A MULTIPLE CRITERIA APPROACH FOR THE INTEGRATION OF NEW ENERGY SOURCES INTO ELECTRICAL DISTRIBUTION SYSTEMS DESIGN

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ABSTRACT

This paper deals with modelling the impact of renewable and energy storage units in electric distribution systems design. This problem is characterized by the existence of at least two main objectives, concerning economical and environmental aspects. Economical considerations are modelled by an objective function that includes capital and operational costs related to new and existing facilities. Other aspects, related to environmental and also social concerns are considered, such as the ones related to pollution, aesthetics, land and reservoirs use and so forth. The model is formulated in such a way that a simple mixed integer linear programming problem with multiple objectives is stated. This formulation allows the selection of best sites and sizes of supply sources and connection lines amongst a set of possible locations. The solution of the problem can be obtained progressively through the use of a decision support system with adequate interaction of the planning engineer into the process. The best compromise solution is then interactively obtained. The application of fuzzy sets theory is also considered, so that a fuzzy decision set as well as the best compromise solution can be generated. It is shown that different types of membership functions can be chosen without moving away from the framework of mixed integer linear programming. In order to show the model possibilities a case study is presented and the results are accordingly analysed and discussed. Eventually conclusions and topics for further development are outlined.

1. INTRODUCTION

A considerable amount of work [1-3] has been devoted to the study of problems related to the areas of design and planning of electrical distribution systems. Most of the papers dealing with these subjects determine the location, timing and sizing of substations and feeders along the system, so as to meet the continuous demand growth. In general, the models consider the problem as a single objective optimisation formulation, in which a cost function is minimised, subject to a set of constraints that impose technical conditions and electricity laws into the formulation.

Moreover there has been a great effort in order to evaluate the benefits of new types of energy sources into electrical power systems. When effectively integrated into the power system operation, renewable units - e.g wind turbine generators - lead to considerable advantages in terms of power system economics as well as a considerably less negative impact to the environment. When the characteristics of consumer load curves are taken into account, the effective introduction of the renewable sources can be established with the use of energy storage units. In reference [4] a linear programming model for the design of electrical distribution systems considering renewable, energy storage and conventional sources is presented so that the composition of operational and investment cost is minimised. However in order to quantify environmental advantages a new formulation must be devised.

The enhanced formulation on this paper considers multiple and conflicting objectives. It is also improved for considering a mixed integer programming formulation so that capital costs, mainly of lines and conventional units, are better represented in the formulation.

LIST OF SYMBOLS

c	-	conventional source index
s	-	energy storage unit index
rn	-	renewable source index
sc, sd	-	storage charge and discharge regimes respectively
i , j	-	node numbers
n	-	total number of nodes
L	-	maximum load demand
L_t	-	current load demand
β = \f(Lmin,L)	-	minimum load coefficient
τ	-	load similarity period
γ = \f(tmin,τ)	-	minimum load duration coefficient
E_l	-	energy demand during period τ
N_c,N_s,N_{rn}	-	installed capacities of conventional, storage and renewable sources, respectively
K_c,K_s,K_{rn}	-	capital costs of energy sources per unit
E_s	-	energy capacity for energy storage units
K_e	-	capital cost per unit of energy capacity (only for storages)
K_f	-	fuel cost for conventional sources
E_c,E_{rn}	-	energy generated by conventional and renewable sources respectively
δ_c,δ_l	-	integer decision variables for the conventional units and lines, respectively
η_c,η_s,η_d	-	efficiency coefficients for charge, storing and discharge regimes respectively
F	-	capacity factor for renewable sources
N_{ct},N_{sct},N_{sdt}	-	current power flow for conventional and storage sources respectively
l	-	connection line (overhead or cable) index and length
P_{lt}	-	current power flow
P_{ij}	-	power flow from node i to node j
K_l	-	capital cost per unit length and power flow
K_{lt}	-	losses coefficient
R_c,R_s,R_{rn}, R_l	-	discount rates for conventional, storage and renewable sources and lines respectively
Ω_c,Ω_{rn},Ω_s,Ω_{el},Ω_{nl}		set of conventional, renewable and energy storage sources and existing and new connection lines, respectively
Ω_i		set of nodes connected to node i

2. MODEL FORMULATION

2.1. STATING THE PROBLEM

The design problem is basically concerned with the determination of new facilities to be installed in the distribution system so that the demand requirements and a set of technical criteria are met. A very large number of feasible alternatives - in the sense that the set of constraints is satisfied - can be generated so that mathematical programming techniques are highly indicated for the solution of such problems. Before formally stating the problem, some considerations should be outlined:

- LOADS: It is assumed for design purposes that the periodic load curve (e.g. daily curve) can be approximated by a two step curve. It is also assumed that loads are given to the planning horizon, for the week-day of heaviest demand in the year. Figure 1 shows the load curve adopted in the model.

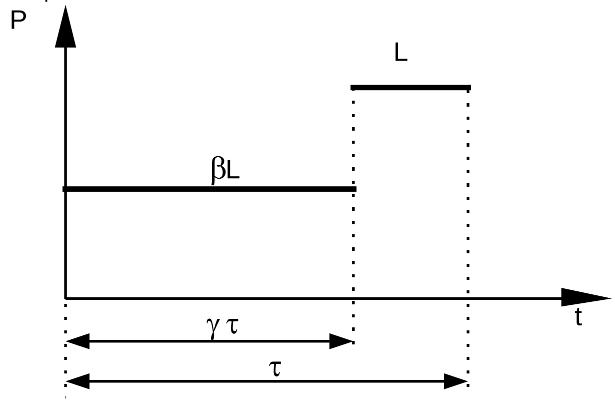

Fig.1 - Load curves

- SOURCES: There are three different types of energy sources available as potential new facilities in the system, namely conventional, renewable and energy storage units. It is assumed that renewable sources generate free energy for a period of time (t_{rn}= F τ) - according to the capacity factor (F) - during the minimum load period, so that a severe operating condition is satisfied by the resultant design (see fig. 2.a). Energy storage units are allowed to charge during the minimum load period and discharge during the maximum load period (see fig. 2.b). Eventually conventional sources are capable of generating energy at any time interval (fig. 2.c).

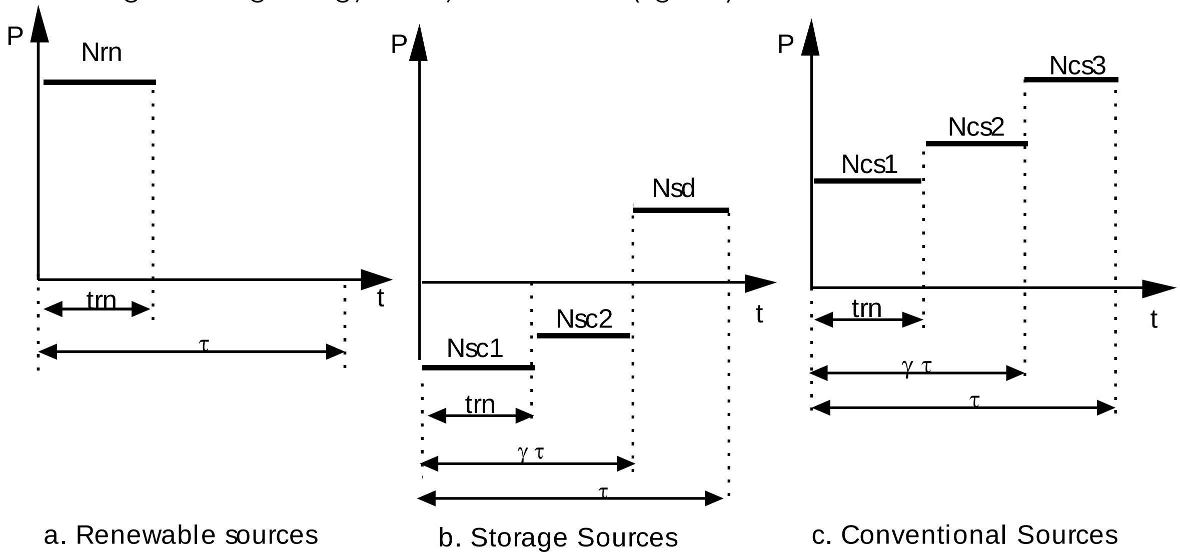

Fig.2. - Dispatch Curves of Supply Units

- LINES: The model presents as input the existing and possible routes of lines to be installed along the network. Losses are basically considered in the cost function and are approximated through piecewise linearisation. Investment costs are considered through integer decision variables.

The problem to be addressed in this paper refers to the location and sizing of system facilities so as to reach the best feasible alternative of system expansion. The best alternative selection is treated later in the paper, since multiple objectives must be well satisfied by the obtained solution.

2.2. PROBLEM FORMULATION

The problem is formulated under two important frameworks of the decision making and operational research areas, namely multiple criteria and mixed integer linear programming. The problem is to be formulated as:

$$\min \ \mathbf{z} = [z_1(\mathbf{x}) \ z_2(\mathbf{x}) \ \ldots \ z_p(\mathbf{x})] = [\mathbf{c}_1 \ \mathbf{c}_2 \ \ldots \ \mathbf{c}_k] \ \mathbf{x} \qquad (1)$$

$$\text{s.t.} \quad \mathbf{A} \ \mathbf{x} \le \mathbf{b}$$

where $\mathbf{x}$: vector of continuous and integer variables

$\mathbf{b}$: right hand side vector

$\mathbf{A_1}$: coefficient matrices

$z_i(\mathbf{x})$: i^{th} objective function

$\mathbf{c}_i$: objective function vectors of coefficients

2.2.1. Set of Constraints

The set of constraints imposes the fulfilling of demand and energy balance requirements as well as the limits of energy sources and lines. They are briefly described as follows:

- *Power Balance Equations* : in order to determine power flows in lines and supply units and be certain that demand requirements are met, three basic intervals of time are considered. According to figures 1 and 2, three intervals must be considered, imposed by the period in which renewable sources can supply energy $[0,t_{rn}]$, the period limited by the minimum load $[t_{rn},\gamma\tau]$ and the period limited by the maximum load $[\gamma\tau,\tau]$. These constraints are given as:

$$N_{rn,i} + N_{C,t,i} - N_{SC,t,i} + \Sigma_{j \varepsilon \Omega l} (P_{ijt}) - \beta_i L_i = 0 \quad (t=1)$$

$$N_{C,t,i} - N_{SC,t,i} + \Sigma_{j \varepsilon \Omega l} (P_{ijt}) - \beta_i L_i = 0 \quad (t=2) \qquad (2)$$

$$N_{C,t,i} + N_{sd,t,i} + \Sigma_{j \varepsilon \Omega l} (P_{ijt}) - L_i = 0 \quad (t=3)$$

- *Energy Balance Equations:* these restrictions are in part satisfied through the above set of equations (2). However, energy storage units usually have a loss of energy due to the efficiency in the charge/discharge cycle and the following inequalities must be added for each energy storage unit:

$$\eta \; [N_{SC,i,1}\, F\tau + N_{SC,i,2}\, (\gamma\tau - F\tau) \;] - \; N_{sd,i} \; (1 - \gamma)\, \tau \geq 0 \qquad i \; \varepsilon \; \Omega_s \qquad (3)$$

- *Capacity Limits*: these constraints impose a set of limitations to existing or new facilities to be installed in the system. In this model, capacity limits of renewable and energy storage units are assumed to be installed in any required value bounded by the maximum available limit:

. Energy storage units: $N_{S,i} \leq N_{si,max}$

. Renewable units: $N_{rn,i} \leq N_{rni,max}$

. Conventional units: $\Sigma_{i\, \varepsilon\, \Omega_c} (N_{Ci}) \geq \Sigma_{j=1,n} \; f(E_{lj},\tau)$ (*1) (4)

existing: $N_{C,i,t} \leq N_{Ci,max}$

new: $N_{C,i,t} \leq \delta_{Ci} N_{Ci,max}$

. Lines: existing: $P_{lC} \leq P_{lmax}$

new: $P_{lC} \leq \delta_l P_{lmax}$

2.2.2.Objective Functions

Multiple criteria problems can be characterised by the existence of multiple objectives that have to be considered simultaneously. In this model a set of objectives is proposed, though it is well known that additional objectives can be formulated according to the specific practical situation:

- *Economical Objective Function:* capital and operational costs are considered for all existing facilities to be installed in the system:

$$f_{obj} = f_C + f_{rn} + f_S + f_l \qquad (5)$$

where:

$f_C = \Sigma_{i\, \varepsilon\, \Omega_c} (R_{Ci} K_{Ci} \delta_{Ci} N_{Cimax} + K_{fi} E_{Ci})$: conventional sources cost function

$f_{rn} = \Sigma_{i\, \varepsilon\, \Omega_{rn}} R_{rn.i} K_{rn.i} N_{rn.i})$: renewable sources cost function

$f_S = \Sigma_{i\, \varepsilon\, \Omega_{rn}} R_S (K_{e.i} E_{S.i} + K_{S.i} N_{S.i})$:energy storage cost function

$f_l = \Sigma_{i\, \varepsilon\, \Omega_l} [(R_l K_{li} l_i \delta_l P_{lmax} + \Sigma_{t=1,3} (K_{lti} l_i P_{lti}))$:connection lines cost function

$E_{Ci} = t_{rn} N_{C1,i} + (\gamma\tau - t_{rn}) N_{C2,i} + (1 - \gamma\tau) N_{C3,i}$

$E_{S.i} = \eta_c [(N_{SC1.i} t_{rn} + N_{SC2.i} (\gamma t - t_{rn}))$

$N_{S.i} = \max [(N_{SC1.i} \;\; N_{SC2.i} \;\; N_{Sd.i})$

- *Environmental Objective Function:* the installation of new types of energy sources has the advantage of improving environmental aspects. In order to take it into consideration in the model,

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*1 Renewable sources are intermittent. Capacity factor F gives some average information but it is quite possible that renewable units are not available during the period τ. In this case, conventional units must be able to face the corresponding demand energy.

an environmental function, related to the emission caused by conventional units, is proposed for minimisation:

$$f_{env} = \Sigma_{i \varepsilon \Omega_C} (E_{Ci}) = \Sigma_{i \varepsilon \Omega_C} t_{rn} N_{C1,i} + (\gamma\tau - t_{rn}) N_{C2,i} + (1 - \gamma\tau) N_{C3,i} \quad (6)$$

- *Amenity Objective Function:* this objective function deals with the visual harassment caused by the installation of overhead lines, which can be avoided both by the distribution of energy sources and installation of underground lines. It is considered by the minimisation of the attribute "total length of aerial lines":

$$f_{am} = \Sigma_{i \varepsilon \Omega_{nl}} (\delta_l . l) \quad (7)$$

- *Other Objective Functions:* many other objective functions can be proposed, according to the situation. Possible objectives include optimisation of attributes as land use area, reservoirs use area, number of rail or motor road crossings, and so forth. These objectives can easily be inserted in the formulation, without loss of generality of the model.

2.3. PROBLEM SOLUTION

The problem stated previously can be included in the framework of multiple objective - mixed integer programming and can be solved by any of the many methods available in the related areas. This paper draws special attention to two different approaches in order to determine the best compromise solution.

The first method is the hybrid ε-constrained technique, devised by Goicoechea et al [5]. This method derives from the ε-constrained technique, suitable for determination of nondominated (or Pareto-optimal) solutions. The decision maker (DM) plays a crucial role during the interactive process. This method basically comprises iterations for the generation of a nondominated solution and a judgement of the solution by the DM. If the solution is satisfactory the process ends. If not, the most satisfactory objective level is relaxed - by bounding the correspondent function and adding it to the set of constraints - allowing improvement of unsatisfactory levels.

The second method considers the proposed design model as a fuzzy programming problem [6]. A membership function is defined for each objective and represents the degree of satisfaction of each solution for the corresponding objective value. Fuzzy sets are then defined as $A(i) = \{ \mathbf{x}, \mu(i)(\mathbf{x}) \mid \mathbf{x} \varepsilon \mathbf{X} \}$. The DM determines the membership functions in a subjective manner. Each function $\mu(i)(\mathbf{x})$ is monotone decreasing and continuous; also $\mu i)(\mathbf{x})$ is equal (or tends) to 1 as $z(i)(\mathbf{x}) \le z(*,i)$ and is equal (or tends) to 0 as $z(i)(\mathbf{x}) \ge z(i*)$ [2]. A fuzzy programming problem can then be written as: max $\{ \mu(1)(\mathbf{x}),.......,\mu(p)(\mathbf{x}) \mid \mathbf{x} \text{ e } \mathbf{X} \}$. In order to determine the overall degree of satisfaction, related to the

[2] $z(*,i) = \{\min z(i)(\mathbf{x}) \mid \mathbf{x} \text{ e } \mathbf{X} \}$ - optimal value of i (th)objective and $z(i*)=\max [\ z(i)(\mathbf{x}_k^*),\ 1 \le k \le p\ ]$ -less acceptable value of i (th)objective ($\mathbf{x}_k^*$ - optimal solution for the k (th) objective)

DM's fuzzy goals, a general aggregation function is defined as $\mu(D)(\mathbf{x}) = \{ \mu(1)(\mathbf{x}),.......,\mu(p)(\mathbf{x}) \}$ and the fuzzy programming formulation can be written as max $\{\mu(D)(\mathbf{x}) \mid \mathbf{x} \in \mathbf{X} \}$. Adopting the minimum operator, suggested by Bellman and Zadeh [7], the formulation results: max $\{ \min \{ \mu(1)(\mathbf{x}),.......,\mu(p)(\mathbf{x}) \} \mid \mathbf{x} \in \mathbf{X} \}$ or still:

$$\begin{aligned} \max \quad & \lambda \\ \text{s.t.} \quad & \lambda \leq \mu(\mathbf{x}) \\ & \mathbf{A}\ \mathbf{x} \leq \mathbf{b} \end{aligned} \tag{8}$$

Two important membership functions are the linear and logistic types. The linear membership function decreases linearly - from 1 to 0 - from the ideal to the anti-ideal value of the objective function whereas the logistic membership function is represented by:

$$\mu(i)(\mathbf{x}) = \frac{1}{1+e^{-d(z_i(\mathbf{x})-z_{med})}} \qquad \text{where } z_{med} = \frac{z_i^{*} + z_{i*}}{2} \tag{9}$$

d is a parameter chosen by the DM

The use of linear membership function leads to a mixed integer programming problem, whereas the logistic function apparently transforms the problem into a non-linear problem. However, with a change of variable $\lambda' = \ln\left(\frac{\lambda}{1-\lambda}\right)$, the problem can be brought back to the framework of mixed integer linear programming. After some arithmetic manipulation the formulation is given as follows:

$$\begin{aligned} \max \quad & \lambda' \\ \text{s.t.} \quad & \lambda'\ \mathbf{d}_i + \mathbf{c}\ \mathbf{x} \leq z_{med} \\ & \mathbf{A}\ \mathbf{x} \leq \mathbf{b} \end{aligned} \tag{10}$$

where $\mathbf{d}_i$ is the vector of logistic parameters, chosen accordingly by the DM

3. CASE STUDY

The network of figure 3 is taken as an example for the application of the method. There are proposed sites for the location of new facilities, namely connection lines, conventional, renewable and energy storage units. Demand and economical data are presented in tables 1 and 2. Moreover capacity limits are 10 MW for connection lines, 20 MW for renewable and energy storage units, 30 MW for conventional units at buses 33 and 44 and 20 MW for conventional units at buses 22 and 55. Discount rates are 20% a.a., the minimum load coefficient (β) is equal to 50%, the minimum load duration coefficient is equal to 50% and the period τ is 24h. Only the economical and environmental objectives are considered during the simulation, since other objectives were not of great concern for this case study.

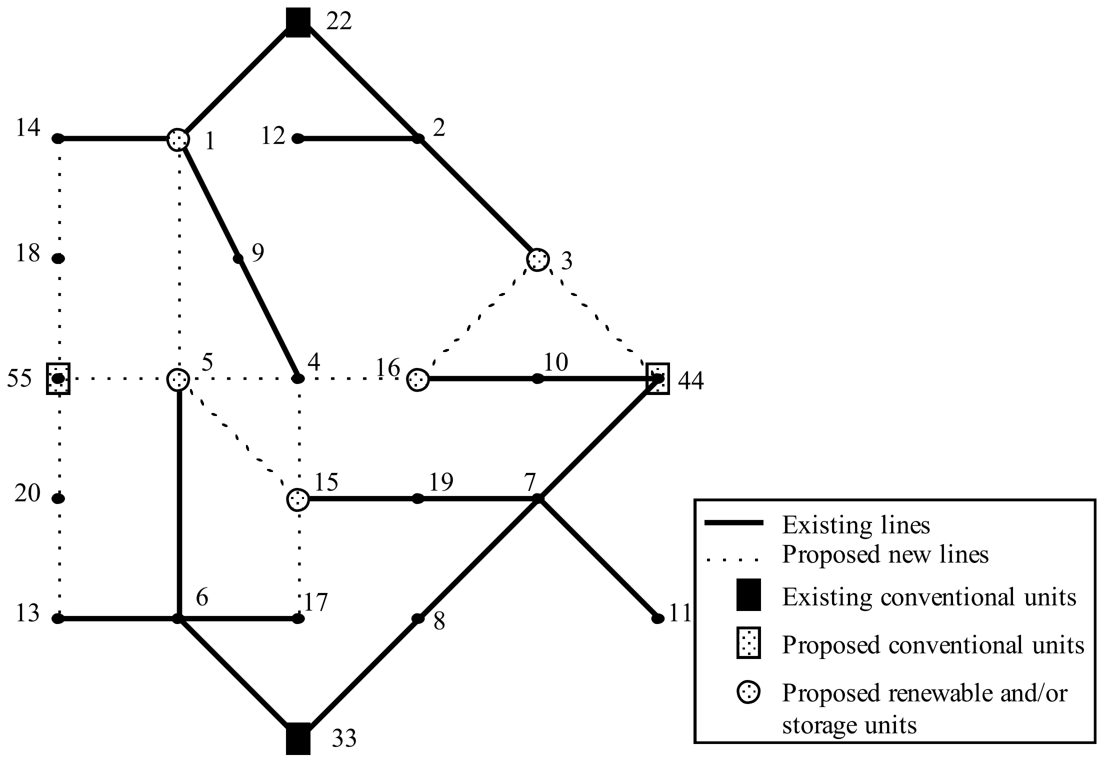

Fig. 3 - Distribution System for the case study

bus	1	2	3	4	5	6	7	8	9	10	11	12
MW	5.42	1.21	3.98	.49	.47	1.44	4.36	.94	1.77	2.40	2.80	1.29
bus	13	14	15	16	17	18	19	20	22	33	44	55
MW	1.35	3.16	1.62	1.22	2.40	2.10	1.81	3.79	12.17	20.33	9.00	4.59

Table 1 - Demand data

Facility	Parameters
Conventional Units	k_C= £500/kW, k_f = £0.0525 / kWh
Renewable Units	k_{rn}=£800/kW, F = 30%
Energy Storage Units	k_s = £200/kW, k_e= £10/kW, η=80%
Lines	k_l = £ 273/kW/km, k_{lt}= £ 0.005 /kWh/km

Table 2 - Economical Data

The efficient frontier, i.e. the set of nondominated solutions, was obtained using the ε-constrained method. The cost function was optimised, while the environmental function was kept as a constraint. Figure 4 illustrates the result of this simulation, in which the tradeoff between the two objectives is very well defined.

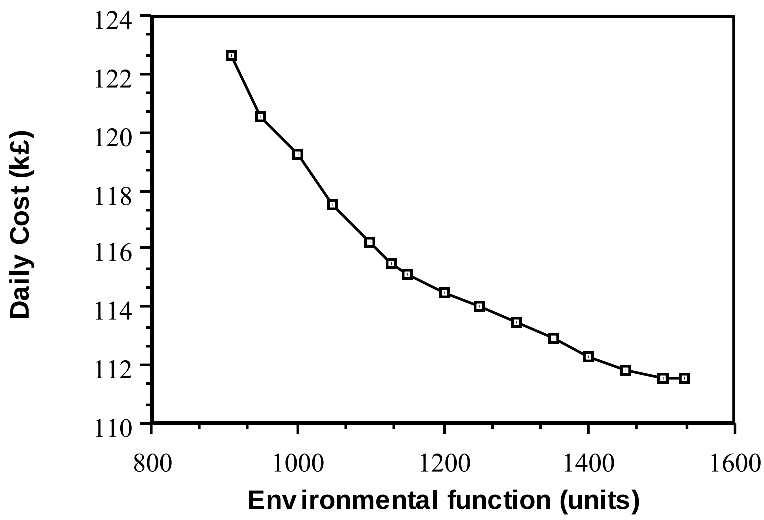

Fig. 4 - Tradeoff between economical and environmental functions

For this simple case, the hybrid ε-constrained technique is not really necessary, since the tradeoffs are perfectly identified and the planner has all the information needed to decide about the best compromise solution. In order to simulate the design problem embedded in the framework of fuzzy programming, two more simulations were performed. The first one considered linear membership functions for both objectives, whilst the second simulation considered logistic membership functions. The fuzzy decision function and the best compromise solutions were obtained for both cases, and the results are shown in figures 5 and 6. The best solution is obtained by maximising the decision membership function. For the linear case the solution with $\lambda = \mu_{cos}(\mathbf{x}) = \mu_{env}(\mathbf{x}) = 0.65$ is the best compromise solution, corresponding to a cost function value of £ 115,460 and environmental function value of 1130 units. The simulation using logistic membership functions resulted in $\lambda = \mu_{cos\_log}(\mathbf{x}) = \mu_{env\_log}(\mathbf{x}) = 0.81$ and the same compromise solution as the linear case. Figures 5 and 6 also depict the "summation" operator of membership functions and it is noticed that its minimisation coincidently leads to the same solution. Figure 7 shows the topology and facilities installed in the system for the compromise solution. Table 3 presents some results concerning capacity installed, where case i corresponds to economical function optimisation; case ii, to environmental function optimisation; and case iii to the compromise solution.

Case	Conventional Units		Renewable Units					Energy Storage Units				
Buses:	44	55	1	3	5	15	16	1	3	5	15	16
i	30	20	5.4	4.0	0.2	1.7	0.6	--	2.0	--	--	--
ii	--	20	20.0	20.0	20.0	20.0	20.0	8.5	12.3	4.5	11.5	18.2
ii	30	--	20.0	12.5	20.0	9.2	6.3	8.5	9.3	12.0	3.0	--

Table 3 - Installed capacities (MW) of energy sources

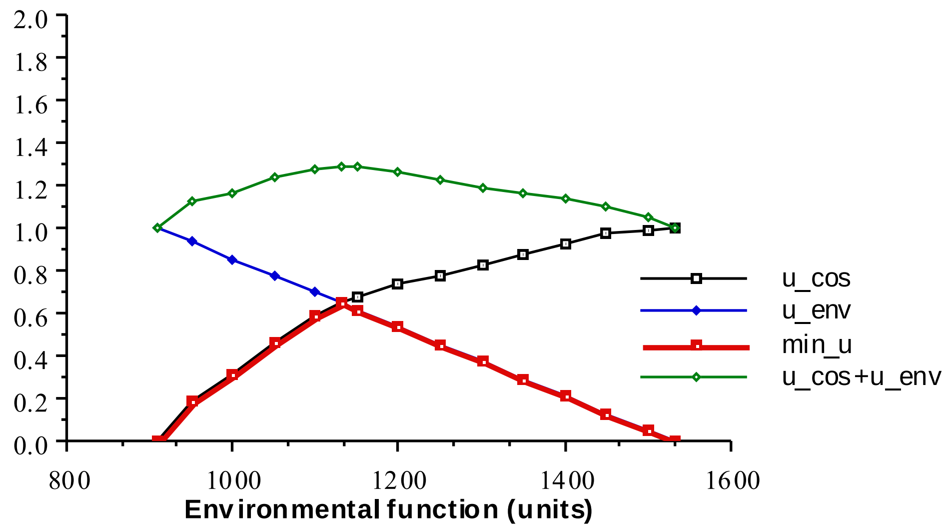

Fig. 5 - Results for linear membership functions

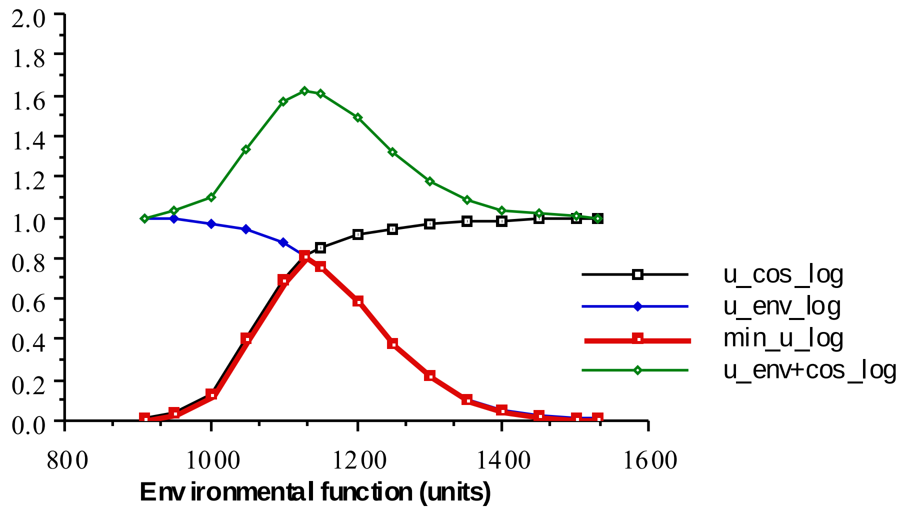

Fig. 6 - Results for logistic membership functions

4. CONCLUSIONS

This work shows the potentialities of multiple objective programming for integrating new energy sources into the problem of electrical distribution systems design. It has also shown that fuzzy set theory is an adequate technique for multicriteria decision problems. The results are very encouraging and permit quantification of the advantages of installing renewable and energy storage units in addition to conventional energy sources.

There still exist many topics to be explored which are currently being addressed by the authors. Amongst the various new aspects to be studied, it is worth mentioning (1) the application of interactive fuzzy programming methods considering fuzzy constraints and (2) improvement of processing times by the application of decomposition techniques.

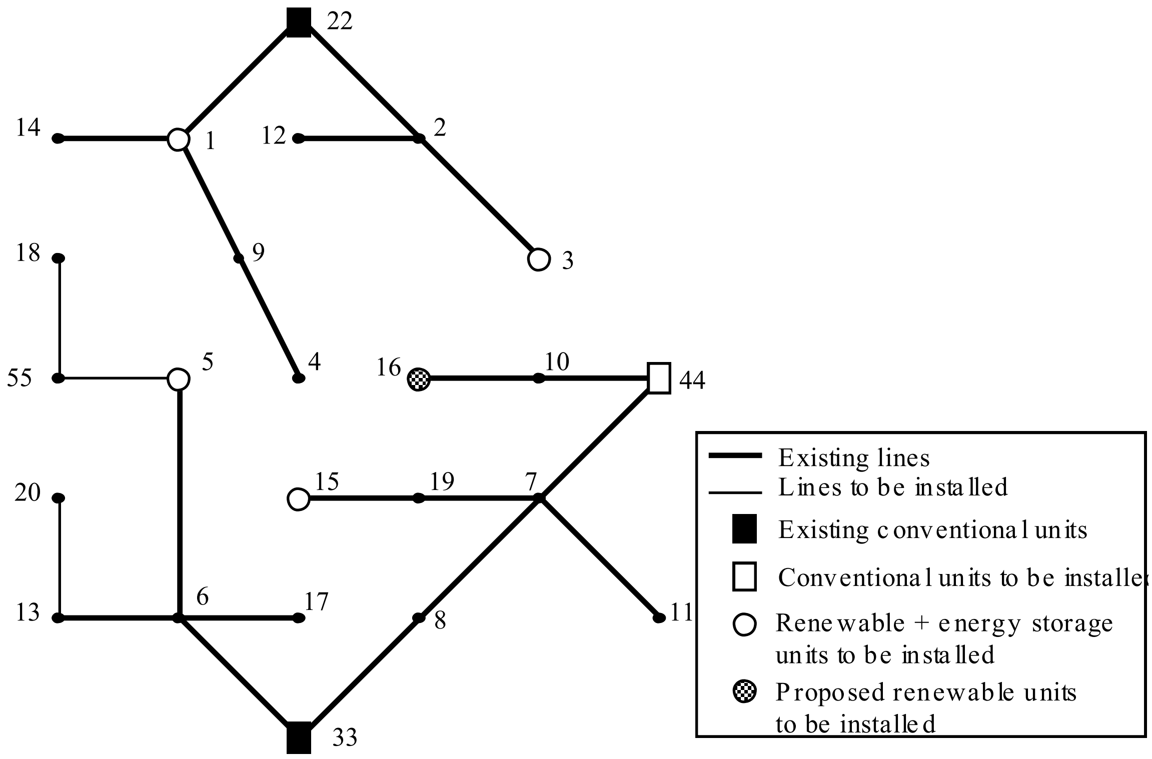

Fig. 7 - Compromise solution configuration

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