

Planning of reliable microgrids in the presence of random and catastrophic events

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SUMMARY

The primary goal of this work is to investigate the problem of integrating distributed generators (DG), from a planning perspective. It relies on an optimization model with vulnerability, reliability and economy as objectives. A vulnerability index in terms of loss of load is proposed to measure potential adverse effects of undesired outages on microgrid security. It is evaluated by enumerating scenarios based on a suitably designed selection criterion. The optimization model is solved by a hybrid approach that combines multi-agent system (MAS) technology and particle swarm optimization (PSO). The encoding scheme of PSO, the hierarchical structure of MAS and the functions of the agents are discussed in detail. Finally, the effectiveness of proposed approach is tested and analyzed in the IEEE RBTS 4-bus system. The results show that an optimal trade-off planning scheme, over the three objectives, has been achieved. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: DG integration; undesired outage; vulnerability; reliability; MAS; PSO

1. INTRODUCTION

Microgrids provide an effective means of collecting and utilizing energy from small-scale renewable sources. Some of the early work on microgrids was performed by CERTS [1] where the various engineering aspects of integrating combined heat and power sources with a compact cluster of loads were investigated; however, the concept has evolved considerably since then, and microgrids have found numerous uses today in applications ranging from rural electrification to backing up utility systems to hardening of military bases. Microgrid plays an important role in solving energy shortage problem nowadays. In most of these applications, one of the key contributions of a microgrid has been to enhance reliability, as explained and exemplified in [2–4]. In addition, microgrid can reduce blackout risk in suffering random and catastrophic events. Those benefits can attract investments in microgrid and in turn promote microgrid development.

A microgrid is characterized by a small-scale power network with embedded distributed generators (DGs) which are basically the micro power sources. The problems of integrating DGs into microgrid have been the subject of much contemporary research and have drawn considerable interest worldwide. In [5], the potential impacts of DG integration on power security, power quality, reliability, losses and voltage profile are analyzed. However, not all DGs have positive impacts on the power network, especially in the cases where DGs are improperly deployed. Taking energy loss as an example, annual energy loss variation as a function of DG penetration level shows a U-shaped trajectory [6]. However, few attempts have been made in DG integration from a planning

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perspective. We aim to find a novel planning strategy for DG integration in accordance with the characteristics of microgrid.

Two main issues differentiate researches in this field that have been published in the literatures: (i) How to perfect optimization models; (ii) How to find effective approaches.

For the first issue, many previous researches are focused on uncertainty involved in planning process. DGs in microgrid are largely affected by weather condition which can hardly be forecasted accurately [7], [8]. Thus, probabilistic models are used in [8] to generate synthetic data. However, there is another type of uncertainty events which do not follow any statistical rule, such as ‘terrorist threat problem’. It is unpredictable when/where intentional attacks will happen. This kind of event has received enough attentions in transmission system since it was first proposed and defined by Salmeron, Wood and Baldick [9]. Afterwards, some reinforcement tasks were put into transmission network as a part of strategic planning measures in [10] and [11]. Microgrid system is a customer-oriented network in which those events are likely to happen; therefore, further studies are still necessary in this low-voltage network.

For the second issue, DG integration is a kind of mixed integer programming problem which includes multi-objectives and non-linear constraints. For this reason, heuristic approaches, such as genetic algorithm [12], differential evolution [13] and particle swarm optimization (PSO) [14], are more likely to be chosen as solution methods than traditional mathematical methods. We will also use a hybrid heuristic method based on PSO.

This paper is organized as follows: Section 2 analyzes undesired outages in the microgrid; then a vulnerability index is defined to measure the impacts of the undesired outages; afterwards, scenario technology is used to calculate the vulnerability index. Section 3 establishes an optimization model which takes economy, reliability and vulnerability into consideration. Section 4 proposes a hybrid heuristic approach based on MAS technique and PSO; a multi-agent system (MAS) with hierarchical structure is designed and agents’ functions are analyzed in detail. In Section 5, the model and the approach are applied to a test system. Section 6 summarizes the paper.

2. VULNERABILITY ANALYSIS

2.1. Undesired outage

Power system reliability was proposed to measure the ability of continuously supplying power to customers in the presence of random failures. The forced outage rate of electric component is used to calculate system reliability index. Its value is normally provided by component manufacturer or evaluated based on statistical results.

There is another kind of failure events named nonrandom uncertainty [15]. These kinds of events are not repeatable, and their statistics cannot be derived from past observations. Unintentional attack is one kind of such events, and it has received some attentions in the planning problem of transmission system [9–11]. Although few malicious attacks are made on microgrids, unintentional attacks should also be considered for the following reasons.

- (1) Extreme weather conditions, such as strong winds, temperature shock and snowstorm. The vulnerability of several weather phenomena in Sweden has been evaluated in [16].
- (2) Unexpected outages in daily life, such as fire, riot, car accident and municipal construction.
- (3) Deliberate attacks, such as pilferages and terrorist attacks. Terrorist attacks in microgrid have less influence to customers and utility compared with transmission system; however, the less investment including human and material resources is also required.
- (4) The operation mode of DG with characteristic ‘plug in and play’ is controlled by the behavior of its owner. The behavior is not in dispatch scheduling of power utility.

All types of outages mentioned above are defined as ‘undesired outage’ in this paper. Although undesired outages are unpredictable by the statistical method, it is certain that they will have serious impacts on system security. Any serious consequence under undesired outages is expected to be avoided during planning period. This study will take this expectation into consideration.

2.2. Vulnerability index

The consequences of undesired outages on the microgrid are analyzed by vulnerability estimation. In analogy to reliability definition, vulnerability is defined to measure the ability of withstanding undesired outages.

Three virtual principal investigators (PIs) — operator, attacker and planner — are introduced to describe vulnerability. It is supposed that all PIs play by the rules, which means they always make wise choices according to individual knowledge and information. Their game relationship shown in Figure 1 is described as follows:

- (1) The target of attacker is to find weak points of microgrid network and to produce undesired outages by deliberate attack plans. The attacker tries to maximize seriousness of the consequence with limited resources or investments.
- (2) Each undesired outage can be regarded as a virtual scenario for the operator. To minimize its impacts, the operator is required to take some corrective actions, such as load transfer or load recovery. Another important task for the operator is to determine which undesired outages need to be considered in advance to avoid serious consequences.
- (3) Planner amends the planning scheme according to vulnerability estimation results provided by the operator.

Although compensatory action will be made by the operator and the planner after the occurrence of undesired outages, the development of planning scheme lags behind terrorist attacks ultimately.

Loss of load under undesired outages is used to estimate microgrid vulnerability. For any given power network, its vulnerability is calculated by Equation (1). A higher value of F_v indicates that the power network is more vulnerable.

$$F_v = \sum_{u \in \Gamma} \sum_{m \in \Lambda} P_{shed}(u, m) \quad (1)$$

Where, Γ is the set of undesired outages; Λ is node set; $P_{shed}(u, m)$ is loss of load at node m under No. u undesired outage.

2.3. Vulnerability estimation based on scenario technology

Each undesired outage caused by the attacker is a virtual optimization scenario for the operator. It is impossible to enumerate all scenarios due to two primary reasons. One reason is that it is unpredictable whether an undesired outage will happen or not. Another reason is it is impractical to afford the computation burden of enumerating all of them. Undesired outages can be divided into single outage, double outage and multiple outage according to the number of components under attack. If component number is N , the number of scenarios which corresponds to i failure components is a combinatorial number represented by C_N^i . The total scenario of scenario is calculated based on Equation (2).

$$n = \sum_{i=1}^N C_N^i \quad (2)$$

Since there are thousands of possible attack scenarios, the scenario number is a very large value for a real network. However, it is unnecessary to include all undesired outages. The objective of planning period is to avoid severe consequences. Therefore, an evaluation mechanism is proposed to judge which undesired outages are more attractive to the attacker.

A criterion based on outage consequence is designed to select undesired outages, and only the selected undesired outages are used in vulnerability estimation. The outage consequence is evaluated by three aspects: loss of load, customer number and load type at fault buses, which are represented by P_{shed} , L_{num} and L_{type} , respectively. In general, multiple outage has a more serious consequence compared with single outage or double outage. However, more budget or resources are also demanded for the attacker. Therefore, the investment E_{inv} should also be included in the judgment process.

This attractive index for the attacker is corresponding to scenario priority for the operator and the planner. For each scenario σ , its scenario priority $I(\sigma)$ is determined by a series of parameters with

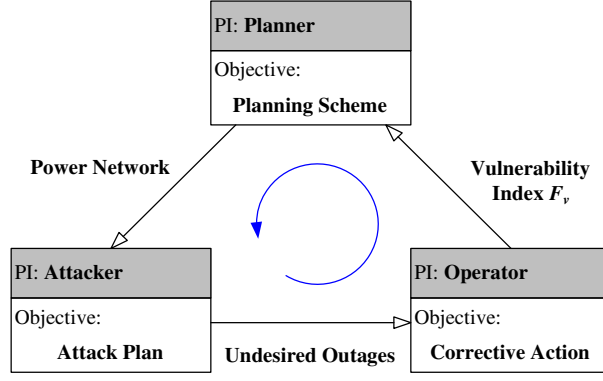


Figure 1. Game relationship among three PIs.

different dimensions. Take four factors mentioned above as an example; there is no unified expression for scenario priority calculation. Engineer experience plays an importance role in this determination process; therefore, empirical formula or analysis hierarchy process [17] is chosen to calculate $I(\sigma)$. And then, scenarios with the n_Ω highest value of $I(\sigma)$ are selected to generate the scenario set Ω which will be used in vulnerability estimation.

$$\Omega = \{\sigma_1, \sigma_2, \dots, \sigma_{n_\Omega}\} \quad (3)$$

The evaluation procedure is given in Figure 2. Undesired outages with a default number N_S ($N_S \gg n_\Omega$) will be enumerated. A larger value of N_S indicates more accuracy and lower calculation speed; it is set to 1000 in this study. Customers without electricity are recovered according to the sequence of load restoration which is based on electrical distance between power source and load point.

Since it is impossible to enumerate all undesired outages, and only n_Ω scenarios are used to estimate F_v , the inequality (4) is always true.

$$\sum_{\sigma \in \Omega} \sum_{m \in \Lambda} P_{shed}(\sigma, m) \leq \sum_{u \in \Gamma} \sum_{m \in \Lambda} P_{shed}(u, m) \quad (4)$$

A normalizing factor $\frac{I(\sigma)}{\sum_{\sigma \in \Omega} I(\sigma)}$ based on scenario priorities is introduced in the formulas of vulnerability index as shown in formula (5). A modified vulnerability index F_v' rather than F_v is used to measure microgrid vulnerability. Although those two indices have different values, F_v is in proportion to F_v' ; the proportionality factor is the number of all undesired outages ideally. In the following sections, F_v' which is still represented by F_v is used for vulnerability measurement.

$$F_v' = \sum_{\sigma \in \Omega} \frac{I(\sigma)}{\sum_{\sigma \in \Omega} I(\sigma)} \cdot \sum_{m \in \Lambda} P_{shed}(\sigma, m) \quad (5)$$

3. FORMULATION OF THE PROBLEM

An optimization model, taking economy index F_e , reliability index F_r and vulnerability index F_v as objective functions, is proposed for DG integration problem. Planning scheme ω which includes DG's location u and DG's scale v is chosen as a variable. The model is described as formulas (6)–(12):

Minimize:

$$\{F_e(\omega), F_r(\omega), F_v(\omega)\} \quad (6)$$

Subject to:

$$P_{M,m}(\omega) - P_{L,m} - \sum_{n \in \Lambda_m} U_m U_n (G_{mn} \cos \delta_{mn} + B_{mn} \sin \delta_{mn}) = 0 \quad (7)$$

$$Q_{M,m}(\omega) - Q_{L,m} - \sum_{n \in \Lambda_m} U_m U_n (G_{mn} \sin \delta_{mn} - B_{mn} \cos \delta_{mn}) = 0 \quad (8)$$

$$|f_{mn}(\omega)| \leq f_{mn}^{\max} \quad (9)$$

$$U_m^{\min} \leq U_m(\omega) \leq U_m^{\max} \quad (10)$$

$$P_{M,m}^{\min} \leq P_{M,m}(\omega) \leq P_{M,m}^{\max} \quad (11)$$

$$Z_M^{\min} \leq z_M(\omega) \leq Z_M^{\max} \quad (12)$$

Where

Λ_m is the set of nodes which are connected to node m
 U_m is voltage at node m
 $P_{L,m}, Q_{L,m}$ are load demand at node m
 G_{mn}, B_{mn} are resistance and reactance of branch mn
 $P_{M,m}, Q_{M,m}$ are power output of DG at point of common coupling (PCC)
 f_{mn} is active power flow on branch mn
 δ_{mn} is phase angle difference
 $P_{M,m}^{\min}, P_{M,m}^{\max}$ are the limits of DG's power output at PCC
 z_M is the installed number of DG in microgrid, $Z_M^{\min}$ and $Z_M^{\max}$ are minimal and maximal values of z_M

Constraints (7) and (8) represent power flow equations, and formulas in standard back/forward sweep method [19] will be modified to meet the special requirement of bi-directional power flows. Branch power flow is bounded by constraint (9). Constraint (10) sets the limitation for node voltage.

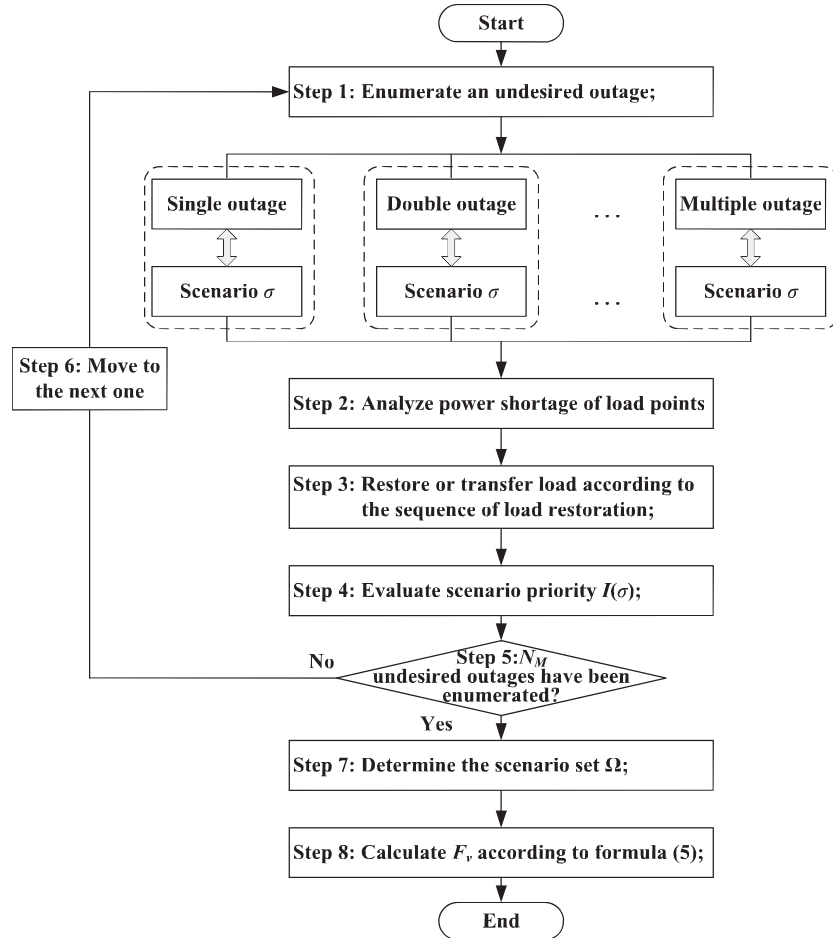


Figure 2. The flowchart of vulnerability analysis.

Constraint (11) provides bounds of DG's capacity at PCC. Constraint (12) bounds the number of installed DGs.

F_r includes six reliability indices: SAIFI, SAIDI, CAIDI, ASAI, ENS and AENS. Their expressions are given as follows, and they can be evaluated by failure mode and effect analysis [18].

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} \quad (13)$$

$$\text{SAIDI} = \frac{\text{Sum of customer interruption durations}}{\text{Total number of customers served}} \quad (14)$$

$$\text{CAIDI} = \frac{\text{Sum of customer interruption durations}}{\text{Total number of customer interruptions}} \quad (15)$$

$$\text{ASAI} = \frac{\text{Customer hours of availability service}}{\text{Customer hours demanded}} \quad (16)$$

$$\text{ENS} = \text{Total energy not supplied} \quad (17)$$

$$\text{AENS} = \frac{\text{Total energy not supplied}}{\text{Total number of customers served}} \quad (18)$$

F_e contains two terms: construction cost and annual power loss fee, as given in formula (19). The first term is converted to uniform annual value by interest rate (γ) and the average service life of DG (T_z). α and β are two parameters related to DG construction cost; p is electricity price; P_{loss} is power loss.

$$F_e = \sum_{z=1}^{z_M} \frac{\gamma(1+\gamma)^{T_z}}{(1+\gamma)^{T_z} - 1} (\alpha P_{M,z}(\omega) + \beta) + 8760 \cdot p \cdot P_{loss} \quad (19)$$

4. SOLUTION BASED ON MAS

A multi-objective and multi-constraint optimization model is established, and it is a complex mixed integer programming problem. Thus, a hybrid approach combined with PSO and multi-agent technology is designed for solution.

4.1. Encoding scheme of PSO

PSO was originated from the simulation of social animal behaviors and was put forward by J. Kennedy and R. Eberhart in [20]. PSO has been applied to many optimization problems in power system [21]. Its remarkable ability in solving complex problem has drawn a lot of attentions from electrical engineering.

Particles with a population size S are used for searching the optimal solution. Each particle θ^j ($j=1,2,\dots,S$) which indicates a planning scheme ω is composed of a set of mixed integer coding bits. The mapping relationship between θ^j and ω is shown in Figure 3.

u_i^j is a binary variable, and a DG is deployed at node i only if u_i^j equals 1 ($i=1,2,\dots,N, j=1,2,\dots,S$). The probability of choosing ' $u_i^j = 1$ ' depends on θ_i^j by using sigmoid function. The relationship between u_i^j and θ_i^j is shown in formula (20). $rand$ is a random value at interval $[0.5 - \varepsilon, 0.5 + \varepsilon]$ (ε is a small positive integer, and it is 0.1 here).

$$u_i^j = \begin{cases} 1, & rand \leq \frac{1}{1 + e^{-\theta_i^j}} \\ 0, & \text{otherwise} \end{cases} \quad (20)$$

The line ' $\theta_i^j = \ln(\frac{rand}{1-rand})$ ' classifies u_i^j into two separate cases in Figure 4: the right side of line indicates ' $u_i^j = 1$ ', and the left side indicates ' $u_i^j = 0$ '. However, the line is movable as ' $rand$ ' changes.



Figure 3. The signification of particles.

θ_i^j with a large value means that there is a relative high probability of choosing ' $u_i^j = 1$ ' case; while θ_i^j with a small value means that it is more likely to choose ' $u_i^j = 0$ '. Both cases may be chosen for a given value θ_i^j , and their probabilities are close to 0.5 in a special condition that θ_i^j is around zero. Thus, the global searching ability of particles will be enhanced after this process.

DG scale at node i (v_i^j) is determined by u_i^j and θ_{N+i}^j ($i = 1, 2, \dots, N$). The maximum value of v_i^j is limited to $P_{M,i}^{\max}$ as given in formula (21).

$$v_i^j = u_i^j \cdot \max \left\{ \theta_{N+i}^j, P_{M,i}^{\max} \right\} \quad (21)$$

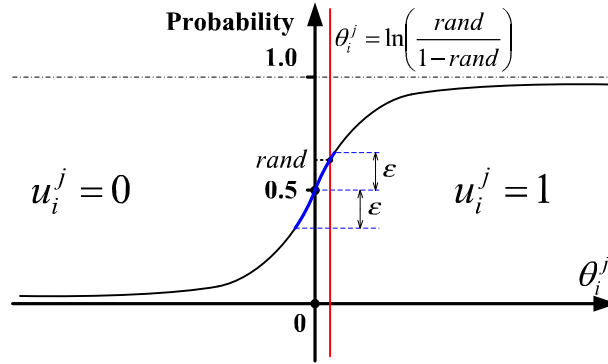


Figure 4. Mapping relation between θ_i^j and u_i^j .

4.2. Communication mode of MAS

A hierarchical structure of MAS is designed in Figure 5. There are three types of agents: central agent, particle agent and operation agent. Furthermore, operation agent is sub-classified into economy agent, reliability agent and vulnerability agent.

Agents accomplish tasks through communication and cooperation among each other. Three communication modes are analyzed in detail.

- (1) '*Point to point*' mode: this mode refers to 'central agent to particle agent' and 'particle agent to operation agent'. Central agent sends commands or global information to particle agent; meanwhile, it receives particle agent's feedbacks of calculation results. Similarly, particle agent sends the planning scheme to operation agents and receives three objective indices from them.

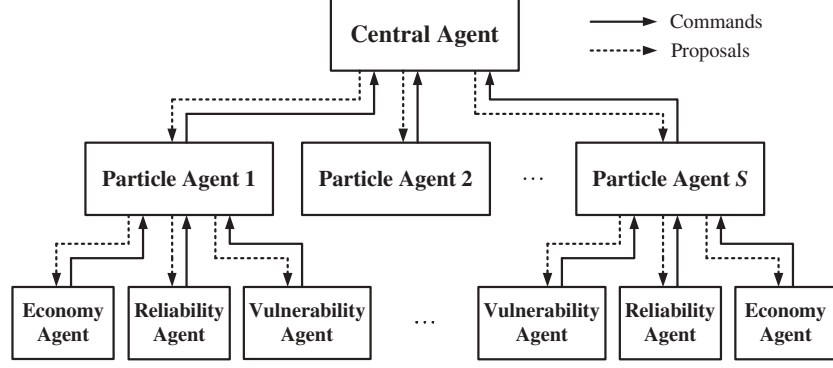


Figure 5. A hierarchical structure of multi-agent system.

- (2) *'Point to plane' mode*: commands or information are transferred from central agent to all particle agents in this mode. For example, central agent determines the fitness sequence of all particles and announces the results to every particle agent. A number of particles with the worst health condition will regenerate their positions.
- (3) *'White board' mode*: this mode is designed to avoid visiting the same position in solution space. All particle agents are demanded to present their spatial information on a 'white board' system. Agents share their information in a public space instead of individual communication among each other.

4.3. Agent functions

The optimization process is accomplished based on the cooperation among agents. Operation agent is responsible for the calculation of objectives, and its functions have been analyzed in above sections. This section will only explain main functions of central agent and particle agent.

(1) Central agent

Central agent is a global manager in the hierarchical system. It allocates particle positions in initialization process. It also determines whether a particle is in the global optimal position according to fitness values of particles. Another important task of central agent is to synthesize three objectives. Since economy, reliability and vulnerability indices do not satisfy dimensional homogeneity, they cannot be added together in a fitness function. Consequently, a membership function $\mu(F_k^j)$ ($j=1,2,\dots,S$) is proposed to normalize F_k^j ,

$$\mu(F_k^j) = \begin{cases} 1, & F_k^j \leq F_k^{\min} \\ \frac{F_k^{\max} - F_k^j}{F_k^{\max} - F_k^{\min}}, & F_k^{\min} < F_k^j < F_k^{\max} \\ 0, & F_k^j \geq F_k^{\max} \end{cases} \quad (22)$$

$F_k^{\min}$ and $F_k^{\max}$ are initially obtained from initialization based on formulas (23) and (24).

$$F_k^{\min} = \min\{F_k^1, F_k^2, \dots, F_k^S\} \quad (23)$$

$$F_k^{\max} = \max\{F_k^1, F_k^2, \dots, F_k^S\} \quad (24)$$

It should be noted that Equation (22) represents the minimization problem and applies to all the objective indices, with the exception of ASAI. As is evident from Equation (16), ASAI is maximized, and therefore its corresponding $\mu(F_k^j)$ is modified as in Equation (25). The function curves of two kinds of problems are shown in Figure 6.

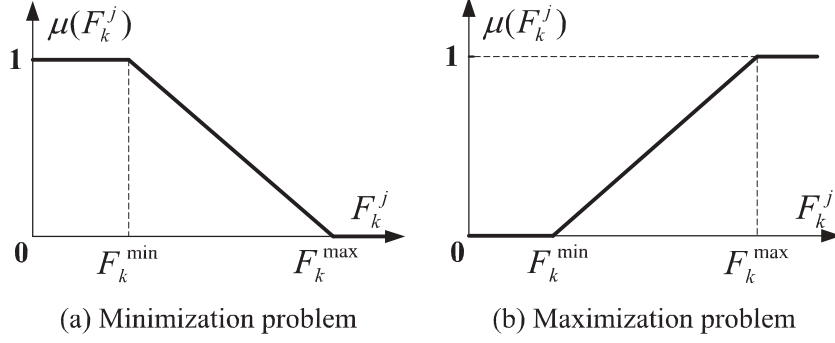


Figure 6. Membership functions.

$$\mu(F_k^j) = \begin{cases} 1, & F_k^j \geq F_k^{\max} \\ \frac{F_k^j - F_k^{\min}}{F_k^{\max} - F_k^{\min}}, & F_k^{\min} < F_k^j < F_k^{\max} \\ 0, & F_k^j \leq F_k^{\min} \end{cases} \quad (25)$$

Since the reliability index of particle j (F_r^j) contains six sub-indices $F_{r,c}^j$ ($c = 1, 2, \dots, 6$), the smallest value is chosen as the final evaluation value of $\mu(F_r^j)$, as shown in formula (26). Moreover, the minimum one among the six F' is also introduced to avoid extreme inequality among three indices, as given in formula (27).

$$\mu(F_r^j) = \min\{\mu(F_{r,1}^j), \mu(F_{r,2}^j), \dots, \mu(F_{r,6}^j)\} \quad (26)$$

$$F' = \min\{\mu(F_e^j), \mu(F_r^j), \mu(F_v^j)\} \quad (27)$$

The membership functions of three indices together with F' are added together to measure the fitness of particle j . Weighting factors λ_k ($k = 1, 2, 3$) are considered for the final evaluation of fitness value F^j .

$$F^j = \lambda_1 \cdot \mu(F_e^j) + \lambda_2 \cdot \mu(F_r^j) + \lambda_3 \cdot \mu(F_v^j) + F' \quad (28)$$

(2) Particle agent

Particle agent is only responsible for particle foraging behavior. It receives commands from central agent and sends orders to operation agent as the planning scheme ω . Particle agents share their position information with each other to avoid visiting the same position repeatedly; in addition, all particle agents receive global optimal position from the ‘white board’ system.

The main steps of foraging process are briefly described in Figure 7. Particle velocity $x_i^j(t)$ and particle position $\theta_i^j(t)$ at iteration t are adjusted as follows according to updating formulas in [22] ($i = 1, 2, \dots, 2N, j = 1, 2, \dots, S$),

$$x_i^j(t+1) = \Psi[x_i^j(t) + c_1 r_1 (y_i^j(t) - \theta_i^j(t)) + c_2 r_2 (y_{ig}(t) - \theta_i^j(t))] \quad (29)$$

$$\theta_i^j(t+1) = \theta_i^j(t) + x_i^j(t) \quad (30)$$

$$\Psi = \frac{2}{|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}|} \quad (31)$$

Where, $y_i^j(t)$ is the best position of each particle j ; $y_{ig}(t)$ is global optimal position; c_1 and c_2 are acceleration factors; r_1 and r_2 are uniformly distributed values at interval $[0,1]$; constriction factor Ψ is determined by φ in Equation (31).

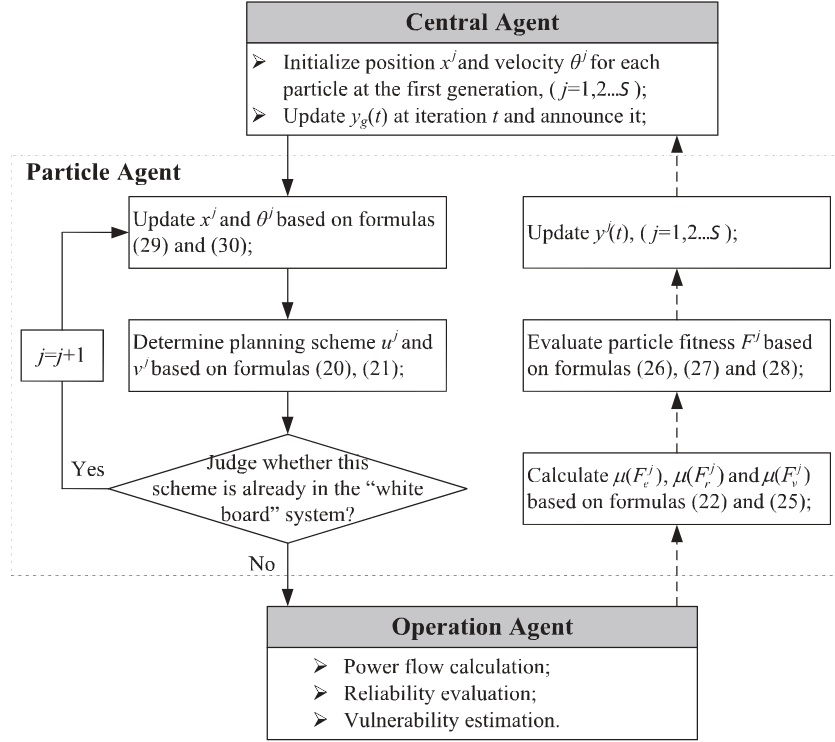


Figure 7. The flowchart of particle's foraging process.

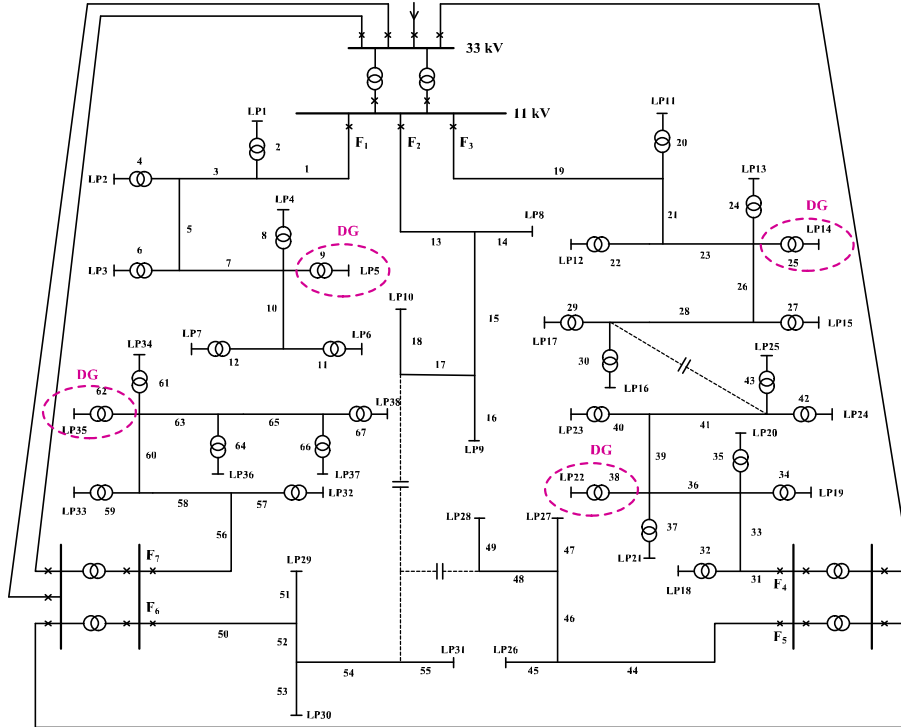


Figure 8. The IEEE RBTS Bus 4 system with DGs.

5. SIMULATION RESULTS

The proposed model has been applied to the IEEE-RBTS bus 4 test system, and all simulations are carried out in MATLAB[®] environment. This system comprises 67 nodes, 71 lines and 38 loads. Its line diagram is shown in Figure 8. Most parameters of this test system can be found in [23], or as given in Appendix (Tables A1–A4). Some are set specially for this study. Peak load value is used; power transfer on tie-line is limited to 2 MW; the rated power of DG is restricted to 1.5 MW, 2 MW, 2.5 MW or 3 MW; $Z_M^{\min}$ and $Z_M^{\max}$ are set to 4 and 6.

Parameters related to three objectives: γ is 6.8%; T_z is 10 yr; α is 1400 k¥/MW; β is 700 k¥; repair time is 5 h; switching time is 1 h; load transfer time is 2 h; n_{Ω} is set as 100; weighting factors λ_k ($k=1, 2, 3$) are 1/3.

For heuristic approach, the maximum generation is 50; population size S is 30; φ is 4.1; both c_1 and c_2 are set to 2.

5.1. Optimal scheme

The optimal scheme achieved is shown in Table I and Figure 8. Four DGs with total capacity of 9.5 MW are deployed in Figure 8. Their positions and scales are listed in Table I.

5.2. Convergence process

A heuristic approach is used to solve the optimization model, and its convergence process is shown in Figure 9. The optimal fitness values at each iteration t are compared with the average value of all particles. Moreover, it can be concluded that the optimal scheme is achieved after 30 iterations according to the convergence curve in Figure 9.

Since three aspects are included in the objective function, a compromise solution needs to be achieved. The trade-off process of objectives is shown by a three-dimensional figure in Figure 10. In addition, the convergence processes of sum value of two fitness values are also given in Figure 10 for comparison.

Table I. DG deployment.

No.	Position (u)	Scale (v)
1	LP5	3.0 MW
2	LP14	2.0 MW
3	LP22	2.5 MW
4	LP35	2.0 MW

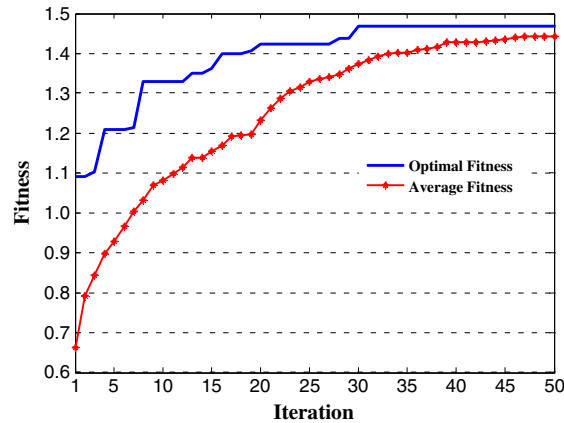


Figure 9. The convergence process of fitness functions.

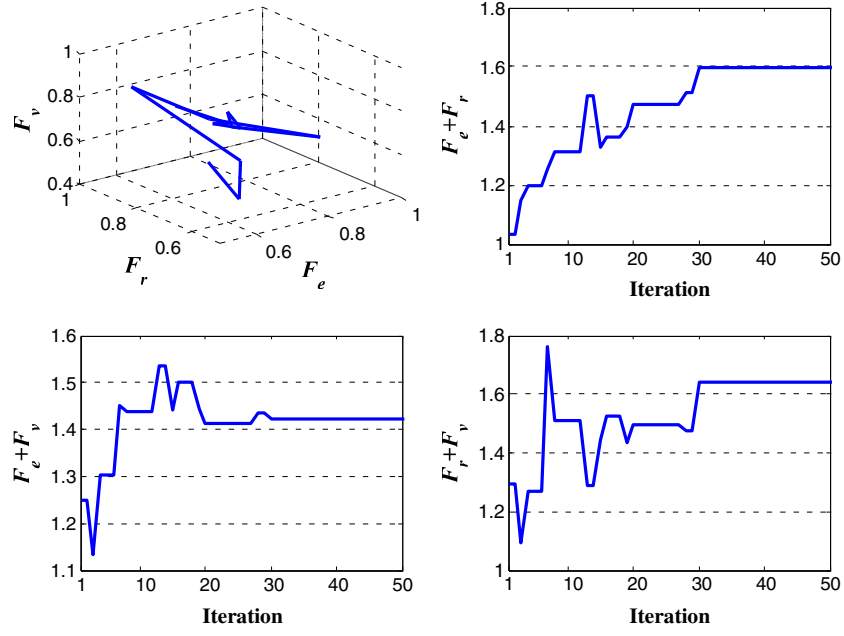


Figure 10. The trade-off process of three objectives.

Table II. Optimization results.

Objectives	F_k	$\mu(F_k)$
F_e	3761.6721 k¥ 0.2997 (int/cus-yr) 3.6835 (h/cus-yr)	0.6918
$F_{r,c}$ ($c = 1, 2, \dots, 6$)	12.2924 (h/int) 0.9996 97615.3 (kWh/yr) 20.4259 (kWh/cus-yr)	0.9075
F_v	2.4218 MW	0.7320

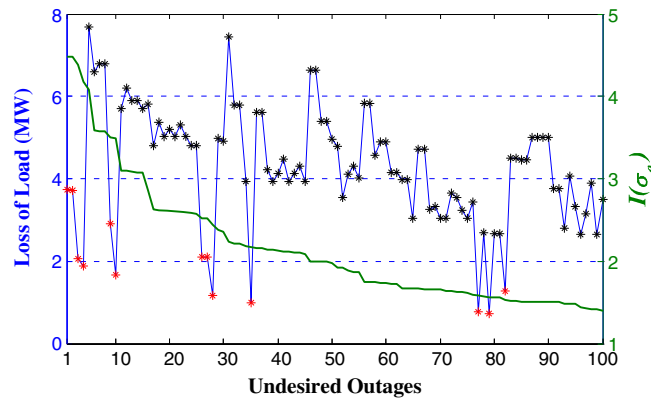


Figure 11. The comparison of scenario priority.

The fitness value of the optimal planning scheme is 1.4689. Three indices and their degrees of membership are given in Table II.

5.3. Vulnerability analysis

Scenario priority is analyzed in order to determine scenario set Ω , and following empirical formula is used to measure $I(\sigma_e)$.

$$I(\sigma_e) = \frac{\frac{L_{num}(\sigma_e)}{200} + \left(1 + \frac{L_{type}(\sigma_e)}{10}\right) \times P_{shed}(\sigma_e)}{2^{N_{attack}}} \quad (32)$$

This study only takes single and double undesired outages into consideration. The scenario set Ω including n_Ω single or double outages is shown in Figure 11, where DGs are deployed according to the optimal planning scheme. Red stars indicate single outages, and black ones are double outages. In addition, loss of load $P_{shed}(\sigma_e)$ and scenario priority $I(\sigma_e)$ ($e=1, 2, \dots, n_\Omega$) are compared in Figure 11. Five most serious single outages occur at 'No.50', 'No.13', 'No.31', 'No.56' and 'No.44' lines. The first five double outages are 'No.19 and No.31', 'No.1 and No.56', 'No.21 and No.31', 'No.19 and No.33' and 'No.3 and No.56'.

Undesired outages that happened in original network are also studied for comparison. Tie-line is the only power transfer source in original network, so even a single outage will cause a serious impact. The five most serious outages for original network occur at 'No. 31', 'No. 56', 'No.1', 'No.19' and 'No.33'.

In Figure 12, a comparison for loss of load under single outages is made between original network and the planning one. It can be concluded that DGs have a positive impact on vulnerability index improvement. In addition, there are not any DGs deployed at power service regions of feeder 'F2', 'F5' and 'F6' according to the optimal scheme. It is because each of them has two mutual stand-by power sources.

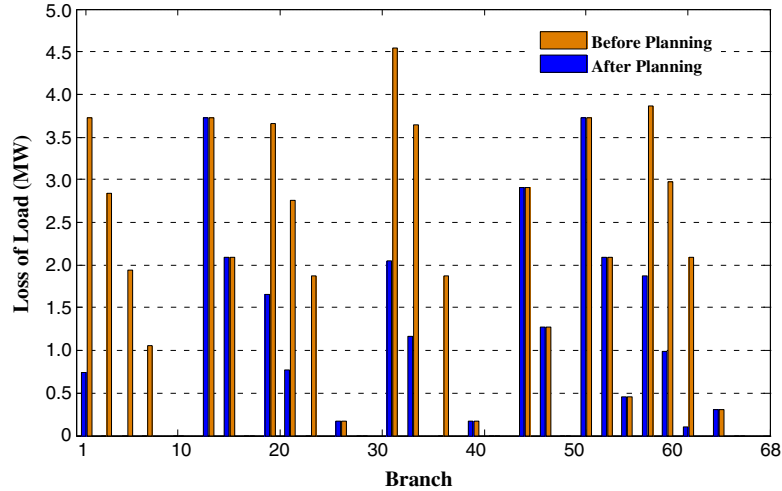


Figure 12. Loss of load under single undesired outages.

5.4. Reliability analysis

Three cases are designed to compare the influences of DG on reliability indices as following.

- Case 1: loss of load is recovered by DGs or tie-line;
- Case 2: it is set to an ideal case in which load can be transferred without any limitation;
- Case 3: load can be transferred by tie-line after outage occurrence.

Reliability indices of microgrid system in those three cases are given in Table III. Reliability indices in Case 2 are the upper limit value if system reliability improvement relies solely on DGs. This conclusion is extremely important in coordinating economic investment and reliability benefit during planning period.

Table III. System reliability indices.

Reliability indices	Case 1	Case 2	Case 3
SAIFI (int/cus-yr)	0.2997	0.2997	0.2997
SAIDI (h/cus-yr)	3.6835	3.4652	3.8801
CAIDI (h/int)	12.2924	11.5641	12.9486
ASAI	0.9996	0.9996	0.9996
ENS (MWh/yr)	97.6153	88.2686	101.4122
AENS (kWh/cus-yr)	20.4259	18.4701	21.2204

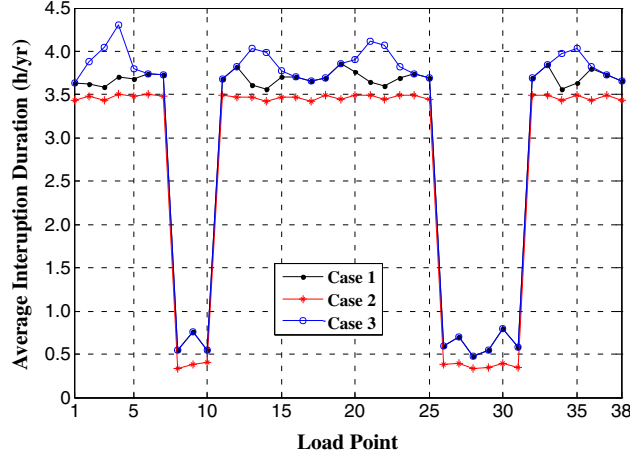


Figure 13. The average interruption durations of customers.

Average interruption durations of three cases are compared in Figure 13. Since no DGs are deployed on power service regions of feeder F2, F5 and F6, no load points in those regions can be benefit from the optimal scheme achieved.

6. CONCLUSIONS AND DISCUSSIONS

6.1. Conclusions

This paper proposes a planning approach for building resilient microgrids, by strategically deploying DG in a distribution system. Undesired outages and their influences in optimization process are analyzed. Scenario technology is used to handle those nonrandom uncertain events. However, only a preliminary research is reported on this research topic. Research is on-going to refine DG models and to take different operation modes of the microgrid into consideration.

6.2. Discussions

A microgrid is a distribution system with embedded generation and may operate in grid-connected or islanded mode. In [24], a microgrid is defined as follows. ‘Under this vision, integrated clusters of small (<200 kW) DERs provide firm power with a guaranteed level of power quality through operation in either grid-connected or island modes.’

In this work, we have assumed the microgrid to be operating in grid-connected mode. If we desired the same level of resilience (in terms of reliability, vulnerability and outage cost) in islanded mode, we could do one of two things:

- Apply the algorithm to the system with the grid supply removed. This would result in a prescription for microsources the total capacity of which would exceed the total system load.
- Except in military microgrids and other specialized applications, the solution in (a) may seem unreasonably expensive, and in such cases we can identify some critical loads in the system

and then apply the algorithm with the grid supply removed. This would result in a prescription for microsources the total capacity of which would exceed the total critical load. In such cases, all but the critical loads would need to be disconnected upon loss of grid supply, and the critical loads would be sustained with the level of resilience prescribed.

In either case, the algorithm itself would remain the same.

7. LIST OF SYMBOLS

Γ	The set of undesired outages
Λ	Node set
P_{shed}	Loss of load
Ω	Scenario set
N	Component number
σ_e	No. e scenario
$I(\sigma_e)$	Scenario priority
$L_{type}(\sigma_e)$	Customer type
$L_{num}(\sigma_e)$	Customer number
$N_{attack}(\sigma_e)$	Component number under attack
F_e	Economy index
F_r	Reliability index
F_v	Vulnerability index
ω	Planning scheme
u	The location of DG
v	The scale of DG
Λ_m	The set of nodes which are connected to node m
U_m	Voltage at node m
$P_{L,m}$	Active load demand at node m
$Q_{L,m}$	Reactive load demand at node m
G_{mn}	The resistance of branch mn
B_{mn}	The reactance of branch mn
$P_{M,m}$	Active power output of DG at point of common coupling (PCC)
$Q_{M,m}$	Reactive power output of DG at PCC
f_{mn}	Active power flow on branch mn
δ_{mn}	Phase angle difference on branch mn
z_M	The number of installed DG
γ	Interest rate
T_z	Average service life of DG
α, β	Parameters related to DG construction cost
p	Electricity price
P_{loss}	Power loss
$\lambda_1, \lambda_2, \lambda_3$	Weighting factors
$x(t)$	Particle velocity at iteration t
$\theta(t)$	Particle position at iteration t
$y^j(t)$	The best position of each particle j
$y_{ig}(t)$	The global optimal position
c_1, c_2	Acceleration factors
Ψ	Constriction factor

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APPENDIX

Table A1. Feeder types and lengths.

Feeder type	Length (km)	Feeder section numbers
1	0.60	2, 6, 10, 14, 17, 21, 25, 28, 30, 34, 38, 41, 43, 46, 49, 51, 55, 58, 61, 64, 67
2	0.75	1, 4, 7, 9, 12, 16, 19, 22, 24, 27, 29, 32, 35, 37, 40, 42, 45, 48, 50, 53, 56, 60, 63, 65
3	0.80	3, 5, 8, 11, 13, 15, 18, 20, 23, 26, 31, 33, 36, 39, 44, 47, 52, 54, 57, 59, 62, 66

Table A2. Customer data.

Load points	Customer type	Load level per load point (peak)/MW	Number of customers
1–4, 11–13, 18–21, 32–35	residential	0.8869	220
5, 14, 15, 22, 23, 36, 37	residential	0.8137	200
8, 10, 26–30	small user	1.63	1
9, 31	small user	2.445	1
6, 7, 16, 17, 24, 25, 38	commercial	0.6714	10
Total		40.00	4779

Table A3. Loading data.

Feeder number	Load points	Feeder load (peak)/MW	Number of customers
F1	1–7	5.704	1100
F2	8–10	5.705	3
F3	11–17	5.631	1080
F4	18–25	6.518	1300
F5	26–28	4.890	3
F6	29–31	5.705	3
F7	32–38	5.847	1290
Totals	—	40.00	4779

Table A4. Reliability data.

Component		λ_P	λ_A	λ_T	λ''	r	r_P	r''	r_C	s
transformers	138/33	0.0100	0.0100	0.050	0.5		15	168	0.083	1.0
	33/11	0.0150	0.0150	0.050	1.0		15	120	0.083	1.0
	11/0.415	0.0150	0.0150			200	10			1.0
breakers	138	0.0058	0.0035	0.050	0.2	8		108	0.083	1.0
	33	0.0020	0.0015	0.020	0.5	4		96	0.083	1.0
	11	0.0060	0.0040	0.060	1.0	4		72	0.083	1.0
busbars	33	0.0010	0.0010	0.010	0.5	2		8	0.083	1.0
	11	0.0010	0.0010	0.010	1.0	2		8	0.083	1.0
lines	33	0.0460	0.0460	0.060	0.5	8		8	0.083	2.0
	11	0.0650	0.0650			5				1.0

Where:

λ_P = permanent (total) failure rate (f/yr);

λ_A = active failure rate (f/yr) λ_T = temporary failure rate (f/yr)

λ'' = maintenance outage rate (out/yr)

r = repair time (h)

r_P = replacement time by a spare (h)

r'' = maintenance outage time (h)

r_C = reclosure time (h)

s = reclosure time (h)