OPTIMAL RELIABLE DISTRIBUTION NETWORK EXPANSION PLANNING USING IMPROVED PSO ALGORITHM

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ABSTRACT

Multistage distribution network expansion because of load growth is a complex problem in distribution planning. The problem consists of minimizing total cost of objective function subject to technical constraints. Additionally, the reliability requirements of customers should be optimally satisfied. In this paper, HV/MV substations, main and reserve MV feeders, DG sources and storage units are considered as possible solutions for multistage distribution expansion planning. Some strategies are proposed for DG and storage units operation to optimize the distribution planning. A modified PSO algorithm is applied to solve the optimization problem. Numerical results of the case studies show ability of the methodology.

INTRODUCTION

Optimal expansion of medium-voltage power network because of load growth is a common issue in electrical distribution network planning. The expansion planning approach determines the location, type and capacity of new equipments that should be expanded and/or added to the system. The problem consists of minimizing total cost of the objective function with technical constraints. Additionally, the optimal system must provide acceptable customer outage profile to ensure that customer reliability requirements are satisfied. The objective function usually includes facilities installation and operation cost and the reliability cost. Distribution expansion planning is a complex problem which should be solved by modern optimization algorithms. However, multistage procedure of planning because of dynamic load growth makes the problem more complicated. Multistage planning approach should define not only optimal location, type and capacity of investment, but also the most appropriate times to carry out such investments. Moreover, the intricacy of the problem is increased critically as the system size becomes large [1].

In conventional distribution expansion planning, HV/MV substations and main and reserve MV feeders installation/upgrade are considered as possible solutions. Today, new capacity options such as Distributed Generation (DG) and storage units are expanded. Due to more flexibility, DG and storage units can be implemented as possible solutions in distribution network planning. Recently some papers have considered either DG or storage units utilization in distribution network planning [1-3].

In this paper, HV/MV substations, main and reserve MV feeders, dispatch-able DG sources and storage units are considered as possible solutions for multistage distribution expansion planning. DG and storage batteries are optimally allocated not only for peak cutting, but also for reliability improvement. The consuming load variation is modeled as a three-level load. To solve the combinatorial optimization problem, a Modified Particle Swarm Optimization (MPSO) is proposed.

PROBLEM STATEMENT

It results in the problem that optimizes the location, type and installation date of new main and reserve feeders as well as the location, capacity and installation date of new DG and storage units and HV/MV substations and/or the capacity increment and the upgrade date of existing HV/MV substations while minimizing the total cost objective function of the network under technical constraints. The objective function includes investment cost, operation cost and reliability cost. Consider the following notation:

OF_s	Objective function of the *s*-th stage ($)
C_s^{INS}	Installation cost of facilities in *s*-th stage ($)
C_s^{OPR}	Operation cost of the network in *s*-th stage ($)
C_s^{RLB}	Reliability cost of the network in *s*-th stage ($)

The total objective function (OF) is as follows.

$$OF = \sum_s OF_s \tag{1}$$

Where

$$OF_s = C_s^{INS} + C_s^{OPR} + C_s^{RLB} \tag{2}$$

The cost functions are calculated for the base year of study regarding the interest and inflation rate.

In this paper, the reliability is included as the cost of expected Energy Not Supply (ENS). The expected outage cost is evaluated for all load points during failure events. Outage cost of every load point is a function of the load type and interruption duration. However, each lost load point may be restored by reserve feeders, DG sources and/or storage units, regarding technical constraints. So, the restoration sources availability should be estimated for every failure event. Moreover, the availability of the storage units is dependent on failure occurrence time and interruption duration.

For multistage approach of distribution planning, at the end of each stage, an intermediate system should be determined. So each selected facility will have a construction date as a decision parameter. Facilities installed in each stage have no construction cost associated with them in the next stages, but they have

associated power loss and operation costs in the next stages.
In every stage, the optimal intermediate distribution system must keep voltage magnitude of all the nodes in the acceptable boundary. Capacity constraints of the substations, feeders, DG sources and storage units can not be exceeded. In addition the configuration of the normal-state network must be radial.

PROPOSED STRATEGIES

Distribution network planning procedure should be evaluated regarding system operation. Optimal power flow may be needed for objective function calculating and constraints evaluation. In this paper, some optimal simple strategies are proposed for system operation, instead of optimal power flow computation. The strategies are proposed for DG sources and storage units operation, assuming a three-load level model for the variable loads.

DG operation strategies

DG sources are allocated for both peak cutting and reliability improvement. DG sources are used to generate electrical power only in high level and normal level of load periods. As a result, DG sources are disconnected from the network in light-load periods. Moreover, DG sources may be used to restore the lost loads during failure events. After every failure event, the failed sections are disconnected from the network using normally closed switches. Then reserve feeders are connected to the network, if they can restore the lost loads. The connection of reserve feeders is performed regarding the network configuration and feeders and HV/MV substations capacity constraints. If the reserve feeders can not restore the lost loads, DG sources are connected to the network regarding DG capacity and priority of lost loads. At first the loads which have the higher priority are connected to DG sources. Then the loads with lower priority are restored if the maximum capacity of DG is not exceeded. In the other words, the free remained capacity of DG sources is assigned to the lost loads consecutively.

Storage operation strategies

Storage units can be used for either peak cutting procedure or reliability enhancement or both. As the first scenario, it is assumed that storage units are inserted only for peak cutting. Then storage units are charged during light-load periods and discharged during high-load times. As a result, storage units are not connected to the network in normal-load periods.
In the second scenario for reliability improvement, similarly to DG sources, storage units are connected to the lost loads regarding the loads priority, if the reserve feeders are disable to restore the lost loads. In this scenario, storage units are discharged only during failure events. As a result, the available power capacity of storage units is a function of failure duration, but not a function of starting time of the failure event.
As the third scenario which is proposed in this paper, storage units are allocated to both peak cutting and reliability enhancement. In normal condition of the distribution system, storage units are charged during light-load periods and discharged during high-load times. The storage units are charged fully during normal-load periods. However, they can restore the lost loads partly in all the periods when reserve feeders are not able to supply the energy lost. As a result, for each failure event, the available power capacity of storage units is dependent on not only the failure duration but also the starting time of failure. The available energy can be estimated easily from periodic charge/discharge curve of the storage units. This curve determines the sequential charge/discharge periods, regarding operation strategy described above.

MODIFIED PARTICLE SWARM OPTIMIZATION (MPSO)

Particle Swarm Optimization (PSO) is a swarm intelligence algorithm which is based on the movement of some groups of particles. Assuming that the searching space is n-dimensional, the i-th particle of the swarm is presented by the vector $\boldsymbol{x}_i = (x_{i,1},...,x_{i,n})$ with a flying velocity $\boldsymbol{v}_i = (v_{i,1},...,v_{i,n})$. The particles move in the searching space regarding their velocities. The velocity vector is updated iteratively with respect to the best previous positions of the particles and the global best position of the swarm. More details can be found in [4].
In this paper, the proposed MPSO algorithm is based on an improved hybrid TS/PSO algorithm which is proposed in [4] for conventional distribution network expansion planning. The MPSO is adapted and applied here for modern multistage distribution expansion planning.
In modified PSO algorithm, the best intermediate solution of i-th stage (i.e. local best position), instead of the best previous position in conventional PSO, is used to update velocity vector. Moreover, a new controller parameter (q) is used in MPSO to increase intensification. The particles are manipulated regarding not only the velocity vector, but also the local best particles (x_i^{LB}), the global best particle (x_i^{GB}) and the new controller parameter ($0 < q < 1$) as follows [4]:

$$x_{i,k} = \begin{cases} 1, & \text{if } \{[\mathrm{rd} < 1/(1+\exp(-v_{i,k}))]\,\mathrm{AND} \\ & \quad [(x_{i,k}^{LB} = 1)\,\mathrm{OR}\,(x_{i,k}^{GB} = 1)\,\mathrm{OR}\,(q < \mathrm{rd})]\} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

Where rd is a function generating random numbers uniformly distributed within the range [0,1]. Here, index k denotes to the elements of all main feeders, reserve feeders, DG sources and storage units sets.
Additionally, to improve the performance of the MPSO, it

is proposed to incorporate local search algorithms with the MPSO. Accordingly, after moving a particle using MPSO in s-th stage, the intermediate solution related to the particle is replaced by the best neighbor intermediate solution.

In this paper, generating of the neighbor solutions is applied to the main feeders using an intelligent local search algorithm which is used in [4]. However, the proposed neighbor generating algorithm, in s-th stage, for particles related to DG sources ($x_{i,s}^{DG}$) and particles related to storage units ($x_{j,s}^{ST}$) is as follows.

1. Select randomly the i-th node in the s-th stage.
2. If $x_{i,s}^{DG}=0$, then set $x_{i,s}^{DG}=1$ and go to step (4).
3. If ($x_{i,s}^{DG}=1$ AND $\text{rd}>0.5$), then set $x_{i,s}^{DG}=0$, otherwise set $x_{i,s}^{DG}=0$ and $x_{i,s}^{ST}=1$.
4. Select randomly the j-th node in the s-th stage.
5. If $x_{j,s}^{ST}=0$, then set $x_{j,s}^{ST}=1$ and STOP.
6. If ($x_{j,s}^{ST}=1$ AND $\text{rd}>0.5$), then set $x_{j,s}^{ST}=0$ and STOP, otherwise set $x_{j,s}^{ST}=0$ and $x_{j,s}^{DG}=1$ and STOP.

As a result, DG and storage units can be exchanged with each other in local search algorithm to pass the probable local optimum solutions.

In this paper, local search for reserve feeders is neglected. However, for all the stages except the first stage, all the existing main and reserve feeders in (s-1)-th stage, must be selected as either main or reserve feeders in s-th stage.

In this paper, the MPSO algorithm is applied to multistage distribution expansion in two phases. In the first phase, only main feeders are considered for optimization. The outcome of this phase is the optimal routing of main feeders in each stage to minimize the total objective function of Eq. (1) subject to technical constraints. In the second phase, only other facilities (i.e. DG sources, storage units and reserve feeders) are embedded in the system for each stage to minimize the objective function in Eq. (1) subject to technical constraints and the output of the first phase.

NUMERICAL RESULTS

The proposed procedure for optimal reliable distribution network expansion planning is applied to a typical 20-kV distribution system using MATLAB 7.5. The typical network consists of an existing 10 MVA HV/MV substation, 13 existing main feeders and an existing reserve feeder. 52 new load points are added to the existing network over 4 stages. Additionally, a new point is considered as candidate HV/MV substation which may be included by the optimal solution. The existing network configuration, new load points and candidate HV/MV substation are presented in Fig. 1.

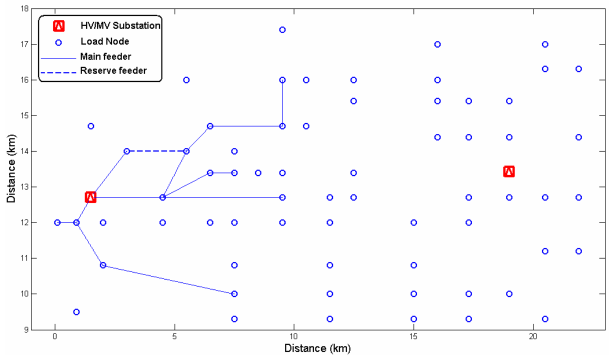

Fig. 1: The configuration of existing network, new load points and candidate HV/MV substation

In this study, storage units are utilized for both peak cutting and reliability improvement. Therefore, storage units with high charge/discharge cycles, such as Zn/Br batteries, are more suitable [2]. Moreover, dispatch-able renewable/nonrenewable DG sources, such as fuel cells units, are considered in this study.

The type of load nodes includes residential, governments & institutions, industrial and commercial loads. The customer sector interruption cost for different load types is obtained from [1]. The loading levels and market price data are shown in Table 1. Other technical and economical parameters are shown in Table 2.

Table 1: Loading levels and market price data

Load level	Percentage of peak load (%)	Time duration (hours/yr)	Market price ($/MWh)
High	100	2190	75
Normal	70	4380	49
Low	50	2190	35

Table 2: Technical and economical parameters

Parameter	Value
Failure rate of feeders ($km^{-1}.yr^{-1}$)	1.49
Failure rate of HV/MV substation (yr^{-1})	0.2
DG investment cost ($/kW)	2000
DG operation cost ($/MWh)	50
DG units size (kW)	1000
Storage investment cost ($/kWh)	225
Unit cost of power electronic for storage ($/kW)	175
Fixed O&M cost for storage ($/kW)	20
Storage replacement cost ($/kWh)	225
Storage efficiency (%)	75
Storage units size (MWh)	2.1
Life time of the project (yr)	30

The configurations of the optimal networks over 4 stages of distribution expansion planning are shown in Fig 2.

Fig. 2 shows that a new HV/MV substation, two DG sources and three storage units should be installed in optimal system over 4 stages.

Two other operation strategies described before, as different scenarios, are considered separately for optimal distribution expansion planning using MPSO algorithm.

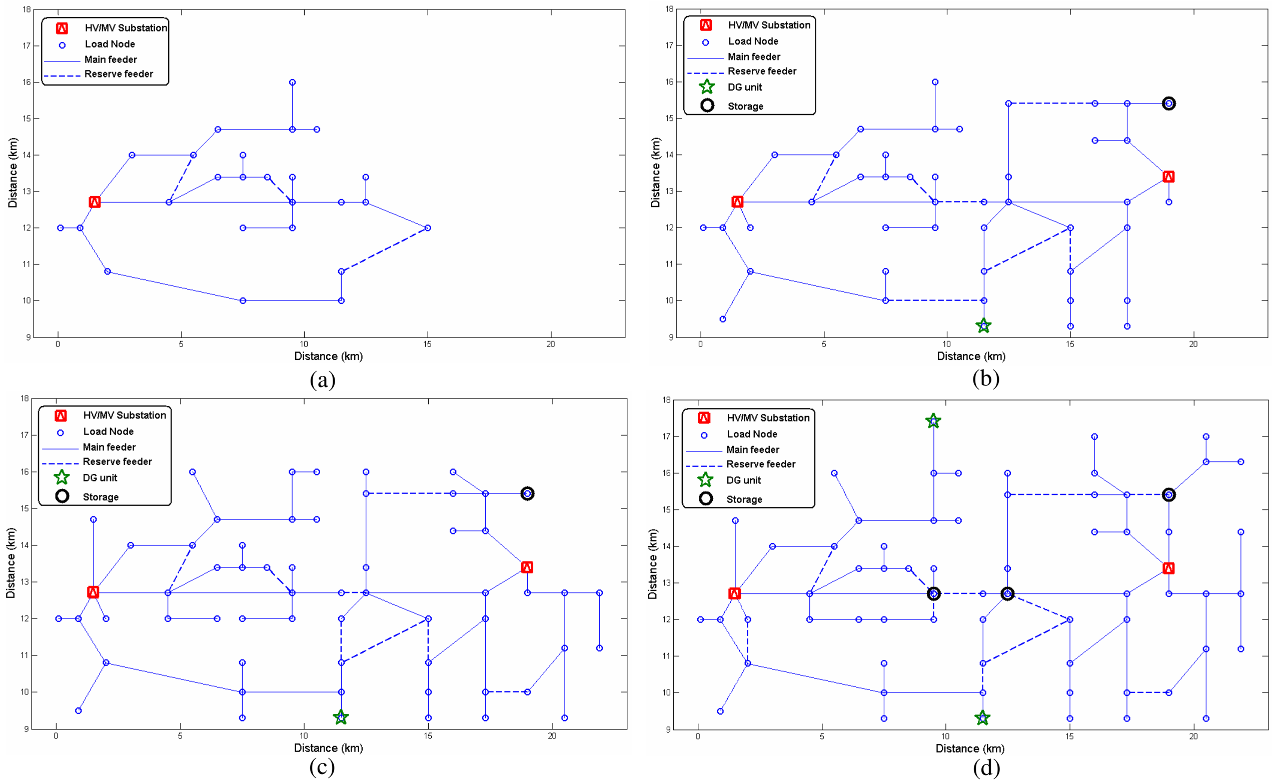

Fig. 2. Configuration of the optimal networks over four stages of the expansion: a) 1st stage, b) 2nd stage, c) 3rd stage and d) 4th stage.

Table 3: Comparison of three strategies for storage operation in distribution expansion planning

Scenarios	No. of all DG sources	No. of all storage units	Optimal objective function (M$)	Outage cost (M$)
1st scenario	3	0	187.16	0.9075
2nd scenario	2	0	186.55	1.0143
Main approach	2	3	185.49	0.6547

The results of these scenarios are compared with the main approach in Table 3. The results show that no storage unit is selected for optimal solution in scenario 1 and 2. As a result, storage utilization is not economical if it is used only for either peak cutting or reliability improvement. However, it may be an optimal choice remarking the proposed operation strategy. Moreover, the optimal solution containing storage units becomes more economical and also more reliable than the other optimal solutions without storage.

CONCLUSION

In this paper, HV/MV substations, main and reserve MV feeders, DG sources and storage units are considered to optimize the distribution system expansion over several stages. Some optimal strategies are proposed for DG sources and storage units operation regarding the load variation. DG and storage units are operated not only for pick cutting but also for reliability enhancement. A modified PSO algorithm is proposed to solve the complex optimization problem. The numerical results show that the proposed operation strategies for DG and storage units can decrease the optimal cost objective function effectively.

As a result, storage units' application in distribution planning is critically dependent on the operation strategy from economical point of view. Since the proposed strategy increases the penetration of storage units in distribution network and it makes the system more reliable, too.

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