RISK BASED PROCEDURE FOR NETWORK AUTOMATION PLANNING IN RADIAL DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

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ABSTRACT

This paper proposes a procedure for network automation planning in radial distribution networks with distributed generation (DGs) taking into account variability in generation and consumption. The proposed procedure is based on fuzzy set concept, mixed integer linear model and risk management analyses. It enables a large number of quality network automation plans to be obtained and evaluated using appropriate tools for measuring and managing risk. Thus, the suggested procedure provides the decision-maker with a means for determination of the network automation plan that responds to all possible futures in the most effective way.

INTRODUCTION

Network automation is one of the most effective strategies to increase the reliability in distribution networks by reducing the duration of the interruptions and the number of the affected consumers/producers. In automated distribution network, remotely controlled switches (reclosers and sectionalizing switches (RCSs)) and fault passage indicators (FPIs) play a fundamental role. The selection of the optimal number, type and location of the automation devices (ADs) to be installed in the distribution networks is a complex combinatorial optimization problem, especially when different types of automation devices are considered simultaneously [1,2]. The (optimal) relocation of the automation devices that are already installed in the network is also an effective strategy for improving reliability and should be considered simultaneously with the placement of new automation devices [3]. Distributed generators (DGs) can additionally improve the reliability in radial networks [4]-[8]. Such improvement depends on DGs operating in islanding mode. An island can be formed if sufficient local generation exists to supply local load and if operational constraints (capacity and voltage) are satisfied within the island. Therefore, the optimal creation of islands using automation devices should be considered in selecting of the best automation plan. Variability and uncertainty in consumption and generation (e.g., wind and photovoltaic generation) increase the complexity of optimal islanding problem and thus the overall problem becomes even more complex. Only a very few proposed approaches for network automation planning dealt with such variability [7,8]. They utilize probabilistic approach which does not address the optimal island formation. Moreover, they do not consider the multiple types of automation device simultaneously nor the relocation capability in the network.

This paper proposes a procedure for network automation planning in radial distribution networks with DGs based on fuzzy mixed integer linear programming model (MILP) and risk management tools.

The proposed fuzzy MILP model is formulated to minimize total expected reliability cost by simultaneously taking into account different types of new automation devices, relocation of the existing automation devices, and optimal creation of islands including the ability of load curtailment. In the model, triangular fuzzy numbers are used to model variability in generation and consumption, thus translating the classical MILP model into fuzzy domain. Such a fuzzy set approach provides that variability in production and consumption is analyzed simultaneously for all possible intervals and hence enables obtaining of a number of different automation plans. In some of the obtained plans violation of operational constraints (voltage and capacity constraints) may occur with certain probability during the islanding operation. These outcomes along with the corresponding probabilities are determined for each fault in the network and for every obtained automation plan. The obtained automation plans, along with corresponding outcomes, are evaluated (economically quantified) and the best automation plan is selected by employing adequate tools for measuring and managing risk. Thus, the suggested procedure enables determination of the optimal network automation plan which responds to variability in generation and consumption in the most efficient way, i.e. it minimizes the risk of considerable financial losses (costs) according to the adopted criterion for measuring risk.

PROBLEM FORMULATION

The goal of network automation planning in radial distribution networks with DGs can be stated as follows: determine the number, type and location of the new ADs, the new locations of the existing ADs and the formation of DG islands so that the total present worth cost is minimized in the planning period. Thus, the network automation planning problem can be expressed as follows:

$$\min\{TCOST = \mathrm{C}^{\mathrm{AD}} + \mathrm{C}^{\mathrm{RL}} + \sum_{t=1}^{\mathrm{T}} \frac{1}{(1+\mathrm{d})^{t}} \cdot \mathrm{CINT}(t)\} \qquad (1)$$

In (1) C^{AD} represents the investment cost of ADs (reclosers, FPIs, RCSs). It consists of purchase, installation, and maintenance cost. The cost of relocation of the existing ADs which consists of de-installation and installation cost is represented by C^{RL}. The annual expected interruption cost due to short-term (e.g., up to 3 minutes) and long-term interruptions of consumers and DGs, taking into account the possibility of DG island operation, is denoted by $CINT(t)$. This cost is calculated for each year (t) in the considered planning period (T) and discounted using the annual discount rate (d). The modeling of the aforementioned costs is presented in details in [9]. The influence of different types of ADs and island operation of DGs on the supply/production interruptions is discussed below.

Figure 1 shows a radial feeder where AD stands for recloser, RCS, or FPI. The possible locations of ADs along the feeder are depicted by square lines. In addition, FH is an automated feeder head circuit breaker, *l* is the length of the feeder sections, and L1-L6 is the connected load.

In the case of a fault, shown in Fig.1, the following cases are considered.

If AD1 is a recloser, then loads L1 and L2 will not experience an interruption. If AD1 is an RCS, loads L1 and L2 will experience a short-term interruption and if it is an FPI, loads L1 and L2 will experience a long-term interruption. In the latter case, FPI will reduce localization and isolation duration of the fault because the localization and isolation steps will be performed at the part of the feeder length *l* instead of at the entire feeder length. After the isolation of the fault loads L1 and L2 will be (re)supplied by closing FH. If the island operation of DGs is not allowed, loads (L3-L6) and DG will be without the supply/production until the fault is localized, isolated, and repaired.

If the island operation of DG is allowed, the sequence of events after a fault occurs is as follows. First, DG is tripped, and the fault is localized and isolated by one or more ADs. Then DG reconnects if it is not within the faulted zone. After the fault is cleared, reclosers synchronize the operation of DG island with the grid. Hence, properly placed reclosers are crucial for achieving the optimal creation of DG islands in radial distribution networks in terms of reliability and investment costs. Now, if AD2 is a recloser and a fault occurs, the recloser enables the creation of the island consisting of loads (L4-L6) and DG. If DG is capable of providing satisfactory service to the islanded zone, the supply/production in the zone will be restored after it has been interrupted. If the total consumption of (L4-L6), along with the losses in the island, is higher than the production of DG, the island could not be formed without load curtailment. Assume that loads L4 and L6 are of higher priority than L5 and disconnecting any of the loads (L4-L6) would enable the creation of the island. In this case, if an RCS is installed at AD3, load L5 will be remotely switched off and the island could be created. However, if the loads and the connected DGs within an island are characterized by variable nature then a risk based approach should be applied in defining the successful/unsuccessful island operation. Variability and uncertainty in production and consumption is considered in this paper by introducing fuzzy concept and appropriate tool for measuring and managing risk, as presented hereunder.

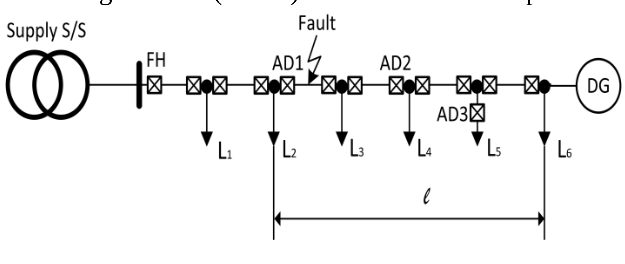

Fig.1. Radial feeder with DG

MODELING OF LOAD AND GENERATION VARIABILITY

Variation in demand and DGs production are modeled here by introducing fuzzy concept. According to this concept values of load and generation are translated into a triangular possibility distribution, using the approach proposed in [10], and described by a triangular fuzzy number (TFN) $\tilde{P}$ shown in Fig. 2. This description defines that the load/generation at the given node will be around the mean value P_M, no less than P_L and no more than P_R. This fuzzy value can be written in the terms of crisp values (de-fuzzified) in the following way:

$$P = P_M + \delta_P \cdot r_{\tilde{P}} \quad (2)$$

$$P = P_M - \delta_P \cdot l_{\tilde{P}} \quad (3)$$

where $\delta_P=1-\alpha$, $r_{\tilde{P}}$ and $l_{\tilde{P}}$ denote the right and left spread of fuzzy number $\tilde{P}$ ($l_{\tilde{P}} = P_M-P_L$, $r_{\tilde{P}} = P_R-P_M$). Expression (2) is related to the right-hand side whereas expression (3) is related to the left-hand side of the triangular fuzzy number.

By applying (2)-(3), the consumption (L) and generation (DG) in the network can be described as follows:

$$L = L_M + \delta_L \cdot r_{\tilde{L}} \quad (4)$$

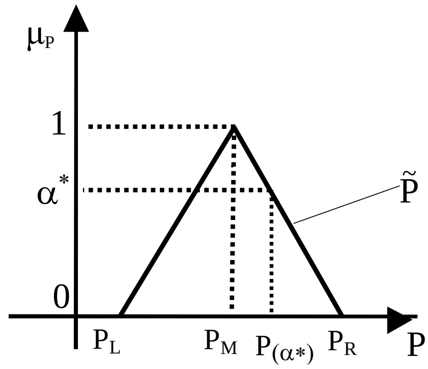

Fig.2. Fuzzy consumption/production representation

$$\mathrm{L} = \mathrm{L_M} - \delta_L \cdot l_{\tilde{L}} \quad (5)$$

$$\mathrm{DG} = \mathrm{DG_M} + \delta_{DG} \cdot r_{\tilde{D}G} \quad (6)$$

$$\mathrm{DG} = \mathrm{DG_M} - \delta_{DG} \cdot l_{\tilde{D}G} \quad (7)$$

Parameter δ_L defines consumption levels that could appear in the demand (load) node whereas parameter δ_{DG} defines production (generation) level that could occur in the generation node. By varying the value of δ_L and δ_{DG} in interval 0 – 1 in (4)-(7) a number of different values (levels) of demand and production could be taken into consideration in each node, i.e. a number of different combinations of load and generation that may appear in the network could be simulated. These simulations are performed in the way that for each possible level of generation (each value of δ_{DG} in the range 0-1 for both sides of TFN) all possible values of δ_L (each value of δ_L in the range 0-1for both sides of TFN) are considered.

RISK BASED PROCEDURE FOR NETWORK AUTOMATION PLANNING

Procedure for obtaining the best network automation plan in radial distribution networks in the presence of variability of load and generation consists of the following steps:

1) A deterministic network automation planning problem is defined for one combination of values δ_{DG} and δ_L, e.g., for one combination of demand and production in the network. This problem is formulated in the terms of mixed integer linear programming model that is presented in [9]. By solving this problem, the automation plan (AP_i) that is optimal for considered combination of demand and production will be obtained. The aforementioned is applied for each combination of δ_{DG} and δ_L by changing their values as described in the previous section. In this way a number of different network automation plans will be obtained.

2) Each network automation plan is evaluated for every fault in the considered network and for all combination of demand and generation. Evaluation and selection of the best automation plan is done according to the maximal expected monetary value (max EMV) criterion for measuring risk [11] as decribed hereunder.

By applying automation plan AP_i in case of fault (k) in the considered network two possible cases (outcomes), O_1 and O_2, can occur with the corresponding probabilities:

- island can be created in the network (feeder) (O_1) with the probability $P_k(O_1,AP_i)$,
- island cannot be created in the network (feeder) (O_2) with the probability $P_k(O_2,AP_i)=(1- P_k(O_1,AP_i))$.

The island cannot be created if load is greater than generation within the island, if the capacity constraint of branches is violated in the island, or if the voltage

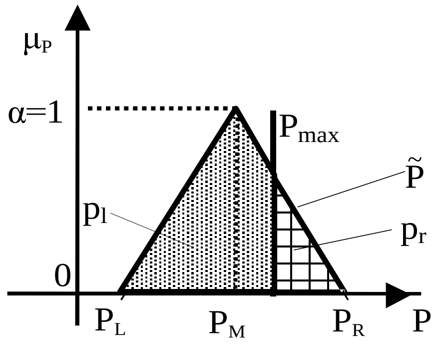

Fig.3. Concept of fuzzy operational constraints

constraint is violated in the island. The probability of appearing of the aforementioned conditions is calculated as follows:

a) Violation of voltage and capacity constraints along with the probability of their occurrence is calculated as shown in Fig. 3 and equation (8) [10]. Hence, the probability of violating constraint (limit) P_{max} is calculated as [10]:

$$S_{P_{max}} = \frac{p_r}{p_l + p_r} \cdot 100 \ [\%], \quad (8)$$

where p_l and p_r are the areas under the membership function, left and right of the constraint/limit P_{max}, respectively (Fig. 3). So, with the probability S_P voltage or thermal constraint P_{max} will be violated.

b) The probability that the load will be greater than the generation in the island is evaluated by comparing two fuzzy numbers, i.e. by calculating the probability that fuzzy load L will be greater than fuzzy generation DG, $P(\tilde{L} \succ \tilde{D}G)$, as shown in Fig.4. This probability is calculated using the approach proposed in [12], which introduces comparison relation on fuzzy numbers based on their α-cut representation and comparison probabilities of interval values.

If more than one of the considered conditions occur then the highest of the aforementioned probabilities is used to represent the probability that the island could not be created, $P_k(O_2,AP_i)$. This outcome, besides the

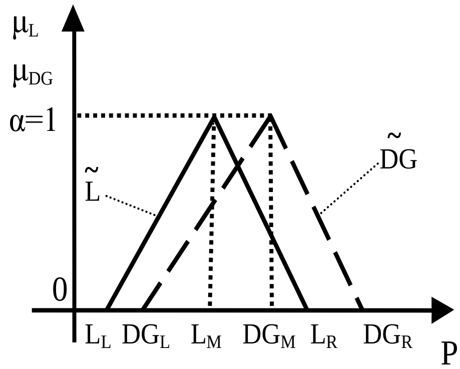

Fig. 4. Comparision of fuzzy load ($\tilde{L}$) and fuzzy generation ($\tilde{D}G$)

probability of occurrence, is characterized by the (fuzzy) cost CINT (see (1)) denoted as CINT(AP_i,O_2). Now, the total expected (fuzzy) costs for an automation plan AP_i, $E(AP_i)$, is obtained by summing up costs for all faults in the network:

$$E(AP_i)=C_i^{AD}+C_i^{RL}+\sum_k\sum_j P(O_j,AP_i)\cdot CINT(AP_i,O_j), \quad (9)$$
$$k\in N_f,\ \ j=1,2,\quad i=1,..,N$$

where:

N – number of obtained automation plans,

N_f – set of all faults in the network,

$E(AP_i)$ – expected *TCOST* for plan AP_i.

3) Automation plans evaluated in step 2) are ranked and the best network automation plan is choosen ($d(AP_{opt})$) according to the maximal expected monetary value (max EMV) criterion for measuring risk. In the network automation planning problem this criterion corresponds with the network automation plan for which the total expected cost, described by (9), is minimal,

$$d(AP_{opt})=\min_i E(AP_i),\quad i=1,...,N\ . \quad (10)$$

NUMERICAL RESULTS

The proposed approach is used to determine the optimal number and location of remotely controlled sectionalizing switches (RCS), reclosers, and FPIs in the 20 kV radial distribution network presented in Fig. 5. It consists of 13 load points, two DGs and 39 possible automation device locations. In Fig. 5 is shown a part of the required data: length of lines (km), capacity of lines, and type of consumers (commercial(C), residential(R), industrial (I)). Variability of loads is modeled by TFN (L_M, r_L, l_L) where L_M is kernel of $\tilde{L}$, given in (kW), whereas r_L and l_L are the right and left spread of $\tilde{L}$, respectively. In the similar way is described the variability of production of DG1 with one wind turbine of 1.5 MW rated power. DG2 is diesel generator with rated power of 0.5 MW and with constant output. Switch at the feeder head (full circuit) is assumed to be remotely controlled. The following is also assumed: time horizon under study is 15 years, annual discount rate is 8%, annual load growth rate is 2% for each consumer type, and annual DG production growth rate is 1% for each DG. Other required data are given in Table 1, Table 2, and in [9].

Table 1 Input Data

Parameters	Branch		
λ^{fault} / λ^{tfault}	0.065/0.015		
TRepair [h]	5		
Cost of inter. [US$]	Short-term		Long-term
Residential	0.03		0.5
Commercial	1.88		15.55
Industrial	2.16		5.39
DG	6		17.11
Cost of device [US$]	CI	IC/DIC	MC
Recloser	6550	500	1384
RCS	4200	500	922.91
FPI	550	50	117.78
Duration	TIZM[h]	T_0[h]	TDG[h]
	1.8	0.85	0.25

Table 2 Branch data

Size	Capacity [MVA]	r [Ω/km]	x [Ω/km]
c1	5	0.383	0.23
c2	8	0.265	0.22
c3	10	0.191	0.20
c4	14	0.123	0.19

Table 3 Test results

Plan	Load	Generation	$E(AP_i)$ [US$]	$C^{AD}+C^{RL}$ [US$]
AP_1	L_R	DG_R	2306690	132852
AP_2	L_R	DG_L	3027885	47913
AP_3	L_L	DG_R	2856516	81528
AP_4	L_M	DG_M	2303111	119513
AP_5	**0.75 L_M**	**DG_M**	**2250248**	**81589**

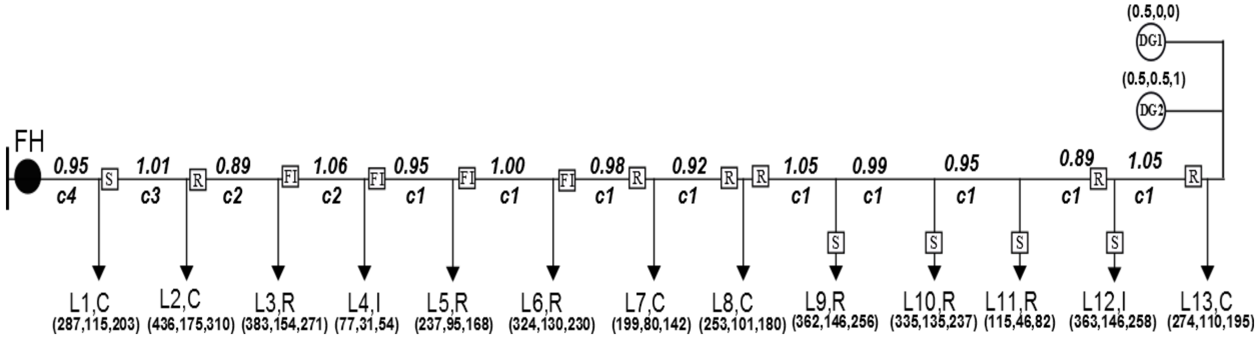

Fig.5. Test network

By applying the proposed procedure 75 different automation plans are obtained. The results for five characteristic cases (AP_1-AP_5) are shown in Table 3. Cases (AP_1-AP_4) describe plans obatined for some of characteristic combinations of load and generation that are ussually analysed in distribution networks. As it can be seen in Table 3 neither of them provides the optimal solution, i.e. total expected (de-fuzzified) cost ($E(AP_i)$) in ecah of those plans is higher comapred to the optimal plan (AP_5), which is obtained according to the $\max \mathrm{EMV}$ criterion. It should be emphasized that difference in budgetary cost ($C^{AD}+C^{RL}$), shown in Table 3, indicates the difference in the number, type and location of ADs obtained in the considered plans. The number, type and location of ADs in the optimal automation plan is denoted in Fig. 2 by squared letters (S (sectionalizing switch), R (recloser), FI (FPI)). In this plan the sum of investment and relocation cost of ADs and expected cost of interruptions is minimal among all obtained plans, i.e. the optimal balance between present worth costs of automation devices and expected costs of interruptions is established within the plan AP_5. Hence, if this plan is chosen the decision maker will "loose" minimal amount of many whatever combination of load and generation occurs, i.e. it responds to variability in generation and consumption in the most efficient way.

CONCLUSION

This paper proposes the procedure for determining the best network automation plan in the presence of load and production variability/uncertainty in the networks where island operation of DGs is allowed. The goal of this procedure is to determine the optimal location, number and type of automation devices that reduces the duration of the interruptions and the number of the affected consumers/DGs and enables creation of islands so that the risk of significant costs is minimized, i.e. to determine the automation plan which responds in the most effective way whatever plausible combination of consumption and generation occurs. It requires a great number of high quality automation plans to be generated and appropriately evaluated. This is achieved by applying fuzzy set concept, mixed integer linear programming model and maximum expected monetary value criterion for measuring risk and selecting the best network automation plan. The presented numerical results show that the proposed procedure has a potential to improve the network automation planning process in radial distribution networks with variable demand and DG production.

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