Optimal Bi-level Planning of Autonomous MGs

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In recent years some researchers have focused on dividing of large distribution grids to autonomous Microgrids (MGs). The benefits of MGs consist of their ability to increase the reliability of distribution networks and reduce the power losses. The distribution resources within the MGs can balance the gap between limited generation capacity and actively growing demands. In this paper, we have proposed new dynamic boundaries for MGs to gain the flexibility in the grid. The proposed method is based on finding the optimal state of switches, sizing and siting of distributed energy resources (DES) in an MG-based distribution network. A bi-level optimization approach is used to solving the proposed problem. In the upper level of the optimization problem, the sizing and siting of DER is implemented and the system is updated to optimal switching in lower level. The stochastic model of wind, solar and load demand is represented. The 94 buses distribution network is modified to the MG-based distribution network for testing and validating the proposed model. The Particle swarm optimization (PSO) is applied to minimize the objective function of upper level and Genetic algorithm (GA) is used for minimization of lower level. According to the results, optimal planning of the autonomous MGs can improve the performance of distribution network operation.

Keywords: Autonomous MGs, Switching, Stochastic modelling, Reconfiguration, Planning, Uncertainty

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Nomenclature

b	Index of lines
mg	Index of MGs
F^{UL}	The total cost of Upper level
INV_{DG}^{n}	Investment cost of DG at Scenario n
$C_{CO_2}^{n}$	Co2 pollution cost at scenario n
CPL^{n}	Active power loss cost
ENS^{n}	Energy not supply cost
N	Number of scenario's
$P_{GEN}^{DG(c)}$	The active power generated c_{th} DG
$P_{GEN}^{DER(m)}$	The active power generated by m_{th} DER
$P_{GEN}^{ESS(w)}$	The active power of w_{th} energy storage
$C_{CO_2}^{ESS}$	The benefit of installation of energy storage device
C_{PLOSS}^{b}	The cost factor for active power losses
C_{ENS}^{l}	The cost factor of energy not supply
V	voltage of bus
$P_{sub_t,1}$	The active power Injected from upstream grid

P_{load}	The total active power of loads
F^{LL}	The total cost of lower level
CSW^{n}	The total cost of Switching
$ENS_{LL}^{(n)}$	The total cost of energy not supply at lower level
$C_{SW(S)}^{n}$	Cost of switching at S_{th} switch
SW_{s}^{n}	The binary variable shows the state of switches
$SWE_{MG_{mq}}$	State of switch at MG_{th} microgrid
R_{n}	The resistance of line
P	Active power
Q	Reactive power

1. Introduction

Micro-grids (MGs) can increase the electrical grids reliability; decrease the cost of energy and pollutant gases. The future threats of grids like cyber-physical attacks, threaten the network at any moment. This threats and economic benefits, getting conventional networks toward splitting to small MGs. MGs must be able to work at islanded and grid-connected mode. In the grid-connected mode, the upstream grid controls the voltage and frequency of MGs, whereas in the islanded mode the autonomous MGs control the voltage and frequency

by hierarchical control levels. The autonomous MGs are separated from the main network by switches located at the point of common coupling (PCC). DERs & DG, located at these autonomous MGs provide the load demand. The proximity of power supply sources to loads reduce the power losses and costs. The dynamic boundaries of the MGs increase the flexibility.

In the previous researches, the boundary of MGs considered constant. In [1-2] stochastic model of DERs, loads and optimal size and site of them is represent. Reference [3] presents an optimal planning of autonomous MGs, considering the active and reactive power losses. The authors in [4] study on DGs, reactive sources and energy storage units which are used for optimizing the MGs and increase the reliability. Reference [5] presents the energy management of a single household, which acts as a consumer and producer of electrical energy. In [6] a dynamic method for feeder reconfiguration and capacitor switching is represented. The probabilistic characteristics of distributed generation (DG) units are also considered by defining two new probabilistic indices representing real and reactive power of the lines. Next, the advantages of installing both distributed energy storage resources (DESRs) and distributed reactive sources (DRSs) are investigated in reference [7] to improve the self-adequacy of the constructed micro-grids. In [8] allocation of energy storage and wind turbine with fuzzy modelling is represent. Reference [9] has studied DG sizing and siting in radial distribution systems, the Exchange market algorithm (EMA) is used for reduce the active power losses. In [10] reconfigurable smart microgrids (RSMGs) as a new generation of MGs is discussed, and the daily risk-based optimal scheduling of RSMG is represented to maximize the profit of MG operator. Reference [11] proposes the hybrid energy storage to improve the power quality in MGs. In [12] assumed that MGs are cyber-physical energy systems with the objective function of operation cost.

In this paper, a comprehensive method is presented for breaking the networked MGs, and investigating their performance. For this purpose, initially, a sample system is built up by optimal sizing and siting of different kinds of DG units in a distribution system. Types of DGs are assumed to be key types of DG units such as wind turbines, PV modules and Wind generators. For each MG a dispatchable generator is considered. This dispatchable generator can help MGs central control, to create a balance between the generation and demand of loads, control the voltage inside each MG.

After optimal allocation of DGs, in the upper level, different scenarios have been followed to build the MG. Each MG is capable of providing its power in an islanded mode. If a fault accrues in the upstream grid, the MGs can change states to islanded mode and reduce the casualties. In lower level by splitting the bulky grid to MGs, and use the DESs inside the MGs the power losses and energy not supplied (ENS) is reduce. The MGs optimal states are very important, the non-optimal states of MGs can increase the losses, ENS and air pollution. In [10] the boundaries of MGs are fixed and inside each MG, some lines are reconfigured to maximize the operator profits. But in proposed method of this paper the networked MGs changes mode to achieve the optimal status. In the other word, splitting the bulky grid to small MGs can protect load and equipment in times of trouble. At any time, depending on the system conditions the states of MGs can change to optimal state to satisfy objective function.

2. MGs reconfiguration

When an MG encounters with a high market price, or a fault or an attack in the upper level, it disconnected from the grid and works in islanding mode. Because of uncertainties in power generation and load-generation mismatch, the successful operation of a single MG is more challenging. Flexible service and planning of MGs

communities with the optimal reconfiguration of MGs clusters can increase the chance of successful operation of MGs. With the optimal reconfiguration of the MGs, the boundaries of MGs can be changed with state of switches between MGs. In case of MG reconfiguration, the permanent predefined MGs with given electrical and geographical boundaries can be merged or separated from the others temporally, to reach the optimal operation cost. In this situation, the scale of MGs varies with the combine of neighbored MGs; a displaceable DER can regulate voltage and frequency of combined MGs.

2.1. Requirements for autonomy

Distribution systems are usually configured because of the peak load on the substation, feeders and the other reasons; the overload of the feeder can occur at a different time of day. The switches of MGs in overload condition able to isolate the customers of MGs. The autonomous MGs increase the reliability and power quality of power systems [14]. When the upstream system encountered with a disturbance, MGs are isolated from the grid. MGs must have some communication links to coordinate the DERs and demand of customers. The MGs central control (MGCC) and two-way communication with the customer and smart meters are needed, and for the flexibility of MGs communication with neighbors self-adequate MGs must be connected. The hierarchical control of MG includes [15-20]:

• Primary control maintains voltage and frequency stability of MG following the islanded mode

• Secondary control makes up the voltage and frequency deflection caused by operation of the primary control

• Tertiary control manages the power flow between the MG and the main grid and simplifies the economical operation of the system

It has three fundamental underlying assumptions, which are listed as follows.

(1) The switches sites are specified by investor and customer economic benefits and topology of the system

(2) In the reconfiguration of networked MGs, the constraints of voltage and load demand should be considered

(3) At first, all MGs are connected, and they can exchange the active and reactive power

Figure 1 shows the topology of the networked MGs two-way exchange of energy and data between four MGs. Each MG has own MGCC and exchanges data and power among upstream grid and other MGs with Distribution Network Operator (DNO) management. During the day, MGs by isolation switches can be isolated from the upstream grid. MGCC can control the DERs and loads, for example, if in MG number 2 in Fig. 2 for some reasons demand of customers exceed the allowed amount the MGCC can feel this disturbance and DNO by new condition reconfigure the MGs to get new optimal conditions.
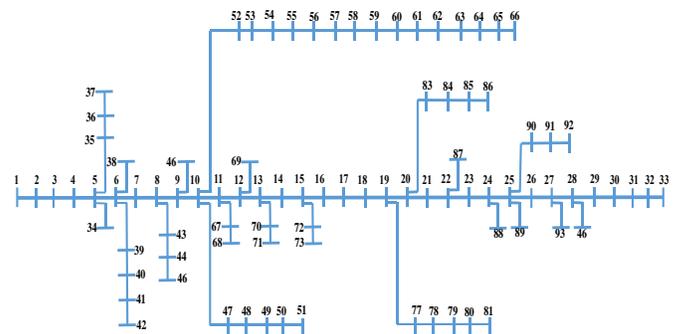

Fig. 1. The 94-bus distribution network of Portugal [13]

2.2. Planning of autonomous MGs

It is clear that transformation of an existing radial distribution system into supportable autonomous MGs requires DERs to be confederate into the networked DGs to integrate with the network. Optimal sizing and siting of these DERs are essential for autonomous MGs. Hence, the heuristic methodology is needed for optimal sizing and siting of DERs and reconfiguring the network.
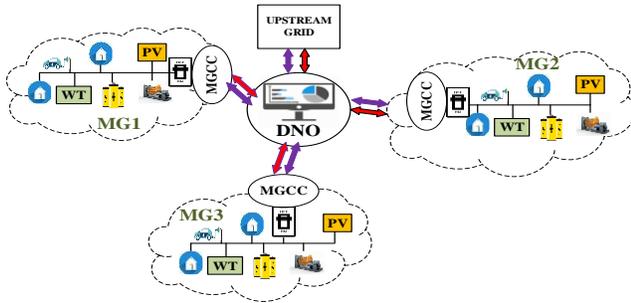

Fig. 2. Networked-MGs and two-way exchange of energy and data

3. Stochastic modelling of DERs and load

In this section, stochastic modelling of the output power of DERs and loads is discussed, based on historical data. These steps are listed below.

3.1. Wind

The generation of wind turbine (WT) depends on wind speed and wind direction. The behaviour of wind speed is given by Weibull probabilistic distribution function (PDF) below [21]:

$$PDF(v) = \begin{cases} \dfrac{\beta}{\alpha} \times (\dfrac{v}{\beta})^{\rho-1} \times e^{(\frac{v}{\beta})^{\beta}} & v \geq 0 \\ 0 & otherwise \end{cases} \quad (1)$$

where α, β are parameters of Weibull function. The power generation of WT is given below [8]:

$$P(v) = \begin{cases} 0 & 0 \leq v \leq v_{ci} \\ P_{rated} \times \dfrac{v - v_{ci}}{v_r - v_{ci}} & v_{ci} \leq v \leq v_r \\ P_{rated} & v_r \leq v \leq v_{co} \\ 0 & v_{co} \leq v \end{cases} \quad (2)$$

Where, v is the wind speed; v_r is the cut-in speed of the wind turbine, V_{co} is cut-out speed. P is the power generation of wind DG. P_{rated} is the rated power generation of wind DG. We have 744 samples that are sampled every 10 minutes. These samples are used to generate the PDF of output power of Wind DGs. The samples for wind speed are illustrated in Fig. 3 and the wind speed probability, which used in this paper given by Fig. 4.
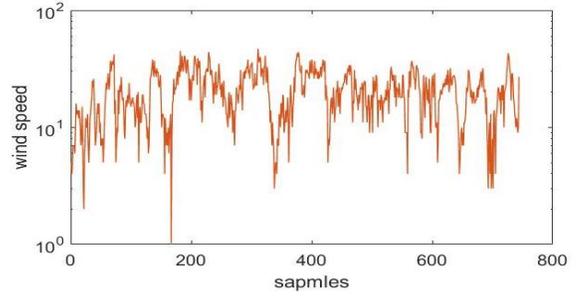

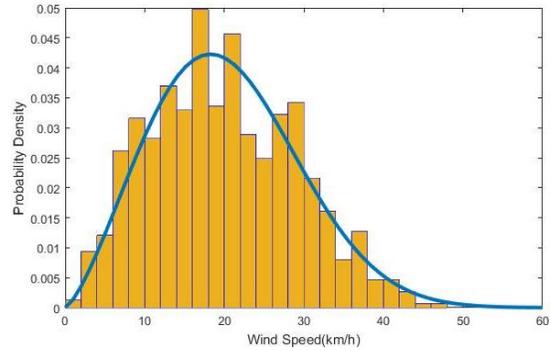**Fig. 3.** Samples of wind speed (km/h).

Fig. 4. Wind speed probability

3.2. Solar DG

The behaviour of Solar DGs generation follows the vehemence of sunlight and the direction of the sun's rays. Irradiance and air temperature are modeled by normal distribution function. The power generation of solar DGs modeled by [22]:

$$T_{cell} = T_{amb} + \frac{NOTC - 20}{0.8} S \quad (3)$$

Where T_{cell} is cell temperature (°C), T_{amb} the ambient temperature, (NOCT) is the nominal operating cell temperature and S is the solar insolation (kW/m2).

$$\begin{cases} I = s[I_{sc} + K_i (T_{cell} - 25)] \\ V = V_{OC} - k_v \times T_{cell} \end{cases} \quad (4)$$

Where K_i, K_v are the current and voltage coefficients; V_{OC}, I_{SC} are the open circuit voltage and short circuit current, respectively. In the equation (5), P is the output power of solar DG, N is the number of solar cells and V_{MPP}, I_{MPP} are respectively, the voltage and current of maximum power point tracking. In Fig. 5, the solar irradiation used in this paper is shown.

$$\begin{cases} P(s) = N \times FF \times V \times I \\ FF = \dfrac{V_{MPP} - I_{MPP}}{V_{OC} \times I_{SC}} \end{cases} \quad (5)$$
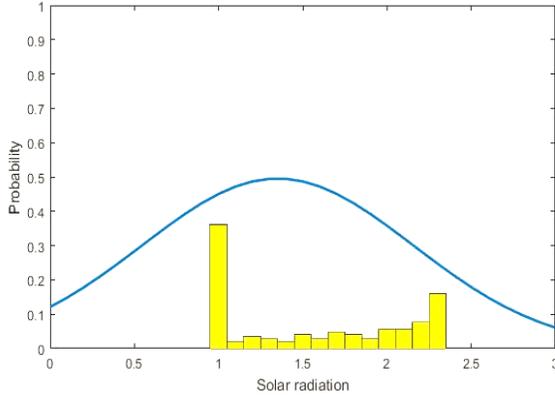
Fig. 5. Solar radiation probability

3.3. Fuel cell

Fuel cell generate the constant output power. In case of fuel supply, it can provide fixed power over the day.

3.4. Load uncertainty

Load demand is variable in the hours of the day. The probabilistic behavior of autonomous MGs load is represented by Weibull PDF function. The samples of historical data are used to generate PDF. The load expenditure P(L) is define by mean value (μ) and the standard deviation (σ) as [21]:

$$
\begin{cases}
P(s) = N \times FF \times V \times I \\
FF = \dfrac{V_{MPP} - I_{MPP}}{V_{OC} \times I_{SC}}
\end{cases}
\tag{6}
$$

4. Scenario generation and reduction

The scenario is the sequential events that repetition in the period. The scenarios model the solar DG's behavior, autonomous MGs load and wind turbine. The sum of probabilities of all scenarios must be equal 1. Equations (7, 8, 9) represent combination of states to build the total possible scenarios. In addition, equation (10) shows that the total probability of all scenarios should be equal to 1.

$$
\lambda_{pl} = (\chi_{pl}^{1}, \chi_{pl}^{2}, \chi_{pl}^{3}, ..., \chi_{pl}^{n}) \in \sum_{1}^{n} \chi_{pl}^{n} = 1
\tag{7}
$$

$$
\lambda_{pw} = (\chi_{pw}^{1}, \chi_{pw}^{2}, \chi_{pw}^{3}, ..., \chi_{pw}^{n}) \in \sum_{1}^{n} \chi_{pw}^{n} = 1
\tag{8}
$$

$$
\lambda_{ps} = (\chi_{ps}^{1}, \chi_{ps}^{2}, \chi_{ps}^{3}, ..., \chi_{ps}^{n}) \in \sum_{1}^{n} \chi_{ps}^{n} = 1
\tag{9}
$$

$$
\lambda_{pl} \times \lambda_{pw} \times \lambda_{ps} = 1
\tag{10}
$$

4.1. Backward reduction algorithm

The scenario-based optimization model needs to generate scenario from samples. Some scenarios are repetitive and invalid so that we can reduce the generated scenarios. In this paper, the backward reduction algorithm is used for this purpose, which acts as follows:

The Kantorovich distance Matrix (KDM) between all pair of

scenarios is computed. The distance between scenarios S, S^{*} is defined as equation (11):

$$
DT(S, S^{*}) = \sqrt{\sum_{i=1}^{nv} (\zeta_{i}^{s} - \zeta_{j}^{s^{*}})^{2}}
\tag{11}
$$

Where nv is the number of stages, $\zeta^{s^{*}}$ is the vector value of the scenario at stage s. Moreover, i and j are the assigned scenario numbers, e.g., 1, 2, 3, n.

(1) For each scenario s, locate the other nearest scenarios i, i.e. scenario S^{*}.

(2) For each pair of scenarios in step 2 Compute min $\{KD(S,S^{*})\} \times p(S)\}$ .where the $p(s)$ is the probability of assessed scenario.

(3) Construct the new KDM after one scenario is eliminated. Add the likelihood of the eliminated scenario to the probability of the scenario, which is closest to it.

(4) Repeat step 2-4 to eliminate one scenario during each iteration until the stopping criterion has been met.

5. Problem formulation

The problem optimization consists of two-stage, in the upper level the sizing and siting of DERs are done. In this level, the PSO-GA algorithm is used for optimization. The lower level reconfigurate the autonomous MGs to get the best site and size of DERs and state of switches. The flowchart of the proposed bi-level approach for solving the problem is represented in Fig .6.

5.1. Upper-level formulation

In the upper level, the investment cost of DERs, the benefit of co_2 gas reduction, active power losses and the energy not supplied cost (ENS) are considered. Constrains (15, 16) shows the power flow in the distribution grid without MGs. Constraint (17) denotes the boundaries of active and reactive power.

$$
F^{UL} = INV_{DG}^{senario(n)} + C_{co_2}^{senario(n)} + CPL^{senario(n)} + ENS^{senario(n)}
\tag{12}
$$

$$
\begin{aligned}
F^{UP} = \sum_{n}^{N} (\sum_{c=1}^{C} C_{GEN}^{DG(c)} \times P_{GEN}^{DG(c)} + \sum_{m=1}^{M} C_{INV}^{DER(m)} \times P_{GEN}^{DER(m)}) \\
+ \sum_{w}^{W} C_{INV}^{ESS(w)} \times P_{GEN}^{ESS(w)} + \sum_{t=1}^{T} (\sum_{c}^{C} C_{OMC}^{DG(c)} \times P_{GEN}^{DG(c)}) \\
+ \sum_{m=1}^{M} C_{OMC}^{DER(m)} \times P_{GEN}^{DER(m)} + \sum_{w}^{W} C_{OMC}^{ESS(w)} \times P_{GEN}^{ESS(w)} + \sum_{m=1}^{M} C_{CO_2}^{DER} \times P_{GEN}^{DER} \\
+ \sum_{w}^{W} C_{CO_2}^{ESS} \times P_{GEN}^{ESS} + \sum_{b}^{B} C_{Ploss}^{b} \times P_{loss}^{b} + \sum_{l}^{L} C_{ENS}^{l})
\end{aligned}
\tag{13}
$$

$$
v_{min} = 0.95 \leq v \leq v_{max} = 1.05
\tag{14}
$$

$$
P_{sub_{t,1}} + \sum_{c=1}^{C} P_{DG}^{c} + \sum_{m=1}^{M} P_{DER}^{m} + \sum_{w=1}^{W} P_{ESS}^{w} - \sum_{b=1}^{B} P_{load}^{b} =
$$
$$
\sum_{i=1}^{B} \sum_{j=1}^{B} v_i \times v_j \times y_{ij} \times \cos(\theta_{ij} + \delta_j - \delta_i)
\tag{15}
$$

$$Q_{sub_{t,1}} + \sum_{c=1}^{C} Q_{DG}^{c} + \sum_{m=1}^{M} Q_{DER}^{m} + \sum_{w=1}^{W} Q_{ESS}^{w} - \sum_{b=1}^{B} Q_{load}^{b} =$$

$$\sum_{i=1}^{B} \sum_{j=1}^{B} v_i \times v_j \times y_{ij} \times \sin(\theta_{ij} + \delta_i - \delta_j) \qquad \textbf{(16)}$$

$$P_{sub_{t,1}} \le P_{rated}$$

$$Q_{DG,DER,ESS} \le Q_{max} \qquad \textbf{(17)}$$

5.2. Lower level formulation

In the lower level, the status of the switches that are located at PCC of MGs is determined. This level specifies that which MGs works in isolated or grid-connected mode. The objective function of the lower level (18, 19) includes the switching and ENS cost. Constraint (20) denotes the state of switches. This state is expressed as binary variable, 0 means that the SWE is close and 1 denotes that the SWE is off. Constrains (21, 22) show the power flow in the distribution grid In the presence of the MGs. Constraints (23, 24) denote the bounds of active and reactive power in networked MGs. The lower level formulation is as follows:

$$F^{LL} = CSW^{senario(n)} + ENS_{LL}^{senario(n)} \qquad \textbf{(18)}$$

$$F^{LL} = \sum_{n=1}^{N} \sum_{s=1}^{S} C_{SW(s)}^{n} \times SW_{s}^{n} + \sum_{t=1}^{T} \sum_{l=1}^{L} C_{ENS(l)}^{n} \qquad \textbf{(19)}$$

Subject to:

$$SWE \in A\{0,1\}$$

$$A \in \begin{Bmatrix} ST_{SW1}, ST_{SW2}, ST_{SW3}, ST_{SW4} \\ , ST_{SW5}, ST_{SW6}, ST_{SW7}, ST_{SW8}, ST_{SW9} \end{Bmatrix} \qquad \textbf{(20)}$$

$$P_{sub_{t,1}} \le P_{rated} \qquad \textbf{(21)}$$

$$Q_{DG,DER,ESS} \le Q_{max}$$

$$\sum_{mg}^{MG} P_{DG}^{mg} - P_{DER}^{mg} \pm P_{DER}^{mg} - P_{loss}^{mg} = 0 \qquad \textbf{(22)}$$

$$P_{loss} = \sum_{b}^{B} R_n \left(\frac{P_n^2 + Q_n^2}{V_n} \right) \qquad \textbf{(23)}$$

6. Simulation results and discussion

In this section, the probabilistic distribution function of solar DGs, wind turbine and load of autonomous MGs are shown in Fig. 4 and Fig. 5. In Fig. 3, the 744 samples selected every 10 minutes, are used for generating solar and wind output power PDF. In this paper, the 94-bus system is used. Fig .6 shows the flowchart of problem optimization, in the upper level the site and size of DERs is optimally determined by PSO (Particle Swarm algorithm), and the result of upper level is saved. The boundaries of MGs aren't specific. MGs are designed to allow a power connection to be connected to the network between each MG. In other words, the islanding of a MG does not prevent the ability to access another MG (Fig. 7). DGs selected randomly in each bus without considering the boundaries of MGs. Figure 8 shows the optimal site of DER, ESS and DG in

MGs and the state of microgrids. Then system update by the result of upper level. Binary GA is used for optimization in lower level. The optimal state of MGs is specified by the SWEs mode (Autonomous MGs or Grid connected).
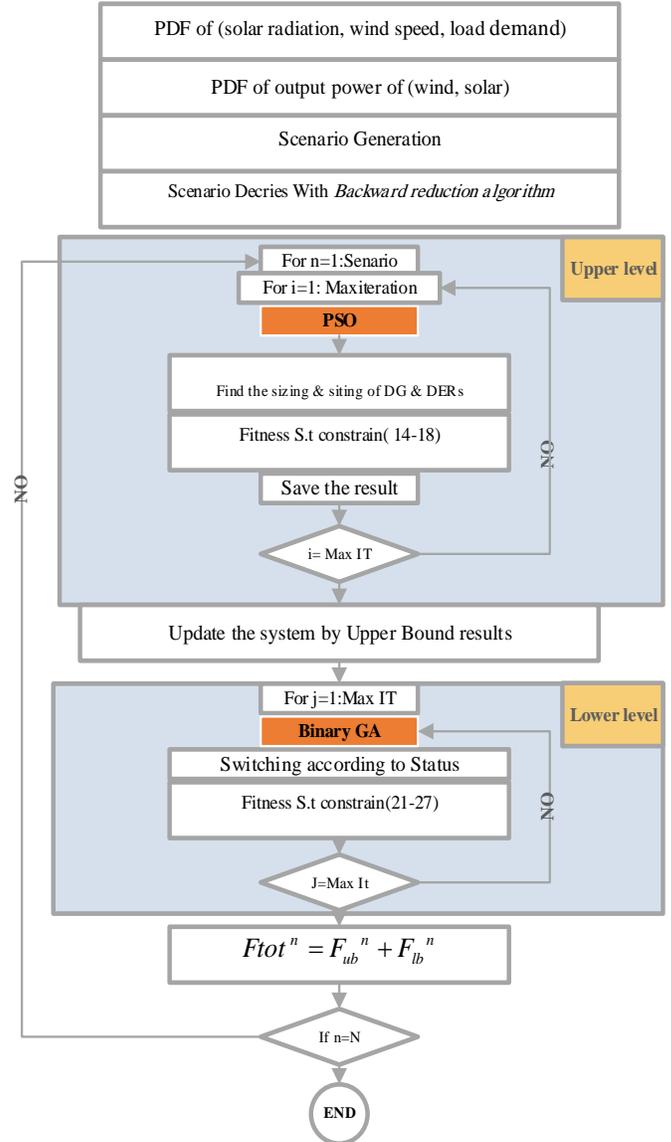

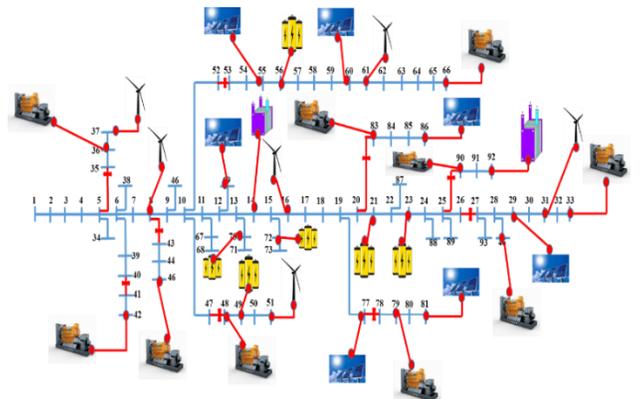**Fig. 6.** Flowchart of the proposed bi-level approach to solving the problem.
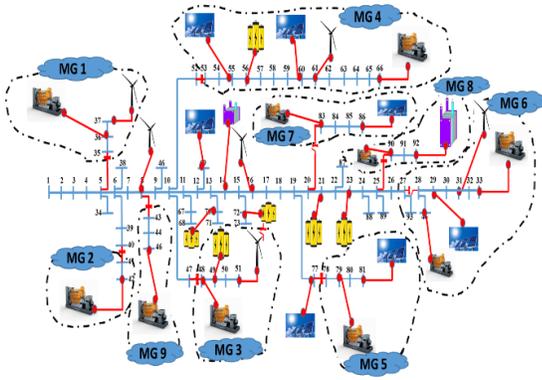

Fig .7 Optimal site of DER, ESS and DGs.

Fig. 8. Optimal site of DER, ESS and DGs in MGs and the State of MGs

6.1. Case study

In this paper, the 94-bus distribution system (Fig. 1) has been used to illustrate proposed bi-level optimization. In this case study, for calculating the reliability indicate, the failure rate is 0.13 f/km/year and the repair time is 10 hours. The average cost of the failed load is considered 26$/kW for 10 hours [3]. The summary of the values of parameters is given in Table 1.

Table 1. Technical characteristics

Parameter	Unit	Value
C_{inv}^{DG}	$/kW	132
C_{inv}^{DER}	$/kW	70.5
C_{INV}^{ESS}	$/kW	125
C_{OMC}^{DG}	$/kWh	0.020
C_{OMC}^{DER}	$/kWh	0.021
C_{OMC}^{ESS}	$/kWh	0.0195
$C_{CO_2}^{DER}$	US$/ton	1400
$C_{CO_2}^{ESS}$	US$/ton	1360
C_{Ploss}^{b}	$/kW	0.360
C_{SW}	$	223.48

6.3. Sizing and siting of DERs and optimal states of SWs

Table IV shows the optimal size and site of DERs &DGs, in the autonomous MGs. The Diesel generator needs to control the voltage and frequency of MG. Figure 6 shows the flowchart of problem optimization, in the upper level the site and size of DERs is optimally determined by PSO (Particle Swarm algorithm), and the result of upper level is saved. Then system update by the result of upper level. Binary GA is used for optimization in lower level. The optimal state of SWs is specified by the mode (Autonomous MGs or Grid connected) of MGs. Voltage in the optimal state of SWs is close to 1 pu. The optimal state of breakers is shown in Fig. 9.

6.2. Comparison of voltage deviation & power losses

Table 2 shows the reactive and active power losses in the three cases. The power losses with proposed bi-level optimization

reduced by 80%. The voltage deviation in the case 2 is at the allowed limit. Figure 10 shows that after optimizing with the proposed bi-level model, the voltage range is between 0.95 and 1.05 and the power losses of this system get better.

Table 2. Power losses

Cases	Real power losses(kW)	Reactive power losses (kVAR)
Before DG & DERs placement	234	221
Optimal state of MGs	180.66	179.8
All of MGs is islanded	375.5	347

Fig. 9. The State of breakers for three scenarios

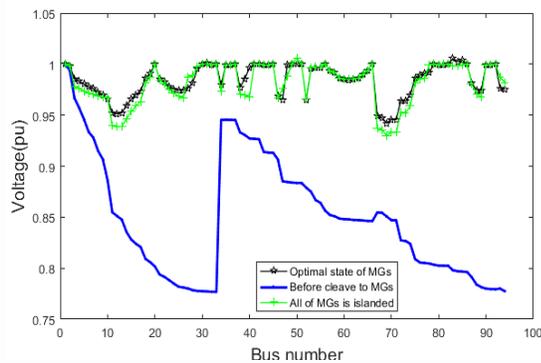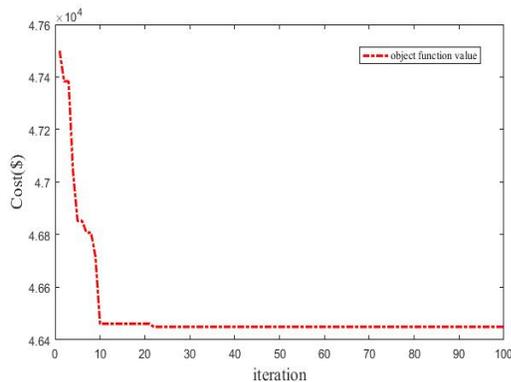### 6.4. Bi-level optimization results

In this paper, 744 scenarios are generated and they are reduced to 24 scenarios. The results of optimization are represented in Table 3. Fig. 11 shows the coverage of PSO-GA algorithm.

Table 3. Cost components

	Scenario 1	Scenario2	Scenario 3
INV (investment cost DG)	147830$	149500$	148000 $
COMC (operation cost)	33412 $	35164$	32240 $
Benefit of reduction (CO_2) C_{CO_2}	139860 $	121053 $	146500 $
Power loss cost (CPL)	9820 $	9986 $	8450 $
ENS cost	1026 $	1670 $	984 $
Switching cost (CSW)	-	4895$	3258 $
Total cost	52228$	80162$	46432$

Table IV. Technical characteristics (scenario 3 optimal states of Mgs)

	Site	Size(kw)
W T	37,31,61,16,8	200,200,200,400,100
PV	55,60,86,81,29,69,77	400,200,200,200,400,800,200
FC	92,14	200,100
DG	36,42,46,48,66,83,90,79,33	400,400,600,400,600,400,600,400,600
ES S	56,49,23,21,70,72	200,200,100,100,100,100

Fig. 10. Voltage profile of system in the three scenarios

Fig. 11. Convergence of the PSO-GA.

7. Conclusion

This paper proposed a bi-level optimization problem for splitting the distribution grids into some small autonomous MGs. The stochastic model of DERs and loads are used for scenario generation. Generated scenarios are reduced to 24 scenarios with backward reduction algorithm. In the upper level, the sizing and siting of DERs are optimized and in the lower level the optimal reconfiguration of MGs is determined to achieve minimum operation cost of the network. The autonomous MGs in optimal ordering, increase the power quality and customer satisfaction. While the proposed configuration can work in autonomous MGs and island operation, its capability with respect to conventional distribution network is more effective. The state of SWs between MGs and the main distribution network can be changed hourly if the PCC is encountered with intentional attack or fault.

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