy process (AHP) is proposed to identify the relative significance of the chosen attributes. Proper integration of different attributes can be achieved by linear additive utility function. Further, the uncertainties are accounted by statistical method like interval based multi-attribute decision making (MADM). MADM technique is applied to three cases: conventional grid, hybrid DG operation and micro-grid. The attributes considered are incremental losses, capital costs and percentage time for which demand is not served for all cases. It is assumed that attributes are not related with each other. The proposed method is demonstrated on a sample system which is derived from a practical system. The effect of loading condition is also considered in the formulation. The results indicate that the proposed decision making technique has an ability to quantify the merits and justify new technology. It is demonstrated that DGs in micro-grid as well as hybrid system are acceptable strategies for low load conditions since they have very small variance of composite distance.

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Multi-attribute Decision Making Approach for Strategic Planning of DGs

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Abstract--The distributed energy sources technology has progressed from isolated operation to hybrid and now to micro-grid operation. The planning strategies initially considered cost-benefit analysis of Distributed Generation (DG). Later supporting advantages of the hybrid system including improvement of the efficiency were also considered for decision making. With increased complexities in DGs planning options along with multiple attributes to be accounted, more sophisticated techniques are needed to arrive at the correct decisions by decision makers. The Analytical Hierarchy Process (AHP) is proposed to identify the relative significance of the chosen attributes. Proper integration of different attributes can be achieved by linear additive utility function. Further, the uncertainties are accounted by statistical method like interval based Multi-Attribute Decision Making (MADM). MADM technique is applied to three cases: conventional grid, hybrid DG operation and micro-grid. The attributes considered are incremental losses, capital costs and percentage time for which demand is not served for all cases. It is assumed that attributes are not related with each other. The proposed method is demonstrated on a sample system which is derived from a practical system. The effect of loading condition is also considered in the formulation. The results indicate that the proposed decision making technique has an ability to quantify the merits and justify new technology. It is demonstrated that DGs in micro-grid as well as hybrid system are acceptable strategies for low load conditions since they have very small variance of composite distance.

Index Terms--Distributed generation, decision support system, feasibility, micro-grid, strategic planning

I. INTRODUCTION

DISTRIBUTED generation (DG) is expected to play an important role in the electric power systems of the near future. DG technologies include all renewables like photovoltaic, wind, solar-thermal, etc., and some of the modular units like fuel cell, micro-turbines, etc. In fact, studies have predicted that DG may account for up to 20% of the all new generation going online by the year 2010 [1]. In

addition to this, with the implementation of some of the recent developments like Micro-grid, i.e., the controlled operation of multiple DGs in a distribution system, the customers will get sufficient amount of choice so as to decide the best possible option under various priorities.

The decision maker is confronted with the strategic planning studies with various options such as grid connection, hybrid systems and now the new option of micro-grid. Micro-grid option has attracted considerable attention from the researchers and though there are many positive points listed for it, they have to be substantiated with the analytical methods which can quantify the benefits. In first phase, one has to identify the significant attributes and the relationships between the components of the system. This is done with the help of AHP. In the second phase, an additive utility function can be evolved with proper weights. The comparative assessment is easy in the light of these functions for various options. However, the uncertainty and accuracy of the input data can distort the results. MADM can effectively handle this situation.

The Multi-attribute decision making approach is one of the best technical aid for strategic planning of electric utilities. It selects the best resource strategy with regard to the chosen attributes [2]. According to [3], MADM will be the appropriate choice for justifying the new technology. Normally, in MADM problems the information available to the decision maker is often imprecise due to erroneous attribute measurements and imperfect priority judgments. However, the responsible decision maker must balance judgments about uncertainties with his/her preferences for possible consequences or outcomes. To attempt any formal analysis of a complex decision problem requires an articulation of the decision maker's objectives and an identification of attributes useful for indicating the extent that these objectives are achieved [4].

The MADM approach was applied to strategic resource planning for the conventional resources. 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, etc. [5, 6]. These all are no doubt important issues but these should not be the only deciding factors. It is very likely that without fulfilling all these requirements, DG may become feasible so as to protect sensitive loads. This paper reports the novel approach of interval based MADM for evaluating the possibilities of various configurations of DGs

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like hybrid DG source, micro-grid, etc. The choice of attributes and application of AHP are followed by additive utility function to envisage the utility of possible options. The comparative assessment of all the individual technologies with all possible options can provide executive summary to the decision maker. There are no investigations reported on application of MADM to planning of various DG resources, and that is the motivation behind this work.

The paper is organized as follows: Section II reviews DG technologies. Section III reports fundamentals of AHP. The mathematical basis for MADM technique and interpretation of the point estimates are elaborated in section IV. The sample system and results are given in section V. The comparative assessment of all results is discussed in the concluding section.

II. DG TECHNOLOGIES

The optimal placement and penetration of modular DG units near the load centers will improve T&D losses and voltage profile in a system [7]. The Locational Marginal Price (LMP) at various nodes is also a very good economic indicator of generation deficiency and hence DG siting can also be done on the basis of LMP [8]. In all, DG will more or less try to alleviate the congestion and improve the overall reliability of the system, but the issues like power quality and reliability of sensitive loads, islanded operation under contingency situation, etc., need to be addressed carefully.

More recently, electrical generation systems based on small generators operated under local controls are gaining popularity. A cluster of loads and micro-sources operating is assumed as a single controllable system that usually provides both power and heat to its local area. This configuration is known as micro-grid. While dependency on the grid has intensified, smaller generation using a diverse mix of technologies, usually collectively called distributed energy resources (DER), has emerged as increasingly competitive with large remote central station generation. Many of these sources generate power directly, e.g., photovoltaic modules (PV), while others involve on-site energy conversion. Waste heat utilization delivers one of the key advantages of small scale generation involving conversion, e.g., from reciprocating engines, fuel cells or microturbines. This heat can be productively applied to many end-uses, but when used for cooling, it lowers the peak power requirement of the site [9].

Some of the salient features of micro-grid are [10]:

a. Single common coupling: The micro-grid is interconnected to macrogrid at a single point of common coupling and it just appears to the grid like any other customer. Some micro-grids can be used to provide the local ancillary services, such as VAR support.

b. Generator control by on-board power electronics: Based on the local frequency and voltage readings, the on-board power electronics of each device enables secure operation of micro-grid that maintains the energy balance. Operation of the micro-grid must take place in two different modes, viz. connected to the grid and disconnected. In the former case,

transients can be covered by the grid, but in the latter stage, micro-grid has to function independently.

c. Slow supervisory control: Slower operational control in the form of Energy Manager is necessary so as to ensure economic commitment and dispatch within environmental and other constraints.

d. Combined Heat and Power (CHP) applications: The thermal generators are usually placed where the heat loads permit useful application of the waste heat. It has a major impact on the economics of the micro-grid.

e. Heterogeneous power quality and reliability: The loads are segregated into three separate circuits. The end-use loads that must be met on top priority are the sensitive loads. The adjustable loads are on the second circuit and the loads that would be abandoned first are on the third i.e., shedable loads circuit.

This concept provides a new paradigm for defining the operation of DG. To the utility, micro-grid can be thought of as a controlled cell of the power system. For example, this cell could be controlled as a single dispatchable load, which can respond in seconds to meet the needs of the transmission system. To the customer, the micro-grid can be designed to meet their special needs; such as, enhancement of local reliability, reduction of feeder losses, support to local voltages, providing increased efficiency through use of waste heat, voltage sag correction or providing uninterruptible power supply functions, etc [11].

The block diagram of typical Micro-Source Distributed Generation is as shown in Fig. 1 [12].

Fig. 1. Block diagram of typical micro-source

It comprises of a primary energy source with optional energy storage and a three-phase dc / ac inverter. The inverter interface makes it possible for them to provide Uninterrupted Power Supply (UPS) functionality, power quality improvement and energy conversion simultaneously at a reasonable cost. The three phase AC output may either feed loads independently in the stand-alone mode of operation, or in conjunction with the electric utility system in the grid connected mode of operation. Usually the micro-sources are located near the sensitive loads and hence during the interruption of grid supply, they may be operated in stand alone mode so as to protect the sensitive loads. Use of multiple sources in the form of a micro-grid, addresses the issue of providing energy especially during outages with a high degree of redundancy. We now build up the background

of decision making process in planning studies in phases. The first phase is defining attributes and hierarchy as described in the next section.

III. ANALYTICAL HIERARCHY PROCESS

The Analytical Hierarchy Process [AHP] is a general theory of measurements and is most suitable for integrated resource planning. It is used to derive ratio scales from both the discrete and continuous paired comparisons. The pairwise comparisons are elementary in AHP. These comparisons may be taken from actual measurements or from a fundamental scale which reflects the relative scale of preferences and feelings [13]. It is very important to decide the focus of the hierarchy and how the elements in the second level serve to fulfill that focus. The process should continue for each parent element and its descendants. Thus the matrix of pairwise comparisons of the criteria with respect to the overall focus is generated at each level. The next step is to derive the scale of priorities (weights). This scale can be obtained by solving for the principal eigenvector of the matrix and then normalizing the result. This is called local derived scale before weighting by the priority of its parent criterion. After weighting, it is called global derived scale. In this paper, the software package supporting the AHP, known as “expert choice” is used to make these calculations so as to guide the decision maker [14]. AHP may also be used to evaluate the scenario probabilities, criteria weights and uni-dimensional utility function [15]. The hierarchy for the planning process can be typically represented as shown in Fig. 2

Fig. 2. Hierarchy of the planning process

AHP analysis can be used in conjunction with the scenario analysis so as to account for uncertainty in the system [15]. The decision maker can generate three different scenarios like high risk scenario, medium risk scenario and low risk scenario, and then all the attributes are evaluated for each scenario. This is rather primitive way of incorporating uncertainty and hence interval based MADM approach with the additive utility function is used here so as to decide the best possible expansion strategy which reflects a risk-neutral attitude of the decision maker [2]. The next section deals with the additive utility function and MADM philosophy.

IV. INTERVAL BASED MADM ANALYSIS [2]

A. Additive Utility Function

Usually most of the MADM problems can be tackled by transforming n -dimensional vector performance into a scalar performance by using multi-attribute utility function (MAUF). The assessment of an appropriate MAUF itself is a big task. MAUF model is comprised of the single utility function and the weighting parameters associated with the chosen attributes. Individual utility functions reflect the decision maker's attitude toward taking a risk, and the weighing parameters reflect the decision maker's priority with regard to different attributes. Conceptually, the composite utility value is a nonlinear function of a single utility function and weighting parameters. One way of analyzing this problem is to decompose MAUF into a series of single attribute assessments. This special form of MAUF model is also known as linear additive form and it can be used only if 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:

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

where,

$Ut(x)$ is the composite utility characterized by the vector of attributes $x = [x_1, \dots, x_n]$,

$Ut_i(x)$ is the single utility function with respect to the i^{th} attribute,

w_i is an appropriate weighting parameter for the i^{th} attribute, representing its relative importance in comparison to other attributes and satisfying $\sum w_i = 1$.

B. Variance of Composite Distance

There are two important terms that are of concern in the construction of linear additive utility model, one is the single utility function and the other is weighting parameter. However, in many MADM applications, the single utility function $Ut_i(x)$ can be represented by the normalized attribute value r_i . If x_i and r_i are the measured and normalized values of the i^{th} attribute, x_i^r is the range of variation of measured attribute values and x_i^* is the optimal value of i^{th} attribute, then the composite distance $Ut_d(x)$ can be represented as:

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

For equation (1), the best alternative is the one for which the value of composite utility will be maximum. On the contrary, the most favorite alternative determined by equation (2) represents a 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 the various planning alternatives can be examined by using a technique of propagation of errors. If there exists a set of numbers and their errors, then the error in some prescribed function involving these numbers can be calculated by using the propagation of errors. For a function $y = f(x_1, x_2, \dots, x_n)$, the general expression for propagation of errors can be written as [3]:

$$\sigma_y^2 = \sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \cdot \sigma_{x_i} \right)^2 \quad (3)$$

where σ_{x_i} is the standard deviation of variable x_i and σ_y is the standard deviation of the prescribed function. Accordingly, the variance of composite distance for linear additive utility function will be:

$$\sigma_d^2 = \sum_{i=1}^n \left(\frac{\partial U_d}{\partial w_i} \cdot \sigma_{w_i} \right)^2 + \sum_{i=1}^n \left(\frac{\partial U_d}{\partial r_i} \cdot \sigma_{r_i} \right)^2 \quad (4)$$

Hence,
$$\sigma_d^2 = \sum_{i=1}^n \left(r_i^2 \sigma_{w_i}^2 + w_i^2 \sigma_{r_i}^2 \right) \quad (5)$$

where σ_d is the standard deviation of composite distance values, σ_{r_i} and σ_{w_i} are the standard deviations, i.e., the error parameters of the normalized i^{th} attribute and its weighing parameter. If p is the number of alternatives to be evaluated, the standard deviation σ_{r_i} for a specific alternative, say j , can then be evaluated as:

$$\sigma_{r_i}^2 = \frac{1}{(x_i^{\max} - x_i^{\min})^4} \cdot \left[\sigma_{x_{ij}}^2 (x_i^{\max} - x_i^{\min})^2 + \sigma_{x_i^{\max}}^2 (x_{ij} - x_i^{\min})^2 + \sigma_{x_i^{\min}}^2 (x_{ij} - x_i^{\max})^2 \right] \quad (6)$$

where,

$x_i^{\min}$ is the minimum of $|x_{ij}|$ for $j = 1, 2, \dots, p$

$x_i^{\max}$ is the maximum of $|x_{ij}|$ for $j = 1, 2, \dots, p$

x_{ij} is the i^{th} attribute for alternative j

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 which further allows the additivity in equation (1) [3].

V. SAMPLE SYSTEM AND RESULTS

In this paper, a medium voltage local distribution system as a part of the largely interconnected network grid is considered. Three independent attributes are considered and the value of each attribute is calculated for various possible expansion strategies. AHP is used for deciding the priorities

among all the attributes, and finally by using additive utility function and MADM approach, the variance of composite distance is evaluated for each expansion strategy. The option with minimum value of variance will be the best option.

A. Details of the Sample System under Study

The sample system under consideration is as shown in the Fig. 3. It shows the small part of the MV distribution system and rest of the HV and EHV network grid. Buses B, C and E constitute the part of EHV system and buses A, D and F are the MV buses in the system.

Fig. 3. Sample system under study

It is assumed that there are areas where little or no T&D capacity expansion is needed in order to accommodate for an additional load; and other areas where major and expensive reinforcement would be required. The dotted line in the Fig. 3 shows the possible location for hybrid DG / microgrid. Two sample cases are considered, one is with low incremental T&D expansion cost for a total load of 100 kW and the other is with high incremental T&D cost for a total load of 500 kW. Along with the conventional grid, the two other options of hybrid DG (wind + diesel) source and micro-grid (micro-turbine + fuel cell + diesel) are also considered so as to serve for both these localized load requirements, i.e., low as well as high load. In all, there will be three planning possibilities and two different load conditions; hence overall six expansion strategies will be available with the decision maker. Three totally independent attributes, i.e., the total capital investment for the proposed load growth (\$/kW), incremental T&D losses (kW) and percentage time duration for which load remains unserved in a month, are considered and they are evaluated for all the six expansion strategies.

The values of various attributes are as shown in Table I. These values are used for calculating the variance of composite distance for various expansion strategies. The option with the minimum value of variance is the best one.

TABLE I
VALUES OF ATTRIBUTES FOR DIFFERENT EXPANSION OPTIONS

Expansion Strategy	Incremental capital cost (attribute 1)	Total T&D losses (attribute 2)	% time duration for which load remains unserved in a month (attribute 3)
Grid + high load	1	1	0.7498
Grid + low load	0.004	0.71428	1
Hybrid DG + high load	0.9035	0.0	0.2499
Hybrid DG + low load	0.0433	0.0	0.1249
Micro grid + high load	0.7465	0.0	0.0166
Micro grid + low load	0.06105	0.0	0.0416

The incremental capital costs for T&D expansion and that for Hybrid DG configuration are taken from [5]. The capital cost of a typical micro-grid is referred from [10]. The incremental T&D losses are calculated by solving the various load flows for all the expansion strategies with different loads as well as generation conditions. The active as well as reactive power generations for hybrid DG and micro-grid are considered as negative loads in the system. Suppose there are additional load of 100 kW and generation of 100 kW on the same load bus, the actual real and reactive power injections at that particular bus will be zero. It is assumed that the total base case load for the system under consideration is around 21 MW with the power factor of 0.85. This includes the entire high voltage transmission network in the vicinity of the medium voltage distribution system under study. The last attribute, i.e., the percentage time for which load remains unserved can be calculated with the help of realistic values of reliability indices for the medium voltage distribution system of [16].

B. Use of AHP for the proposed approach

According to the hierarchy of the proposed planning process as shown in Fig. 4, the values of different weights for all the attributes are calculated by using the software package known as “Expert Choice”. In this particular software the decision maker has to decide the priority of one attribute over the other, i.e., suppose, earlier discussed (previous subsection) three attributes are to be compared from customer point of view then the preference of each attribute has to be decided from customer’s perspective. Intuitively, the percentage time for which load remains unserved should have the highest priority among all the three attributes. Accordingly, with respect to utility, the incremental T&D losses and the duration of unmet load are having the same importance. For hybrid DG / micro-grid, the capital cost investment is on top priority.

The values of weights for different attributes will decide the overall importance of each attribute for achieving the goal. In this case, the % time for which the load remains unserved will have the highest priority ($w_3 = 0.539$) as compared to T&D losses ($w_2 = 0.302$) and capital cost ($w_1 = 0.159$). The overall maximum inconsistency for the whole AHP process will be 0.10.

Fig. 4. Hierarchy of the proposed planning process

C. Implementation of MADM for Evaluating the Variance of Composite Distance

The various normalized attribute values and error parameters of the normalized attributes for different expansion strategies are tabulated below:

TABLE II
NORMALIZED ATTRIBUTE VALUES AND ITS ERROR PARAMETERS

*ES	Error parameters of normalized attributes (σ_r^2)			Normalized attribute value (r^2)		
	Att. 1	Att. 2	Att. 3	Att. 1	Att. 2	Att. 3
GH	1.59	1.837	0.952	1	1	0.556
GL	0.426	0.904	1.794	0	0.510	1
HH	1.260	0.163	0.202	0.815	0	0.056
HL	0.409	0.163	0.240	0.001	0	0.012
MH	0.804	0.163	0.273	0.555	0	0
ML	0.401	0.163	0.265	0.003	0	0.0006

*ES – Expansion strategies, GH – Grid with high load, GL – Grid with low load, HH and HL are for hybrid DGs with high load and low load. Similarly MH and ML are for micro-grid with high as well as low load.

The behavior of various point estimates (for different attributes) with respect to different expansion strategies is as shown in Fig. 5. It is clearly seen that the value of point estimates for 4th and the 6th expansion strategy are the lowest among all the other options and hence this is the best planning alternative. The individual contributions of the each attribute (as shown in fig. 5) are quite indicative of the fact that the third attribute i.e. the percentage time duration for which load remains unserved in a month, dominates over the other two.

Fig. 5. Total point estimate for various expansion strategies

After the normalization of various attributes and completion of AHP process, the variance of composite distance will be calculated for each expansion strategy as shown in equation (5). The different values for the total variance of composite distance will be given as:

TABLE III
VALUES OF THE VARIANCE OF COMPOSITE DISTANCE

Expansion Strategy (ES)	Variance of composite distance
Grid + high load (GH)	0.690
Grid + low load (GL)	0.804
Hybrid DG + high load (HH)	0.186
Hybrid DG + low load (HL)	0.097
Micro grid + high load (MH)	0.162
Micro grid + low load (ML)	0.102

VI CONCLUSIONS

The MADM technique is used for strategic planning of DGs. The choice of attributes and their relative weights is left to the decision makers' expert judgment. Table II shows normalized attribute values and their variances. Fig. 5 shows contributions of each attribute to all strategies. Six strategies shown in Table III consider the loading conditions. For hybrid DG with low load and micro-grid with low load, the variance of composite distance is comparable and is in the same range. These both strategies are equally acceptable. The attributes do not consider the diversity factor which may give edge to micro-grid strategy. Future work can include more attributes and trade off/risk analysis. With the limited experience gained from the sample system one can conclude that the method seems to be promising for decision making of DG planning.

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