DISTRIBUTED GENERATION EXPANSION PLANNING IN ACTIVE DISTRIBUTION NETWORK

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ABSTRACT

In the context of the electric power industry restructure, and due to increasing awareness of potential environmental, technical and economical benefits of distributed generation (DG) the exploitation of the DG units has attracted great attention in distribution system's expansion planning. Up to now, almost all of the previous DG planning studies have been done under the "fit and forget" fashion, referring to the passive distribution system operation, in which the distribution networks are generally operated independently of distributed generations. This results in inefficient use of the distribution network assets as well as severely limiting the capacity of distributed generation that may be connected to the network. However, the suggested new paradigm for operation and management of distribution system, i.e. active management of distribution system, provides the possibility for DG to be treated as "network equipment" and to provide additional services required for system support for the distribution system operator (DSO). Yet, little attention has been paid to such DG's capabilities in the context of expansion planning in literature. By this work, the objectives of DG planning problem are developed in accordance with the expansion of DSO tasks in an active distribution network. In accordance with using DG in system management task, the presented model is capable to include the new components in the planning problem. Thus, a rational coordination can be established between obtainable gain from operational activities and the value of investments in distributed generation in an active distribution network.

INTRODUCTION

Current policy of installing DG has been focused on connection rather than integration; typically, DG has been installed with a “fit and forget” approach, based on the legacy of a passive distribution network [1]-[3]. Clearly, under this regime, DG is not visible to the system so while it can replace the energy produced by centralized units, it lacks the conditions required to provide system supports and security activities. So centralized generation capacities must be retained to perform this function. With growing pressure to increase DG penetration, this passive approach will lead to raising the costs of investment and operation of the system and ultimately impact the pace of DG adoption [1].

Expanded use of DG that due to the technical, economic, and environmental reasons is raised as the solution for sustainable development of energy is in contrast with this operation philosophy (“fit and forget”). In other words, the expanding use of DG with the current philosophy of operation is not achieved and for increasing deployment and penetration of DG in distribution network it is necessary that this philosophy be discarded. The reason is that the deployment of DG into the existing passive distribution networks is reaching a critical point whereby it can no longer be installed without impacting network operation and stability [3].

This is a challenging and fascinating subject for researchers and has been followed in recent studies [1]-[8]. In the context of relevant studies new solution based on integrating DG into the network operation has been proposed [2], [6]. These solutions now are at the beginning of their development path and necessity of extensive research in this area is felt. Based on these studies active management of distribution networks is the appropriate solution for exploitation of DG. Active management mode takes DG as one component of the distribution network, and active control is taken according to the requirement of the system operation.

In this context, the traditional planning patterns such as the worst case planning principle of DG interconnection in passive network does not have a good performance and should be replaced with new paradigm(s) of DG expansion planning in which, in addition to considering the traditional role of distributed generation in power production, the role of DG in system management and security should be regarded in the expansion planning objectives.

This article deals with this issue and proposes a model for implementing the DG expansion planning in active distribution network.

FUTURE DISTRIBUTION NETWORK

Efficient integration of DG is unlikely to be made without changes to transmission and distribution network structure, planning, and operating procedures. Indeed it is envisaged that there will be less of a distinction between these network types, as distribution networks become more active and share many of the responsibilities of transmission. Distribution grids will become active and will have to accommodate bi-directional power flows [9]. In active distribution network generators are dispatched according to market forces and the grid control centre undertakes an overall supervisory role (active power balancing and ancillary services such as voltage stability) [9].

In future, the system operation will be shared between central and distributed generators. Control of distributed generators could be aggregated to form the so-called microgrids or virtual utilities to facilitate their integration both in the physical system and in the market [9]. To solve this problem, *DG* should be integrated into system operation under an active control paradigm which allows it to participate in both energy and ancillary service markets. This goal can be achieved via any approach which is to aggregate *DG* either for the purpose of trading electrical energy or to provide system support services (such as Virtual Power Plant *VPP* concept). The *DSO* is in the best place to do such activities because (1) in future power systems the responsibility of provision of ancillary services is shared between independent system operator (ISO) and *DSO*. This sharing and decentralizing of responsibility (which in the current paradigm of system management is the responsibility of *ISO*) is in line with the concept of active distribution network management by *DSO*, and may fulfill the full benefits of *DG* to be achieved; and (2) all the information (load consumption, network impedances etc.) required for distribution system management is in the hands of *DSO*.

PROBLEM FORMULATION

The proposed planning model is formulated and presented in this section. The formulation sets out to determine the optimal time, place, and size of *DGs* with different technologies to be installed in the distribution system in order that the net profit during the planning period can be maximized. This is a multistage expansion planning problem.

Objective function

Objective function to be optimized is the plan's net present value (NPV). It has three parts: a) the investment costs ($C_t^{inv}(\cdot)$); and b) the cash flow after tax ($CFAT_t(\cdot)$), representing the net profit during the operational planning; and c) assets' value at the planning horizon (BV_T^{inv}).

$$\begin{aligned} NPV(\bar{x}, P_D, R_D) = & \sum\nolimits_{t=1}^{T0} \left[-\delta_t^{inv} C_t^{inv}(\bar{x}) \right] \\ & + \sum\nolimits_{t=1}^{T} \left[\delta_t^{oper} \cdot CFAT_t(P_D, R_D) \right] \\ & + \delta_T^{inv} \cdot BV_T^{inv} \end{aligned} \tag{1}$$

Where, T is the number of stages / years on the planning (assessment) horizon and $T0$ is the number of stages on the investment horizon. C_t^{inv} represents the cost of investment in the *DG*s, $CFAT_t$ stands for the cash flow after tax at year t. δ_t^{inv} and δ_t^{oper} are present value factors for the investment costs and for the operational costs at year t. BV_T^{inv} is the book value of the installed *DGs*, on the planning horizon. $\delta_T^{inv} \cdot BV_T^{inv}$ in the equation (1) denotes the *NPV* of the investment in *DGs* on the planning horizon. $\bar{x}$ represents the investment decisions.

$$\delta_t^{inv} = (1 + I_{inv})^{-t} \tag{2}$$

$$\delta_t^{oper} = (1 + I_{oper})^{-t} \tag{3}$$

$$BV_T^{inv} = \sum\nolimits_{ug \in \Phi_{DG}} BV_{ug}^{DG,T} \tag{4}$$

Φ_{DG} and ug stand for the set of *DGs* installed in the network, and the index for selecting *DG*. $BV_{ug}^{DG,T}$ is the book value of an installed *DG* on the planning horizon. I_{inv} and I_{oper} are rate of interest for a given time period.

$$C_t^{inv}(\bar{x}) = \sum\nolimits_{g \in \psi^{DC}} \sum\nolimits_{G \in \psi_g^{DG}} C_g^{DG,G} x_{g,t}^{DG,G} \tag{5}$$

$x_{g,t}^{DG,G}$ is a binary variable, having the value 1, when investing in candidate G at node g at stage t, and the value zero, when no investment is made. ψ^{DG} and ψ_g^{DG} are the nodes identified as the most likely candidates for installing *DGs*, and set of *DG*s as candidates for installing at node g, respectively. $C_g^{DG,G}$ is the cost imposed by installing the candidate G at node g.

The cash flow after tax at each year can be calculated as:

$$CFAT_t = \left[PR_t^{oper}(P_D, R_D) \right] (1 - T_r) + D_t \cdot T_r \tag{6}$$

Where D_t stands for the depreciation of installed *DGs* at year t, T_r represents the tax rate, and PR_t^{oper} is the profit (revenue-cost) of all of the operating activities (energy retail sales to the end users, cost of energy purchase from or revenue of energy sale to the upper market, selling reserve commodity to the reserve market, and operating costs of DG units) at year t. PR_t^{oper} is calculated as:

$$PR_t^{oper}(P_D, R_D) = \sum_{dl=1}^{N_{dl}} \tau_{dl} \times PR_{dl,t}(P_D, R_D) \tag{7}$$

Where $PR_{dl,t}(P_D, R_D)$ is the profit pertaining to an hour at demand level dl at year t. τ_{dl} stands for the duration of demand level dl, and N_{dl} is the number of considered demand level. $PR_{dl,t}$ is calculated as [7]:

$$\begin{aligned} PR_{dl,t}(P_D, R_D) = & \bar{\lambda} \cdot P_{DM} + \lambda_{LMP}^{R} \cdot R_D \\ & - C_{ICF}(P_D + \rho \cdot R_D) \\ & - \lambda_{LMP}^{E}(P_D - P_{ZEP}) \end{aligned} \tag{8}$$

Exactly, $PR_{dl,t}$ is an extended profit model for participating the aggregated capacity of *DG* units (dispersed in distribution level) in joint energy and reserve markets (in hourly bases).

It is to be noted that *DGs* located in distribution network don't have any direct access to the energy and reserve markets which usually exist in transmission level, the method proposed by [7], [8] for aggregating *DGs* capacity provides the opportunities for *DGs* to participate in both markets.

Consequently, based on the Eq. (8) *DGs* are involved by *DSO* in providing ancillary services (here spinning reserve) required for system support, in addition to producing energy commodity. $\bar{\lambda}$ is the retail energy rate, P_{DM} is the total demand, λ_{LMP}^{E} and λ_{LMP}^{R} are the market prices of energy and reserve, respectively. They can be estimated using proper forecasting techniques [10]. P_{ZEP} is the amount of power imported from transmission system when all *DGs* are regarded off. P_D and R_D are decision variables in operational planning, by them the volume of the proposals for energy and reserve markets are determined.

Ready-for-service payment structure is considered for remuneration of reserve provider in reserve market in the above formulation. ρ represents the summoning coefficient in real-time. ρ varies between 0 to 1 and directly affects the costs of real-time generation in the reserve market.

$C_{ICF}(\cdot)$ is representative of the marginal cost function in relation to delivering $P_D + \rho \cdot R_D$ mega watts at the connection point of distribution and transmission system, and is determined by using a successive procedure (introduced in [7]) of solving the security constraints economic dispatch (SCED) problems. $C_{ICF}(\cdot)$ is completely independent of volatility of market prices.

Constraints

Constraints on the Investment Resources: DISCO is often obligated to take investment planning decisions within its financial constraints. Accordingly, a limit is imposed on the capacity the *DISCO* can invest in. The financial constraints at any stage and during the whole investment period are expressed as:

$$\sum_{g\in\psi^{DG}} \sum_{G\in\psi_g^{DG}} C_g^{DG,G} x_{g,t}^{DG,G} \le BL_t \quad \forall t=1,\ldots,T0 \quad (15)$$

$$\sum_{t=1}^{T0}\left[\delta_t^{inv}\left(\sum_{g\in\psi^{DG}} \sum_{G\in\psi_g^{DG}} C_g^{DG,G} x_{g,t}^{DG,G}\right)\right] \le BL \quad (16)$$

BL and BL_t stands for total budget and budget at the stage t, respectively.

Constraints on the quantity of DG installation at each node: for any investment stage, t, any node candidate for *DG* installation accepts only one, if any, *DG* unit.

Furthermore, in the present study, all the operational constraints (*DGs'* generating limits, nodes' voltage limits, feeders' thermal capacity limits, substations' capacity limits, and load–supply balancing) are applied to the operational planning and to the phase during which the *DISCO's* equivalent unit is constructed.

SOLUTION METODOLOGY

Here genetic algorithm (GA) optimization technique is used for the multistage *DG* expansion planning. For any chromosome (candidate solution), the value of the fitness function (1) is related to the economic performance of that solution which in turn depends on the number, size, installation time, and location of the *DGs*. Each chromosome can be constructed using a matrix in which the number of rows is equal to the number of the investment stages (T0), and the number of columns is equal to the number of the candidate locations for *DG* installation.

The penalizing strategy is used for the unfeasible solutions. The numerical value of the penalty is directly proportional to the deviation of the objective function from the feasible space. The algorithm stops if there is no improvement in the objective function for a certain number of consecutive generations.

RESULTS AND DISCUSSIONS

The approach proposed to *DG* expansion planning is exemplified by a case study on a distribution test system introduced by the next subsection. Two scenarios on the budget limits (with and without budget limit) are investigated. For either of the scenarios, the planner determines the best-laid plan —as to what *DG* technology, where, when, and in what size should be invested in— to maximize its net profit during the assessment period.

For every year, three different load levels each with specific time duration are considered. A uniform annual load growth of 8% is assumed for all the nodes in the network.

The project appraisal takes account of all the economic factors (depreciation, taxes, and inflation rates of capital and operational costs). For each type of *DG* technology, different rates of inflation in the capital and operational cost components are considered.

ρ varies between 0 and 1 [11]. The value 0 represents an optimistic solution and the value 1 represents a pessimistic one. In this study, it is assumed to be 0.5.

The planning or assessment horizon (T), *the phase during which the information about the investment project decision is collected and the decision is made*, is assumed to be 5 years. The time period ahead of investment (the time period over which the investment is not expected to be made) is assumed to be one year. Each plan is implemented in a short lead time. The investment period is assumed to be 3 years dividing into an initial two-year stage and a final one-year stage.

Network characteristics

The proposed methodology is applied to the 9-bus primary distribution network depicted in Fig. 1. Table I presents the characteristics of a network with a 132 kV/33 kV substation of 20 MVA capacity (bus-9) serving eight aggregated loads (33 kV/11 kV service transformers at buses 1–8) at the normal operation. The system has four primary distribution feeders.

DGs characteristics

Twelve *DG* units as likely candidates for installation are assumed to be of two different technologies (gas turbine and internal combustion engine, for example). The characteristics of these candidates are shown in Table II.

It is assumed that no *DG* can be installed at nodes 9 (i.e. the substation's node) and 8. This restriction can be explained in different ways, such as geographical limitations, unavailability of the primary energy resources (e.g. gas piping) etc.

Multistage DG expansion planning without

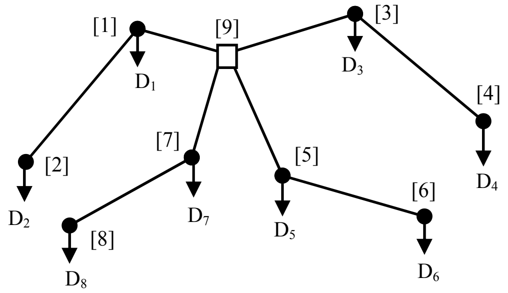

Fig.1Primary distribution system under study

imposing budget limits (Scenario A):

Table III shows the optimal plan including the time of investment in *DG*s, *DG*s' locations and capacities, as well as their types of technology over the investment period.

No budget limits are imposed on investments at the investment stages. Therefore, only the technical constraints of the network and *DG*s mark the boundary of the problem's search space.

Investment levels during the first and second stages are \$16.48 million and \$5.81 million respectively. The calculated *NPV* for the investments on *DG* during the investment period on the planning horizon is about \$7.025 million. In other words, *NPV* of *DISCO*'s assets (while taking account of depreciation in value) on the assessment horizon is \$7.025 million. With regard to the operation costs and revenues over the whole assessment period, *NPV* of the plan is about \$17.38 million.

Under the suggested scenario, where *DISCO* is considered as an active market player, the penetration and capacity levels of the *DG* may approach or rise above 100 percent. 33 MW is the total installed capacity of the *DG* which is slightly greater than the peak's load of the planning horizon. The reason is that *DSO* exercises its control and dispatch over all *DGs* (i.e. centralized dispatch is applied and *DGs* are integrated into the system operation), and *DISCO* is here permitted to gain from the new market activities.

It is to be toted that, in active distribution networks, through centralized dispatch and management, negative aspects of *DG* on stability and security of the network reaches a minimum. *DG*, as the network equipment, will be integrated into the network operation. Since *DSO* is responsible for providing stability and system security, *DSO* considering constraints related to system security and stability, will dispatch the whole system. The method used in this article for system dispatch is based on the approach of [7], in which *SCED* is used and therefore the system security has been regarded.

TABLE I
Characteristics of 9-bus system

From	To	R (Ω/km)	X (Ω/km)	Thermal Limits (MW)	Length (km)	Node	Candidate DG
9	1	0.556	0.902	5	8	1	1:8
9	3	0.834	1.153	5	12	2	1:8
9	5	0.904	1.466	5	13	3	1:8
9	7	0.659	1.128	5	10	4	1:8
1	2	1.112	1.804	3	16	5	1:8
3	4	1.112	1.804	3	16	6	5:12
5	6	0.973	1.578	3	14	7	5:12
7	8	0.834	1.353	3	12	8	—
						9	—

TABLE II
Characteristics of the Candidate DGs

Options	Technology	Size (MW)	Inv. (M$)	Cost function		
				α ($\$/\mathrm{MW}^2$)	β ($/MW)	γ ($)
1	A	2	1.28	0.005	60	12
2	A	2	1.12	0.006	70	10
3	B	2	1.04	0.008	65	8
4	B	2	0.92	.0105	55	15
5	A	5	3.6	0.007	45	20
6	A	5	3.2	0.009	60	32
7	B	5	2.8	0.011	50	45
8	B	5	2.4	0.012	55	50
9	A	7	4.96	0.02	70	15
10	A	7	4.48	0.03	80	12
11	B	7	4	0.055	75	10
12	B	7	3.68	0.045	65	18

TABLE III
Utility Investment Plan

NODE	Scenario A: No Budget Limits			Scenario B: With Budget Limits		
	Technology	Inv. Sub-periods		Technology	Inv. Sub-periods	
		Stage1	Stage2		Stage1	Stage2
1	G,G	3 (2MW)	4 (2MW)	G,G	4 (2MW)	7 (5MW)
2	D,G	5 (5MW)	4 (2MW)	G	0	4 (2MW)
3	G,D	3 (2MW)	5 (5MW)	G	4 (2MW)	0
4	G	5 (5MW)	0	G	0	4 (2MW)
5		0	0		0	0
6	D	5 (5MW)	0	D	5 (5MW)	0
7	D	5 (5MW)	0	D	5 (5MW)	0
8		—	—		—	—
Tot Cap		24MW	9MW		14MW	9MW

Multistage DG Expansion Planning with budget limit (Scenario B)

Here, in addition to the aforesaid constraints, the effect of budget limits on the optimal plan choice at any investment stage and over the total investment period is taken into consideration. The imposed budget limit at each stage is assumed to be \$10 million. The total budget limit is assumed to be \$17 million. To sum up, there is interdependence between the various investment stages in this case, e.g. if \$10 million is invested in *DG* at the first stage, only \$7 million will be available for investment at the second stage.

In this case, the budget limits narrow the search space down, and some good plans of the previous case, especially the optimal one fail. The utility's investment optimal plan in this case is shown in Table III, too. Investment levels during the first and second stages are \$9.04 million and \$5.02 million respectively. The calculated *NPV* for the investments on the *DG* during the investment period on the planning horizon is about \$4.638 million. In regard to the operation costs and revenues over the whole assessment period, *NPV* of the plan is about \$15 million. Therefore, the achieved optimal plan with imposed budget limits delivers a poorer economic performance than that of the previous case.

CONCLUDING REMARKS

This paper has presented a new model for implementing the multistage expansion planning of the *DG*s in active distribution network in deregulated environment. By the proposed model, the benefits of the integration of the *DGs* into the market have been reflected in the investment decisions. By generating a significant new revenue stream from the market activities, the investments in *DGs* are stimulated.

The model has been applied to a case study of which the results show that if *DSO* (as the aggregator of DG units) plays the role of an active market player (that bids into the energy and ancillary services markets), the penetration and capacity levels of the *DGs* may approach or rise above 100 percent.

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