Internal Combustion Engine as a New Source for Enhancing Distribution System Resilience

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Abstract—**Enhancing distribution system resilience is a new challenge for researchers. Supplying distribution loads, especially the residential customers and high-priority loads after disasters, is vital for this purpose. In this paper, the internal combustion engine (ICE) vehicles are firstly introduced as valuable backup energy sources in the aftermath of disasters and the use of this technology is explained. Then, the improvement of distribution system resilience is investigated through supplying smart residential customers and injecting extra power to the main grid. In this method, it is assumed that the infrastructure of distribution system is partially damaged (common cases) and it can be restored in less than one day. The extra power of residential customer can be delivered to other loads. A novel formulation for increasing the injected power of the smart home to the main grid using ICE vehicles is proposed. Moreover, the maximum backup duration in case of extensive damages in the distribution system is calculated for some commercial ICE vehicles. In this case, the smart home cannot deliver extra energy to the main grid because of its survivability. Simulation results demonstrate the effectiveness of the proposed method for increasing backup power during power outages. It is also shown that ICE vehicles can supply residential customers for a reasonable amount of time during a power outage.**

Index Terms—**Internal combustion engine (ICE), smart home, building energy management system (BEMS), distribution system resilience.**

I. Introduction

BECAUSE of recent climate changes, inevitable disasters have become more frequent and intense, which causes a considerable increase in the severity and frequency of power outages. Experiences from recent cases of power outage in the world such as hurricane Sandy which led to power outage for 7.5 million customers across Washington and 15 states [1]-[3] motivated the introduction of resilience concept to complement other power system issues such as reliability, risk, security, and stability in studying high-impact low-probability (HILP) incidents. As a result of disasters such as earthquakes, hurricanes, floods, blizzards, and other extreme events, the rising number of outages has made the resilience increasingly critical [4].

The severe weather has the highest probability causing power outage in a variety of disasters. According to [5], 87% of cases of the power outage in the U.S. are a consequence of weather disasters, and distribution systems are most vulnerable against such events. In [5], about 90% of cases of the power outage in the U.S. occur in distribution systems. As noted in [6], "system resilience is the ability to prepare for and adapt to changing conditions, withstand, and recover rapidly from disruptions." Based on this definition, the system resilience includes three major parts: prevention, survivability, and recovery. Therefore, this paper attempts to introduce a new method for increasing survivability capability using the internal combustion engine (ICE) vehicles in distribution systems as a backup source.

Diesel generators, uninterruptable power supply (UPS), and distributed generators are typical power suppliers in emergency situations in residential areas. However, they are usually installed in critical loads such as hospitals and police stations. Therefore, their usage is not currently extensive. On the other hand, ICE vehicles are popular around the world. Although the popularity of electric vehicles (EVs) is considerably increased, the number of ICE vehicles will still be large in the future, and the death of ICE vehicles will occur in the far future [7], [8].

The vehicle-to-grid (V2G) technology has a significant capability for providing power to power grids [9]. With this technology, EVs provide cost-effective solutions for supplying residential loads in emergency situations. Noteworthy research has been conducted on the concept of V2G. For instance, the voltage and frequency control through V2G was considered in [10]-[13], and the storage and renewable energy with the integration of V2G concepts were studied in [14]-[16].

Vehicle-to-home (V2H) is defined as a small version of V2G in supplying homes with the power of EVs. There are few papers considering plug-in hybrid EVs (PHEVs) as a power source [17]-[20]. In [17], [18], the concept of using PHEVs was introduced with integrating rooftop photovoltaic (PV). With the help of batteries of PHEV, the off-grid operation of PV was enabled. In this case, the energy for supplying the appliances in the home was obtained by the battery of PHEV and an on-board engine in addition to PV generation. Note that the home was completely isolated from the main grid because of the power outage. The gasoline tank in the PHEVs provided considerable energy backup in emergency situations. In [18], a smart strategy for controlling battery

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and engine generator was introduced to increase the backup duration without considering the capability of smart homes. In [19], the optimized V2H system was introduced for a securely long backup duration for survival during long power outages. In this paper, the on-board engine generator was modeled to solve the optimization problem without considering capabilities of smart homes as well. Furthermore, in [20], PHEVs and EVs were considered as the backup energy supply in homes. The consumption of gasoline was analyzed for different types of EVs and PHEVs. A building energy management system (BEMS) was used for decreasing the home consumption in emergency and extreme emergency situations.

In the previous research mentioned above, PHEVs or EVs were solely used for supplying the energy of homes in emergency conditions, and homes were assumed to be isolated from the main grid. In these papers, authors attempted to increase backup duration by using smart management and modeling the accurate consumption of gasoline. There are various types of disasters causing short power outages which are usually resolved in less than a day. In these situations, there is no need to increase the backup duration, but the power outage of distribution systems must be avoided as much as possible, for the number of power outages is the concern of system operators. In fact, homes with the capability of V2G should be used to produce energy for other customers in addition to their own usage. Thus, we aim to produce the maximum energy and power for local distribution systems in order to energize other customers. It is proposed that a smart home connected to the local network should participate in supplying emergency power with the assumption that the local network has no protection problems and can deliver energy to critical loads. The BEMS in smart homes can have considerable effects on increasing produced energy. We aim to introduce ICE as a backup power source and fill the above-mentioned gaps. The main contributions of this paper are as follows.

1) Introducing ICE as an emergency power source for enhancing resilience.
2) Using the gasoline energy of ICE vehicles in the BEMS.
3) Introducing a novel formulation for increasing the power injected to the distribution systems in the emergency situations.

The rest of this paper is organized as follows: in Section II, power outages in distribution systems and the need to conduct the study in a short period are explained. The capability of ICE vehicles in using gasoline storage for producing energy is introduced in Section III, and the challenge of implementation is also explained. In Section IV, the V2G operation formulation is presented. In Section V, the simulations are presented and the results are discussed. Finally, conclusions are drawn in Section VI.

II. Power Outages in Distribution Systems

According to [21], the power outages caused by weather-based disasters are predictable and can be usually resolved in shorter than one day, as given in Table I.

TABLE I
ILLUSTRATION OF DISASTER CHARACTERISTICS BASED ON AFFECTING TIME

Type	Predictability	Affecting time
Hurricane, tropical storm	24-72 hours	Hours to days
Tornado	0-2 hours	Minutes to hours
Blizzard, ice storm	24-72 hours	Hours to days
Tsunami	Minutes to hours	Minutes to hours

Therefore, strategies used for supplying power for home areas should be designed based on these time periods. As explained before, ICE vehicles can be utilized as an emergency backup power, and it requires several minutes to prepare them. According to the predictability of weather-based disasters shown in Table I, there is no problem for connecting ICE vehicles to V2H systems. In this paper, a method is introduced for disasters with short affecting time, through which the power system is restored quickly. Note that the affecting time is predictable for power system experts according to the level of damages in distribution systems. The proposed method focuses on providing the maximum power and energy to the main grid in addition to supplying energy for home appliances, which helps the power system operator to restore the system more quickly than before and considerably decrease power outages.

III. ICE as a New Resilience Source

ICE vehicles are working only with petrol. The electricity consumed in this kind of vehicle is produced with a small generator known as the alternator. In this case, the gas engine of vehicle spins the wheels under the hood and cranks a wheel on the alternator to generate energy. The location of alternator in the engine is depicted in Fig. 1.

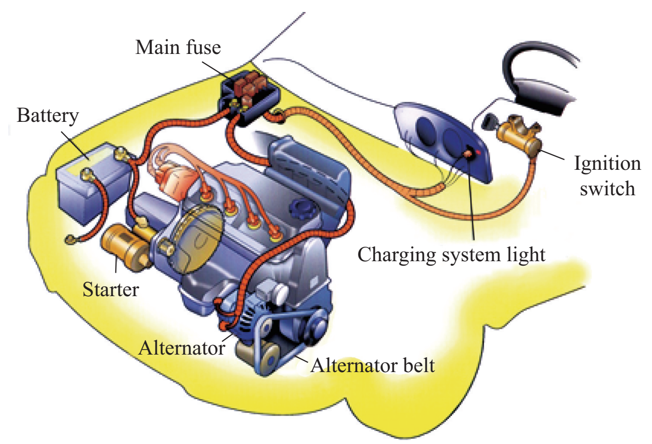

Fig. 1. Location of alternator in internal combustion engine.

The generated energy is applied for the on-board electric network in the vehicles. The vehicle uses electricity for air conditioning, entertainment, telecommunications, and components for enhanced safety and driving dynamics such as active steering, suspension management, engine management, and the anti-lock braking system (ABS). Because of new electric demands such as the entertainment and telecommunication in vehicles, the usage of on-board electric network of vehicle is increasing.

Modern vehicles have a range of power consumption of approximately 2 kW to 5 kW. A complete explanation of alternators was provided in [22]. The increasing 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 vehicle is running, continuous consumption cannot deplete the battery because it is continuously charged by the alternator.

Nowadays, new vehicle models such as Toyota Land Cruiser and Toyota FJ Cruiser have special AC outlets for supplying AC appliances. It is clear that these outlets usually have a low power range and are used for charging laptops and cellphones and supplying the energy when the vehicle is not running. The manufactures can design special outlets with higher power range near the alternator which can be used only in the condition that the vehicle stops in a place while the engine has been started. In this condition, the outlet has a considerable power range to use in emergency situations. If the vehicle does not have a proper outlet, the inverter can be utilized instead. There are numerous inverter brands available for supplying homes with batteries. These inverters are known as home inverters. When using home inverters, it is usually assumed that the vehicle is not running, and some limitations are assumed. If the vehicle is running, the battery depletion will not be an issue, and the alternator can supply the battery until the petrol tank is used completely. Home inverters have a wide variety of ranges. Commercial home inverters often have a capacity between 100 W and 5 kW. Note that the power range of the inverter must be smaller than the alternator range, because of internal energy losses. Home inverters are commonly employed for supplying some low-load facilities in the home in emergency situations and have not been used as power sources since they are usually assumed to be used when the vehicle engine has stopped.

Assume that the ICE vehicle is running until its petrol tank is emptied, the home inverter or vehicle inverter can provide considerable energy for participating in resilience improvement and acts as diesel generators in emergency situations. As previously explained, the new technology in modern vehicles provides a better condition for using alternators as well as inverters with higher power, making this concept more rational contrary to the past due to the low power range of alternators. Usually, due to short periods of outage, environmental concerns are not considered and these vehicles do not have any irreparable effects on the environment.

IV. V2H/V2G Operation Under Power Outage

In this paper, ICE vehicles are employed as emergency power sources in the smart home to inject power to the grid in addition to supplying home consumption. In this section, the problem formulation is presented, with the goal of the optimization model being the maximization of the power injected to the main grid during emergency situations. As depicted in Fig. 2, the energy in the fuel tank is firstly converted to AC energy with the alternator, and then converted to DC energy with a battery charger and stored in the battery. To use ICE vehicles as backup power, the energy stored in the battery is converted to the AC energy with a home inverter and supplies home appliances. It is noteworthy that battery chargers are usually integrated with alternators, and the output of alternators is usually DC energy.

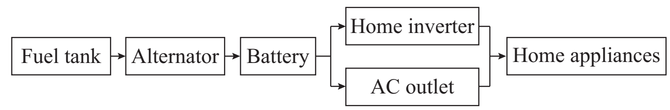

Fig. 2. Process of using ICE vehicles as backup power.

The home appliances utilized in the smart home include the refrigerator, water heater, air conditioner, oven, electronic devices, washing machine, dryer, and dish washer along with lighting. It is assumed that the BEMS only controls the controllable devices and does not have the ability to control other loads. The controllable devices in this model include the washing machine, dryer, and dish washer. The BEMS runs the optimization model to specify the time of use of controllable loads. As previously explained, the goal for using ICEs in this paper is to provide the maximum backup power in outages with a short period. In fact, the main goal in this paper is not to increase the backup duration, although the ability of ICE vehicles for providing the maximum backup duration will be considered. In the short-period outages, injecting more power is much more important than increasing backup duration from the perspective of distribution system operators. Since distribution system operators want to decrease the number of power outages and the main concern for them in short-period outages is the power supplied. It is noteworthy that the energy limit in short-period outages is not a concern, and the fuel tank in ICE vehicles usually has a sufficient capacity to supply home consumption for some days. In the following, the optimization model for maximizing the power injected to the main grid in short-period outages is explained. The proposed model is formulated as a mixed-integer linear programming (MIP) model. The objective function is to maximize the power injected to the main grid as follows:

$$Obj=\sum_{t=T_{fault,in}}^{T_{fault,out}} P_{injected}(t) \tag{1}$$

where Obj is the objective function; $T_{fault,out}$ and $T_{fault,in}$ are the end time and start time of the power outage, respectively; and $P_{injected}(t)$ is the active power injected to the main grid. The load balance between the power production and consumption is described as follows:

$$l_n(t)+\sum_i P(t,i)+P_{injected}(t)-P_{ICE}(t)-P_{network}(t)=0 \tag{2}$$

$$P(t,i)=I(t,i)l_c(i) \tag{3}$$

where $P_{network}(t)$ is the power injected to the home from the main grid; $P_{ICE}(t)$ is the power of ICE vehicles; $l_n(t)$ is the sum of non-controllable loads; $I(t,i)$ is the binary variable which determines the on and off states of controllable loads; and $P(t,i)$ is the amount of controllable loads.

In (4), the limits on controllable loads are satisfied, which must be lower than the power production.

$$l_n(t)+\sum_i P(t,i)\leq P_{ICE}(t)+P_{network}(t) \tag{4}$$

The fuel usage and fuel tank capacity in the optimization model are described as follows:

$$F_{tank}(t+1)=F_{tank}(t)-F_{usage}(t) \quad \forall t\leq T-1 \tag{5}$$

$$F_{usage}(t)=\frac{P_{ICE}(t)}{9\eta_{thermal}\eta_{electrical}^2} \tag{6}$$

$$\sum_t F_{tank}(t)\leq C_{tank} \tag{7}$$

$$F_{tank}(t)=C_{tank} \quad \forall t=1 \tag{8}$$

$$\sum_t F_{tank}(t)\geq 0.1C_{tank} \tag{9}$$

where $F_{usage}(t)$ and $F_{tank}(t)$ are the fuel usage and fuel tank capacity in time t, respectively; C_{tank} is the maximum tank capacity; $\eta_{thermal}$ and $\eta_{electrical}$ are the thermal efficiency of ICEs and the electrical efficiency of converters, respectively; and the number 9 describes the equivalent energy in kWh of 1 liter according to [20].

Equations (7) and (8) describe the maximum limit and the initial state of the fuel tank capacity, respectively. Equation (9) shows that at least 10% of fuel tank capacity is not able to be used considering the welfare of drivers.

Equation (10) describes that the start time of the dryer and washing machines is related to each other, and the dryer machine cannot start before the washing machine. Every controllable appliance will run for a specific time period if it starts. The time period lengths of appliances depend on the technical specification of each appliance and are usually different from each other.

$$\sum_{n=1}^{t} I(n,d)\leq[T_{on,dryer}(1-I(t,c)+I(t-1,c))+ \\ T_{on,dryer}(1-I(t,c)-I(t-1,c))] \tag{10}$$

where $T_{on,dryer}$ is the time period of dryer machine; n is the time set; $I(t,d)$ and $I(t,c)$ are the binary variables which determine the on and off states of dryer and washing machines, respectively.

Equations (11) and (13) satisfy the constraint that, if the appliance starts, it must work until the end of its time period. These limits are similar to the minimum start time in the operation of power plant and is extracted from [23].

$$\sum_{t=1}^{G(i)+1} 1-I(t,i)=0 \tag{11}$$

$$\sum_{n=t}^{t+T_{on}(i)+1} I(n,i)\geq T_{on}(i)(I(t,i)-I(t-1,i)) \\ \forall t>G(i)+2, t<T-T_{on}(i)+1 \tag{12}$$

$$\sum_{n=t}^{T} I(n,i)-I(t,i)+I(t-1,i)\geq 0 \tag{13}$$

where $G(i)=\min\{24,(T_{on}(i)-T_{on}^0(i))I(i,T_{fault,in})\}$, $T_{on}^0(i)$ is the duration that controllable load i is on, and $I(i,T_{fault,in})$ is the binary variable which shows the on or off state of controllable loads before the event occurs. The ICE vehicles cannot inject power to the main grid before power outage and cannot supply the load of home after restoration, because it is expected that ICE vehicles would only work during power outage and the main grid would supply the load of home in other time. It is also assumed that ICE vehicles have the ability to supply all loads of the home itself (the inverter has enough power output), and the main grid does not inject power to the home during the power outage. Equations (14)-(17) describe the limits.

$$P_{injected}(t)=0 \quad \forall t>T_{fault,out}, t<T_{fault,in} \tag{14}$$

$$P_{network}(t)=0 \quad \forall t\leq T_{fault,out}, t\geq T_{fault,in} \tag{15}$$

$$P_{ICE}(t)=PEV \quad \forall t\leq T_{fault,out}, t\geq T_{fault,in} \tag{16}$$

$$P_{ICE}(t)=0 \quad \forall t>T_{fault,out}, t<T_{fault,in} \tag{17}$$

where PEV is the constant generation power of ICE vehicles.

In order to illustrate the effectiveness of using ICE vehicles as backup power in emergency situations, even if the duration of power outage is not shorter than a day, the maximum backup duration of some commercial vehicles is considered. If there is a condition in which power outage is extended beyond a day, home-owners generally do not intend to participate in supplying power to the main grid, and all the energy stored in ICE vehicles is used for power consumption of their homes. It is assumed that the maximum backup duration is obtained by calculating the duration of depleting the fuel tank to its minimum amount (zero), and the relation between fuel consumption and energy supply is assumed to be linear. The formulations for calculating the maximum backup power are as follows:

$$E_{DC}=9\eta_{thermal}C_{tank}\eta_{electrical} \tag{18}$$

$$E_{AC}=E_{DC}\eta_{electrical} \tag{19}$$

$$T_{\max}=\frac{E_{AC}}{L_d} \tag{20}$$

where E_{DC} is the energy produced with the alternator; E_{AC} is the available energy after conversion with the home inverter; $T_{\max}$ is the maximum backup duration; and L_d is the average load of a day. Equations (18)-(20) demonstrate that the energy of the fuel is first converted to AC energy with the alternator, and then is converted to DC energy with the battery charger and saved in the battery of vehicle. Finally, as backup power, it is converted to AC energy with the home inverter.

V. Simulation Results

The proposed method is examined based on the load data in [20]. The data are revised minimally and are available in [24]. In the simulation, the real operation characteristic of appliances with a one-minute data resolution is used. The data describe the real condition in the smart home. To simplify the optimization, the loads of the washing machine, dryer, and dish washer are assumed constant and equal to 250, 2000, and 800 W, respectively. The thermal efficiency of the combustion engine is assumed to be 0.4, and the electrical efficiency of inverters is considered 0.9 [20]. The proposed MIP model is solved using Gurobi solver in a GAMS 24.8.2 optimization tool [25]. To illustrate the effectiveness of the proposed method for enhancing the resilience, different scenarios are considered as in Table II.

TABLE II
SCENARIOS IN RESILIENT SMART HOME

Scenario	Start time of power outage (min)	End time of power outage (min)	Power output of ICE vehicle (W)	Start time of controllable load before power outage (min)
1	20	500	6000	
2	20	1300	6000	
3	20	1440	6000	
4	20	1440	5500	
5	500	1000	6000	
6	500	1000	6000	450 (dish washer)
7	5000	1000	6000	450 (dish washer), 480 (washing machine)

In Scenarios 1 to 3, the duration of power outage is considered. Scenario 4 explains the effect of power output of ICE on controlling controllable loads. Finally, Scenarios 5 to 7 describe the influence of controllable loads starting before the power outage. Figure 3 illustrates the load management in Scenario 1.

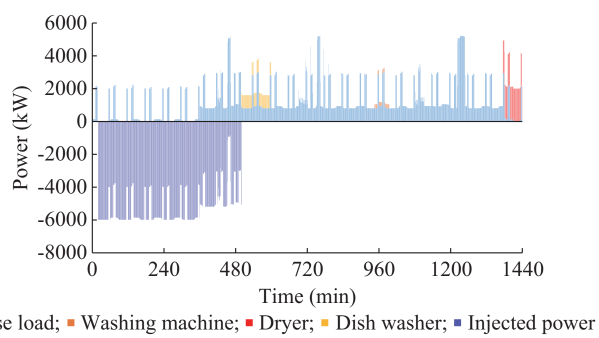

Fig. 3. Load management in Scenario 1.

It is evident that, because the duration of power outage is not long, some of controllable loads in the BEMS start after the end time of power outage, and all the inverters of ICE vehicles are dedicated to injecting power to the main grid. In Scenario 2, the length of power outage increases. As depicted in Fig. 4, all controllable loads start after the end time of power outage. Figure 5 shows the load management of controllable loads in the condition where the length of power outage covers nearly a day. In this case, because the maximum power production of the ICE vehicle is more than the maximum load, the start time of controllable loads is not important, and they can start at any time.

In fact, the BEMS has no effect on load management. In Scenario 4, the maximum power production of the ICE vehicle decreases to 5.5 kW. It can be observed in Fig. 6 that the result is different from that in Fig. 5, because the maximum power production of the ICE vehicle limits the load management, and BEMS starts controllable loads when the production limit is not constrained. In Scenarios 5 to 7, the effect of starting some appliances before the start time of power outage is considered.

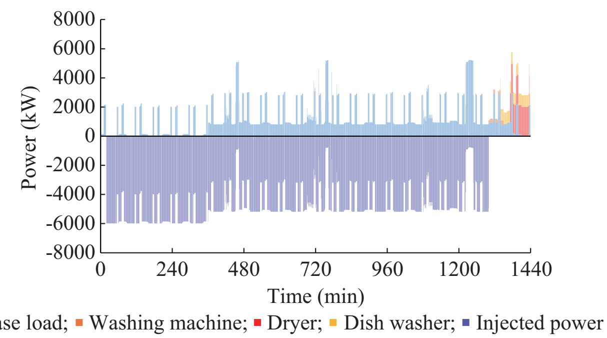

Fig. 4. Load management in Scenario 2.

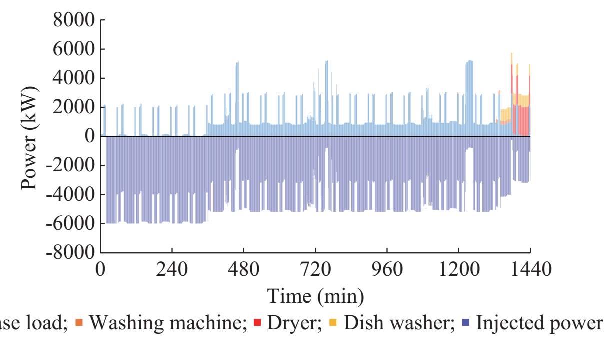

Fig. 5. Load management in Scenario 3.

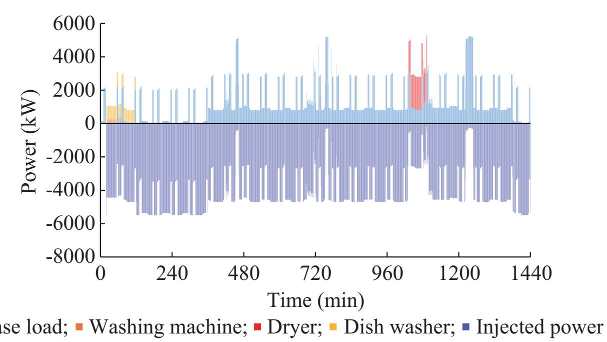

Fig. 6. Load management in Scenario 4.

Figure 7 depicts the load management of BEMS when the dish washer is not started before the start time of power outage, and Fig. 8 indicates the load management when the dish washer is started. It can be seen that because of the continuous working limits of appliances, i.e., (11) to (13), the dish washer has to work. BEMS controls the start time of other appliances and starts them after the end time of power outage. Figure 9 depicts the load management of controllable loads when the dish washer and washing machine are started before the start time of power outage. Based on Fig. 9, the BEMS only controls the dryer and shifts its start time after the end time of power outage.

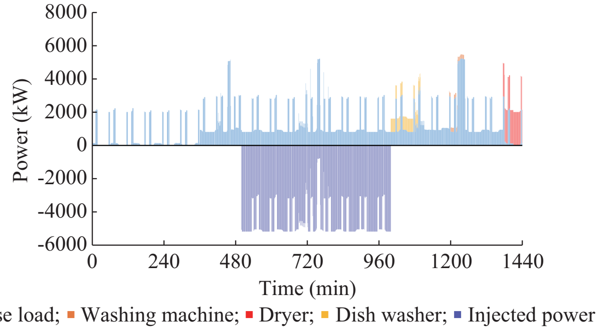

Fig. 7. Load management in Scenario 5.

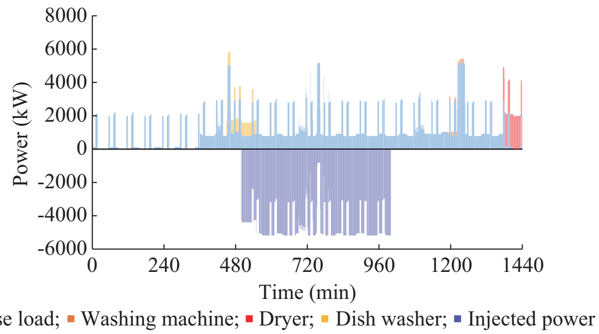

Fig. 8. Load management in Scenario 6.

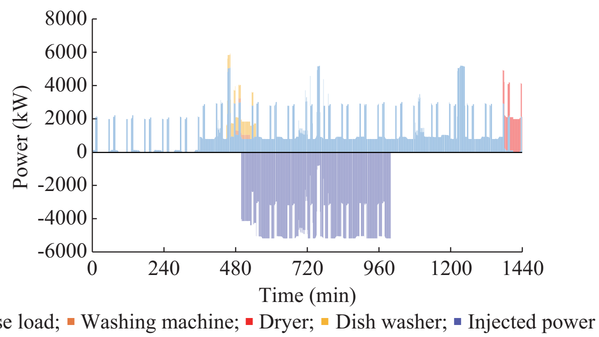

Fig. 9. Load management in Scenario 7.

In order to illustrate the effectiveness of the proposed method in increasing power injection during the power outage, a comparison is performed with and without BEMS. As demonstrated in Fig. 10, with BEMS, the injected power is considerably increased during the power outage. For example, in Scenario 1, the average injected power with and without BEMS are 5.16 kW and 4.69 kW, respectively. Using the proposed method, power injection is increased by about 500 W, making the cumulative power of homes play a vital role in decreasing the number of power outages. By increasing the duration of power outage, the average injected power with and without BEMS becomes closer. In Scenarios 3 and 4, the two amounts become the same. If any appliance starts before the start time of power outage, the average injected power decreases with respect to other scenarios as shown in Fig. 10.

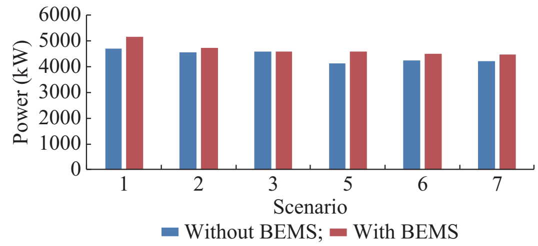

Fig. 10. Comparison of injected power in different scenarios with or without BEMS.

In order to demonstrate the effectiveness of using ICE vehicles as backup power in emergency situations, even if the duration of power outage is not shorter than a day, the maximum backup duration of some commercial vehicles is calculated. The considered vehicles are Toyota Camry Accord, Hyundai Accord, Hyundai Santa, and Toyota Yaris. The thermal efficiency of all brands is assumed to be 0.4, and the electrical efficiency for the battery charger and home inverter is assumed to be 0.9 [20]. Two scenarios for the load of home are considered. In the first scenario, the home owner consumes energy in a normal condition, and in the second scenario, the home owner consumes energy in an extreme condition and turns off all controllable loads.

Table III shows the available DC energy produced using ICE vehicles and the AC energy available for supplying home appliances. As depicted in Table IV, the ICE vehicle can supply home appliances for 3.61-6.12 days in normal conditions, and the backup duration increase to 4.06-6.87 days in emergency conditions. By assuming that the vehicle has half capacity of fuel tank, the backup durations are also considerable and can supply home appliances in an average of three days in emergency conditions.

VI. Conclusion

Providing backup power after extreme disasters is vital for enhancing the distribution system resilience and supplying critical loads. In this paper, the feasibility of using ICE vehicles in providing power for the home and the distribution system is investigated. A novel formulation for increasing the injected power to the main grid is introduced.

TABLE III
Total Energy Available for Supplying AC Loads in Resilient Smart Home

Vehicle (2018 model)	Tank capacity (L)	Equivalent power (kWh)	Electrical efficiency	Thermal efficiency	Available DC energy (kWh)		Available AC energy (kWh)	
					Full capacity	Half capacity	Full capacity	Half capacity
Toyota Camry Accord	56	503.2	0.9	0.4	181.152	90.576	163.0368	81.5184
Hyundai Accord	70	629.0	0.9	0.4	226.440	113.220	203.7960	101.8980
Hyundai Sonata	71	639.2	0.9	0.4	230.112	115.056	207.1008	103.5504
Toyota Yaris	42	377.4	0.9	0.4	135.864	67.932	122.2776	61.1388

TABLE IV
MAXIMUM BACKUP DURATION

Vehicle (2018 model)	Normal condition (day)		Emergency condition (day)	
	Full capacity	Half capacity	Full capacity	Half capacity
Toyota Camry Accord	4.82	2.41	5.41	2.70
Hyundai Accord	6.02	3.01	6.76	3.38
Hyundai Sonata	6.12	3.06	6.87	3.44
Toyota Yaris	3.61	1.81	4.06	2.03

With the proposed method, millions of customers will be able to have backup power in emergency situations, supply power to their own appliances, and inject the extra energy to the main grid for helping distribution system operators. To increase the simulation accuracy, detailed characteristics of major appliances are used. Simulation results demonstrate the effectiveness of the proposed method in increasing the power injected to the main grid.

Durations of maximum backup power are also calculated for understanding the usefulness of ICE vehicles during extreme power outages when the smart home only provides power to its own loads and cannot inject power to the main grid. Based on the simulation results, some commercial vehicles can supply the home for about seven days, which is a considerable amount of time in emergency situations.

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