DISTRIBUTION NETWORK RECONFIGURATION TO REDUCE LOSSES AND ENHANCE RELIABILITY USING BINARY GRAVITATIONAL SEARCH ALGORITHM

Hamid Reza ESMAEILIAN
Graduate University of Advanced Technology – Iran
hamidreza_89esm@yahoo.com

Roohollah FADAEINEDJAD
Graduate University of Advanced Technology – Iran
rfadaein@ieee.org

Sayyed Mahmoud ATTARI
South Kerman Electric Power Distribution Company – Iran
m_attari@sked.kr.ir

ABSTRACT

The main aim of distribution companies is to reduce the cost of customer interruptions and energy losses in order to achieve optimal utilization of network. Network reconfiguration is an effective method to achieve this goal. This paper presents an algorithm for optimal network reconfiguration to reduce loss and improve reliability using Binary Gravitational Search Algorithm (BGSA) based on Graph Theory (GT). The cost function of optimization problem includes the overall annual cost of the network energy losses and Energy Not Supplied (ENS) to customers. The state enumeration method based on the Weibull–Markov stochastic model of the network components is used to assess the system reliability. The proposed method is performed on a real grid in province of Kerman, Iran. Simulation results show both loss reduction and reliability enhancement compared to the situation before reconfiguration.

INTRODUCTION

Due to low voltage level, high flowing current, multiplicity of faults, and radial structure of distribution networks, the distribution system has the most portion power loss and the lowest reliability among three sections of power system that are generation, transmission, and distribution. Therefore, Distribution Companies (DisCo) attempt to cut the cost of the network energy loss and ENS by many alternatives such as capacitor placement, distributed generation resources installation, sectionalizing switches placement, the network reconfiguration, and etc. The network reconfiguration is an effective method to improve the distribution system efficiency without paying any investment cost.

The distribution networks are reconfigured in order to improve the system operating conditions by altering in open/close status of switches. The design of distribution networks is usually performed ring-shaped to enhance reliability, but they are operated radially to facilitate their protection scheme and reduce short circuit current. In normal operating conditions, the position of tie switches in the system is determined to reduce loss, balance load, and improve voltage stability. However, in abnormal operating conditions, the status of switches affects the failure frequencies, the interruption durations, and outage cost at the load points. Hence, the appropriate status choice of switches in the distribution system is a multi-task problem.

The network reconfiguration has been applied in many papers to reduce power loss. Branch and bound, switch exchange, and loop cutting heuristic type methods are used to reduce losses in [1-3]. In many previous papers, metaheuristic algorithms such as Genetic Algorithm (GA) [4], PSO [5], Ant Colony Algorithm (ACA) [6], and Tabu Search Algorithm (TSA) [7] were employed to find the network minimum loss configuration. Using metaheuristic algorithms, the optimal network configuration can be obtained in multi-objective problems. In [8], the network reconfiguration is applied to reduce the power loss and improve the voltage stability. In [9], the loss reduction, the load balancing, and the voltage profile improvement are considered in a fuzzy multi-objective function. The network reconfiguration is performed to reduce loss and improve the system reliability in [10]. They made a trade-off between the loss and the reliability of the network.

In this paper, the reconfiguration is employed to reduce the energy loss and improve the reliability of a real distribution network using BGSA. To verify and demonstrate the effectiveness of proposed method several cases are studied. At first, the network minimum energy loss reconfiguration, and then the network maximum reliability reconfiguration are accomplished as single-objective optimization problems. Thereafter, optimal configuration is achieved in order to minimize the system cost. The computational results show that maximum cost saving is obtained in considering both the energy loss and ENS in the objective function.

RELIABILITY ASSESSMENT IN RADIAL DISTRIBUTION NETWORK

Considering fault detection and repair duration of a system component state, the switching times aren't the same in real conditions, hence the reliability assessment of distribution systems should be performed probabilistic. The Weibull-Markov stochastic model of the system components is adopted in order to assess the system reliability in this paper. This method is presented in [11] and employed in DIgSILENT software. Moreover, since the reliability assessment by sequential Monte Carlo simulation is time-consuming especially for large scale distribution networks, hence, the state enumeration method is utilized to assess reliability of the network different configurations in this paper.

The system reliability assessment indices, defined by the Inter-American Committee of Regional Electricity-CIER, are as follows:

$$F = \frac{\sum_{i=1}^{N_c} P_i.\lambda_i}{\sum_{i=1}^{N_c} P_i} \tag{1}$$

$$T = \frac{\sum_{i=1}^{N_c} P_i.U_i}{\sum_{i=1}^{N_c} P_i} \tag{2}$$

$$ENS = \sum_{i=1}^{N_c} P_i . U_i \quad (3)$$

$$U_i = \sum_{k=1}^{M} f_k . r_k \quad (4)$$

$$\lambda_i = \sum_{k=1}^{M} f_k \quad (5)$$

where F is system average interruption frequency index and T is system average interruption unavailability index. The expected interruption cost can be calculated by Probability Density Function (PDF) of Weibull distribution for interruption duration as equation (6) [11]. Sector Customer Damage Function (SCDF) is given for customer types in Table I.

$$ECOST = \sum_{i=1}^{N_c}\left(\sum_{k=1}^{M}\left(f_k \times \sum_{j=1}^{T_c} \Pr(T_{j-1} < D < T_j).C_i(T_j)\right)\right) \quad (6)$$

Table I: SCDF for types of customer ($/kW) [12]

User Sector	1 min	20 min	60 min	120 min
Industrial	1.625	3.868	9.085	14.44
Commercial	0.381	2.969	8.552	16.141
Residential	0.001	0.093	0.482	1.959

LOAD MODEL

In a real distribution network, there are different types of load such as residential, industrial, and commercial at the load points. The load model type affects power flow equations and the costumer interruption cost, hence it should be taken into account in the reconfiguration problem. In this paper, the polynomial load model is adopted for modelling load types at the load point. Dependency of the power to the voltage for load types is expressed in equation (7) and Table II. Moreover, annual load profile of the studied network is considered in the optimization problem to increase accuracy of the optimal configuration.

$$\begin{aligned} P &= P_0\left(a_P\left(\frac{V}{V_0}\right)^{e-aP} + b_P\left(\frac{V}{V_0}\right)^{e-bP} + c_P\left(\frac{V}{V_0}\right)^{e-cP}\right) \\ Q &= Q_0\left(a_Q\left(\frac{V}{V_0}\right)^{e-aQ} + b_Q\left(\frac{V}{V_0}\right)^{e-bQ} + c_Q\left(\frac{V}{V_0}\right)^{e-cQ}\right) \end{aligned} \quad (7)$$

Table II: Exponential parameters' values in equation (7) [13]

	Industrial (a)	Commercial (b)	Residential (c)
P	0.1	0.6	1.7
Q	0.6	2.5	2.6

OPTIMIZATION PROBLEM FORMULATION

The objective function is considered to minimize the cost of the energy loss and ECOST for DisCo as follows.

$$f = \min\left(K_E \times \sum_{i=1}^{T_N} P_{loss_i} \cdot \tau_i + ECOST\right) \quad (8)$$

subjected to

- the radial structure of the network should be maintained, and all loads should be energized in the reconfigured structure;
- the current of each branch and the power of each transformer shouldn't violate of its rating capacity, according to equations (9) and (10);
- the buses voltages should be maintained within acceptable limits as equation (11).

$$|I_i| \le I_i^{\max} \quad (9)$$

$$|S_t| \le S_t^{\max} \quad (10)$$

$$|V_i^{\min}| \le |V_i| \le |V_i^{\max}| \quad (11)$$

GRAVITATIONAL SEARCH ALGORITHM

GSA is a new optimization search algorithm that is introduced by Rashedi et al. [14]. The GSA has many advantages compared to the PSO algorithm, such as less memory consumption, considering fitness values and position of agents in updating procedure to achieve better solution. It is derived from gravity and motion laws. In this algorithm, the searcher agents are considered as masses in the search space of the problem, so that their mass value is proportional to their fitness value. Force acting on a mass from other masses leads to a movement toward heavier masses (better solutions) in order to search space. In [14], GSA has been applied to many benchmark functions. The obtained computational results show better performance of GSA in achieving global optimum solution compared to GA and PSO algorithms. Considering discrete nature of the reconfiguration problem, binary GSA [15] is adopted to determine the optimal status of the network switches, in this paper. The main steps of the GSA are briefly described as follows.

The initial position of the agents is randomly chosen at the beginning of the algorithm. In each iteration, the fitness value of each agent is evaluated by the objective function, and then the worst and best values among population are specified. Using the fitness values, the mass of each agent is obtained as equation (12). The force acting upon each agent corresponds to its mass value that can be calculated by equation (13). Updating procedure is performed by equations (14) to (15).

$$M_i(t) = \frac{\dfrac{fit_i(t) - worst(t)}{best(t) - worst(t)}}{\sum_{\substack{j=1 \\ j\ne i}}^{N} \dfrac{fit_j(t) - worst(t)}{best(t) - worst(t)}} \quad (12)$$

$$F_i^d(t) = \sum_{j\in kbest,\, j\ne i}^{N} rand_j \times G(t)\frac{M_i(t)\times M_j(t)}{R_{ij}(t)+\varepsilon}(X_j^d(t) - X_i^d(t)) \quad (13)$$

$$V_i^d(t+1) = rand_i \times V_i^d(t) + \frac{F_i^d(t)}{M_i(t)} \quad (14)$$

$$\begin{aligned} &if \;\; rand < \tanh|V_i^d(t+1)| \;\;\; then \;\; X_i^d(t+1) = Complement(X_i^d(t)) \\ &else \;\; X_i^d(t+1) = X_i^d(t) \end{aligned} \quad (15)$$

PROPOSED ALGORITHM

The proposed algorithm, used to minimize cost for DisCo by the network reconfiguration, is illustrated in Fig.1. The number of dimensions of each agent corresponds to the number of loops in the network. In order to decrease nonfeasible agents in the population, each dimension of the agent is related to a fundamental loop of the network. Each agent shows binary code related to the switches number that should be opened in the network. The structure of each agent is evaluated by GT [4]. If the agent is feasible, then the switches status will be loaded in DIgSILENT in order to perform power flow and reliability assessment; otherwise a penalty factor will be applied to the fitness function. The algorithm finds the optimal position of tie switches when no more cost reduction is available.

SIMULATION RESULTS

To assess the applicability of the proposed method, Bardsir region medium voltage distribution network in Kerman province, Iran, is studied as a real grid. This network includes 13 feeders and 36 tie switches that is fed from two 230/20 kV and 132/20 kV substations. Fig.2 shows the initial configuration of the network. Outage data including mean failure and repair rates of the network components are obtained from statistical data for five years. The energy price is set to 0.05 $/kWh and the SCDFs are given in Table I.

Three cases have been investigated on the studied network; Case 1: reconfiguration to minimize the energy loss; Case 2: reconfiguration to minimize the ENS; Case 3: reconfiguration to minimize the summation of the energy loss cost and ECOST.

The computational results are shown in Table III. In case 1, although the energy loss is reduced to 25.12%, but the ENS increased to12.46 %. In case 2, the reconfiguration leads to improve the system reliability indices whereas the energy loss is increased to 2.32%. Therefore, in order to achieve an effective operation, the network should be studied in the both of normal and abnormal operating conditions. According to the obtained results in case 3, it is observable that minimum cost is procured in considering both of the loss and ENS in the cost function so that the network energy losses and ENS are reduced to **12.55%** and **6.9%** respectively after the reconfiguration. In this case, the obtained cost saving value for DisCo is **259207.8** $/yr.

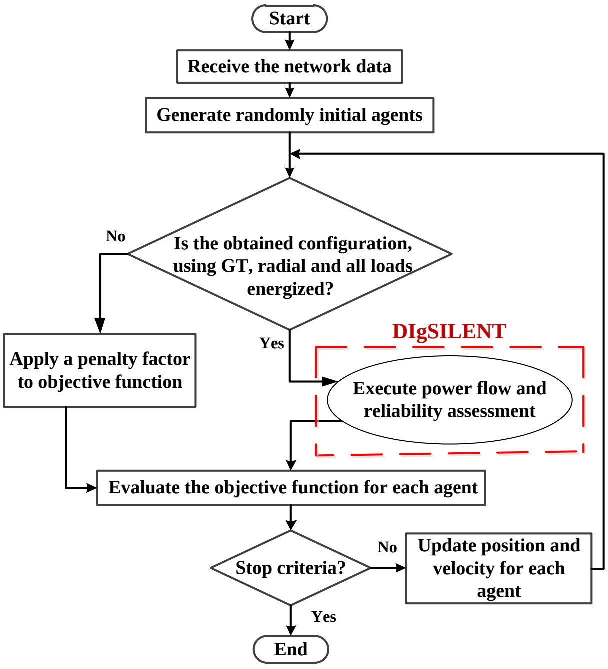

Fig. 1: The proposed algorithm

Moreover, the F and T reliability indices are reduced to 15.31% and 19.85% respectively than initial configuration.

CONCLUSION

In competitive environment, DisCos attempt to reduce the cost and enhance the system performance. In this paper, the optimal reconfiguration of a real distribution network is performed to reduce energy loss and improve reliability using BGSA. The obtained results show a remarkable improvement in the network operating conditions compared to situation before the reconfiguration. Therefore, using an effective reconfiguration can cut the cost and improve the system efficiency.

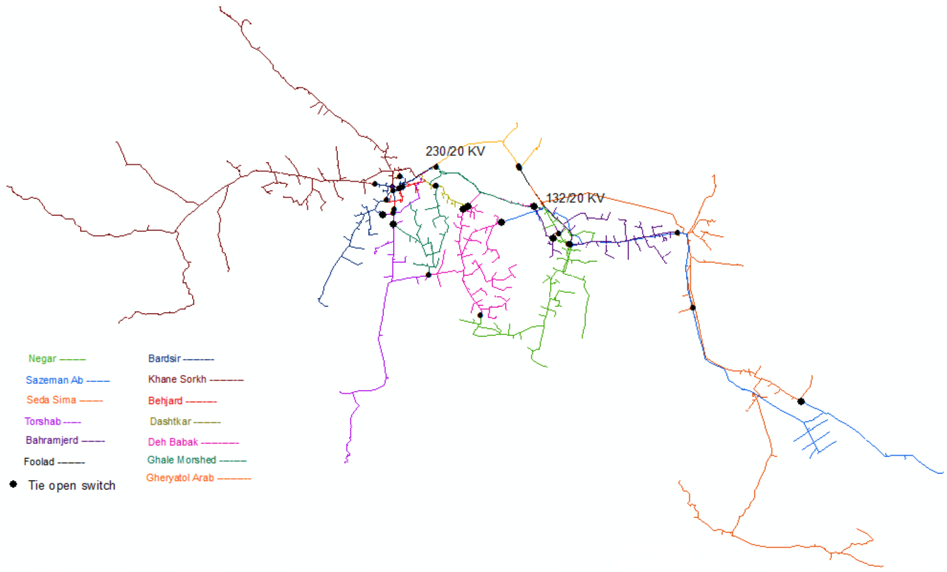

Fig. 2: Bardsir region distribution network [4].

Table III: Reconfiguration results of Bardsir region distribution network.

Items	Energy losses (MWh/yr)	ENS (MWh/yr)	Cost Function ($/yr)	Cost saving ($/yr)	T (h/yr)	F (f/yr)
Base case	9418.185	332.04	2833547.4	–	9.852	14.944
Case 1	7052.15	373.4	2809266.3	24281.1	12.179	18.35
Case 2	9636.53	283.96	2613098.4	220449	6.523	11.233
Case 3	8236.24	309.16	2574339.6	259207.8	7.896	12.656

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NOMENCLATURE

λ_i	interruption frequency at load point *i* (1/yr)
U_i	unavailability at load point *i* (h/yr)
r_k	load point interruption duration due to failure *k*
f_k	frequency of the *kth* system state (1/yr)
Pr	PDF of Weibull distribution for interruption time
M	the number of different system states which lead to an interruption at load point
N_c	the number of load points in the network
C(T)	Customer Damage Function (CDF)
T_c	the number of time intervals in the CDF
T_N	the number of time intervals in annual load profile
τ_i	duration of the *ith* time interval (h)
P_i	average load at load point i
K_E	energy price ($/kWh)
N	population size of BGSA
T	the number of iterations in BGSA
M_i	the mass value of agent i
G(t)	gravitational constant (G(t)=2-t/T)
R_{ij}	hamming distance between two masses *i* and *j*
X_i^d (t)	position of agent i in dimension d at the *tth* iteration
V_i^d (t)	velocity of agent i in dimension d at the *tth* iteration
K_{best}	set of agents with the best fitness values
P_{lossi}	average power loss in the *ith* time interval
S_t	output power of the *tth* transformer
S_t^{max}	rating power of the *tth* transformer
I_i^{max}, I_i	rating and calculated values of the *ith* branch current
V^{min}	acceptable upper limit of the bus voltage
V^{max}	acceptable lower limit of the bus voltage