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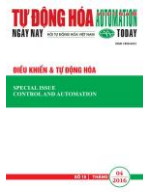

Vehicle-to-grid application to improve microgrid operation efficiency

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Abstract

Currently, the penetration rate of renewable energy sources (RESs) into the grid is increasing, especially solar and wind energy sources. This brings many benefits but also challenges since these sources inherently have unstable output power because they depend on practical factors. Microgrid (MG) with energy storage systems (ESSs) is a solution to utilize these RESs effectively. However, ESSs like battery storage system has high cost, making application deployment difficult. Therefore, the application vehicle-to-grid (V2G) technology with appropriate control methods to MG will bring more efficiency and potential when electric vehicles (EVs) develop in the future. This article will study and evaluate the effectiveness of using V2G in combination with the droop control method to support islanded MG when encountering power imbalance using Matlab/Simulink. The results show a positive influence of V2G on the stability and operation efficiency of the MG.

***Keywords**: HESS; Microgrid; RES; Supercapacitor; Vehicle to Grid.*

Abbreviations

DG	Diesel Generator
ESS	Energy Storage System
EV	Electric Vehicle
HESS	Hybrid Energy Storage System
MG	Microgrid
PV	Photovoltaic
RES	Renewable Energy System
SC	Supercapacitor
SOC	State of charge
WE	Wind Energy
V2G	Vehicle to Gird

Tóm tắt

Hiện nay, tỉ lệ xâm nhập các nguồn năng lượng tái tạo vào lưới điện ngày càng lớn, đặc biệt là năng lượng mặt trời và gió. Điều này mang lại nhiều lợi ích nhưng cũng không kém thách thức khi mà các nguồn này vốn có công suất đầu ra không ổn định vì phụ thuộc vào yếu tố thực tế. Microgrid (MG) là một giải pháp để tận dụng hiệu quả nguồn năng lượng này. Tuy nhiên, MG với các hệ thống lưu trữ có giá thành cao, khiến việc triển khai ứng dụng còn khó khăn. Do vậy, việc ứng dụng công nghệ xe điện nối lưới (V2G) với phương pháp điều khiển phù hợp vào MG giúp mang lại tính hiệu quả và tận dụng sự tiềm năng của xe điện để phát triển trong tương lai. Bài báo sẽ nghiên cứu và đánh giá sự hiệu quả của việc sử dụng V2G kết hợp với phương pháp điều khiển độ dốc để hỗ trợ MG độc lập khi có sự mất cân bằng công suất bằng Mathlab/Simulink. Các kết quả cho thấy được sự ảnh hưởng tích cực của V2G đối với sự ổn định và hiệu quả vận hành của MG.

1. Introduction

Conventional power plants inherently use fossil fuels and emit large emissions into the environment. This leaves potential challenges in the future when fossil fuel resources are limited and emissions also contribute to global warming. On the other hand, renewable energy (RE) generation systems are considered clean and cheaper compared to traditional synchronous machine-based power generations so they are increasingly recommended. Among RE generation systems, solar and wind systems are the most promising due to their lower generation cost and their capability of maximum power point tracking over a wide range of wind and sunlight variations [1]. However, the output power from these sources is stochastic due to the dependence on nature of wind and sunlight. RE power plants do not contribute to the system inertia, because they are connected to the network by power electronics, and they are electrically isolated from the network [2]. Thus, the high level of penetration of RESs into the grid can cause stability and reliability issues such as low inertia, fault ride-thourgh issues, and low power quality. Among the problems, the reduction of system inertia is the most detrimental to the electrical system. Since the frequency control is directly affected when the system inertia is low. Microgrid with ESSs is a solution to mitigate the negative effects of the high penetration of RESs.

Currently, there are types of energy storage including compressed air energy storage (CAES), flywheel energy storage (FES), pumped - hydro energy storage (PHES), battery energy storage (BES), fuel cell energy storage (FC), supercon-

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ducting magnetic energy storage (SMES), supercapacitor energy storage (SCES), etc. However, different storage technologies will have their own advantages and disadvantages [3]. The solution is to use a hybrid energy storage system (HESS) to combine the feature of different technologies to achieve the desired performance.

Based on available technologies, control methods as well as cost optimization, HESS using batteries and supercapacitors (SC) are most widely used. Batteries with high energy density are used to compensate for the low average power. However, its lifetime will be reduced if there are frequent transient power fluctuations. SC is used to meet this problem in HESS [4]. This combination can effectively deal with various power fluctuations and puts less stress on the battery system [5].

But with a battery system, the initial investment is quite expensive, especially for large power applications. In fact, electric vehicles are on the rise, if taking advantage of the ESSs in electric vehicles, they will contribute to reducing the cost of the system. According to [6], EV uses electric motor and battery energy for propulsion, which has higher efficiency and lower operating cost compared to the conventional internal combustion engine vehicle. According to a study, most non-commercial light-duty vehicles, including EVs, are utilized for only about 5% of the time for the prime purpose of transportation [7]. This makes the vehicles potentially available for 95% of the time to be connected to the grid for ancillary services to the power grid. At this time, the concept of vehicle to the grid was born. V2G uses EVs as an energy storage source for the grid, this increases the total power generation as well as improves the stability, reliability, and efficiency of the grid [7]–[9]. In addition, V2G also provides ancillary services to the grid such as regulation services (voltage and frequency), spinning reserve load-leveling, peak power, renewable energy storage and backup [10], [11]. In return, EV owners can enjoy appealing revenues for their participation in the V2G services [10]. However, EVs can not access to the grid freely and unmanageably because it will cause negative impacts to the grid [8]. Therefore, it is necessary to investigate the V2G technology to coordinate the charging/discharging behaviours between vehicles and grid so that it will not affect the power grid operation [8].

The article proposes a HESS using V2G and SC in combination with droop control and diesel generator (DG) to improve stability and operation efficiency of MG in the presence of photovoltaic (PV) system and wind energy (WE) system.

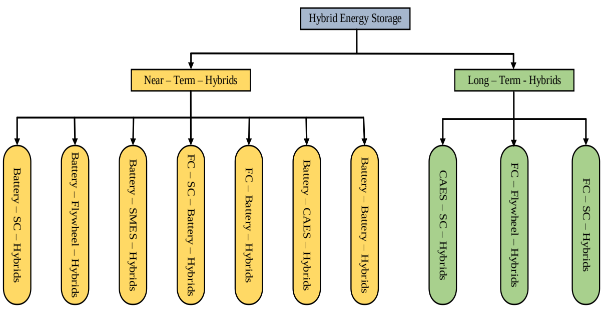

Fig. 1: Combination of storage technologies.

2. Microgrid

Microgrid is a small-scale power grid consisting of distributed generators combined with ESS that provide electricity to loads (industry, household, lighting, ...). In addition, this system also integrates components of the main grid to be able to operate in grid-connected mode [12], [13]. MG can operate in two modes: grid-connected and islanded.

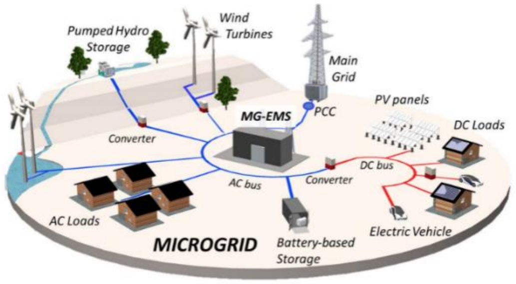

Fig. 2: General Scheme of a Microgrid.

2.1. Dynamic model of Micogrid

According to [14], a dynamic model of MG is given:

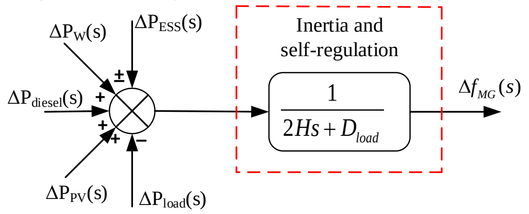

Fig. 3: Dynamic model of Microgrid.

where: ΔP_{ESS}, ΔP_W, ΔP_{diesel}, ΔP_{PV}, ΔP_{load}, are the output variation power of the ESS, WE, diesel generator, PV source and load variation respectively. Δf_{MG} is the system frequency deviation, H is the equivalent inertia constant of the system and D_{load} is the damping constant.

Based on the dynamic model of MG shown in Fig. 3, we can analyze the influence of RESs and ESSs on the change of frequency in the Microgrid.

2.2. Droop control method

To be able to distribute the power accurately and instantaneously among the ESSs and DG in the primary control level to respond to fluctuations for stabilizing frequency, the droop control method as shown in Fig. 4 is used [14].

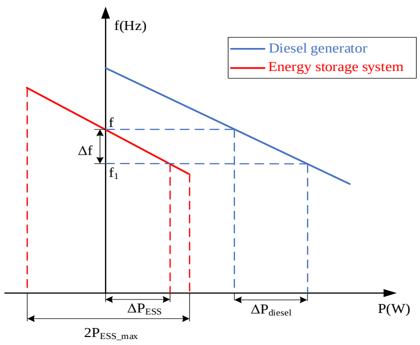

Fig. 4: *P*-*f* droop characteristics.

The system only engages in frequency control when the instantaneous frequency f_1 deviates from the rated value f. The DG droop equation (1) is given according to [15], where s_{diesel} is the droop value.

$$\Delta P_{diesel} = -\frac{1}{s_{diesel}}(f_1 - f) \quad (1)$$

The operation of the storage system is divided into two modes: discharging or charging when the frequency offset (f_1 –f) is negative or positive, respectively [16]. The variation in the active power of the ESSs are obviously within the range between the maximum charging and discharging capacity of the storage devices. The reference value of storage capacity P_{ESS} is given as:

$$P_{ESS}(f) = -K_{ESS}(f_1 - f) \quad (2)$$

where K_{ESS} is the coefficient expressing the stored energy of the storage system, expressed by:

$$K_{ESS} = \frac{1}{S_{ESS}} \frac{2.P_{ESS\_max}}{f} \quad (3)$$

where S_{ESS} is the droop factor, P_{ESS_max} is the maximum power that can be charged or discharged of the storage system.

3. Energy storage system

ESS is a solution to support the grid with high penetration of RESs. One of the typical storage systems is a hybrid storage system between a supercapacitor and a battery. HESS takes advantage of the supercapacitor's fast response and the battery's long-term power response, thus improving the efficiency of storage devices.

3.1. Hybrid energy storage system

HESS using supercapacitors and electrochemical batteries are among the popular applications for MG systems. SC have a higher capacitance than ordinary capacitors (about 20 times). SC responds faster than battery when sudden power change occurs in very short time, it is used to quickly compensate for sudden power change. Batteries with higher energy density are used for long-term energy storage due to slower response. However, this solution involves high investment costs, so the storage capacity must be calculated appropriately. According to [17] for Lithium-Ion batteries, the cost is 700 – 1000 Euro/kWh, the lifecycle is 3000 cycles at 80% deep discharge, which leads to the use of batteries to improve the penetration rate of RES into grid is a challenge. The use of HESS also increases battery life, reduces storage system costs, response times, and increases the reliability of the microgrid [3].
When the MG is in grid-connected mode, HESS will contribute to smoothing output power to help minimize fluctuations of RESs, preventing them from being transmitted to the grid and adversely affecting the grid's power quality. At the same time, HESS also supports power generation as required by the grid [18]. In islanded mode, HESS can support voltage and frequency stability thanks to SC's quick response and battery's long-term response, while reducing diesel power output. This article conducts research in the case of MG operating in islanded mode.

3.2. Vehicle to Grid – V2G

With the evolution of EVs in the future, the use of storage systems in EVs to embark the grid for the purpose of replacing batteries in order to improve the integrated ability of RES and operating efficiency of MG is currently in tendency.
There are three types of electric vehicles in current market: battery electric vehicles, hybrid electric vehicles, and fuel-cell electric vehicles. All these vehicles can generate clean AC power at power levels from 10kW to 200kW. For V2G implementation, three elements are required: (1) power connection for electrical energy flow from vehicle to grid, (2) control or logical connection, needed for the grid operator to determine available capacity, request ancillary services or power from the vehicle, and to meter the result, and (3) precision certified metering on board the vehicle. For fueled vehicles (fuel cell and hybrid), a fourth element, a connection for gaseous fuel (natural gas or hydrogen), could be added so that on board fuel is not depleted.
Ancillary services for the grid provided by V2G are mentioned above. In the peak power service, V2G will support a portion of the generator's power during peak device’s power. The required duration of peaking units can be 3 to 5 hours, then V2G is suitable for this. In load-leveling service, EVs can provide power during peak times to relieve pressure on electrical system components, while the power consumption and charging of the vehicle are carried out during off-peak hours., Spinning reserve service for the grid is also provided, is an additional generation that provides fast response, generally within 10 minutes to compensate the generation outage [19]. EVs are paid as “spinning” for many hours, just for being plugged in, while they incur relatively short periods of generating power. It means spinning reserves are paid for the amount of the time in which EVs are available and ready. Regulation services such as frequency and voltage regulation are also supported by V2G by matching generation with load demand and compensate reactive power. There are two types of regulation: regulation up – the EVs will charge its battery and “regulation down – the battery could be discharged into the grid to support power [10], [20]. Besides, the integration of RESs is also supported by V2G. Because of intermittent in output power of the solar and wind energy, the support of EVs is required to match the fluctuating supply to the already fluctuating load. The intermittency issue of RESs can be solved by utilizing a fleet of EVs as energy backups or energy storages. The EV fleets act as the energy backups to supply necessary power when the RESs generation is insufficient. Meanwhile, they act as energy storages to absorb the excessive power generated by RESs, which would otherwise be curtailed [19]. In short, EVs can help match demand to generation by discharging, charging, and storing excess RE for future purposes.
Despite having many benefits to the power grid ,V2G still has many challenge that need to be overcome such as: battery degradation, negative effects on distribution equipment, high investment cost and social barriers [6], [20].
The battery cells will deteriorate gradually under the battery charging and discharging cycles. The irreversible chemical reaction in the battery will increase the internal resistance and reduce the battery useable capacity. The aging rate of battery depends on many factors, which include the charging and discharging rates, voltage, depth of discharge and tem-

perature. Participations of EVs in the V2G technology require more battery charging and discharging cycles which are likely to result in quicker battery degradation. Studies show that battery cycle should be maintained around the middle ranges of state of charge (SoC) to minimize the increase rate of equivalent series resistance. Also, it is very important to retain the battery depth of charge lesser than 60 percent. Battery health should also be taken into consideration for the implementation of V2G technology.

Another challenge to the V2G implementation is the high investment cost required to upgrade the power system. Improvements in hardware and software infrastructure are needed for the V2G implementation because V2G could cause the distribition system to be overload [20]. In addition, the V2G implementation requires frequent charge and discharge cycles and these processes involves energy conversions which will contribute to more conversion losses. When being charged, the EV becomes a load and can cause an increase in peak demand if EV penetration in the system is high. The uncoordinated charging of EV will cause increase in peak demand of electric network. Therefore, it is advisable to charge the EV in the coordinated way when the off peak load periods are in frame [21]. In [22], [23], dividing or delaying charging time for EVs, charging at night or coordinated charging will help reduce power to the system during peak hours, not causing peak demand.

Last is the social barrier. Since taking part in the V2G technology requires EV owners to share the EVs batteries energy with the power grid, this will create the range anxiety among the EV owners. Also, EV owners tend to ensure a guaranteed amount of energy stored in the EV battery for emergency use and unpredicted journey in most cases. In order to reduce the social barriers for V2G implementation, a well-planned EV charging network is necessary. In addition, V2G management control needs to consider the EV SoC level. V2G connectivity needs to be cut off when the EV SoC is lower than an initially preset percentage to ensure the battery has enough energy for the daily driving usage.

The profitability in V2G of EV owners is also a concern. In general, EV owners can get revenue when participating in V2G, but that is not really attractive. The main reason is the degradation of the batteries in EV when participating in V2G, causes the repair and maintenance of vehicles to increase rapidly, so the economic benefit of V2G is reduced [24], [25]. Therefore, for EVs to participate in V2G technology and avoid the deterioration of battery life, participating in the frequency and voltage regulation service in the ancillary service is a potential solution, because EV owners still get paid without charging or discharging power (particularly, the spining reserve as mentioned above). In addition, EV owners will still benefit when V2G participates in other ancillary services. According to [26], EV owners always benefit from V2G peak shaving service. In [27], peak shaving product or a renewable consumer/flexible product are recommended. In the peak shaving product, EVs will gain additional revenue by discharging during peak hours and charging during off-peak hours. For a renewable/flexible consumer product, EVs can have additional revenue to prevent wind or solar cuts and make up for the shortfall of renewable resources. The economic benefits for not only of the EV owner but also of the power system are still being studied. In the near future, the battery prices are expected to decrease, and the potential of other ancillary services that V2G can participate in, making research on V2G is worth evaluating further.

3.3. V2G power calculation

According to [28], a way to calculate the capacity as well as the power to be provided by an EV in the station for the grid is proposed. The number of vehicles stored in station can be arbitrary, depending on the station space, but only vehicles with SoC between 20% and 80% can participate in V2G to support the grid. The available capacity in the station of n vehicles with the corresponding SoC is:

$$\Psi^{Avl}_{(n)EVs} = \sum_{i=1}^{n} \Psi^{Avl}_{EV(i)} = \sum_{i=1}^{n} \left(\Psi^{T}_{EV(i)} \times SoC_{EV(i)} \right) \quad (4)$$

where Ψ^{T}_{EVs} and SoC_{EV} are the rated capacity and SoC of a vehicle, respectively. The power that a vehicle must supply to the grid is:

$$P^{*}_{EV(i)} = \frac{\Psi^{Avl}_{EV(i)}}{\Psi^{Avl}_{(n)EVs}} P^{*}_{(inv)} \quad (5)$$

where $P^{*}_{(inv)}$ is the required V2G power for the grid.

Assuming in the station, there are only Nissan LEAF electric cars with the rated capacity of the battery system is 23,4 kWh [65Ah, 360V] [28]. The station space is holding 50 EVs, in which 15 cars have SoC of 40% and 35 cars have SoC of 70%. The aggregated available capacity of 15 EVs with SoC = 40% and 35 EVs with SoC =70% are calculated by (3), respectively:

$$\Psi^{Avl}_{(n)EVs\,40\%} = 15 \times (65 \times 40\%) = 390 \ (Ah)$$

$$\Psi^{Avl}_{(n)EVs\,70\%} = 35 \times (65 \times 70\%) = 1592,5 \ (Ah)$$

In addition, at the time of power balance, assuming the total power supplied by the PV and WE system to the grid is 500 kW, load demand is 1100 kW and power provided by diesel generator is 500 kW. Therefore, the required V2G power for the grid at this time is:

$$P^{*}_{(inv)} = 1200 - 500 - 600 = 100 \, (kW)$$

The power each vehicle with SoC = 40% and SoC = 70% must supply to the grid are respectively calculated by (5):

$$P^{*}_{EV(i)40\%} = \frac{65 \times 40\%}{390 + 1592,5} \times 100 = 1,31 \ (kW)$$

$$P^{*}_{EV(i)70\%} = \frac{65 \times 70\%}{390 + 1592,5} \times 100 = 2,3 \ (kW)$$

4. Simulation and discussion

The application of V2G technolgy combined with the droop control method will be evaluated in a islanded Microgrid system involving supercapacitors, diesel generators and renewable energy sources (PV and WE). There are two scenarios to be considered: MG with and without the participation of V2G.

Table 1: Parameters of MG system.

Parameter	Meaning	Value
P_{load}	Initial load value	1 MW

P_{PV}	Initial PV output power	200 kW
P_{Wind}	Initial WE output power	200 kW
$P_{diesel-init}$	Initial diesel generator output power	600 kW
H	Inertia constant	10^6
D_{load}	Damping constant	0

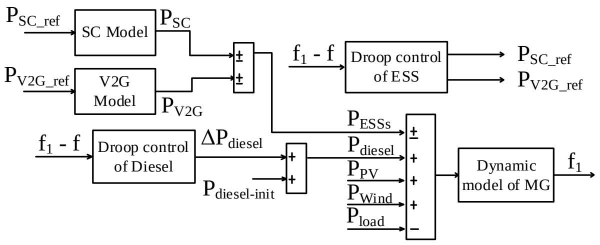

Fig. 5. General simulation scheme of the system.

The general simulation scheme and parameters are shown in Fig. 5 and Table 1, respectively. The load curve is shown in Fig. 6, its value is changed according to the step function. The initial value is 1 MW, increased to 1.2 MW at 40th second and returns to 1 MW at 60th second, then increased to 1,1 MW at 75th second and decreased to 1,025 MW at 90th second.

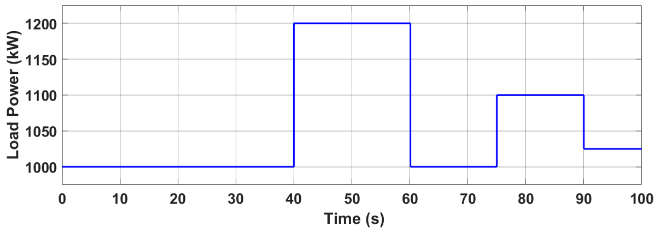

Fig. 6: Load curve.

The simulation scenario of RESs is shown in Fig. 7. During the first 10s, the PV and WE output power value is stable at 200 kW then start to change. The maximum achievable power of PV and WE is 250 kW and 300 kW, respectively.

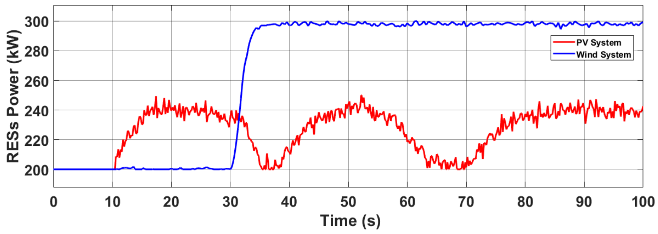

Fig. 7: Ouput power of PV and WE source.

4.1. System frequency response analysis

The frequency response results of MG with V2G and without V2G are shown in Fig. 8. At the interval when the RESs output power value increases (10th to 30th second) and when the load value decreases suddenly (60th second and 90th second), the total output power of the system is greater than load demand, leading to an increase in MG frequency. When the load value increases suddenly (40th second and 75th second), the output power of the system is lower than the load, leading to a decrease in the frequency of the system.

It can be seen that V2G has some positive effects for MG's frequency, such as: less oscillation, slower rate of change, less deviation and faster steady-state time when encountering consecutive power imbalance. This shows the effectiveness of having V2G participating in frequency support.

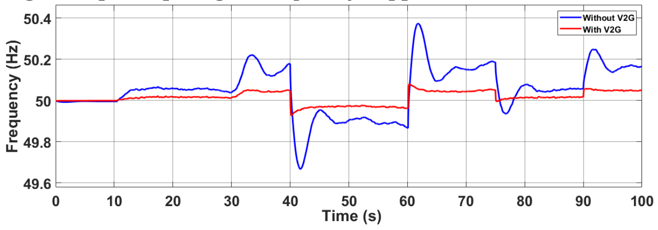

Fig. 8: Frequency response of MG with and without V2G.

4.2. System power response analysis

The frequency response results obtained in Fig. 8 and can be explained by analyzing the system power response: in the absence of V2G, the sudden power changes are compensated quickly by SC (blue line, Fig. 9) and the long-term power changes in the system are only compensated only by the diesel output active power (blue line, Fig. 10). Since the response power of the DG has a delay, so the amount of power compensation is not fast enough, leading to more fluctuations in the frequency after the power imbalance occurrence.

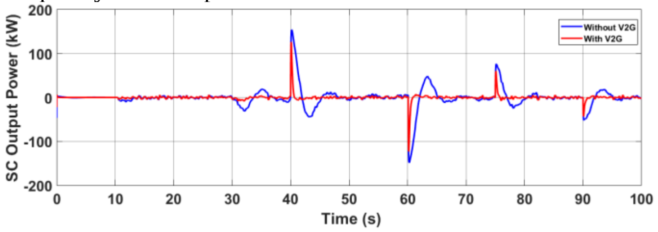

Fig. 9: SC output power response.

On the contrary, when V2G is present, the sudden power changes are still compensated by SC and the power adjustment based on long-term changes in the system are compensated by V2G along with DG (red line, Fig. 10, 11). Since V2G has faster power response time than DG, the power compensates faster for the generation demand imbalance, resulting in fewer frequency fluctuations and less deviation. This reduces the possibility of frequency deviations out of the allowable limit which activates load shedding or generation cut when there is a larger power imbalance. Therefore, the reliability and efficient operation of the power system are ensured.

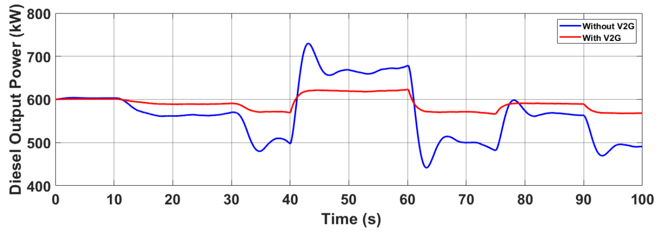

Fig. 10: DG output power response.

In addition, the required power from the SC is reduces when V2G is involved (Fig 9), thereby the calculated capacity and investment cost for the SC is reduced. Simultaneously, the variation in output power and power requirements from the DG are also reduced (Fig 10) therefore reducing operating costs and increasing the lifetime of the DG. These benefits mentioned above show the positive effect on MG operation when V2G is involved.

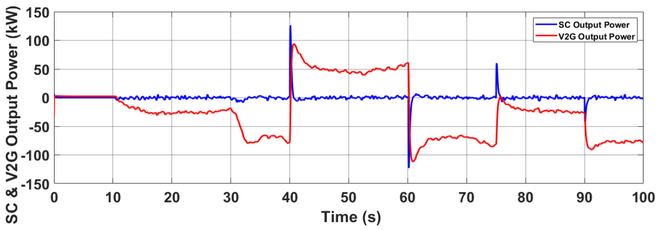

Fig. 11: Power response of V2G and SC.

5. Conclusion

This article studies and evaluates the effectiveness of V2G in combination with droop control in frequency stabilization and in the operation efficiency of islanded Microgrid with the participation of SC and DG. The results show an improvement in the system frequency when MG with the participation of V2G encounters generation demand imbalance. The frequency has less oscillation, slower rate of change, less deviation and faster steady-state time as the system encountering power imbalance. Besides, the required power from SC is reduced, leading to the decrease of investment costs for SC. In addition, the variation in output power and power requirements from the DG are also reduced, therefore reducing operating costs and increasing the lifetime of the DG. These have shown positive effects on the frequency stability and operation efficiency of MG with the participation of V2G.

However, the results also show that the the frequency nominal value is not achievable after an oscillation occurrence. There's still a deviation (from the nominal value) in the steady value of the frequency. The reason is that the droop control method used in the model is not optimal, so the next research direction of the article is to improve or use other frequency support methods to improve the system frequency response after oscillation, so it can be returned to the nominal value.

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