OPTIMAL NUMBER, TYPE AND LOCATION OF AUTOMATION DEVICES IN DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION

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ABSTRACT

In this paper is proposed mixed integer linear programming based approach for determining the optimal number, type, and location of remotely controlled and supervised automation devices in distribution networks where island operation of DGs is allowed. The proposed approach enables simultaneous consideration of different types of automation devices (sectionalizing switches, recloseres, fault passage indicators (FPIs)) taking into consideration all relevant costs that influence the selection of the best automation strategy. Simultaneously, the island operation of DGs, i.e. possibility of creating islands is considered in determining the optimal number, type and location of automation devices.

INTRODUCTION

Improvement of the network reliability is one of the main drivers of various enhancements in distribution networks. Network automation is one of the most effective strategies in distribution networks to increase the reliability by reducing the duration of the interruptions and the number of the affected consumers/producers. Distributed generators (DGs) can also improve network reliability, as they can additionally reduce the interruption duration and restoration time. However, such improvement depends on DG systems operating in islanding mode. An island can be formed when sufficient local generation exists to supply local load. Therefore, the optimal creation of islands should be considered and thus the selection of the optimal number, type and location of automation devices to be installed in the distribution networks becomes even more complex. A number of algorithms have been proposed to solve the switch optimization problem in distribution networks with DG. In [1], an optimization approach based on the ant colony system (ACS) algorithm was developed to determine the optimal recloser and DG locations by minimizing a composite reliability index. A fuzzy multi-objective approach for sectionalizing switch placement using an ACS algorithm was developed in [2] whereas a genetic algorithm for simultaneously allocating DG units and automatic switches was presented in [3]. In [4] the MILP based approach is proposed to determine the optimal placement of sectionalizing switches in the network with DGs taking into account the cost of switches and the cost of momentary and long-term interruptions. However, the proposed approaches do not consider multiple types of automation devices simultaneously in determining the best automation strategy. Therefore, in this paper is proposed MILP based approach for determining the optimal number, type and location of different remotely controlled and supervised devices (remotely controlled reclosers, sectionalizing switches, and remotely supervised fault passage indicators (FPIs)) in the presence of DGs in distribution networks where island operation of DGs is allowed. The proposed approach is tested on the Bus 4 of RBTS test system. The results show the importance of considering different types of automation devices simultaneously and the influence of island operations on the reliability improvement.

SOLUTION APPROACH

The MILP based model for determining the optimal strategy for improving reliability in distribution networks with DGs is given in the sequel.

Objective function

In the objective function (1) the following symbols are used:
T, d – time horizon under study (e.g. 15 years) and annual discount rate, respectively,
C(k), C(j) – cost of long-term interruption of consumer of type (k) and DG in the node (j), respectively,
NF, NLP_f, NDG_f, CLP_j – set of feeders in the considered network, set of load and DG nodes at feeder (f), and set of consumer types in the node (j), respectively,
$NDGL(f,i)$, $NLPL(f,i)$ – set of DGs and loads in the local network formed at feeder (f) due to the fault (i), respectively,
NC_f – set of sections (branches) at the feeder (f); distribution substation (MV/LV) is considered as a branch with a unit length (1 km) and appropriate failure rate,
L(f,i) – length of the branch (i),
LD(f,j,k), DG(f,j) – load of consumer of type (k) and production of DG in the node (j), respectively,
NR_f, NS_f ,NFI_f – set of possible locations of reclosers, sectionalizing switches, and remotely supervised fault passage indicators (FPIs) at the feeder (f), respectively,
$\lambda^{fault}(f,i)$, $\lambda^{tfault}(f,i)$ – failure rate of permanent and transient faults of the element (i) [number of permanent (transient) faults/year/km], respectively,
$p(k)$,$p(j)$– annual load and production growth rate of consumer of type (k) and DG in node (j), respectively,
$\mathrm{CI}(f,s)$, $\mathrm{CIS}(f,s)$, $\mathrm{CIF}(f,s)$ – investment cost of reclosers, sectionalizing switches, and FPIs, respectively,
$\mathrm{IC}(f,s)$, $\mathrm{ICS}(f,s)$, $\mathrm{ICF}(f,s)$ – installation cost of reclosers, sectionalizing switches, and FPIs, respectively,
$\mathrm{MC}(f,s)$, $\mathrm{MCS}(f,s)$, $\mathrm{MCF}(f,s)$ – total present worth operation cost of reclosers, sectionalizing switches, and

$$\begin{aligned}\min\Big\{&\sum_{t=1}^{T}\frac{1}{(1+d)^t}\cdot\Big\{\sum_{f\in NF}\sum_{i\in NC_f}\lambda^{\text{fault}}(f,i)\cdot \mathrm{L}(f,i)\cdot\Big[\sum_{j\in NLP_f}t(f,i,j)\cdot\sum_{k\in CLP_j}(1+p(k))^t\cdot \mathrm{LD}(f,j,k)\cdot \mathrm{C}(k)+\sum_{j\in NDG_f}t(f,i,j)\cdot(1+p(j))^t\cdot \mathrm{DG}(f,j)\cdot \mathrm{C}(j)\Big]+\\ &+\sum_{f\in NF}\sum_{i\in NC_f}\lambda^{\text{tfault}}(f,i)\cdot \mathrm{L}(f,i)\cdot\Big[\sum_{j\in NLP_f}\sum_{k\in CLP_j}[(1+p(k))^t\cdot \mathrm{LD}(f,j,k)\cdot c^{tfault}(f,i,j,k)+\sum_{j\in NDG_f}(1+p(j))^t\cdot \mathrm{DG}(f,j)\cdot c^{tfault}(f,i,j)\Big]+\\ &+\sum_{f\in NF}\sum_{i\in NC_f}\sum_{j\in NDGL(f,i)}\lambda^{\text{fault}}(f,i)\cdot \mathrm{L}(f,i)\cdot(1+p(j))^t\cdot \mathrm{C}(j)\cdot[(wdg(f,i,j)\cdot \mathrm{DG}(f,j)-dg(f,i,j)\cdot \mathrm{TRepair}(f,i)]\Big\}+\\ &+\sum_{f\in NF}\sum_{s\in NR_f}(\mathrm{CI}(f,s)+\mathrm{IC}(f,s)+\mathrm{MC}(f,s))\cdot w(f,s)+\sum_{f\in NF}\sum_{s\in NS_f}(\mathrm{CIS}(f,s)+\mathrm{ICS}(f,s)+\mathrm{MCS}(f,s))\cdot ww(f,s)+\sum_{f\in NF}\sum_{s\in NFI_f}(\mathrm{CIF}(f,s)+\mathrm{ICF}(f,s)+\mathrm{MCF}(f,s))\cdot[wfi(f,s)-(w(f,s)+ww(f,s))]\Big\}\end{aligned}\tag{1}$$

FPIs, respectively,

$c^{tfault}(f,j,k)$ – variable that represents cost due to momentary interruption for consumer/producer of type (*k*) in the node (*j*) at the feeder (*f*), respectively,

$w(f,s)$, $ww(f,s)$, $wfi(f,s)$ – binary decision variables that take value 1 if recloser, sectionalizing switch, or FPI is installed at location (*s*) at the feeder (*f*), respectively.

$wdg(f,i,j)$ – binary decision variable that takes value 1 if DG at location (*j*) operates in the islanding mode at the feeder (*f*) in the case of the fault (*i*),

t(f,i,j) – variable that describes the total interruption duration of the node (*j*) due to the fault (*i*) at the feeder (*f*).

The first term in (1) describes the total present worth expected cost of consumers and producers (DGs) due to the long-term interruptions caused by the permanent faults at network elements. This term takes into account load/production growth in the network in the considered period (T). The second term in (1) describes total present worth expected cost of consumers/producers due to momentary interruptions caused by the transient faults in the network. The third term describes cost of undelivered energy of DGs during island operation. The total present worth cost (investment cost, installation cost, and operation cost) of reclosers and sectionalizing switches is described by the fourth and the fifth term, respectively. The sixth term describes the total present worth cost of FPIs. This term, along with the constraint (12), takes into account the ability of reclosers and sectionalizing switches to act as the FPIs. In the equations presented in the sequel is assumed that the following hold: $f\in NF$, $i\in NC_f$, $j\in(NLP_f\cup NDG_f)$, $k\in CLP_j$ unless otherwise indicated.

Constraints

Momentary interruptions

Constraints (3) and (4), shown below, are applied if the transient fault (*i*) occurs.

$$c^{tfault}(f,i,j,k)\ge \mathrm{CC}^{tfault}(f,j,k)\cdot(1-\sum_{s\in \mathrm{S}^R(f,i,j)}w(f,s)),\ j\in NLP_f\tag{2}$$

$$c^{tfault}(f,i,j)\ge \mathrm{CC}^{tfault}(f,j)\cdot(1-\sum_{s\in \mathrm{S}^R(f,i,j)}w(f,s)),\ j\in NDG_f\tag{3}$$

$$\mathrm{S}^R(f,i,j)=\mathrm{S}^{IN}(f,i,j)\cap \mathrm{S}^{FH}(f,i),\tag{4}$$

where $\mathrm{CC}^{tfault}(f,j,k)$, $\mathrm{CC}^{tfault}(f,j)$ is the momentary interruption cost of the consumer of type (*k*) and DG in node (*j*) due to transient faults, [U.S.$/kW], respectively; $\mathrm{S}^{IN}(f,i,j)$ is the set of locations between the fault (*i*) and the node (*j*) where the considered automation device could be installed; $\mathrm{S}^{FH}(f,i)$ is the set of locations between the fault (*i*) and the feeder head where the considered automation device could be installed. Constraints (2), (3), and (4) define that the cost of interruptions due to transient fault will be zero for the node (*j*) if a recloser is installed at a location that belongs to the set $\mathrm{S}^R(f,i,j)$.

Localization and isolation of permanent faults

$$\begin{aligned}tiz(f,i,j)\ge \mathrm{TIZM}(f,i)-&\sum_{s\in(\mathrm{S}^{IN}(f,i,j)\cup S^{OUT}(f,i,j))}\Delta\mathrm{TIZF}(f,i,s)\cdot wfi^{virt}(f,i,s)-\\ -\mathrm{TIZM}(f,i)\cdot[(w_{load}(f,i,j)+&wdg(f,i,j))+\sum_{s\in \mathrm{S}^R(f,i,j)}(w(f,s)+ww(f,s))]\end{aligned}\tag{5}$$

$$wfi^{virt}(f,i,s)-wfi(f,s)\le 0,s\in(\mathrm{S}^{IN}(f,i,j)\cup S^{OUT}(f,i,j))\tag{6}$$

$$\sum_{s\in(\mathrm{S}^{IN}(f,i,j)\cup s\in S^{OUT}(f,i,j))}wfi^{virt}(f,i,s)\le 1\tag{7}$$

$$\begin{aligned}&tiz(f,i,j)\ge \mathrm{TDG}(f,j)\cdot\prod_{s\in \mathrm{S}^R(f,i,j)}(1-w(f,s)),\\ &j\in(NDG_f\setminus NDGL(f,i))\end{aligned}\tag{8}$$

where $wfi^{virt}(f,i,j,s)$ is the artificial binary variable; $w_{load}(f,i,j)$ represents binary variable that takes value 1 if load at the node (*j*) is supplied during island operation; $tiz(f,i,j)$ is the variable that describes duration of localization and isolation of the permanent fault (*i*) from the standpoint of the node (*j*) at the feeder (*f*); TDG(*f,j*) represents the duration of unavailability of DG at location (*j*) after it is tripped; $\mathrm{TIZM}(f,i)$ represents the duration of localization and isolation of the fault (*i*) at feeder (*f*) performed by a crew; $\Delta\mathrm{TIZF}(f,i,s)$ represents reduction in localization and isolation duration if there is an automation device (FPI, recloser, sectionalizing switch), at location (*s*) that belongs to $(\mathrm{S}^{IN}(f,i,j)\cup S^{OUT}(f,i,j))$, as defined by (13); $S^{OUT}(f,i,j)$ is the set of locations at feeder (*f*) that do not belong to the set $\mathrm{S}^{IN}(f,i,j)$. Constraints (5)-(8) define that duration of localization and isolation of fault (*i*), from the standpoint of the node (*j*), will be zero if there is a recloser or sectionalizing switch at a location $s\in \mathrm{S}^R(f,i,j)$, except for DGs at these locations, as defined by (8). The same will be if $\mathrm{S}^R(f,i,j)=\{\varnothing\}$ and the island is formed in which node (*j*) is supplied by DGs. If aforementioned is not fulfilled but there is a FPI at a location $s\in(\mathrm{S}^{IN}(f,i,j)\cup S^{OUT}(f,i,j))$, the duration of fault localization and isolation seen by (*j*) will be reduced by $\Delta\mathrm{TIZF}(f,i,s)$. It should bear in mind that recloser or sectionalizing switch installed at any location at feeder (*f*) will be considered as FPI.

Supply restoration

$$trs(f,i,j) = (1-(w_{load}(f,i,j)+wdg(f,i,j)))\cdot \mathrm{TRepair}(f,i) + \\ +(w_{load}(f,i,j)+wdg(f,i,j))\cdot TIsl(f,i) \tag{9}$$

$$trs(f,i,j) = \mathrm{TRSC}^{FH}(f,i)\cdot(1-w(f,s)),\ s = s_{FH}\ , \tag{10}$$

where $trs(f,i,j)$ is the variable that describes duration of supply restoration of the node (*j*) if the permanent fault (*i*) occurs; $\mathrm{TRSC}^{FH}(f,i)$ represents the duration of supply restoration if the restoration process is performed by closing the feeder head switch manually; s_{FH} is the switch at the feeder head. Constraint (9) is used if supply cannot be restored through a feeder head switch but there is a possibility to be restored by island operation of DGs. Constraint (10) is used if there is a feeder head switch through which is possible to restore supply to the node (*j*). Now, the total interruption duration ($t(f,i,j)$) of the node (*j*) if the fault (*i*) occurs at the feeder (*f*) is as follows:

$$t(f,i,j) = tiz(f,i,j) + trs(f,i,j)\ . \tag{11}$$

Logical and Miscellaneous Constraints

$$(w(f,s)+ww(f,s)) - wfi(f,s) \le 0,\ s\in(\mathrm{S}^{IN}(f,i,j)\cup S^{OUT}(f,i,j)) \tag{12}$$

Constraint (12) along with the sixth term in (1) takes into account the ability of reclosers and sectionalizing switches to act as FPIs. The influence of FPIs, and other automation devices than can act as FPIs, on the duration of fault localization and isolation is modeled as follows:

$$\Delta\mathrm{TIZF}(f,i,s) = (\mathrm{TIZM}(f,i)-\mathrm{T}_0(f)) - \\ -(\mathrm{TIZM}(f,i)-\mathrm{T}_0(f))\cdot\frac{l(f,i,s)}{\mathrm{L}_f}\ , \tag{13}$$

where $\mathrm{T}_0(f)$ is the average time required for gathering the crew and reaching the faulted feeder (*f*); *l*(*f*,*i*,*s*) is the total length of the part of the feeder (*f*) at which the isolation and localization steps should be performed in the case of fault (*i*) if the automation device that acts as FPI exists at (*s*); L_f is the total length of the feeder (*f*).

Local Network and Islanding

Local network is the network that consists of the radial network downstream from the fault (*i*) and at least one DG capable of operating in islanding mode. Faulted branch (*i*) is modelled by adding an artificial node at the middle of the branch with the artificial load greater than the sum of maximal capacities of all DGS in the local network. In this way is ensured the isolation of the faulted branch. The fault in MV/LV substation is modelled by adding aforementioned artificial load in the existing load node. Optimal configuration of the island(s) within the local network is obtained on the basis of the equations (14)-(21) using remotely controlled switches.

Power balance in the local network

$$\sum_{a\in T(f,i,j)}(x(f,a,i)+x'(f,a,i)) - \sum_{a\in F(f,i,j)}(x(f,a,i)+x'(f,a,i)) = \\ = w_{load}(f,i,j)\cdot\sum_{k\in CLP_j}\mathrm{LD}(f,j,k) - dg(f,i,j) \tag{14}$$

$$dg(f,i,j) \le wdg(f,i,j)\cdot\mathrm{DG}(f,j) \tag{15}$$

$$j\in(NDGL(f,i)\cup NLPL(f,i))\ ,(T(f,i,j)\wedge F(i,j,f))\in A(f,i)$$

Capacity constraints in the local network

$$x(f,a,i) - (1-w^{virt}(f,a))\cdot\mathrm{x}_{\max}(f,a) \le 0 \tag{16}$$

$$x'(f,a,i) - (1-w^{virt}(f,a))\cdot\mathrm{x}_{\max}(f,a) \le 0 \tag{17}$$

Logical constraints in the local network

$$(1-w_{load}(f,i,j)\cdot(1-ww^{virt}(f,j,i))\cdot\sum_{path(j)=1}^{NDGL(f,i)}\prod_{a\in A(path(j))}(1-w^{virt}(f,a,i))\cdot \\ \cdot\sum_{j\in NDGL(f,i)} wdg(f,i,j) = 0 \tag{18}$$

$$j\in NLPL(f,i)$$

$$w^{virt}(f,a,i) - \sum_{s\in a} w(f,s) \le 0\ ,\ ww^{virt}(f,j,i) - ww(f,s) \le 0 \tag{19}$$

$$TIsl(f,i) \ge \sum_{s\in A(f,i)} w(f,s)\cdot\mathrm{T_{rec}} + \sum_{s\in NLPL(f,i)} ww(f,s)\cdot\mathrm{T_{sec}} \tag{20}$$

$$TIsl(f,i) \ge wdg(f,i,j)\cdot\mathrm{TDG}(f,j) \tag{21}$$

where *x*(*f*,*a*,*i*) and *x'*(*f*,*a*,*i*) are variables that describe power flow over the branch (*a*) in the local network created in the case of fault (*i*) in one or another direction, respectively; *path*(*j*) represents the path between node (*j*) and a DG in the local network (number of paths is equal to the number of DGs in the local network); A(*path*(*j*)) represents the set of branches that exists at the *path*(*j*); A(*f*,*i*) is the set of branches in the local network created in the case of the fault (*i*) at the feeder (*f*); *dg(f,i,j)* is variable that represents the output power of a DG during the island operation; $\mathrm{x}_{\max}(f,a)$ represents maximal capacity of the branch (*a*). Constraint (14) ensures power balance in the local network. Constraint (15) defines maximal generation of DGs in the local network. Constraints (16), (17), and (19) define thermal capacity and power that flows over the branches in the local network. Constraint (18) defines that the load can be unsupplied in the following cases: if a recloser is opened in any branch through which the load is connected with DG(s) in the local network, if there is no production in the local network, and if the transformer switch, through which the load is supplied, is opened in the MV/LV substation. Constraints (20) and (21) define the duration of creation of the island(s) (*TIsl*(*f*,*i*)) taking into account switching time of all switches involved in forming the island(s) as well as the unavailability of DGs (TDG (*f*,*j*)). In the proposed approach is assumed that only reclosers are involved in reconnecting the island(s) with the supply substations after the fault is cleared by synchronizes their reclosing operations with the DG.

NUMERICAL RESULTS

The MILP model (1)-(21) is used to determine the optimal number and location of remotely controlled sectionalizing switches, reclosers, and FPIs in the test network connected to Bus 4 of the RBTS [5], presented in Fig. 1. It consists of 38 load points and 89 possible automation device locations. For testing purposes the original network [5] is modified by adding 10 DGs of the same type, as shown in Fig. 1. In Fig. 1 is shown a part of the required data: length

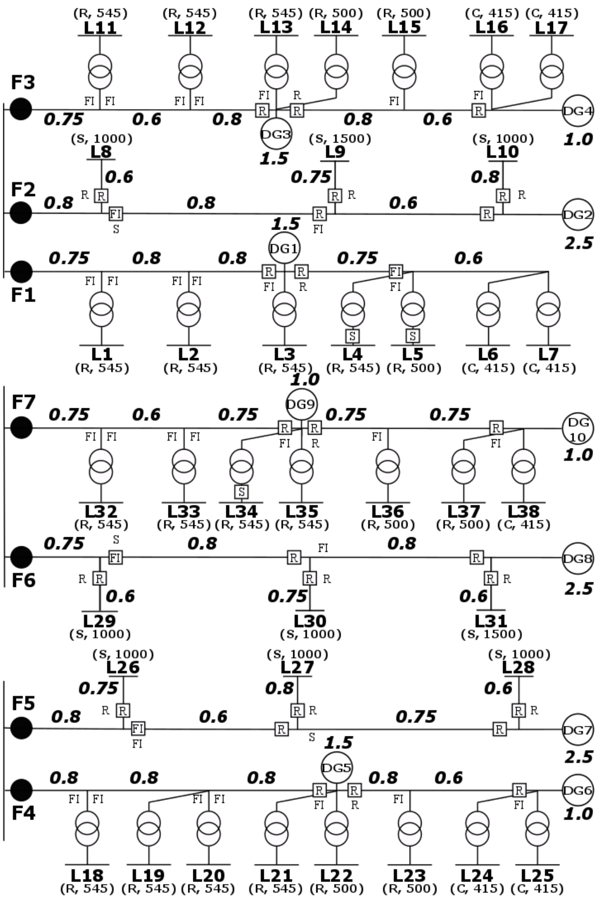

Fig. 1. Test network

of lines (km), type of consumers (commercial(C), residential(R), small-user(S)), average load (kW), average generation (MW). Switches at the feeder heads (full circuits) are assumed to be remotely controlled. The following is also assumed: T_{rec}=T_{sec}=15 seconds, the 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 I and in [5].

Two cases are considered, network with and without possibility of DG islanding. The results in the second case are depicted by ordinary letters (S (sectionalizing switch), R (recloser), FI (FPI)) while in the first case squared letters are used, as shown in Fig.1. Total present worth reliability cost (value of the objective function (1)) in the first case, which ensures noticeably better reliability, is 1696837U.S.$ whereas in the second case it is 5598445 U.S.$. This result highlights the influence of DG's island operation on improving reliability. It should be emphasized that number, type and location of automation devices differs noticeable in the considered cases. It should also be noted that the sectionalizing switches are used to disconnect load in the MV/LV substations to enable creating of the optimal islands in the first case whereas there are not used in the second case.

TABLE I. INPUT DATA

Parameters	Branch		Substation
λ^{fault} / λ^{tfault}	0.065/0.015		0.015/0.004
TRep [h]	5		10
Cost of interruption [U.S.$]	CC^{tfault}		C
Residential	0.03		0.5
Commercial	1.88		15.55
Industrial	2.16		5.39
DG	6		17.11
Cost of device [U.S.$]	**CI**	**IC**	**MC**
Recloser (R)	6550	500	1384
Sectionalizing switch (S)	4200	500	922.91
FPI	550	50	117.78
Duration	TIZM[h]	T_0 [h]	TDG [h]
	1.8	0.85	0.25

CONCLUSION

This paper proposes the MILP based approach for determining the optimal reliability improvement strategy in the networks where island operation of DGs is allowed. The proposed approach defines 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 optimal creation of islands so that the total present worth reliability cost is minimized. This cost consists of the cost of momentary and long-term interruptions of consumers and DGs, cost of undelivered energy of DGs during island operation, and the total cost of various types of automation devices.

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