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A New Model for a Resilient Distribution System After Natural Disasters Using Microgrid Formation and Considering ICE Cars

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ABSTRACT The severe impact of natural disasters on distribution system (DS) infrastructure highlights the importance of enhancing the resiliency of such systems. The loss of critical loads, one of the worst results of these events, increases the significance of resilient restoration approaches. In addition to distributed generators (DGs), which are common resources in restoration schemes, internal combustion engines (ICE) cars can considerably affect DS resiliency. This article first introduces an idea for using ICE vehicle as energy resources in a DS to enhance the system's flexibility during restoration efforts after natural disasters. The amount of electrical consumption of modern cars and the availability of home inverters makes this idea practical. In addition, a novel comprehensive method is proposed based on the optimal formation of dynamic microgrids (MGs) that satisfies operational constraints and considers the ICE vehicles and is not based on path-based or children-parent nodes concepts. Moreover, the proposed method considers the integration of DGs in one microgrid. The proposed method is based on two-stage stochastic mixed-integer linear programming (MILP), and considers uncertain load consumption and demand response (DR). Finally, the effectiveness of the proposed method is evaluated using a modified 33-bus IEEE test system. The results show that integration of DGs leads to restoring more loads. Moreover, distribution and selection of the buses corresponding to ICE cars affect directly on the amount of restored load. Budget limitation is also considered in this article. Evaluation of the proposed method shows the considerable effectiveness in increasing the resiliency of DS.

INDEX TERMS Internal combustion engine (ICE) cars, MG formation, resiliency.

NOMENCLATURE

Indices and sets

$N_{bus,}\ N_{master}$	Set of DS buses, indexed by i,r
T	Set of time indexed by t
L	Set of lines indexed by l
N_{master}	Set of master units
M	Set of MGs indexed by m
W	Set of scenario indexed by w
$\partial_l,\ \chi_l$	Sets of start and end points of lines
$sl(l)$	Set of tie-switches
ICE	Set of ICE cars indexed by ice
D	Set of load control blocks
N_{DR}	Set of buses with load control capability

Parameters

C_l	Load priority
π_w	Probability of scenario w
T_{start}, T_{End}	Start and end time of outage
F_1, F_2	Electrical parameters
$Line_l^{initial}, Bus_i^{initial}$	Initial status of lines and buses
$BTL_{l,i,r}$	binary parameters, 1 if there is a line between bus i and r, 0 otherwise
$P_i^{predicted}, Q_i^{predicted}$	Predicted active and reactive load
$P_i^{DR,\max}, P_i^{DG,\max}$ $Q_i^{DG,\max}, Q_i^{DG,\min}$	Max/Min active/reactive power of DG
$P_{i,d,t}^{block}$	Load control blocks
$F_l^{line,P\max}, F_l^{line,Q\max}$	Maximum limits of active and reactive power flow

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$P_{ice}^{\max -ICE}$	Maximum limits of discharge
$Fuel_{ice}^{initial-tank,ICE}$	Initial fuel tank amount of ICE
$Fuel_{ice}^{minimal-tank,ICE}$	Minimum fuel tank amount of ICE
$\eta_{electrical}^{ICE}, \eta_{thermal}^{ICE}$	Electrical and thermal efficiency
$eps, bigM$	Epsilon and big number

Variables

$a_{i,m}$	The binary variable, 1 if bus i is in MG m, 0 otherwise
b_m	The binary variable, 1 if bus m is selected, 0 otherwise
$\ell_{i,d,t}^{sch}, \ell_{i,d,t,w}^{dep}$	The binary variable indicating the selection of load control block
$P_{i,m,t}^{L,sch}, P_{i,m,t,w}^{L,dep}, Q_{i,m,t,w}^{L,dep}$	Scheduled and deployed active and reactive power of loads
$P_{i,m,t}^{DR,sch}, P_{i,m,t,w}^{DR,dep}$	Scheduled and deployed load consumption
$P_{i,m,t}^{DG,sch}, P_{i,m,t,w}^{DG,dep}, Q_{i,m,t,w}^{DG,dep}$	Scheduled and deployed active/reactive power generation of DGs
$\Delta P_{i,m,t,w}^{LC}$	Difference in scheduled and deployed load control
$Line_l$	The binary variable, 1 if line l is energized, otherwise 0
$\beta_{l.m}$	The binary variable, 1 if line l is energized in MG m, otherwise 0
$F_{i,r,m,l}$	Fictitious power flow
$w_{r,m}$	Main bus generation of root bus r in MG m in radiality constraint
$A_{i,r}$	Binary variable, 1 if there is power flow between i and r
$F_{i,m,t,w}^{line,P}, F_{i,m,t,w}^{line,Q}$	Active and reactive flow
V, δ	Voltage and angle of bus
I_{ice}^{ICE}	The binary variable indicating whether the ICE is generating energy
$ICE_{ice,m}^{aux}$	Binary variable, 1 if ICE *ice* is in MG *m,* 0 otherwise
$Fuel_{ice,m,t}^{tank,sch}, Fuel_{ice,m,t,w}^{tank,dep}$	Scheduled and deployed fuel tank amount of ICE cars
$P_{ice,m,t}^{ICE,sch}, P_{ice,m,t,w}^{ICE,dep}, Q_{ice,m,t,w}^{ICE,dep}$	Scheduled and deployed active/reactive power generation of ICE cars
$Fuel_{ice,m,t}^{usage,sch}, Fuel_{ice,m,t,w}^{usage,dep}$	Scheduled and deployed fuel consumption of ICE cars

I. INTRODUCTION

Inevitable disasters have become more frequent and intense because of recent climate changes. This phenomenon leads to a considerable growth in the frequency and severity of power outages. Recent power outage experiences in the world, such as that during Hurricane Sandy, which affected 7.5 million customers across Washington and 15 other states [1]–[3], has motivated the introduction of a critical concept, called resiliency, to complement other power system topics such as reliability, risk, security, and stability in studying high-impact low-probability (HILP) incidents [4].

Severe weather is the major cause of power outage. According to [5], 87% of power outage cases in the United States are short-term and a consequence of weather disasters, and distribution systems are most vulnerable against such events [5]. As noted in [6], power system resiliency consists of three major parts: prevention, survivability, and recovery. In this article, the authors attempt to introduce a new method for increasing survivability using internal combustion engine (ICE) vehicles and the MG formation capability in distribution systems.

A well-known approach for restoring loads is breaking the distribution system into self-supplied MGs and supplying customers in each MG during the power outage [7], [8]. Breaking the distribution system into small clusters (named microgrid) was proposed in [7] in order to improve the management of DGs in distribution system. Reference [8] proposed a schedueling statergy for reconfugurable microgrid by considering the forcast error of generated power of renewable energy resources. In this situation, there is no MG in the distribution system before the event, and the distribution system operator (DSO) configures the MGs by using smart technologies and remote control switches. Usually, multiple faults happen during natural disasters, a fact that has been neglected in many researches [9], [10]. The idea of MG formation by assuming multiple faults due to natural disasters was first proposed in [11]. The suggested linear model considered a fixed or predetermined number of MGs, and the capabilities of different configurations were not included. The fixed number of MGs meant that in each MG, there could be only one DG, and integration of DGs with each other was not considered. In this condition, the number of MGs equals the number of DGs (if the DGs can supply the connected buses). The authors in [12] developed the algorithm presented in [11] and reduced the computational burden. However, the number of MGs was predetermined as in [11] and fixed. These two papers assumed that each bus has a switch and did not consider a limitation on the number of sectionalizers in the grid. They also did not model the tie-switches. Moreover, the proposed model missed the failure period and the event time characteristic.

Other studies ([13]–[18]) have used the base model presented in [11] in different applications such as the proactive management of a distribution system [13], using electric bus in MG formation problem [14], scheduling of transportable energy storage system (TESSs) during outage [15], pre-disaster and real-time placement of mobile DGs [16], MG management and MG formation in a distribution system via a two-layer structure [17], allocating the distributed energy resources in order to maximizing the restored load and optimizing the restoration time [18]. In those studies, the MG formation method was based on using a fixed number of DGs (only one DG in each MG), and integrating DGs with one another was not considered.

Reference [19] introduced a new method for modelling MG formation after disasters. In the model introduced, the integration of master and slave units were considered, while that of master DGs was not modeled. Therefore, the number of MGs and master units were fixed. In other words, two master units cannot be located in one MG (one master unit in each MG) in the presented model. The authors of [20]–[22] used the basic idea of [19] in crew scheduling ([21], [22]) and initial mobile-DG placement ([20]). However, they did not consider the integration of DGs.

The authors in [23] proposed a linear two-stage method that considered renewable energy and demand response programs and improved the ideas presented in [11] and [19]. The presented model was comprehensive and proposed the integration of DGs using the master-slave concept. It was shown in [23] that a predetermined number of MGs (with one master DG in each MG) decreased the load restoration capability of the proposed method and is thus not practical. The results presented in [23] clarified the effectiveness of the model proposed compared to other methods. However, the radiality constraints in this method were based on the path-based method, which depends on fault locations. In order to guarantee radiality constraints, the DSO would need to run an extra algorithm for each event, which is not practical in a network with multiple DGs. Moreover, the model is based on the parent-children node concept, which increase the complexity of the problem (see [23]) and cannot be used in some strategies that need a dynamic process.

The resiliency of other critical sources such as water distribution system was also studied in recent works. The planning of integrated power and water distribution system was considered in [24]. The placement of backup generators and hardening of lines were studied in the integrated networks. In addition to line hardening, the sizing of water tank and energy storage systems of microgrid were considered in [25], [26]

Different kinds of distributed energy sources (DERs), such as mobile DGs, stationary/mobile energy storage systems, and electric vehicles have been the focus of many recent studies of resiliency improvement strategies [15], [16], [27].. In addition to the numerous DERs that can be used after natural disasters and be effective, there is a new energy source that can be used temporarily after natural disasters to assist in restoring loads. The idea of using ICE cars was first introduced in our previous work ([28]). Nowadays, ICE cars are capable of producing AC or DC power to supply homes with backup generation. This capability can be used also in distribution systems. In this article, we apply the ICE car concept to an MG formation problem.

To summarize, there are two types of MG formation schemes. The majority of recent works ([13]–[17], [19]), which have adopted the first scheme, have used the basic idea of the MG formation problem presented in [11]. In addition, only one DG can be used in each MG in their models, and they have ignored the concept of integrating the DGs. Moreover, the time characteristic of natural disasters and load uncertainty were not considered. The second scheme, presented in [19] and [23], did consider DG integration, thereby improving the basic idea in [11]. However, the presented radiality constraint was complicated and required running an extra algorithm before the main program, which is not practical in real cases because of the unknown location of faults before events. This model is also dependent on the parent-children concept or path-based methods (complicated methods).

In the current paper, the authors improve the method presented in [23] and introduce a comprehensive framework for the MG formation problem in DS. They also revise the radiality constraints ([19]) to be used in the master-slave concept. The proposed method is not path-based and has low complexity compared to other methods presented in the MG formation scheme. Moreover, they also demonstrate the effect of ICE cars on DS resiliency, which has not been considered in any of the reviewed papers. Therefore, in this article, a novel stochastic two-stage framework based on mixed integer linear programming and considering the ICE cars effect is introduced in order to address the shortcoming of previous studies. A comparison of recent works to the proposed method is illustrated in Table 1. In summary, the main contributions of this article are as follows:

- A novel linear two stage stochastic method is proposed that introduces a comprehensive formulation for modelling the master-slave concept and topological constraints of distribution systems. This technique is not based on children and parent nodes concept or path-based methods such as the one presented in [23].
- A radiality constraint presented in [19] is adopted and improved to be used in the MG formation problem to model the integration of more than one master unit in one MG.
- The ICE car is introduced as an emergency backup source during the disaster.
- Internal combustion engine cars are modeled and their effect on improving the resiliency of distribution systems is considered.
- MG formation considering ICE cars is considered.

To be noted that the proposed method is based on availability of ICE cars in distribution system after the disaster occurrence and having a contract with their owner before the disaster. Therefore, the proposed method is not proper for type of disasters such as earthquake which are not predictable.

The rest of this article is organized as follows: In section II, ICE cars are introduced as new resources during

TABLE 1. Comparison of recent papers to the proposed method.

	MG formation	Integration of master and slave units	Integration of master units	Simple model of radiality constraints	Independence from path-based and children-parent concepts	Consideration of ICE cars	Consideration of ICE cars in MG formation method
[11]	*			*			
[12]	*			*			
[13]	*			*			
[14]	*			*			
[15]	*			*			
[16]	*			*			
[17]	*			*			
[18]	*			*			
[19]	*	*			*		
[20]	*	*			*		
[21]	*	*			*		
[22]	*	*			*		
[23]	*	*	*				
[28]						*	
The proposed method	*	*	*	*	*	*	*

outage. In Section III, a novel MG formation formulation is presented. Section IV presents the simulations and discusses the results. Finally, the conclusions are drawn in Section V.

II. INTERNAL COMBUSTION ENGINE (ICE) CARS

Nowadays, ICE cars are popular around the world. Although the popularity of electric vehicles (EVs) is considerably increased, there will still be a large number of ICE cars in future, and they are not expected to disappear until the far future [29]. ICE cars are those operate only with petrol. The electricity consumed in this kind of vehicle is produced by a small generator known as the alternator. In this case, a car's gas engine spins the wheels under the hood and cranks a wheel on the alternator to generate energy. The alternator and its location in the engine are depicted in Figs. 1 ([30]).

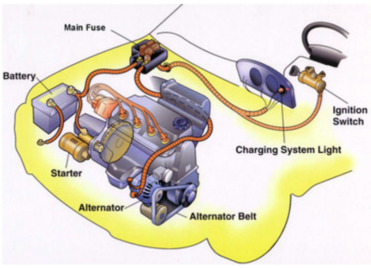

FIGURE 1. The location of an alternator in internal combustion engine [30].

The generated energy is used for the on-board electrical network in the cars. Because of new electricity demands in cars, such as entertainment and telecommunication, the energy consumption of the on-board electric network in the car is increasing [29], [31]–[33].

Modern cars have a consumption range of approximately 2 kW to 5 kW. Therefore, the alternators have to supply this amount of power continuously. This increased range of the alternator gives the power system an opportunity to use this available source in emergency situations. The alternator converts the mechanical energy provided from petrol ignition to electrical energy and saves it in the battery. Then, whenever needed, the saved energy is used for on-board electrical consumption. If the car is running, continuous consumption cannot deplete the battery because it is continuously charged by the alternator.

The electrical energy is available via AC outlets (especially in modern cars) or inverters. If the car does not have a proper outlet, the inverter can be utilized instead. These inverters are now being used as backup generators for supplying houses and camps. There are numerous inverter brands available for supplying homes with batteries. These inverters are known as home inverters. Fig. 2 depicts one brand of such inverters that has a 2kW power exchange capability. Commercial home inverters often have a capacity between 100 W and 5 kW. Home inverters are commonly employed for supplying some low-load facilities in the home in emergency situations. If it is assumed that the ICE car is running until when its petrol tank is emptied, the home-inverter/car-inverter can provide considerable energy (about 5 kW) to contribute to resiliency improvement and can act as a diesel generator in emergency situations. The home inverter power (100-5kW) is comparable to EVs level 2 charger power (3.3kW-11kW).

FIGURE 2. A type of home inverter.

As previously explained, the new technology in modern cars provides a better opportunity for using higher-power alternators inverters, making this concept more rational, contrary to the past, due to the low range of alternators. Usually, environmental concerns are not considered due to the short periods of outage, and these cars do not have any irreparable effects on the environment. It should be noted that in this article, the authors' sole focus was on the impact of ICE cars on DS after natural disasters and not on comparing them to other energy sources, such as mobile generators or electric buses. ICE cars represent a new energy resource that can be an effective solution in addition to other available energy resources.

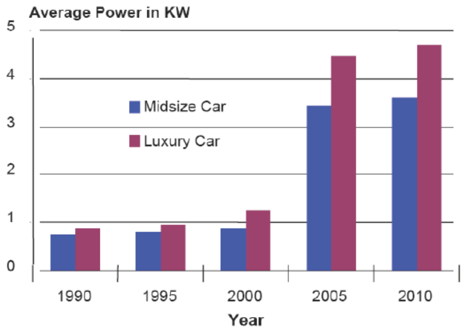

FIGURE 3. Vehicle electrical load versus years ([29]–[31]).

The proposed conceptual framework of the participation of ICE cars in supplying power to the grid is shown in Fig. 4. As is depicted, the battery management system controls the alternator, inverter, and the switch that would be on during the use of ICE cars as a generator. At the same time, the alternator supplies the electrical loads of the car. The amount of loads is low when the car is stationary and not used. This amount is neglected in this article. The comment of participating ICE cars is sent from DSO to the car's computer center.

III. MICROGRID FORMATION PROBLEM

When a distribution system operator faces multiple faults after natural disasters and isolates parts of the DS into some unsupplied islands, as mentioned before, the approved method in this condition is to divide a distribution system into some self-supplied MGs. In this article, a two-stage mixed integer linear stochastic programming model is proposed which considers the topological and electrical specification of the distribution system. The uncertainties of load consumption and demand response (DR) programs are also considered. The proposed model follows the master-slave control framework, which means that in each configured MG, only one DG controls the voltage and frequency of the MG, and the other DGs act as slave units ([19], [23]). In the first stage, the scheduling of DERs (etc. DGs and ICE cars) and topological situations of each MG are considered. The first variables are topological variables (the status of the lines and buses and the configuration of each MG), electrical variables (scheduling amount of DERs), and the selected number of ICE cars at each bus. In the proposed model, the forced outage of loads in each MG is performed only with the DR program. In the second stage, the real-time operation of DERs is determined. The flowchart of the proposed scheme is depicted in Fig. 5. It must be noted that modeling the uncertainty of load consumption is implied by the scenario-based approach. Accordingly, by using the historical data or utilizing the probability function, numerous scenarios are generated. Then, by using a reduction method, the number of scenarios is reduced to decrease the computational burden [34]–[36].

A. OBJECTIVE FUNCTION

The objective of the proposed method is to restore loads according to their priority. As shown in (1), the objective function maximizes the average supplied loads of the scenarios.

$$Objective = Max\left\{\sum_{t\in T}\sum_{i\in N_{bus}}\left(C_l \times \sum_{m\in M}\left[P^{L,sch}_{i,m,t} - \sum_{w\in W}\pi_w \times \Delta P^{LC}_{i,m,t,w}\right]\right)\right\} \tag{1}$$

B. TOPOLOGICAL CONSTRAINTS

Graph theory is used to consider the topological constraints of MG formation and to carry out switching operations, select master and slave DGs, and determine the configuration of the DS.

As the first step, a network graph must be extracted in which the edges are represented by lines (L) and the buses (N_{bus}) by nodes. In the proposed method, the tie lines are considered and are represented by the edges of the network graph.

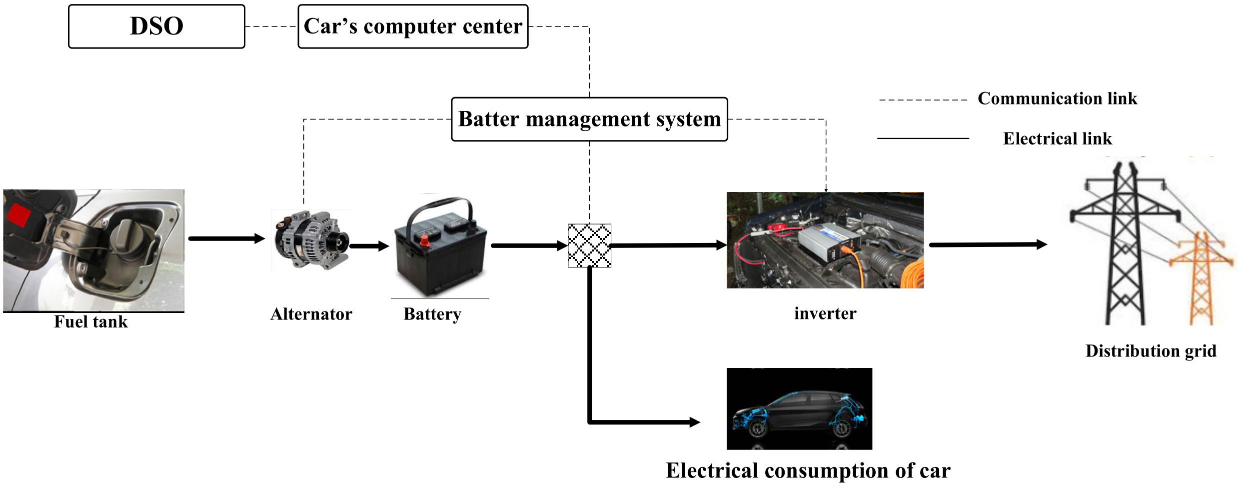

FIGURE 4. Conceptual framework of ICE cars' participation in resiliency improvement scheme.

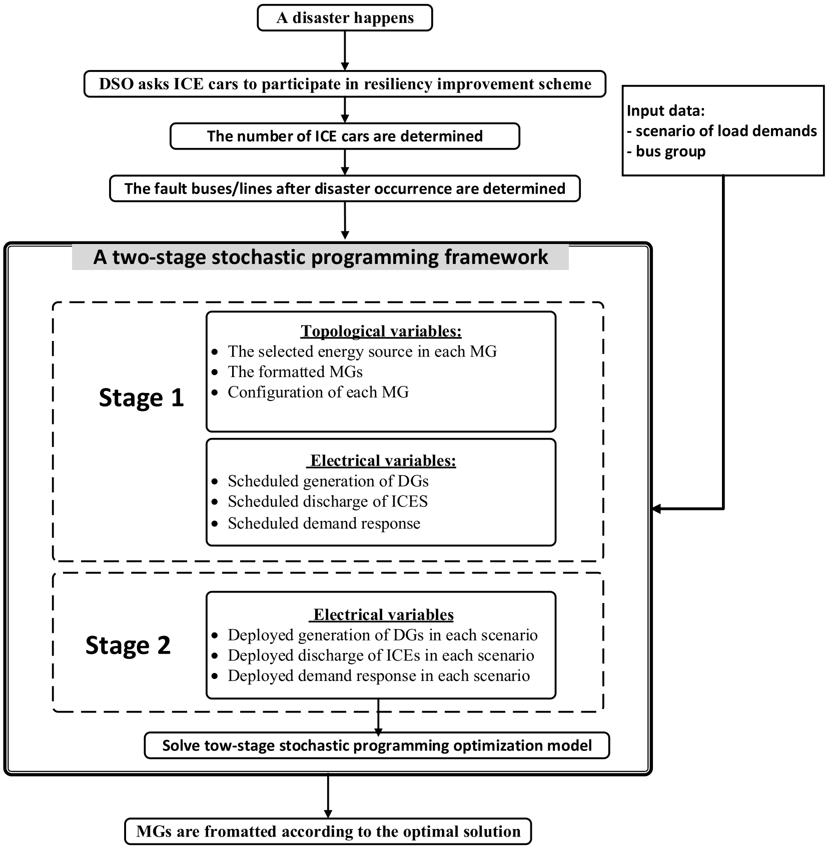

FIGURE 5. Flowchart of the proposed scheme.

Thus, the network includes some loops. In contrast to similar works by [19], [23], the formulation presented in this section does not need running an algorithm for detecting paths and the connected sub-graph, which considerably reduces the modeling complexity. This feature is the main difference of the proposed model from others. As mentioned, in each configured MG, there must be a DER, named the master unit that can control voltage and frequency. When several DGs in an MG have this capability, one of them acts as a master unit and the others act as slave units. The set of nodes that can work as master units is denoted by $\mathrm{N_{master}}$, and the set of nodes that are connected to DGs is shown by $\mathrm{N_{DG}}$. In the proposed model, we can ultimately have $\mathrm{N_{master}}$ MGs, and the m-th member of $\mathrm{N_{master}}$ corresponds to the m-th MG. Thus, if the m-th member of $\mathrm{N_{master}}$ is chosen as the master unit for arranging the MG, the MG label will be m, and the corresponding node is chosen as a root bus for that MG. Other constraints of the MG will be analyzed with respect to this bus.

Each node of the network can belong to one of the configured MGs or none of them. Therefore, (2) models this concept.

$$\sum_{m=1}^{N_{master}} a_{i,m} \leq 1 \quad \forall i \in N_{bus} \tag{2}$$

The variable $a_{i,m}$shows that if node i belongs to MG m, $a_{i,m}$will be 1 and the m-th member of N_{master} is chosen as the master unit.

Node i can be connected to MG m if only the root bus of MG m is the m-th member of $\mathrm{N_{master}}$ ($r = N_{master}(m)$) and $a_{r,m}$ equals 1. r is the root bus and the connected node to the master unit m. This constraint is shown as follows:

$$\sum_{m=1}^{N_{master}} a_{i,m} \leq a_{r,m}, r = N_{master}(m) \quad \forall i \in N_{bus},\ \forall m \in M \tag{3}$$

During the formation of the MGs, if the two sides of a line do not belong to the same MG, the binary variable shows that the status of the line ($Line_l$) must be set to zero. To consider the mentioned constraint, equations (4) to (7) must be employed.

$$Line_l = \sum_{m} \beta_{l,m}, \quad \forall l \in L \tag{4}$$

$$\beta_{l,m} \leq \sum_{i \in \partial(l)} a_{i,m}, \quad \forall m \in M, \forall i \in N_{bus} \tag{5}$$

$$\beta_{l,m} \leq \sum_{i \in \chi(l)} a_{i,m}, \quad \forall m \in M,\ \forall i \in N_{bus} \tag{6}$$

$$\beta_{l.m} \geq \sum_{i\in\chi_l} a_{i,m} + \sum_{i\in\partial_l} a_{i,m} - 1 \quad \forall m \in M,\ \forall i \in N_{bus} \tag{7}$$

In typical distribution systems, not all lines of the system have sectionalizers. Also, it is not logical from an economic prospective to install them on all lines. Therefore, it is required to model the fact that there are no switches on some lines in the DS, as shown in (8) to (10). Moreover, in the case of damage to a line or a node, the relevant line must have an inactive status.

$$Line_l \leq Line_l^{initial}, \quad \forall l \in L \tag{8}$$

$$a_{i,m} \leq Bus_i^{initial}, \quad \forall i \in N_{bus}, \forall m \in M \tag{9}$$

$$a_{i,m} = a_{r,m}, \quad \forall m \in M,\ \forall i, r \in N_{bus}, \\ \forall l \in L, l \notin sl(l)\ \ and\ \ BTL_{l,i,r} = 1 \tag{10}$$

C. MODELING THE RADIALITY CONSTRAINT

In this section, the radiality method introduced in [19], [37] is adopted and improved for use in the MG formation problem by considering the master-slave concept and the integration of master DGs. Theoretically, as explained in [38], the necessary and sufficient conditions for radiality constraints in each MG are that (a) the number of lines (closed lines) must be equal to the number of nodes (buses) minus one, and (b) each MG must fulfill the connectivity constraint. Compared to the method introduced in [19], the method proposed in this article does not need to detect the number of sub-graphs. Moreover, it is not a path-based method, as that presented in [23]. The presented method is adopted from [19], [37] and is revised to be used in the master-slave concept. Therefore, the complexity of finding the number of sub-graphs and paths because of unknown fault locations is eliminated in the proposed method. To achieve the first conditions, the number of lines is set equal the number of buses in each MG minus 1(if the MG is formatted), and equations (11) to (13) are employed.

$$\sum_l \beta_{l,m} = \sum_i a_{i,m} - b_m \quad \forall m \in M \tag{11}$$

$$\sum_i a_{i,m} \leq bigM \times b_m, \quad \forall m \in M \tag{12}$$

$$b_m \leq bigM \times \sum_i a_{i,m}, \quad \forall m \in M \tag{13}$$

The spanning tree method, which is a common method for radial-system connectivity constraints [39], is no longer practical for guaranteeing the connectivity constraint because of the existence of more than one DG and tie-switches. Moreover, loop-based or path-based methods require an algorithm to be implied before MG formation for detecting the network loops or certain paths [39]. First, the defect in the spanning tree method is explained. The general formulation in the spanning tree method to guarantee connectivity constraints is as follows:

$$A_{i,r} + A_{i,r} = Line_l, \quad \forall i, r \in N_{bus},\ \forall l \in L \tag{14}$$

$$\sum_{\substack{r\in N_{bus}\\ r\notin N_{master}}} A_{i,r} = 1, \quad \forall i \in N_{bus} \tag{15}$$

$$A_{i,r} = 0, \quad \forall r \in N_{bus},\ \forall i \in N_{master} \tag{16}$$

As shown in (14)-(16), if node r is a parent node of i, $A_{i,r}$ equals 1. According to (15), each node in the system has one parent node, and (16) shows that the master unit has no parent node. As depicted in Fig. 6, because of the existence of one slave unit in a loop, which is made by closing the tie-switch, equations (11)-(16) are guaranteed, but the network is not radial. Hence, this method is not practical any more in MG formation based on the master-slave concept. A new radiality method is proposed based on the single commodity flow method [19], [37] and improves it according to the MG formation problem. In the proposed method, the connectivity constraints are guaranteed by a fictitious network. In the network, each MG has one energy source and all other buses are load buses with 1 p.u demand. The fictitious network has the same topology as the original distribution network; thus, if a node is supplied, there must be a connection or path to the main source (see Fig. 7). The formulation for modeling the connectivity is as follows:

$$\left[\sum_l \sum_{i\in\chi(l)} F_{r,i,m,l} \times BTL_{l,i,r} - \sum_l \sum_{i\in\partial(l)} F_{i,r,m,l} \times BTL_{l,i,r}\right] \\ = -a_{r,m} \quad \forall r \in N_{bus},\ \forall m \in M, \forall r \notin N_{master} \tag{17}$$

$$[\sum_l \sum_{i\in\chi(l)} F_{r,i,m,l} \times BTL_{l,i,r} - \sum_l \sum_{i\in\partial(l)} F_{i,r,m,l} \times BTL_{l,i,r}] \\ = w_{r,m} - a_{r,m} \quad \forall r \in N_{master},\ \forall m \in M \tag{18}$$

$$1 \leq w_{r,m} \leq bigM \times a_{r,m}, \quad \forall r \in N_{master},\ \forall m \in M \tag{19}$$

$$-bigM \times \beta_{l,m} \times BTL_{l,i,r} \leq F_{i,r,m,l} \\ F_{i,r,m,l} \leq bigM \times \beta_{l,m} \times BTL_{l,i,r} \\ \forall i, r \in N_{bus},\ \forall m \in M,\ \forall l \in L \tag{20}$$

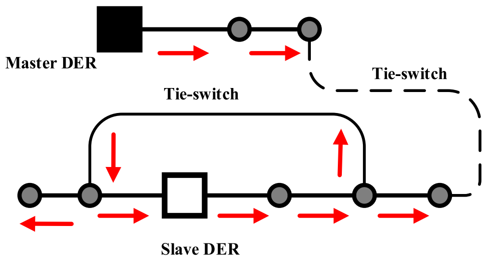

FIGURE 6. Connectivity constraints based on spanning tree method.

Therefore, the required formulations for guaranteeing the radiality constraint are (11)-(13) and (17)-(20).

D. ELECTRICAL CONSTRAINT OF MG FORMATION

In this section, the electrical constraints of MG formation are explained. As mentioned earlier, the proposed method is based on a stochastic two-stage framework which includes

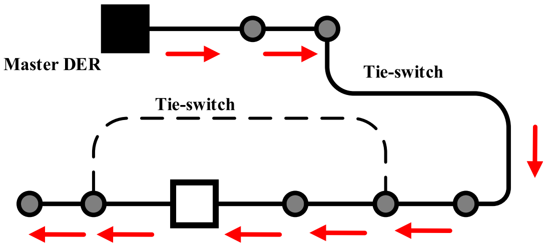

FIGURE 7. **Connectivity constraints based on the proposed method.**

scheduling and operation stages. In each stage, the electrical constraints of MG formation are explained.

1) SCHEDULING STAGE

In the proposed method, it is assumed that the distribution system operator (DSO) can directly control some of the loads by using DR contracts. Equations (21) and (22) describe the scheduled active power at the first stage in each bus with or without DR capabilities.

$$P^{L,sch}_{i,m,t} = a_{i,m} \times P^{predicted}_{i,t} - P^{DR,sch}_{i,m,t}, \quad \forall i \in N_{DR},\ \forall m \in M,\ \forall t \in T \tag{21}$$

$$P^{L,sch}_{i,m,t} = a_{i,m} \times P^{predicted}_{i,t} \quad \forall i \in N_{bus} \quad \forall i \notin N_{DR},\ \forall m \in M,\ \forall t \in T \tag{22}$$

In the DR program, it is assumed that the program follows some load control steps. The control capabilities of the loads are explained as follows:

$$P^{DR,sch}_{i,m,t} \leq a_{i,m} \times P^{DR,\max}_{i,t}, \quad \forall i \in N_{DR},\ \forall m \in M,\ \forall t \in T \tag{23}$$

$$\sum_{m} P^{DR,sch}_{i,m,t} = \sum_{d=1}^{D} \ell^{sch}_{i,d,t} \times P^{block}_{i,d,t}, \quad \forall i \in N_{DR},\ \forall t \in T \tag{24}$$

$$\sum_{d=1}^{D} \ell^{sch}_{i,d,t} \leq 1, \quad \forall i \in N_{DR},\ \forall t \in T \tag{25}$$

The active power limits on the output of DGs in the first stage are shown in (26).

$$P^{DG,sch}_{i,m,t} \leq a_{i,m} \times P^{DG,\max}_{i}, \quad \forall i \in N_{DG},\ \forall m \in M,\ \forall t \in T \tag{26}$$

Equation (27) ensures the active power balance in the first stage at time t in each MG.

$$\left[\sum_{i\in N_{DG}} P^{DG,sch}_{i,m,t} + \sum_{ice\in ICE} P^{ICE,sch}_{ice,m,t} - \sum_{i\in N_{bus}} P^{L,sch}_{i,m,t}\right] = 0 \quad \forall m \in M,\ \forall t \in T \tag{27}$$

2) OPERATING STAGE

In the operating stage, the required electrical constraints for each scenario are described. Equations (28) to (29) describe the active and reactive amount of load in scenario w at time t in MG m.

$$P^{L,dep}_{i,m,t,w} = P^{L,sch}_{i,m,t,w} - \Delta P^{LC}_{i,m,t,w}, \quad \forall i \in N_{DR},\ \forall m \in M,\ \forall t \in T,\ \forall w \in W \tag{28}$$

$$Q^{L,dep}_{i,m,t,w} = a_{i,m} \times Q^{predicted}_{i,t} - \tan(\partial_i) \times P^{L,dep}_{i,m,t,w}, \quad \forall i \in N_{DR},\ \forall m \in M,\ \forall t \in T,\ \forall w \in W \tag{29}$$

The load control model for DR-capable buses in the second stage are as follows:

$$P^{DR,dep}_{i,m,t,w} \leq a_{i,m} \times P^{DR,\max}_{i,t} \quad \forall i \in N_{DR},\ \forall m \in M,\ \forall t \in T, \forall w \in W \tag{30}$$

$$\sum_{m} P^{DR,dep}_{i,m,t,w} = \sum_{d=1}^{D} \ell^{dep}_{i,d,t,w} \times P^{block}_{i,d,t} \quad \forall i \in N_{DR},\ \forall t \in T\ , \forall w \in W \tag{31}$$

$$\sum_{d=1}^{D} \ell^{dep}_{i,d,t,w} \leq 1, \quad \forall i \in N_{DR},\ \forall t \in T,\ \forall w \in W \tag{32}$$

The difference in load control programs is shown as follows:

$$\Delta P^{LC}_{i,m,t,w} = P^{DR,dep}_{i,m,t,w} - P^{DR,sch}_{i,m,t} \quad \forall i \in N_{DR},\ \forall m \in M,\ \forall t \in T,\ \forall w \in W \tag{33}$$

The active and reactive power balance in each node in the second stage is according to (34)-(35). $H_{ice,i}$ is a parameter that shows the connection of car ice to bus i.

$$\sum_{m\in M}\left[Q^{DG,dep}_{i,m,t,w}\Big|_{i\in N_{DG}} + Q^{ICE,dep}_{ice,m,t,w} \times H_{ice,i} - Q^{L,dep}_{i,m,t,w}\Big|_{i\in N_{bus}}\right] = \sum_{l\in L} F^{line,Q}_{l,t,w} \quad \forall w \in W,\ \forall t \in T \tag{34}$$

$$\sum_{m\in M}\left[P^{DG,dep}_{i,m,t,w}\Big|_{i\in N_{DG}} + P^{ICE,dep}_{ice,m,t,w} \times H_{ice,i} - P^{L,dep}_{i,m,t,w}\right] - \sum_{l\in L} F^{line,P}_{l,t,w} = 0 \quad \forall w \in W,\ \forall t \in T \tag{35}$$

If master unit m is selected for arranging the MG, the voltage angle of the node that master unit m is connected to is set to zero, and its voltage magnitude is set to the controlled value (1 p.u). Equations (36)-(37) model the mentioned explanation.

$$V_{i,m,t,w} = a_{i,m} \times V^{set}_{m}, \quad \forall m \in M,\ \forall i \in N_{master},\ \forall t \in T,\ \forall w \in W \tag{36}$$

$$-(1 - a_{i,m}) \times \delta^{\min} \leq \delta_{i,m,t,w} \leq (1 - a_{i,m}) \times \delta^{\max}, \quad \forall m \in M,\ \forall i \in N_{master}, \forall t \in T,\ \forall w \in W \tag{37}$$

The active power and reactive power constraints in the second stage, line flow limits, and node voltage and angle limits are also modeled (refer to [23]).

The linear distribution power flow method introduced in [40] is used for calculating the load flow in the distribution system. The proposed method employs linear approximation for voltage and angle calculation and also considers the reactive power of the lines.

E. ICE CARS

ICE cars are a new concept in the distribution system operation. The number of these vehicles is very large, and we can assume that they can be accessible at each bus. ICE car owners who have home inverters/AC outlets can take part in the resiliency improvement scheme (according to Fig. 4). Due to the very large number of these vehicles, it is not practical to use all of them when a fewer number of them are useful. To be noted that, in this article for simplification, aggregator concept is not considered. Before the occurrence of disasters, the DSO signs contracts with a number of ICE car owners in specified buses for them to participate in the program and be available during the power outage (this concept will be considered in future research). These specified buses are named a *bus group* in this article. In the proposed scheme, it is assumed that the ICE cars participating in the proposed scheme are available during the outage and are already connected when the outage starts. Therefore, the fuel tank state of all ICE cars and the availability of the ICE cars are known, but the exact number (on/off states) and the amount of energy that they generate are determined after running the proposed scheme. As explained before, because of the concept of disaster and the conceptual framework of ICE cars, these cars do not follow a stochastic behavior and their presence and fuel tank conditions are determined upon the onset of a disaster. The power of ICE cars can be adjusted, but they cannot be on or off during the outage (the difference with other energy resources); hence, their status must be fixed during the power outage. The formulation presented in this section represents the modeling of ICE cars and determines their number. The thermal and electrical efficiencies of ICE cars are considered in the presented model. Equations (38)-(44) model the scheduling stage, and (45)-(50) model the operating stage. The number 9 represents the equivalent kWh energy of 1 liter of fuel according to [41].

$$ICE_{ice,m}^{aux} = \sum_{\substack{i\in N_{bus}\\ H_{ice,j}=1}} a_{i,m}, \forall ice \in ICE, \forall m \in M \tag{38}$$

$$\begin{aligned} Fuel_{ice,,m,t}^{tank,sch} &= \left[Fuel_{ice,m,t-1}^{tank,sch} - Fuel_{ice,m,t}^{usage,sch}\right) \\ &\quad \forall t \in (T_{start}, T_{End}], \forall ice \in ICE, \forall m \in M \end{aligned} \tag{39}$$

$$\begin{aligned} Fuell_{ice,m,t}^{tank,s\ ch} &= \left[\, Fuell_{ice}^{initial-tank} - Fuel\ _{ice,m,t}^{usage,s\ ch}\right] \\ &\quad \forall t = T_{start}, \forall ice \in ICE, \forall m \in M \end{aligned} \tag{40}$$

$$\begin{aligned} Fuell_{ic,,m,t}^{usage,sch} &= P_{ice,m,t}^{ICE,sch} / \left(\eta_{thermal}^{ICE} \times \eta_{electical}^{ICE} \times 9\right) \\ &\quad \forall t \in [T_{start}, T_{End}], \forall ice \in ICE, \forall m \in M \end{aligned} \tag{41}$$

$$\begin{aligned} Fuell_{ice,m,t}^{tank,sch} &\geq \left[\, Fuel\ _{ice}^{minimal-tank} \times ICE_{ice,m}^{aux}\right] \\ &\quad \forall t = [T_{start}, T_{End}], \forall ice \in ICE, \forall m \in M \end{aligned} \tag{42}$$

$$\begin{aligned} Fuel_{ice,m,t}^{usage,sch} &\leq bigM \times ICE_{ice,m}^{aux} \\ &\quad \forall t \in [T_{start}, T_{End}], \forall m \in M, \forall ice \in ICE \end{aligned} \tag{43}$$

$$P_{ice,m,t}^{lCE,sch} \leq P_{ice}^{\max-lCE} \times ICE_{ice,m}^{aux} \tag{44}$$

$$\begin{aligned} P_{ice,m,t}^{ICE,sch} &\leq P_{ice}^{\max-ICE} \times I_{ice}^{ICE} \\ &\quad \forall t \in [T_{start}, T_{End}], \forall m \in M, \forall ice \in ICE \end{aligned}$$

$$\begin{aligned} Fuell_{ice,m,t}^{tank,dep} &= \left[\, Fuel_{ice,m,t-1,w}^{tank,dep} - Fuel\ _{ice,m,t,w}^{usage,sch}\right] \\ &\quad \forall t \in (T_{start}, T_{End}], \forall ice \in ICE, \\ &\quad \forall m \in M, \forall w \in W \end{aligned} \tag{45}$$

$$\begin{aligned} Fuell_{ice,m,t,w}^{tank,dep} &= \left[\, Fuell_{ice}^{initial-tank,ICE} - Fuel\ _{ice,m,t,w}^{usage,sch}\right] \\ &\quad \forall t = T_{start}, \forall ice \in ICE, \forall m = M, \\ &\quad \forall w = W \end{aligned} \tag{46}$$

$$\begin{aligned} Fuell_{ice,m,t,w}^{usage,dep} &= P_{ice,m,t,w}^{ICE,dep} / \left(\eta_{thermal}^{ICE} \times \eta_{electical}^{ICE} \times 9\right) \\ &\quad \forall t \in [T_{start}, T_{End}], \forall ice \in ICE, \\ &\quad \forall m \in M, \forall w \in W \end{aligned} \tag{47}$$

$$\begin{aligned} Fuell_{ic,m,t,w}^{tank,dep} &\geq \left[\, Fuel\ _{ice}^{minimal\text{l-t}ank,ICE} \times ICE_{ice,m}^{aux}\right] \\ &\quad \forall t = [T_{start}, T_{End}], \forall ice \in ICE, \\ &\quad \forall m \in M, \forall w \in W \end{aligned} \tag{48}$$

$$\begin{aligned} Fuell_{ice,m,t,w}^{usage,dep} &\leq \mathrm{big}\,M \times ICE_{ice,m}^{\alpha\pi\alpha} \forall t \in [T_{start}, T_{End}], \\ &\quad \forall w \in W, \forall ice \in ICE, \forall m \in M \end{aligned} \tag{49}$$

$$\begin{aligned} P_{ice,m,t,w}^{ICE,dep} &\leq P_{ice}^{\max-ICE} \times ICE_{ice,m}^{aux} \\ P_{ice,m,t,w}^{ICE,dep} &\leq P_{ice}^{\max-ICE} \times I_{ice}^{ICE} \\ &\quad \forall t \in [T_{start}, T_{End}], \forall m \in M, \\ &\quad \forall ice \in ICE, \forall w \in W \end{aligned} \tag{50}$$

IV. NUMERICAL RESULTS

In this section, the performance of the proposed method is tested on a modified IEEE 33-bus test system. The proposed model is implemented using GAMS 2010 and solved by Cplex solver. The test is done on a computer with a Core i5 2.5 GHz processor and 8 GB of RAM. The simulation takes about 4 seconds and is efficient computationally.

The modified 33-bus test system is adopted from the standard IEEE 33-bus test system [42]. In the test system, there are 5 DGs in which 4 of them are assumed master units. DG 5 is a slave unit. The specification of DGs and their bus number are shown in Table 2.

The load scenarios are depicted in Fig. 8. Buses 4, 7, 8, 14, 24, 25, 29, 30, 31, and 32 are capable of controlling their loads. These buses can only perform load shedding. The load control blocks are assumed to be 100 kW. The maximum number of blocks is five. In the last block, if the load falls below 100 kW, it will be disconnected completely. It is assumed that ICE cars at a limited number of buses can generate power. These buses act as slave units. ICE cars

TABLE 2. Generation resources.

DG	Bus	Master unit	Active power(kW)	Reactive power (kVAr)
1	11	Yes	300	[-250,250]
2	21	Yes	300	[-250,250]
3	24	Yes	1000	[-800,800]
4	30	Yes	400	[-300,300]
5	26	No	100	[-50,50]

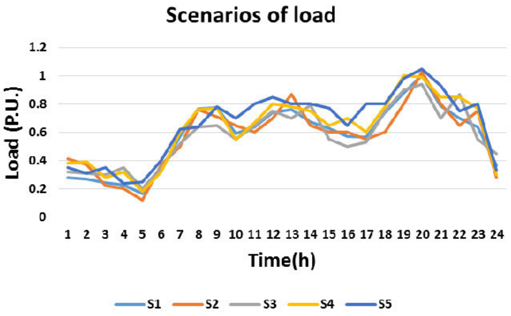

FIGURE 8. Load scenarios.

are distributed uniformly in the selected buses. Because of budget limitation, logically, not all of them can be used in the proposed scheme. The maximum power of home inverters is 10 kW (it is reasonable because of the increasing trend in the alternator power of recent cars), and their fuel tank capacity is assumed to be 40 liters. The maximum number of MGs is 5 and each MG label is shown in Table 3. The load scenarios are uploaded in [43].

TABLE 3. MGs and their master units.

MG Number	MG1	MG2	MG3	MG4
Master units' bus number	11	21	24	30

In order to take into account different conditions, two events with moderate and severe conditions are considered. In the first event, four faults happen after the natural disaster in the distribution system. Lines (1,2), (2,3), (33,18), and (32,33) become faulty, and the DS is disconnected from the main grid. In the second event, in addition to the faults in event 1, lines (13,14) and (25, 29) also become broken, representing a more severe situation. The modified 33-bus test system with fault lines in case 1 is shown in Fig. 9. It is to be noted that each load has the same priority and the supplied load amount is selected as a resiliency index for validating the proposed method. To explain the effect of using ICE cars on the proposed methods, 4 cases are assumed as follows:

- Case 1: DS with no ICE cars
- Case 2: DS with 45 ICE cars and bus group 1
- Case 3: DS with 45 ICE cars and bus group 2
- Case 4: DS with 60 ICE cars and bus group 3

In order to demonstrate the capability of the proposed method compared to previous methods, case 1 is chosen as a benchmark where no ICE cars are used. Case 2 and case 3 show the effect of using ICE cars in the proposed method. The number of the ICE cars and buses are the same in both cases. The buses selected in case 3 is different from those in case 2. Case 4 represents the distribution of buses and their effect on the proposed method. It is to be noted that in all case studies, the DR program is employed. The bus groups are 1) [5,9,15,17,20,23,26,29,32], 2) [5,9,15,17,20,23,26,27,32], and 3) [5,9,12,15,17,20,23,24,26,27,29,32]. These bus groups and DGs' locations are selected based on feasibility studies or expert viewpoints. These studies are out of the scope of this article and will be considered in future works. Budget limitation is also considered in this article. The price of DG output, demand response, discharge of ICEs cars are assumed 2, 10 and 3 $/kWh. The presence of ICE cars costs 50 $/each car. The budget limitation is assumed 10000 to 100000 $. The performance of the proposed method in each case study is explained below.

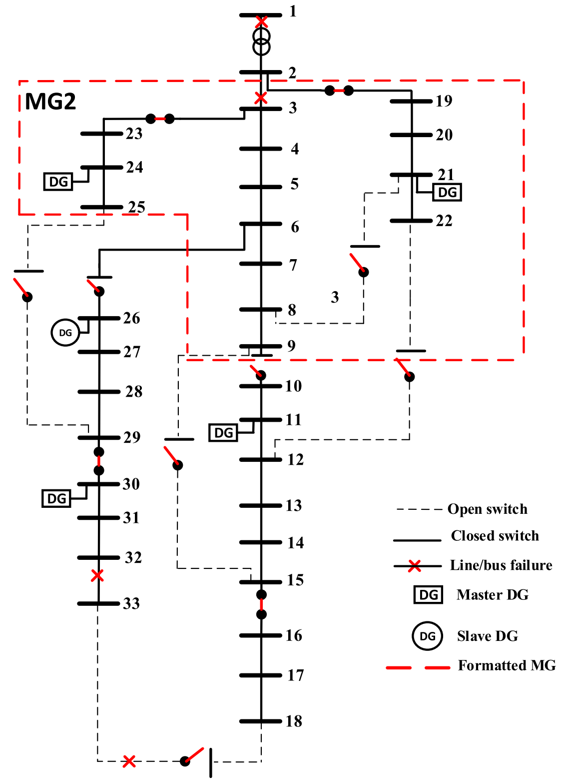

FIGURE 9. Formatted MGs in the proposed method (case 1).

As illustrated in Fig. 9, the number of MGs in case 1 is one, and MGs cannot be formed in other areas because of insufficient generation. It must be noted that the DGs at bus 11 and 30 cannot configure MGs because of insufficient generation and insufficient load shedding capability. In this case, the DERs are responsible for supplying the loads. There are two units with the capability of being master units in the configured MG, and the DG located in bus 24 acts as the master unit. In this case, there are no ICE cars, and only DGs supply the loads. In order to compare the proposed method to other

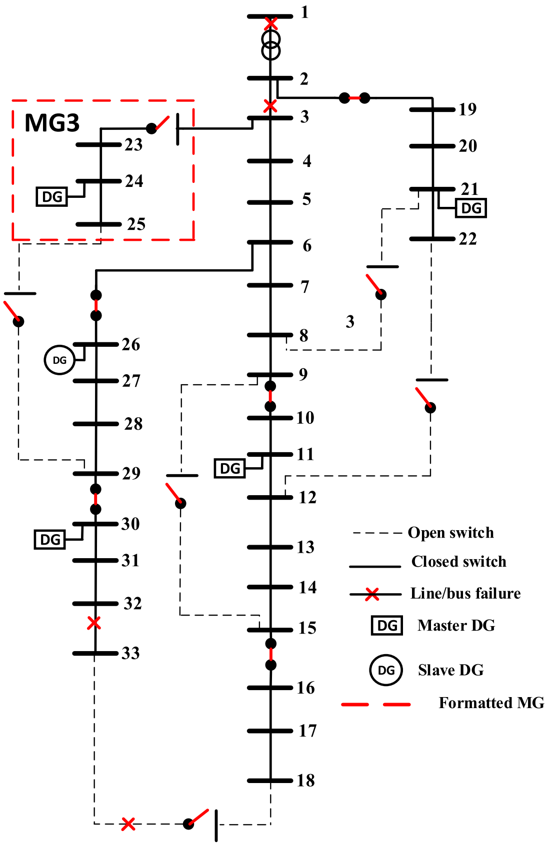

FIGURE 10. Formatted MGs based on [13].

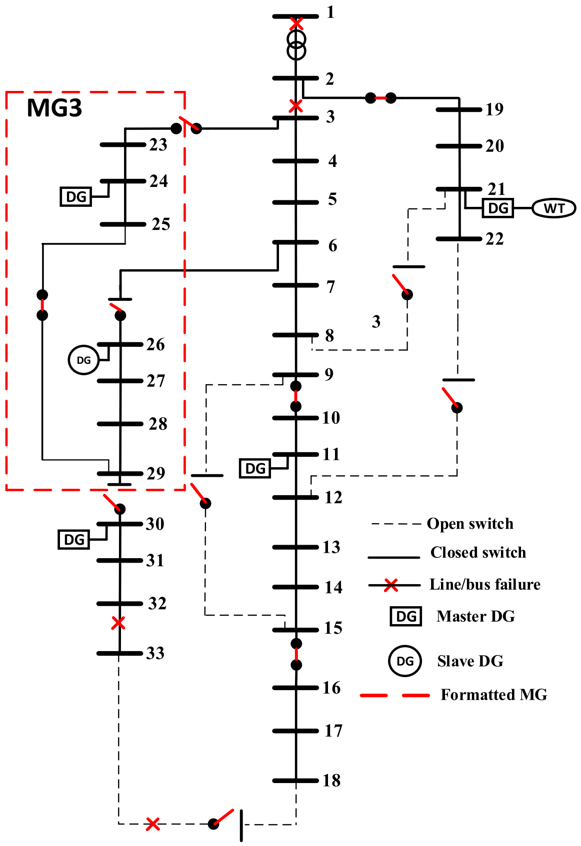

FIGURE 11. Formatted MGs based on [21].

methods, simulation are performed based on the methods proposed in [11] and [19]. As illustrated in Fig. 10, if we do not use tie-switches and limit each MG to one DG, the number of MGs and supplied loads are reduced according to the method proposed in [11]. Without considering tie-switches, the control scheme does not have enough flexibility to supply more loads. Fig. 11 shows that guaranteeing one master unit for each MG (according to [19]) leads to a decrease in the supplied loads because the cooperation of multi-master units results in more generated energy (see Fig. 9). A comparison between different methods is done in Table 4. As can be seen, the proposed method shows better performance in the more severe event (event 2). In event 2, the load reduction between events 1 and 2 in the proposed method is about 0%, but this value for the methods in [11] and [19] are 0 and 14 %, respectively (see Fig. 12). By deploying ICEs cars in DS as depicted in Fig. 13, the MG configuration changes, and more areas are covered. The DSO can determine the number of deployed ICE cars according to the condition of the DS. Fig.13 shows the MG formation in case 3 with 25 ICE cars. The number of ICE cars in each bus is shown in Table. 5. It is shown that the focus is on buses 5, 9, 19, 20 and 23, respectively.

TABLE 4. Comparison between different methods.

MG Number		[11]([12]-[18])	[19]([20]-[22])	Proposed method
Objective funciton (kWh)	Event 1	8484	9840	14765
	Event 2	8484	8484	14765

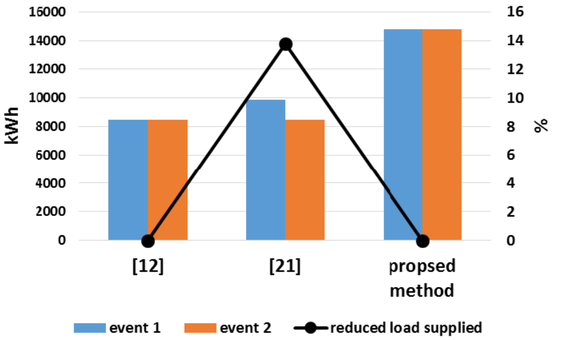

FIGURE 12. Load supplied (objective function) in different methods and load reduction percentages between event 1 and 2.

To show the influence of the bus selection on resiliency improvement, two bus group are deployed with a maximum number of 45 ICE cars. As depicted in Fig. 14, resiliency improvement in case 2 is carried out with more ICE cars. However, in case 3, it can be accomplished with fewer cars. Case 2 and case 3 are different from each other only by

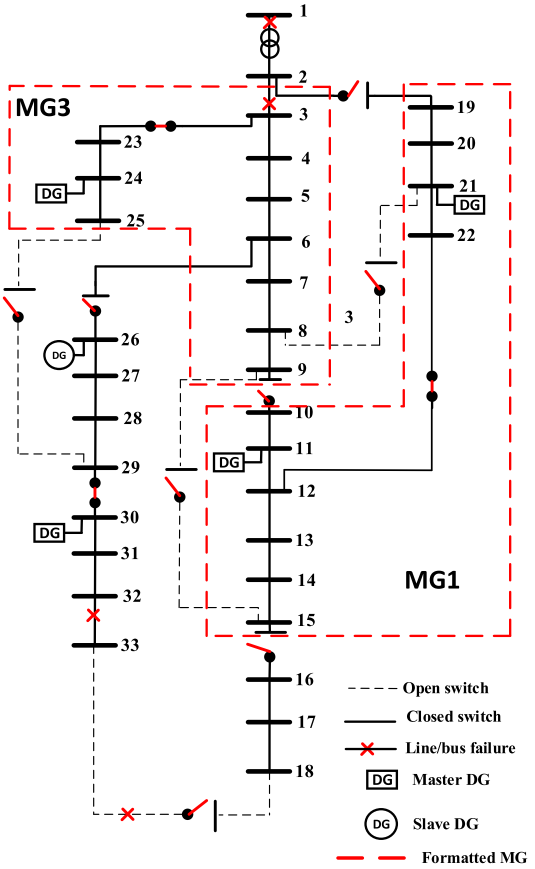

FIGURE 13. Formatted MGs by considering ICE cars (case3).

TABLE 5. Number of ICE cars at each bus in event 1 in case 3 (25 number).

Bus number	5	9	15	17	20	23	26	27	32			
Case 3	5	5	5	0	5	5	0	0	0			
Bus number	5	9	12	15	17	20	23	24	26	27	29	32
Case 4	4	5	2	4	0	5	1	4	0	0	0	0

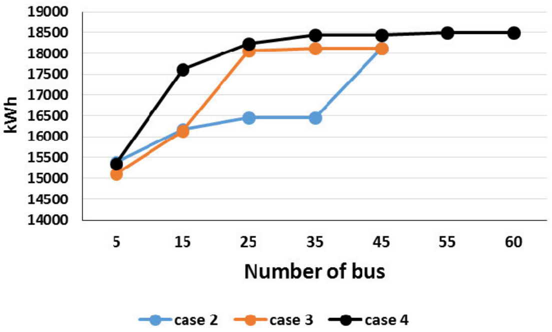

FIGURE 14. Objective value in different case studies.

one bus (bus 29 in bus group 1 and bus 27 in bus group 2). Therefore, it can be seen that selecting the buses corresponding to ICE cars affects the resiliency improvement process considerably.

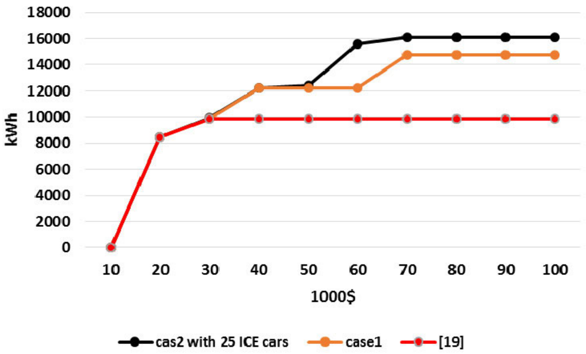

FIGURE 15. Objective value in different budget limits.

The buses corresponding to ICE cars in case 4 are more distributed, and the maximum number of ICE cars are increased to 60 (Fig. 14). The results showed that when the buses corresponding to ICE cars are more distributed in the system (case 4), better performance is achieved for the same number of ICE cars as in cases 2 and 3. The results also revealed that even if we used fewer ICE cars in case 4 (compared to cases 2 and 3), better performance than in cases 2 and 3 is obtained with the appropriate distribution of the ICE buses.

In order to consider the budget limitation in the proposed method, a comparison is done in Fig. 15. Three case studies are considered in this figure: case 1, case 2 with 25 ICE cars and the presented method in [19]. As shown in Fig. 15, the proposed method has same performance in in low budget (below 30000 \$). Then above 30000 \$, the effectiveness of the proposed method appears. Moreover, ICE cars affect the resiliency improvement in budget above 50000 \$.

V. CONCLUSION

In this article, a novel model for MG formation after natural disasters is proposed. The model is based on the stochastic two-stage mixed-integer linear programming (MILP). The proposed method presents a comprehensive model of MG formation which fulfils the gaps of previous works. The results of the simulation model show the effectiveness of the proposed model compared to previous studies. The proposed method increases the supplied load by about 75% and 50% under moderate conditions (event 1) compared to the previous studies [11] and [19], respectively. It also increases the supplied load by about 75% in severe conditions (event 2) compared to both previous studies ([11] and [19]) by integrating master units and selecting the optimal number of MGs.

ICE cars are also introduced as new energy resources, and the ability of this type of car in supplying energy in future power grids during a power outage due to a natural disaster is explained. In addition, the required formulation for modeling these resources is presented.

Using ICEs cars increases the supplied loads considerably because of the larger flexibility they provide. It is shown that using ICE cars increases the area covered by DGs. It is also shown that the choice of number and locations of buses corresponding to ICE cars in the distribution system can influence the load that can be supplied during a natural disaster. Moreover, in the budget limitation condition, the proposed method shows the better performance.

REFERENCES

[1] L. Che, M. Khodayar, and M. Shahidehpour, "Only connect: Microgrids for distribution system restoration," *IEEE Power Energy Mag.*, vol. 12, no. 1, pp. 70–81, Jan. 2014, doi: 10.1109/MPE.2013.2286317.

[2] S. Li, C. Gu, J. Li, H. Wang, and Q. Yang, "Boosting grid efficiency and resiliency by releasing V2G potentiality through a novel rolling prediction-decision framework and deep-LSTM algorithm," *IEEE Syst. J.*, early access, Jun. 29, 2020, doi: 10.1109/JSYST.2020.3001630.

[3] M. Khederzadeh and S. Zandi, "Enhancement of distribution system restoration capability in Single/Multiple faults by using microgrids as a resiliency resource," *IEEE Syst. J.*, vol. 13, no. 2, pp. 1796–1803, Jun. 2019.

[4] W. House, "Economic benefits of increasing electric grid resilience to weather outages," Exececutive Office President, Washington, DC, USA, Tech. Rep., 2013.

[5] R. Arghandeh, M. Brown, A. Del Rosso, G. Ghatikar, E. Stewart, A. Vojdani, and A. von Meier, "The local team: Leveraging distributed resources to improve resilience," *IEEE Power Energy Mag.*, vol. 12, no. 5, pp. 76–83, Sep. 2014, doi: 10.1109/MPE.2014.2331902.

[6] D. Gritzalis, M. Theocharidou, and G. Stergiopoulos, *Critical Infrastructure Security and Resilience*. Cham, Switzerland: Springer, 2019.

[7] R. H. Lasseter, "Smart distribution: Coupled microgrids," *Proc. IEEE*, vol. 99, no. 6, pp. 1074–1082, Jun. 2011.

[8] G. Liu, M. Starke, B. Xiao, X. Zhang, and K. Tomsovic, "Microgrid optimal scheduling with chance-constrained islanding capability," *Electr. Power Syst. Res.*, vol. 145, pp. 197–206, Apr. 2017.

[9] Y. Xiaodan, J. Hongjie, W. Chengshan, W. Wei, Z. Yuan, and Z. Jinli, "Network reconfiguration for distribution system with micro-grids," in *Proc. Int. Conf. Sustain. Power Gener. Supply*, Apr. 2009, pp. 1–4.

[10] J. Li, X.-Y. Ma, C.-C. Liu, and K. P. Schneider, "Distribution system restoration with microgrids using spanning tree search," *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 3021–3029, Nov. 2014.

[11] C. Chen, J. Wang, F. Qiu, and D. Zhao, "Resilient distribution system by microgrids formation after natural disasters," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 958–966, Mar. 2016, doi: 10.1109/TSG.2015.2429653.

[12] T. Ding, Y. Lin, G. Li, and Z. Bie, "A new model for resilient distribution systems by microgrids formation," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 4145–4147, Sep. 2017.

[13] M. H. Amirioun, F. Aminifar, and H. Lesani, "Resilience-oriented proactive management of microgrids against windstorms," *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 4275–4284, Jul. 2018.

[14] H. Gao, Y. Chen, S. Mei, S. Huang, and Y. Xu, "Resilience-oriented pre-hurricane resource allocation in distribution systems considering electric buses," *Proc. IEEE*, vol. 105, no. 7, pp. 1214–1233, Jul. 2017, doi: 10.1109/JPROC.2017.2666548.

[15] S. Yao, P. Wang, and T. Zhao, "Transportable energy storage for more resilient distribution systems with multiple microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 3331–3341, May 2019.

[16] S. Lei, J. Wang, C. Chen, and Y. Hou, "Mobile emergency generator pre-positioning and real-time allocation for resilient response to natural disasters," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 2030–2041, May 2016.

[17] M. Zadsar, M. R. Haghifam, and S. M. M. Larimi, "Approach for self-healing resilient operation of active distribution network with microgrid," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 18, pp. 4633–4643, Dec. 2017.

[18] S. Poudel and A. Dubey, "Critical load restoration using distributed energy resources for resilient power distribution system," *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 52–63, Jan. 2019.

[19] T. Ding, Y. Lin, Z. Bie, and C. Chen, "A resilient microgrid formation strategy for load restoration considering master-slave distributed generators and topology reconfiguration," *Appl. Energy*, vol. 199, pp. 205–216, Aug. 2017.

[20] B. Taheri, A. Safdarian, M. Moeini-Aghtaie, and M. Lehtonen, "Distribution system resilience enhancement via mobile emergency generators," *IEEE Trans. Power Del.*, early access, Jul. 8, 2020, doi: 10.1109/TPWRD.2020.3007762.

[21] B. Taheri, A. Safdarian, M. Moeini-Aghtaie, and M. Lehtonen, "Enhancing resilience level of power distribution systems using proactive operational actions," *IEEE Access*, vol. 7, pp. 137378–137389, 2019.

[22] B. Taheri, A. Safdarian, M. Moeini-Aghtaie, and M. Lehtonen, "Distribution systems resilience enhancement via pre- and post-vent actions," *IET Smart Grid*, vol. 2, no. 4, pp. 549–556, Dec. 2019.

[23] S. Mousavizadeh, M.-R. Haghifam, and M.-H. Shariatkhah, "A linear two-stage method for resiliency analysis in distribution systems considering renewable energy and demand response resources," *Appl. Energy*, vol. 211, pp. 443–460, Feb. 2018.

[24] J. Najafi, A. Peiravi, and A. Anvari-Moghaddam, "Enhancing integrated power and water distribution networks seismic resilience leveraging microgrids," *Sustainability*, vol. 12, no. 6, p. 2167, Mar. 2020.

[25] J. Najafi, A. Peiravi, A. Anvari-Moghaddam, and J. M. Guerrero, "Resilience improvement planning of power-water distribution systems with multiple microgrids against hurricanes using clean strategies," *J. Cleaner Prod.*, vol. 223, pp. 109–126, Jun. 2019.

[26] J. Najafi, A. Peiravi, A. Anvari-Moghaddam, and J. M. Guerrero, "An efficient interactive framework for improving resilience of power-water distribution systems with multiple privately-owned microgrids," *Int. J. Electr. Power Energy Syst.*, vol. 116, Mar. 2020, Art. no. 105550.

[27] Y. Li and K. Li, "Incorporating demand response of electric vehicles in scheduling of isolated microgrids with renewables using a bi-level programming approach," *IEEE Access*, vol. 7, pp. 116256–116266, 2019.

[28] A. Abessi and S. Jadid, "Internal combustion engine as a new source for enhancing distribution system resilience," *J. Mod. Power Syst. Clean Energy*, early access, Jul. 22, 2020. [Online]. Available: https://ieeexplore.ieee.org/document/9146493, doi: 10.35833/MPCE.2019.000246.

[29] R. D. Reitz *et al.*, *IJER Editorial: The Future of the Internal Combustion Engine*. London, U.K.: Sage, 2020. [Online]. Available: https://sage.altmetric.com/details/67514053

[30] *Alternator Location*. Accessed: Dec. 30, 2020. [Online]. Available: https://i.pinimg.com/236x/8d/37/0a/8d370a882c90c159122a94b551d7b8d0–auto-maintenance-auto-mechanic.jpg

[31] M. A. M. Shrud, "A systematic approach to the development of automotive electrical power system architectures," Dept. Elect., Univ. Derby, Derby, U.K., Tech. Rep., 2008.

[32] D. M. Whaley, W. L. Soong, and N. Ertugrul, "Extracting more power from the Lundell car alternator," in *Proc. Australas. Universities Power Eng. Conf. (AUPEC)*, 2004, pp. 1–2.

[33] *Alternator Power Trends*. Accessed: Dec. 30, 2020. [Online]. Available: https://www.greencarcongress.com/2006/09/bmw_introduces_.html

[34] A. J. Conejo, M. Carrión, and J. M. Morales, *Decision Making Under Uncertainty in Electricity Markets*, vol. 1. Cham, Switzerland: Springer, 2010.

[35] A. Safdarian, M. Fotuhi-Firuzabad, and F. Aminifar, "Compromising wind and solar energies from the power system adequacy viewpoint," *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 2368–2376, Nov. 2012.

[36] S. Mohammadi, S. Soleymani, and B. Mozafari, "Scenario-based stochastic operation management of microgrid including wind, photovoltaic, micro-turbine, fuel cell and energy storage devices," *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 525–535, Jan. 2014.

[37] Y. Lin and Z. Bie, "Tri-level optimal hardening plan for a resilient distribution system considering reconfiguration and DG islanding," *Appl. Energy*, vol. 210, pp. 1266–1279, Jan. 2018.

[38] R. Balakrishnan and K. Ranganathan, *A Textbook of Graph Theory*. Cham, Switzerland: Springer, 2012.

[39] V. Borozan, D. Rajicic, and R. Ackovski, "Minimum loss reconfiguration of unbalanced distribution networks," *IEEE Trans. Power Del.*, vol. 12, no. 1, pp. 435–442, Jan. 1997.

[40] H. Yuan, F. Li, Y. Wei, and J. Zhu, "Novel linearized power flow and linearized OPF models for active distribution networks with application in distribution LMP," *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 438–448, Jan. 2018.

[41] K. Rahimi and M. Davoudi, "Electric vehicles for improving resilience of distribution systems," *Sustain. Cities Soc.*, vol. 36, pp. 246–256, Jan. 2018.

[42] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Power Eng. Rev.*, vol. 9, no. 4, pp. 101–102, Apr. 1989.

[43] *Data*. Accessed: Dec. 30, 2020. [Online]. Available: https://drive.iust.ac.ir/index.php/s/dDic43LQJtMx9yY

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