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Energy Router for Emergency Energy Supply in Urban Cities: A Review

Research paper

Yu Nie[1], Hui Xu[1,*], Yihua Hu[1], Xianming Ye[2]

[1]Department of Electronic Engineering, University of York, York, United Kingdom
[2]Department of Electrical, Electronic & Computer Engineering, University of Pretoria, Pretoria, South Africa

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Abstract: The current emergency power supply (EPS) measures are not perfect and standardised in response to large-scale power failures, such as city-wide ones. This review paper focuses on reasonably using the emergency electric power source to supply power in case of an abnormal urban power grid, to ensure the regular operation of urban electrical equipment and the daily life of the people. This study first introduces the different kinds of main emergency electric power sources and analyses their advantages and disadvantages. The battery of an electric vehicle as a new potential emergency power source is introduced that can also avoid the loss caused by unexpected power failure. Finally, three different EPS methods are explained in detail for different emergency occasions. Among them, the energy router is reviewed comprehensively considering it is the most potential emergency power distribution approach in the future because of its various applications.

Keywords: *emergency electric power source • emergency power supply method • energy router*

1. Introduction

The reason people need emergency energy is that there are lots of unexcepted accidents causing the paralysis of the urban power grid, which has a severe effect on people's lives. For example, a significant power scale power failure in China was caused by a snow disaster. About 4.5 million people lived without electricity for about 2 weeks in 2008 (Zhou et al., 2011). There was also a large power outage in Northeast Brazil because of an accidental breakdown of the dam power supply system (Byrd and Matthewman, 2014). Nearly one-third of the Brazilian population was caught in a power outage for about 4 h. More than 600 million Indians in India suffered from a large power outage for about 2 days because the power supply could not meet the peak demand (Buragohain et al., 2010). More importantly, some malignant social events can also cause a large power outage. A total of 9 million people living in New York once experienced power failure for the whole 24 h (Graham and Thrift, 2007). Various reasons can lead to large power outages, and the harm of a large-scale power outage is also severe. First, the most direct impact is the damage to power grid equipment which can cost a lot in terms of human resources, material, financial, and time to repair and rebuild (Bhattacharyya et al., 2007). Second, people can be seriously affected that their life and work will become inconvenient. Because of the power outage, people have to live by candlelight (Nye, 2010). Besides, a power outage can also be life-threatening. For example, a doctor is forced to operate without the assistance of any electronic medical equipment in case of emergency, which significantly increases the risk and difficulty of operation (Halperin et al., 2008). Therefore, emergency energy is reasonably necessary because it can replace the urban power grid to supply power when the urban power grid is abnormal.

Various applications of electricity that need to be introduced have been an essential part of human life which means almost all industries need electricity to drive the corresponding electrical equipment to complete the work. This causes a serious problem that cannot be ignored. When a power outage happens, a severe problem can be

* Email: hui.xu@york.ac.uk

caused that people cannot complete their regular work, which further results in economic loss and even loss of life and safety. Considering the above reasons, it is necessary to prevent these losses in an unexpected power failure. So far, emergency electric power sources and related distribution methods which are explained concretely in this review have been considered effective. Up to now, three kinds of emergency electric power sources and two emergency power distribution methods have been widely used in daily life, but a new emergency electric power source and a new emergency power distribution method which is the energy router have been proposed and proved to be feasible. This new emergency power source and energy routers are analysed and explained in detail in this review. In particular, the energy router is also considered the most potential emergency power distribution method. Not only it can apply multi types of different emergency electric power sources as input at the same time, but it can also be applied in the current hot research areas: smart power grid and microgrid. Considering its function such as high energy utilisation, multiple power forms, energy storage and monitoring the state of the main power grid, the energy router is quite suitable to be the power supply in the smart power grid and microgrid.

This review aims to provide the different kinds of emergency electric power sources and the distribution methods that can be used in supply power, including the controlling method. Additionally, this paper reviews a new potential emergency power source and its connecting and controlling method. The whole paper contains six parts. Section 2 introduces different types of emergency electric power sources and their advantages and disadvantages. Section 3 introduces a new potential emergency electric power source to supply power when unexpected situations occur. Section 4 shows the three methods of using emergency electric power sources when the power grid is paralysed. Finally, Section 5 concludes.

2. Emergency Electric Power Sources

There are mainly three kinds of emergency electric power sources that are used to supply emergency power, such as a Diesel/Gas generator set, uninterrupted power supply (UPS) and emergency power supply (EPS) are shown in Figure 1. This section introduces the following types of power supplies used as urban emergency electric power sources: Diesel/Gas generator set, EPS, UPS.

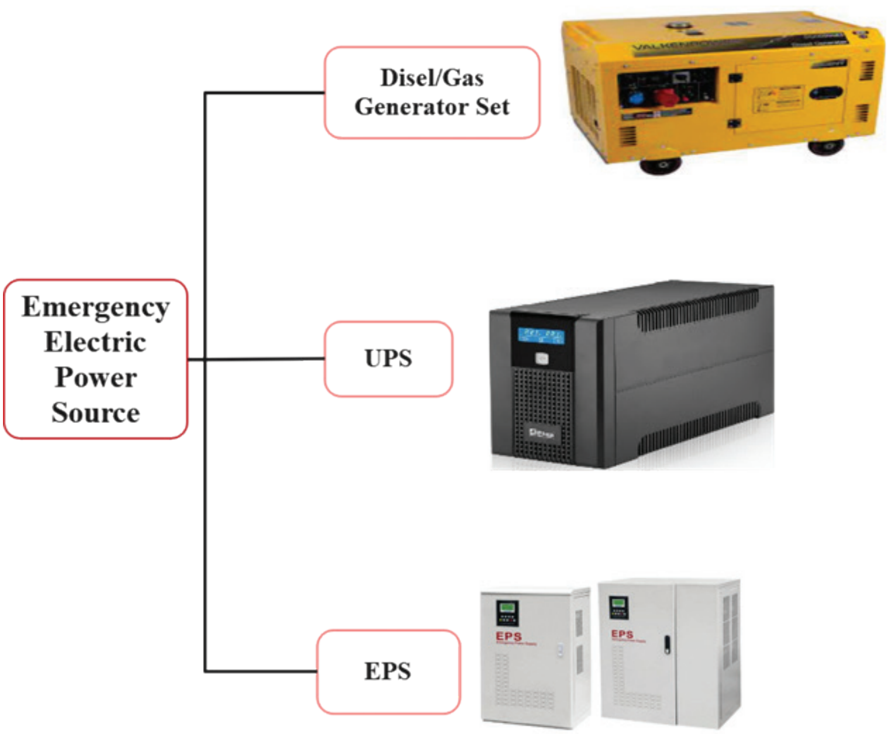

Fig. 1. Different kinds of emergency electric power sources. EPS, emergency power supply; UPS, uninterrupted power supply.

2.1. Diesel/gas generator set

In terms of the Diesel/Gas generator set, the Diesel generator set, and Gas generator set are generator sets that use different fuels but have the same power supply principle. Therefore, these two generator sets are regarded below as the same emergency electric power source.

The diesel generator set is a power generation equipment, which uses diesel as fuel and a diesel engine as a prime mover. Furthermore, the diesel engine is a machine that drives a generator to generate electricity. The whole generator set generally consists of a diesel engine, generator, control box, fuel tank, and other components. The diesel engine comprises two mechanisms and four systems, including a crankshaft connecting rod mechanism, valve train, oil supply system, lubrication system, cooling system, and starting system (Wong and Tung, 2016). The generator set applies to various loads with allowable interruption of power supply time >15 s. Using a generator set as an emergency electric power source is the most common emergency standby electric power source used in most applications at present. Due to its large capacity, parallel operation, and long continuous power supply time, the generator set has a long application history. However, no matter how fast the generator starts, it takes at least tens of seconds to several minutes. This is the starting period from when the generator receives the start signal after a power failure to when the generator voltage and frequency are stable and can supply power. During this period, all connected electrical equipment loses power, which may cause damage to a few pieces of equipment or the life safety and property. On the other hand, the application of diesel generators in emergency electric power sources has the following disadvantages: (1) In high-rise buildings, the diesel generator set is generally placed in the basement, which is a challenge to design and high cost. The facilities such as air inlet, cooling, smoke exhaust, shock absorption, and silencing need to be fully considered; (2) There is a potential fire hazard, and its oil tank is like an extremely dangerous ’bomb’ in case of fire; (3) The daily maintenance is frequent, and the workload is heavy; (4) The diesel generator is noisy and (5) There is a large amount of sulphur dioxide in the smoke exhaust, which is seriously polluted and affects environmental protection. Although the generator set is practical and ordinary, the risks of the generator set should be considered carefully.

2.2. Uninterrupted power supply

The second emergency electric power source is UPS. UPS is a constant voltage and constant frequency power supply equipment. It is mainly composed of the rectifier, battery, inverter, and static switch which are shown in Figure 2. (1) Rectifier is a device that converts alternating current (AC) into direct current (DC). It has two main functions: first, it converts AC into DC; second, it acts as a charger to provide charging voltage to the battery. (2) Storage battery is a device used by UPS to store power. It is composed of several batteries in series. Its first function is that when the main power is normal, it converts the electric power into chemical energy and stores it in the battery. Its second function is that when the main power fails, it converts the chemical energy into power and provides it to the inverter or load. (3) Inverter is a device that converts DC into AC. It consists of an inverter bridge, a control logic, and a filter circuit. (4) Static bypass switch is composed of thyristors with positive and negative polarity connected

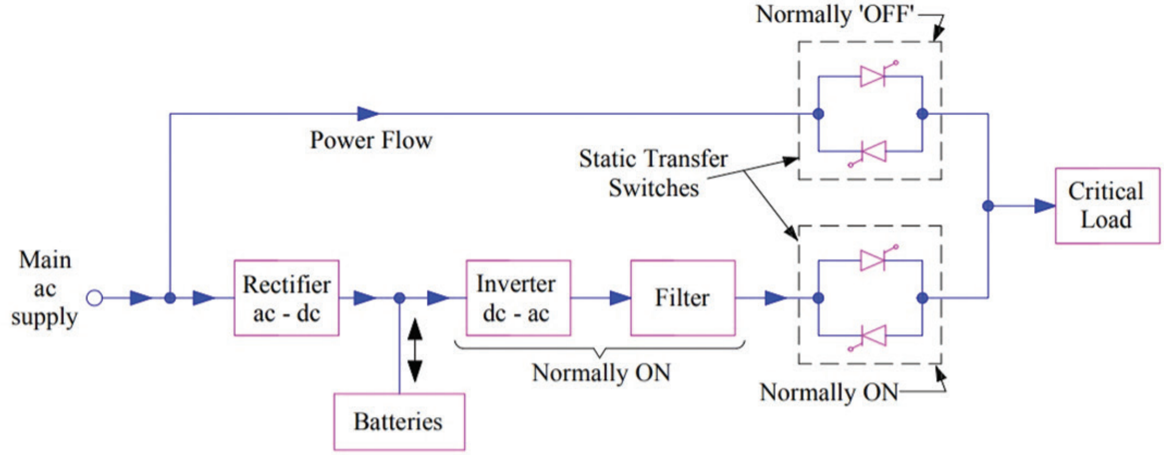

Fig. 2. Working principles of UPS (Electrical Concepts, 2022). UPS, uninterrupted power supply.

in parallel. When the inverter is overloaded or fails, the inverter will cut off the output and the static switch will be switched on automatically. After that, the main power will directly supply power to the load. The static switch is an intelligent high-power contactless switch with a conversion time of 2–3 ms (Muhammad et al., 2016).

UPS is equipment that can replace the urban power grid supply with a continuous power supply in case of power failure. Its power comes from the battery pack and continues to be supplied to the load. It is mainly used to provide power to a single computer, computer network system or other power electronic equipment. UPS can stabilise the main power grid and supply it to the load when the power grid input is normal. Currently, UPS is an AC main power grid regulator, and it also charges the battery at the same time. However, if the main power grid is interrupted (accidental power failure), UPS will immediately supply the power stored in the battery to the load through inverter conversion for a period. Therefore, there are two advantages of UPS. One is that the power supply is uninterrupted. In the case of typical power failure, the load powered by UPS will not have any impact. The other is that when the normal power supply voltage fluctuates abruptly, UPS also acts as a voltage regulator.

2.3. Emergency power supply

EPS is a piece of equipment composed of fire-fighting facilities, emergency lighting, and other first-class load power supply equipment. EPS mainly adopts Sinusoidal Pulse Width Modulation (SPWM) (AC pulse band modulation) technology, and the system includes explicitly a rectifier charger, battery pack, inverter, mutual switching device, and so on (Rathore and Rajagopal, 2017). The function of the rectifier is to convert AC into DC to supply power to the battery and inverter module. The inverter is the core, and the function of the inverter is to convert DC into AC to supply stable and continuous power to load equipment. The mutual switching device ensures the smooth switching of load between the main power grid and inverter output. Battery detection and shunt detection circuits are designed in the system, and the backup operation mode is adopted. There are two main power working modes through which the EPS can work, such as battery inverter working mode and manual maintenance bypass mode (Emadi et al., 2017). Figure 3 shows the whole function diagram of EPS. The main power working mode of EPS is bypass priority. When the main's power is normal, it comes directly from the bypass to load. At the same time, the battery is charged, and the inverter is on standby. When the main power is abnormal, the electric energy stored by the battery is inverted by the inverter to supply power to the load (Zhang et al., 2019). Furthermore, when online maintenance is required under the continuous power supply, the manual maintenance bypass switch can be directly closed, and the output switch and bypass switch can be disconnected to completely disconnect the circuit part, input, and output of the EPS power supply without interrupting the user's output (Yang et al., 2007).

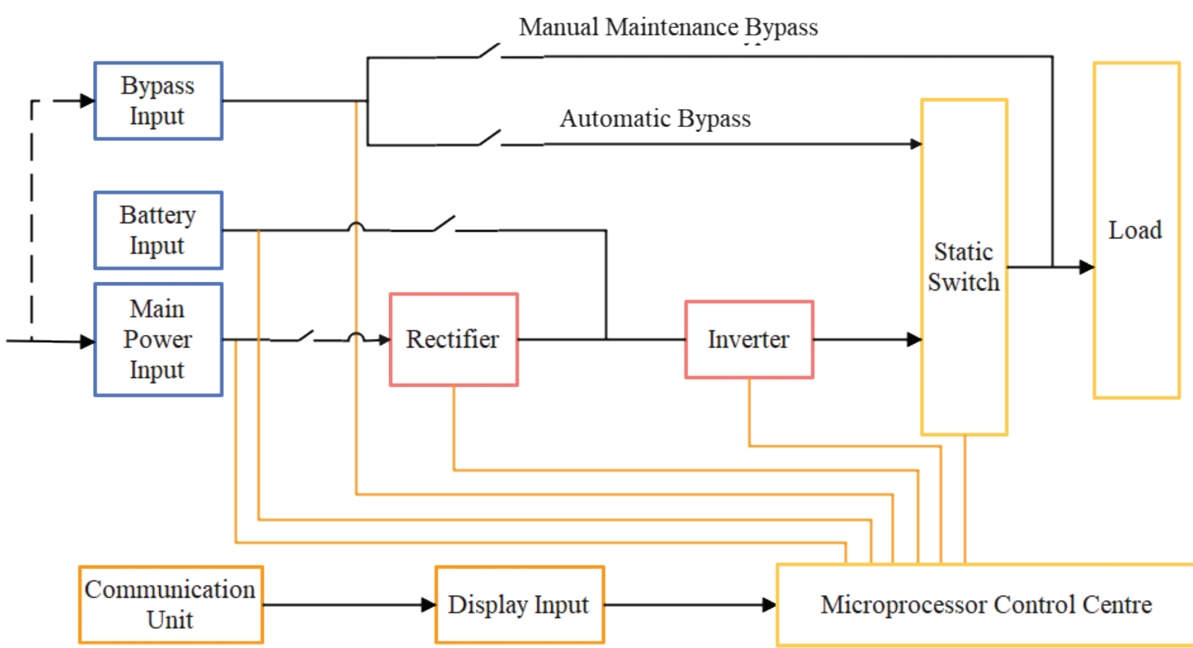

Fig. 3. The whole function diagram of EPS. EPS, emergency power supply.

Compared with UPS, EPS has a lot of advantages (Wu et al., 2021). The inverter has large redundancy. It can operate normally under 120% load and has incoming and outgoing feeder functions and a multi-channel mutual switching function. There are measures to prevent high and low temperatures, damp heat, salt fog, dust, vibration, rat movement, and rat bite. It adopts an off-line operation mode, with high efficiency, energy-saving, and low noise. Thus, the inverter can only be carried out when the power grid is off, which causes the service life of the host to be relatively long, generally 15–20 years. Finally, the total cost of EPS is less expensive than that of UPS of the same capacity (Yang et al., 2007).

2.4. The comparison between EPS, UPS, and diesel/gas generator set

Table 1 is the comparison between EPS and UPS. EPS is better at many aspects such as structure, power saving, noise, price, and life span. EPS has the advantages of a wide application environment, high power-saving performance, low noise, high economy, long service life, many types of applicable loads and wide application. However, UPS has the fastest response time, which means that if the main power grid is paralysed, UPS can supply the power to the load immediately. This is the main reason why UPS cannot be replaced by EPS.

Table 2 compares EPS and Diesel/Gas Generator Set. EPS performs better than the Generator Set in terms of the start time, environment protection, maintenance cost, power supply status, overload and protection, and construction and operation cost. The generator cannot be started in time. The generator also needs to add environmental protection facilities of about 11,000–14,000 pounds/set, fire prevention facilities of 5,800–7,000 pounds/set, and labor-management fees and regular maintenance fees of 3,500 pounds/set. In addition, the power supply quality of the generator is poor, and the ap-applicable environmental capacity is poor. On the contrary, EPS

Characteristic	EPS	UPS
Structure	Large redundancy, and can normally operate for >10 min under 120% rated load Incoming cabinet and outgoing cabinet, fire protection multi-channel mutual switching function, and special measures for dehumidification, mildew prevention and corrosion prevention	Small redundancy, generally required to work at 80% of the rated current No incoming cabinet and outgoing cabinet, fire protection, and mutual switching functions
Power saving	The bottom power consumption state when the power grid is normal. Efficiency is >90% when there is no power grid	When the supply of the power grid is normal, the efficiency is only 80–90%
Noise	The grid is normal with no static noise. When there is no power supply on the grid, its noise is <55 dB	55–65 dB
Price	Low maintenance price	Expensive maintenance price
Life span	Generally, >20 years	Generally, 5–8 years
Load adaptability	Especially suitable for inductive load	Only suitable for capacitive and resistive load (computer load)

EPS, emergency power supply; UPS, uninterrupted power supply

Table 1. Comparison between EPS and UPS Yang et al. (2007).

Characteristic	EPS	Diesel/gas generator set
Start time	<0.2 s	5–30 s
Environment protection	No smoke exhausts, noise, vibration, and pollution	A large amount of harmful gas, great noise, and vibration, and required to be fireproof
Maintain	Simple maintenance, unattended automatic operation, and computer monitoring	Special personnel shall be assigned to take care of and maintain regularly
Power supply status	Strong voltage stability, Stable frequency, no interference, and high efficiency	Unstable voltage and frequency, and low efficiency
Overload and protection	Strong overload capacity, perfect protection function, and low power capacity and load power, generally 1:1	Weak overload capacity, general protection function, and high ratio of standby generator set to load power, generally at least 1:1.5 times
Construction cost and operation cost	One time investment, basically no follow-up operation cost	The lower procurement cost of generator set equipment, but the high cost of auxiliary facilities, and many subsequent operation costs

EPS, emergency power supply.

Table 2. Comparison between EPS and diesel/gas generator set Sigarchian et al. (2015).

The daily electricity consumption of an ordinary family ()	10–20 kWh
Specific energy of the battery of an electric vehicle	15–60 kWh

Table 3. The daily electricity consumption of an ordinary family and the specific energy of the battery of an electric vehicle.

has a low comprehensive cost, easy to manage, has more stable and reliable power generation, and has a small floor area. However, the most significant advantage of the Diesel/Gas Generator Set is its long-time power supply. EPS and UPS can only supply power for a few hours depending on their capacities. A generator set can usually supply power for a few days without interruption.

The allowable power failure time of the load and the site of the load are two of the most important factors when considering how to choose and use the appropriate emergency electric power source. Based on the different needs of various loads, the combination of UPS, EPS and generators can also be applied (Sabita et al., 2015).

3. New Potential Emergency Electric Power Source: Electric Vehicle

There are always some unexpected situations that the current EPS technology cannot solve. Thus, discovering a new potential emergency electric power source can also be extremely meaningful. With the development of the electric vehicle industry, more and more electric vehicles are running in the cities. This means that the power source of each electric vehicle can be a new potential emergency power source to deal with power failure. Table 3 shows the daily electricity consumption of an ordinary family and the specific energy of the battery of an electric vehicle. According to Table 3, the daily electricity consumption of a typical family is 10–20 kWh, and the specific energy of the battery of an electric vehicle is 15–60 kWh. This means that one battery of an electric vehicle can meet 2–3 families' daily electricity demands (Young et al., 2013).

The most significant advantage of the battery of the electric vehicle is that it almost has no cost because it is only needed to be the emergency electric power source when an unexpected power failure occurs, and in a normal situation, it can also be used as the power source of the electric vehicle. This means that people do not need to buy an emergency electric power source. The electric vehicle can also be maintained by the electric vehicle company considering that it is also one part of an electric vehicle. There are some other advantages, such as decreasing the pressure of supplying emergency power to the government when a large-scale power outage occurs in view that some families have the electric vehicle to supply emergency power on their own. With the number of electric vehicles increasing, the battery of electric vehicles has the full potential to become a new kind of emergency power source.

To ensure that the private electric vehicle can be used as an emergency electric vehicle, vehicle-to-grid (V2G) is a technology that is firstly proposed by Kempton and Tomić (2005)] ensuring the bidirectional energy flow between the Electric Vehicles (EVs) and the power grid. V2G has improved the efficiency and profitability of the power grid and made significant progress in environmental protection, such as reducing greenhouse gas emissions. In addition, it also effectively reduces the cost of power consumption for each user. However, as explained in the article (Sovacool et al., 2018), V2G still needs a lot of research not only at the technical level but also in the use of natural resource use and externalities, discourses and narratives as well as social justice, gender, and urban resilience considerations. Once the V2G technology can be applied in the multi-port energy router (MER), the battery of the EV is a significant new emergency electric power source.

4. Power Supply and Control Methods

4.1. Distributed power

When it comes to using the above five kinds of emergency electric power sources in an emergency power failure situation, there are two of the most popular ways to supply emergency electric power. Distributed generation is an emergency measure prepared in advance before power failure occurs. It means that the emergency electric power source is set near the facilities requiring a power supply after the power failure. The emergency electric power source is also connected to the power grid to test if the power grid is normal (Yue et al., 2010). The basic principle of

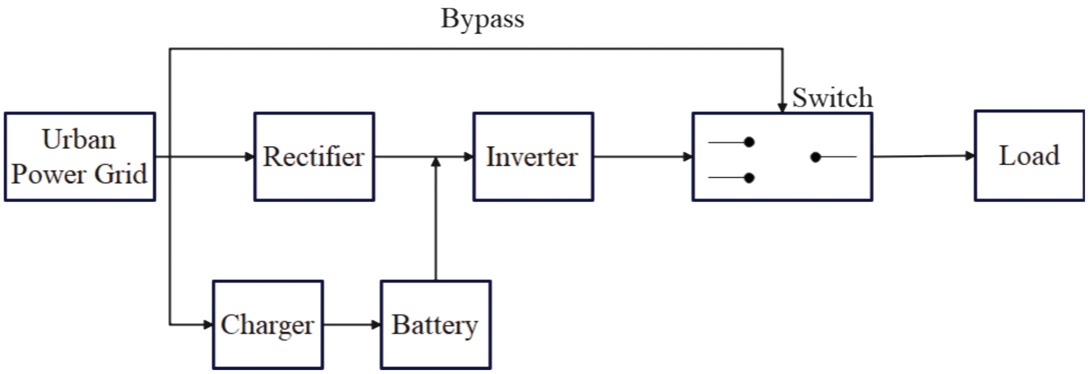

Fig. 4. Function diagram of distributed power.

distributed power is that when the urban power grid is normal, the load is supplied by the urban power grid directly through the bypass, and UPS is charged by the urban power grid through the charger, too. Once the urban power grid is abnormal, the switch will be switched to the other side and the distributed power will turn on the emergency electric power source to supply power to the load instead of the urban power grid which is shown in Figure 4.

The choice of the emergency electric power source of distributed power depends on the allowable failure time of the load. If the load is a computer system or medical facility, UPS is the best choice. However, if the load is a first-class load such as lighting systems, UPS can be the most suitable choice (Daley and Siciliano, 2003). The advantages of distributed power are various. The first advantage is easy construction and less costly. Since the single-unit capacity and power generation scale are small, there is no need to build large power plants, substations, and distribution stations. As a result, the civil engineering and installation cost is low, the construction period is short, and the investment is less. Distributed power is also close to users and has simple power transmission and distribution with low loss. Close to power users, it can generally directly supply power to the load nearby without long-distance high-voltage transmission lines. The loss of transmission and distribution is small, and the construction is simple and cost-effective. The third advantage is less pollution and good environmental compatibility. It also has the advantage of high energy efficiency. Combined with cogeneration, the waste heat of power generation can be recycled for heating and refrigeration, to realise the cascade utilisation of energy scientifically and reasonably. The fifth advantage is flexible operation and guaranteed safety and reliability. The startup and shutdown of small units are fast and flexible. It can be used as a standby power supply. Finally, distributed power can make network operations, with the ability to provide auxiliary services. It can operate jointly with the power grid and complement each other, which can not only improve its power supply reliability but also provide auxiliary services for the large power grid (Willis and Scott, 2018).

4.2. Emergency power vehicle

The second method is the emergency power vehicle whose main function is to supply the power load that needs to be able to reply quickly and extend the power supply time to a certain time during power failure after the accident. Emergency power vehicles are suitable for use in large-scale civil construction projects, such as some hospitals, high-rise office buildings, airports, satellite launch measurement and control bases, large stadiums, archives, more important scientific research buildings and so on. The emergency power vehicle has two advantages. On the one hand, the vehicle can quickly arrive at the site which has a power failure when the emergency electric power source is not prepared in advance. On the other hand, it has a fast start power supply performance after the failure of the urban power grid when the emergency power vehicle is connected to the loads (Kempton and Tomić, 2005). The rapid start-up power supply of the power supply vehicle is one of the important characteristics of the EPS vehicle. Its speed can be divided into three levels according to the reaction time: (1) Instantaneous power supply, (2) Power supply within 5 s and (3) Power supply for 5 min. In terms of instantaneous power supply, UPS is equipped in the power supply vehicle to automatically detect the municipal electric signal. When the urban power grid is cut off, the UPS will be automatically started immediately. After the generator set is started for power supply, it will automatically switch to the generator set for power supply without interruption. This mode applies to class I load and power protection operations in major public activity places. In terms of power supply within 5 s, EPS is equipped in the power supply vehicle to automatically detect the municipal electric signal. In the hot standby state of the generator set, after the urban power grid is cut off, it will automatically switch to the generator set aside for power supply within 3–5 s. After the urban power grid is restored, it can automatically switch back to the urban power grid within 3–5 s. In terms of power supply for 5 min, for ordinary power supply vehicles, the Generator Set starts to supply power from the cold standby state (Saravanan and Thangavel, 2014). The warm-up time of the Generator Set is generally >3 min, and it is switched on manually. This means that even renewable energy which needs more preparation time can be used in this situation. This mode applies to power maintenance operations in public activity places and temporary power supply for emergencies (Zhao et al., 2017).

4.3. Energy router and relating control method

Sometimes, there is more than one kind of emergency electric power source that can supply the emergency power to the load at the same time. However, the emergency power from different emergency power sources cannot connect to the load directly at the same time. This can cause damage to the load and increase the pressure bearing the burden of circuit lines. Thus, to integrate and distribute this emergency power from different kinds of emergency power sources, an energy router device can be used between different kinds of emergency power sources and loads (Son et al., 2021).

4.3.1. An AC–DC hybrid multi-port energy router

An energy router is developed from solid-state transformer (SST) (Hambridge et al., 2015). Based on the function of SST, energy routers also need to achieve intelligent management and real-time communication of the smart grid, electrical power sources, and load. This means that the energy router has obvious advantages in many aspects such as active management of bidirectional power flows (Nguyen et al., 2011), convenient access to electrical power sources (Kado et al., 2016; She et al., 2012), energy management optimisation (Gao et al., 2018; Sandgani and Sirouspour, 2017), etc. Figure 5 is the structure of an AC–DC hybrid MER which includes five parts: a grid-connected part, an energy storage part, a medium voltage DC part, an AC part, and a low-voltage DC part (Liu et al., 2019).

In the grid-connected part, there are two components: a filter and an AC/DC converter to realise bidirectional power flow between the power grid and the MER. The energy storage part which is an essential part to make energy management and high power supply reliability come true consists of a DC/DC converter and filter inductance. The medium voltage DC part comprises some support capacitors and provides a 750 V DC port to get access to the

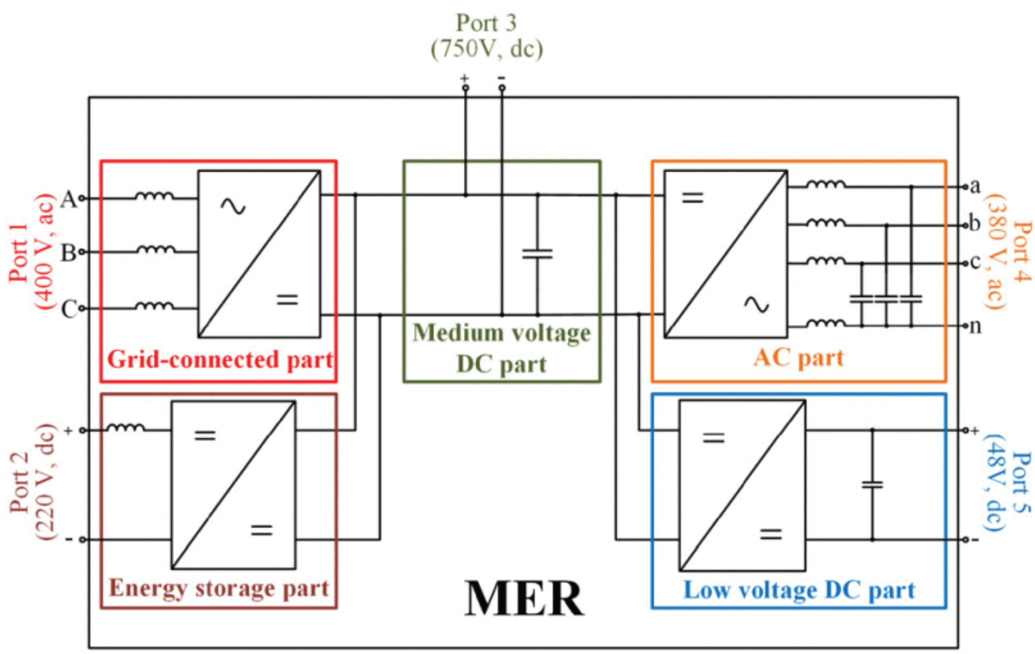

Fig. 5. Structure of MER Liu et al. (2019). MER, multi-port energy router.

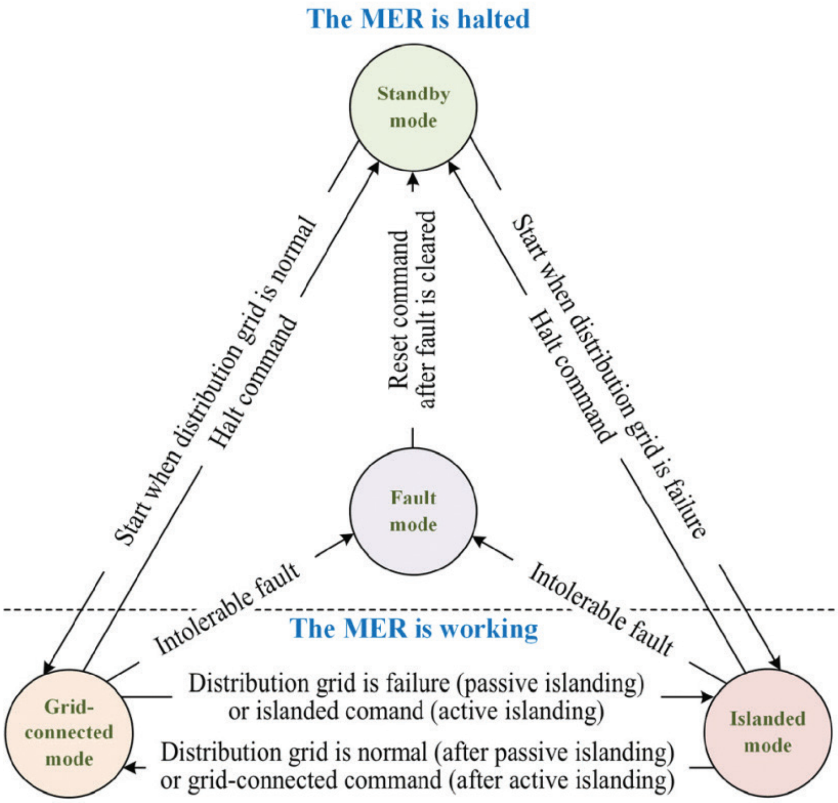

Fig. 6. Operation mode transition of MER Liu et al. (2019). MER, multi-port energy router.

other parts. The AC part is composed of a DC/AC converter and a filter to transfer DC power into AC power to satisfy the needs of the AC load. The low-voltage DC part is made up of a DC/DC converter and filters which decrease the DC voltage to supply a lower DC voltage to the DC load (Liu et al., 2019).

There are mainly four modes to operate this MER: standby mode, grid-connected mode, islanded mode, and fault mode. The relationship between these four modes is shown in Figure 6.

In the standby mode, the MER is not working until a start command is received. If the power grid is normal, MER will be switched into the grid-connected mode. Otherwise, MER will be switched into the islanded mode (Liu et al., 2019).

When MER is in the grid-connected mode, the ports in the grid-connected part are connected to the power grid. The controllers in the grid-connected part ensure the voltage stability of the medium-voltage DC link (Liu et al., 2019). The controller in the energy storage part will control the charge and discharge state of the battery according to the power that the load needs and the power that the power grid supplies.

If MER is in the islanded mode, the grid-connected part will stop working and the energy storage part will be responsible for supplying the power to the load. Besides, the controller in the energy storage part will ensure the voltage stability of the medium voltage DC link instead of the controller in the grid-connected part (Liu et al., 2019). Two situations make the MER work in the islanded mode. One is when the power grid is abnormal, the MER must work in the islanded mode to ensure safety. The other is that MER receives a command that asks it to work in the islanded mode.

When a local fault occurs in the energy storage part, AC part and low voltage DC part, MER will shut down the part which has a fault to make sure the normal working of the rest of the parts. However, if an unboreable fault such as overvoltage of a medium DC bus occurs, MER will be switched into fault mode to protect all the systems and shut down all the ports. In fault mode, MER will not be switched into standby mode until the fault is fixed and a reset command is received (Liu et al., 2019). With these four operation modes, MER can work regularly and make sure reliable power is supplied to the load.

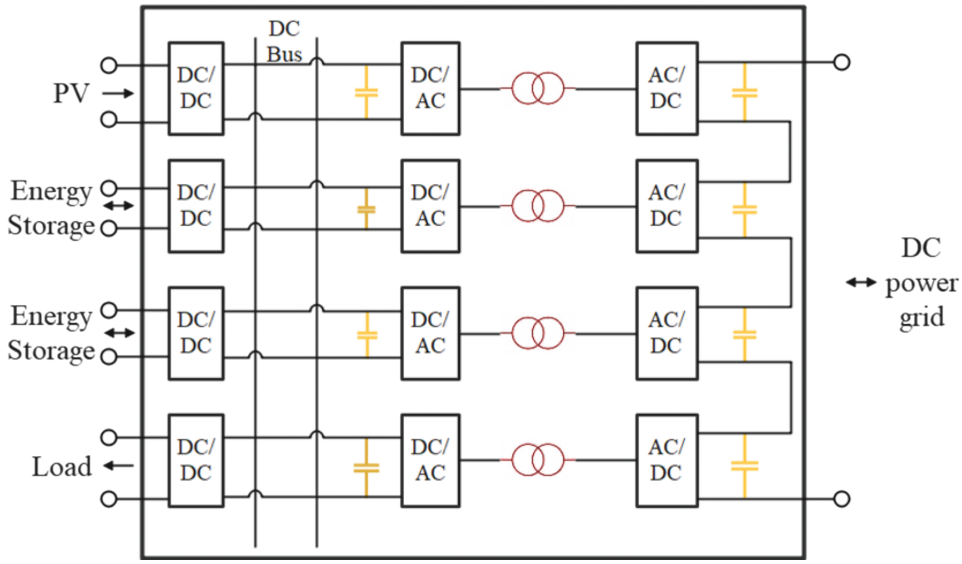

Fig. 7. Topology of energy router based on power electronic transformer.

4.3.2. An energy router based on a power electronic transformer and relating control method

This section introduces an energy router based on a power electronic transformer (Lai et al., 2017). This energy router can connect the medium voltage distribution network and low-voltage regional network, regulate the low-voltage DC bus, and provide a low-voltage DC bus for renewable energy equipment, energy storage devices, and load to realise the two-way flow of energy. Based on the above requirements, the designed energy router is a multi-input and multi-output plug-and-play interface circuit, which mainly consists of a power electronic transformer, photovoltaic system, energy storage device, and DC load like what is shown in Figure 7.

If the system is connected to the grid, the high-voltage DC bus can supply power to the load through the power electronic transformer, the DC microgrid can also feed the distribution network through the DC transformer. In case of system failure, photovoltaic power generation and energy storage devices can form a low-voltage DC microgrid and operate in islanded mode. The power electronic transformer here adopts the cascade form of a double-active full-bridge converter (DAB) to realise voltage conversion and electrical isolation (Lai et al., 2017). Multiple identical DABs are connected in series to the medium voltage DC distribution network at the high-voltage end and connected in parallel to the low-voltage DC microgrid at the low-voltage end and serve as a plug-and-play interface for photovoltaic system, energy storage device, and load, compatibility, and flexibility. The interface circuit of the photovoltaic power generation unit is the boost circuit, and the energy storage device consists of a battery and bidirectional Boost/Buck converter.

To control when and which emergency power sources supply the emergency power to the load, the energy router also needs a control system for energy management. This energy router uses a hierarchical control system design. The hierarchical control system design is shown in Figure 8, where I_{PV} is the photovoltaic current; U_{pv} is the photovoltaic voltage; U_b is the terminal voltage of the battery; I_b is the output current of the battery; U_{load} is the load voltage; I_{load} is the load current; U_{dc} is DC voltage, and I_{dc} is the DC current. The control system is divided into three layers: the upper layer is the function customisation layer; the middle layer is the energy management layer, and the lower layer is the executive layer (Lai et al., 2017).

The function customisation layer takes the photovoltaic output power, the residual capacity of the battery, real-time electricity price, and other information as input signals to determine the system scheduling mode. The system scheduling mode is mainly divided into economic mode and user-defined mode (Liu et al., 2019). Under the economic mode, users can sell power to the external power grid to obtain economic benefits if the residual capacity of the energy storage system is sufficient and the electricity price is high. When the remaining capacity of the energy storage system is insufficient and the electricity price is low, power is absorbed from the external power grid to charge the energy storage system. In terms of the user-defined mode, when the external power grid outputs the specified power, users can determine the energy use strategy according to their own energy use. In both modes, the system operating mode signal will be generated. The energy management layer determines the working mode of

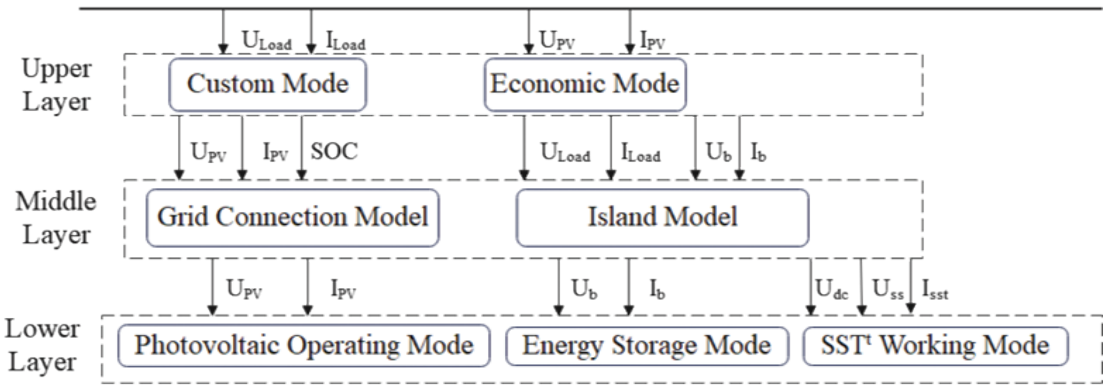

Fig. 8. Hierarchical control system. SST, solid state transformer.

the system according to the control signal generated by the upper layer, the output power of the photovoltaic and the residual capacity of the energy storage battery, which is grid-connected mode and islanded mode. At the same time, the corresponding logic control signal is generated and transmitted to the execution layer. The main function of the execution layer is to receive the logic control signal, make the logic combination and enable the controller, calculate according to the specific algorithm, further generate the pulse modulation signal, and generate the corresponding drive tube pulse according to the pulse modulation signal. The system only needs to send instructions to the converter, and each converter can execute according to the instructions.

The energy management of this energy router is carried out from two working modes: grid-connected mode and islanded mode (Lai et al., 2017). In the grid-connected mode, due to the high cost of renewable energy power generation such as photovoltaic power generation, it is generally set to maximum power tracking (MPPT) mode to fully utilise the electric energy generated. In the user-defined mode, when the external power grid is in constant power generation if the power currently is higher or lower than the load demand power, the energy storage is responsible for maintaining the power balance and voltage stability in the microgrid. In the economic model, if the electricity price is high and the remaining energy storage capacity is sufficient, the energy storage battery discharges at constant power. In contrast, when the electricity price is low and the remaining energy storage capacity is insufficient, the battery is charged with constant power. Besides, if the output power of distributed generation is greater than the demand power of load, the external power grid can absorb additional power to prevent the rise of bus voltage. However, when the output power of the distributed generation cannot meet the demand of the load, the external power grid can supplement the power shortage of the distributed generation to prevent the drop in bus voltage.

When the DC microgrid dominated by photovoltaic and energy storage is disconnected from the external DC bus, the local DC microgrid is in islanded mode. Currently, the power in the system mainly consists of photovoltaic output power, battery output power, and load demand power. Generally, the photovoltaic interface converter works in MPPT mode and only injects power into the bus, while the energy storage unit is used to maintain the bus voltage and balance the power flow in the system. For example, when the power injected into the bus is large, the energy storage battery enters the charging state to suppress the rise of bus voltage. If the power injected into the bus is small, the energy storage battery enters the discharge state to suppress the drop in bus voltage. If the photovoltaic output power is higher than the load demand power and the energy storage charging state reaches the extreme value, the energy storage battery will no longer maintain the bus voltage, and the photovoltaic will be switched from MPPT mode to constant voltage mode. When the total output power does not meet the demand of the load, the bus voltage is lower than the minimum required by the DC microgrid. At this stage, the bus voltage of the DC microgrid will decrease significantly, resulting in the paralysis of the microgrid. Therefore, to maintain stability, it is necessary to selectively cut off the unimportant load according to the load-shedding algorithm to avoid bus voltage collapse.

4.3.3. Energy router based on an integrated circuit building block (ICBB)

An ICBB type of energy router for a power electronic converter can extremely decrease the volume of the component and improve the power processing efficiency (Ahsanuzzaman et al., 2017). This ICBB consists of two segmented half-bridges and all the components that are used to make mixed-signal current programmed mode (CPM) control come true which are shown in Figure 9.

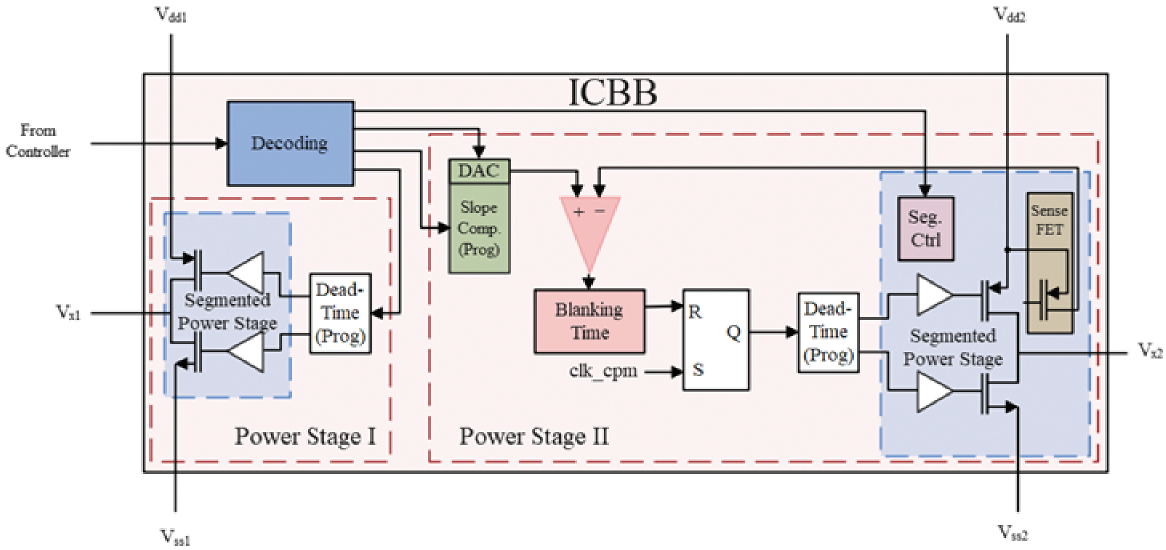

Fig. 9. Block diagram of low-power ICBB Ahsanuzzaman et al. (2017). ICBB, integrated circuit building block.

These two-segmented half-bridges have the same design. However, power stage II has an extra circuit called Sense Field Effect Transistor (SenseFET) for current sensing which makes mixed-signal CPM controllability possible. This design fulfils two needs which are the possibility of operating at high switching frequencies, and low-power consumption. Besides, this design can be sure to be used with the online efficiency optimisation schemes at the same time which can improve the efficiency of power processing by compromising between the ON-resistance and gate charge of the switches. Furthermore, through segmentation, the problems of the limited speed and high-power consumption caused by the conventional SenseFET current measurement circuits can be solved to make full use of the multi-levels of different sources. The topology which uses ICBB modules is shown in Figure 10.

This converter allows various kinds of DC sources and converts these different input voltages into one output voltage synthesis through ICBB modules which include DC/AC conversion. This design makes the adjusting of voltages easier so that the efficiency of the energy collecting can be improved.

4.3.4. An energy router supplying AC and DC load separately

Some energy routers can supply power to the DC load and AC load at the same time (Li et al., 2021). There is a new topology that has two imports and two exports. One import is connected to the grid directly, and the other import is connected to renewable energy. With the combination and complementation of these two kinds of energy forms, the problems of one single power form supply and low utilisation of renewable energy can be solved (Chi et al., 2021). According to Figure 11, this MER consists of a three-phase cascaded H-bridge, isolated DC/DC converters, a three-level inverter, and a Buck/Boost converter. The grid transfers its power to the medium-voltage DC bus through a cascaded H bridge and isolated DC/DC converters. DC load can be supplied by the medium-voltage DC bus directly. AC load needs the AC power transferred by the three-level inverter from a medium-voltage DC bus. The power from renewable energy can be accessed into the medium-voltage DC bus through Buck/Boost converter.

The more concrete topology is shown in Figure 12 on the high-voltage side. The capacitor at the medium-voltage DC side is designed to reduce the voltage ripple and improve power quality (Messo et al., 2013). According to Kirchhoff's voltage law, Eqs (1) and (2) can be obtained

$$\begin{cases} E_{xi} = S_k U_{dc1-xi} \\ E_x = L_s \dfrac{di_x}{dt} + R_s i_x + \sum_{i=1}^{n} E_{xi} \end{cases} \tag{1}$$

$$U_{dc2-xi} = S_{k1} S_{k2} k U_{dc1-xi} \tag{2}$$

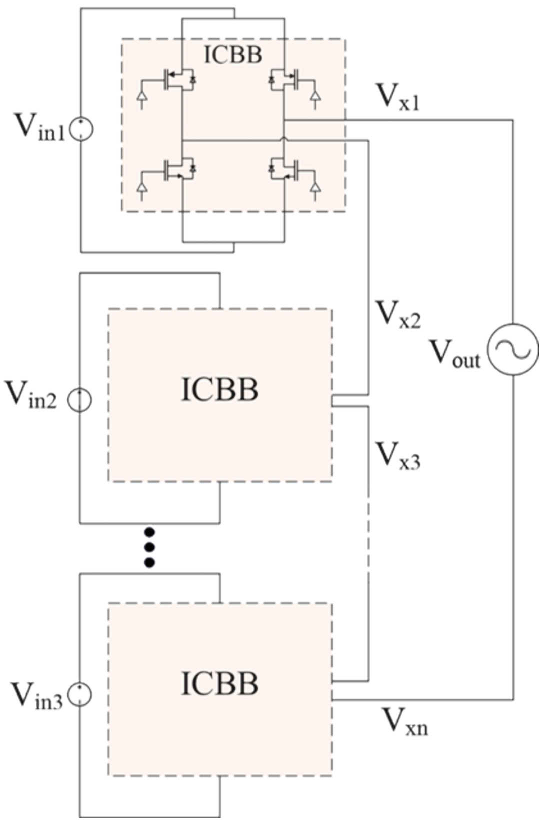

Fig. 10. Multilevel inverter implementation utilising ICBB modules Ahsanuzzaman et al. (2017). ICBB, integrated circuit building block.

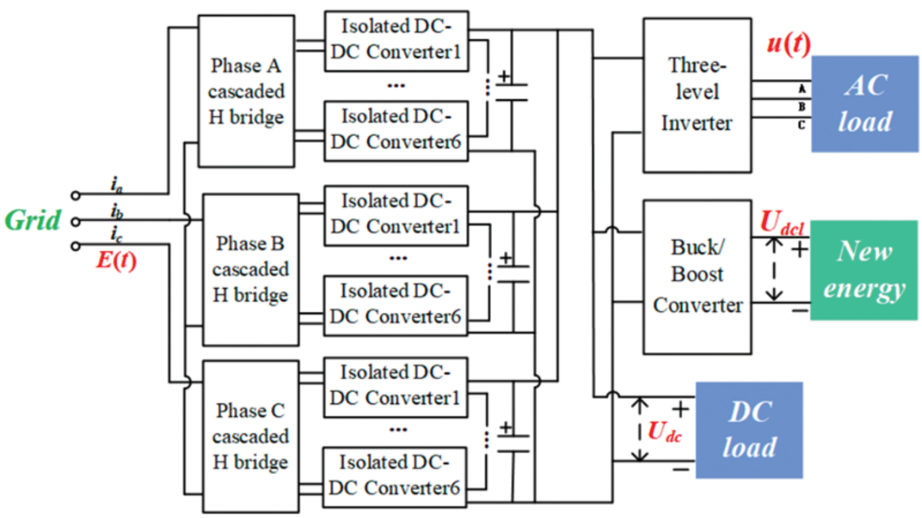

Fig. 11. A topology of MER Chi et al. (2021). MER, multi-port energy router.

where E_x is the grid voltage (x = a, b, c), i_x is the grid current, E_{xi} is the AC voltage of the *i*-th cascaded H-bridge, $U_{dc1\text{-}xi}$ and $U_{dc2\text{-}xi}$ are pre-stage voltage, and post-stage voltage of the i-th isolated DC/DC converter, S_k is switching function of cascaded H-bridge, L_s and R_s are equivalent inductance and resistance on the grid side, S_{k1} and S_{k2} are the switching functions of the pre-stage and post-stage of the isolated DC/DC, and *k* is the ratio of the high-frequency transformer (Chi et al., 2021). From Eq. (1), the output DC voltage can be controlled by changing the value of S_k.

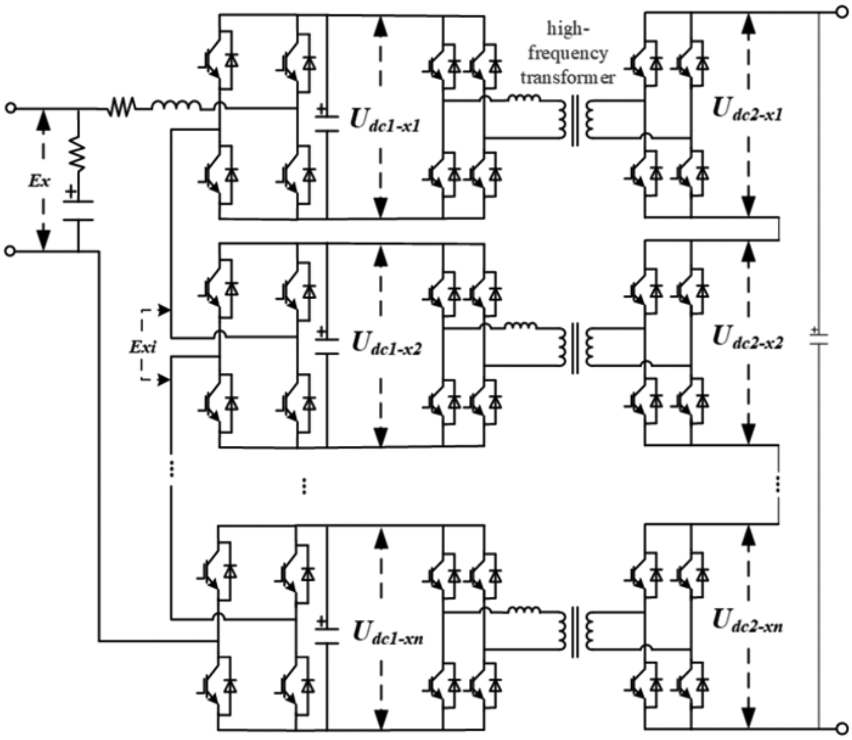

Fig. 12. Topology of high-voltage side Chi et al. (2021).

According to Eq. (2) the output voltage at the low-voltage side can be controlled by the value of S_{k1}, S_{k2} and k. Therefore, the transmission power $P_{DC/DC}$ can be obtained.

$$P_{DC/DC} = \frac{U_{dc1-xi}U_{dc2-xi}}{2k\pi f_s L_m}\delta\left(1-\frac{|\delta|}{\pi}\right) \tag{3}$$

where f_s is the switching frequency, L_m is the leakage inductance of a high-frequency transformer and δ is the pulse shift angle (Chi et al., 2021). According to Eq. (3), the $P_{DC/DC}$ can be controlled by changing the value of δ.

In terms of this topology of the high-voltage side, the sub-modules can be turned on or off separately because the bridge arm reduces the voltage and current change rate with the cascade structure existing. This means the switch has less stress and the total output voltage is less possible to distort. Besides, the high-frequency transformers have a significant influence in weakening the high-frequency harmonics and decreasing the noise. Finally, this design can ensure there is no interference between the grid and the secondary sides.

On the low-voltage side, there are two topologies: a topology of a DC/DC converter and a topology of a DC/AC converter. The DC/DC converter is used for renewable energy to access the medium-voltage DC bus. This DC/DC converter's non-isolated Buck/Boost structure is adopted in this DC/DC converter. The topology of this DC/DC converter is shown in Figure 13. In Figure 13, U_{dc1} is the low-voltage side that connects to the renewable energy module, and U_{dc} is the medium-voltage side that connects to the medium-voltage DC bus. If the renewable energy module can supply power to the medium-voltage DC bus, DC/DC converter works in Boost mode. It can increase the input voltage and supply a stable DC voltage to the medium-voltage DC bus. On the contrary, when the power storage module needs to be charged, the DC/DC converter works in Buck mode. It can charge the power storage module by converting the voltage from the medium-voltage DC bus. Eq. (4) can calculate the output voltage of this converter

$$U_{dc1} = D\frac{U_{dc}}{1-D} \tag{4}$$

where D is the duty ratio of the converter.

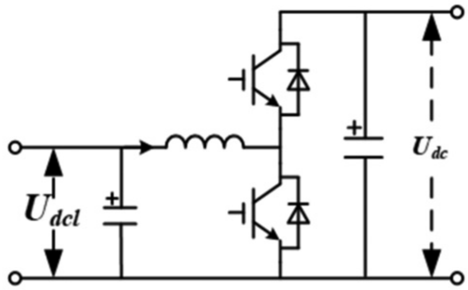

Fig. 13. Topology of DC/DC converter Chi et al. (2021).

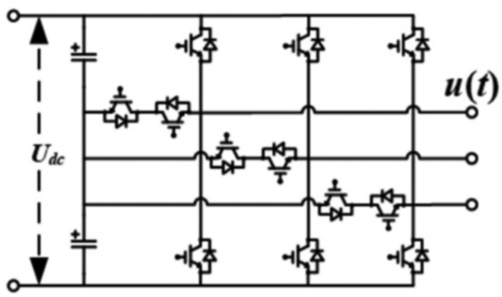

Fig. 14. Topology of DC/AC converter Chi et al. (2021).

DC/AC inverter is used to convert the DC power in the medium-voltage DC bus into AC power which is supplied to the AC load. This DC/AC converter uses a three-level structure. The topology of this DC/AC converter is shown in Figure 14. According to Figure 14, the output voltage is

$$u(t) = \frac{U_{dc}}{2}(d_x + n_x) \tag{5}$$

where d_x is the duty ratio and n_x is the benchmarking function for the conversion between the switch status of the three-level inverter, $n_x = \begin{cases} 1, O \to P \to O \\ 0, N \to P \to N \end{cases}$ (Chi et al., 2021). This three-level structure of a DC/AC converter has less harmonic and better power quality than a two-level DC/AC converter (Choudhury et al., 2014).

4.3.5. A parallel coordinated control strategy based on virtual capacitor control in the four-port isolated DC/DC converter

With the development of renewable energy and batteries, the electric power sources used for an energy router are mostly DC sources. However, the DC micro-grid usually has small inertia. This means that its bus voltage will easily be affected by the power fluctuations caused by intermittent renewable energy and local load changes (Dragičević et al., 2013; Soni et al., 2013). Therefore, to control the bus voltage in the DC micro-grid to improve the inertia and stability of the DC micro-grid, there is a parallel coordinated control strategy based on virtual capacitor control in the Four-port isolated DC/DC converter (FPIC) to make sure that each output power of energy storage unit is allocated according to the remaining capacity and the charge state of each energy storage unit is balanced (Liang et al., 2020).

According to Figure 15, there is a two-stage isolated bidirectional DC/DC converter that connects the Photovoltaics (PV) source and two energy storage to a 400 V DC bus. On the other side, there is also a three-port DC converter connecting with the DC load. The front stage of the two-stage converter is CLLC resonant circuit with the rear stage being the interleaved Buck/Boost circuit. u_{dc} is the DC bus voltage, i_{dc} is the DC output current; n_T is the transformer turns ratio; L_m and L_r are the resonance inductance and resonance inductance of the resonator; C_1 and C_2 are the resonance capacitance; C_{in}, C_M, and C_O are the input of FPIC respectively Capacitor, intermediate stage capacitor, and output capacitor (Liang et al., 2020).

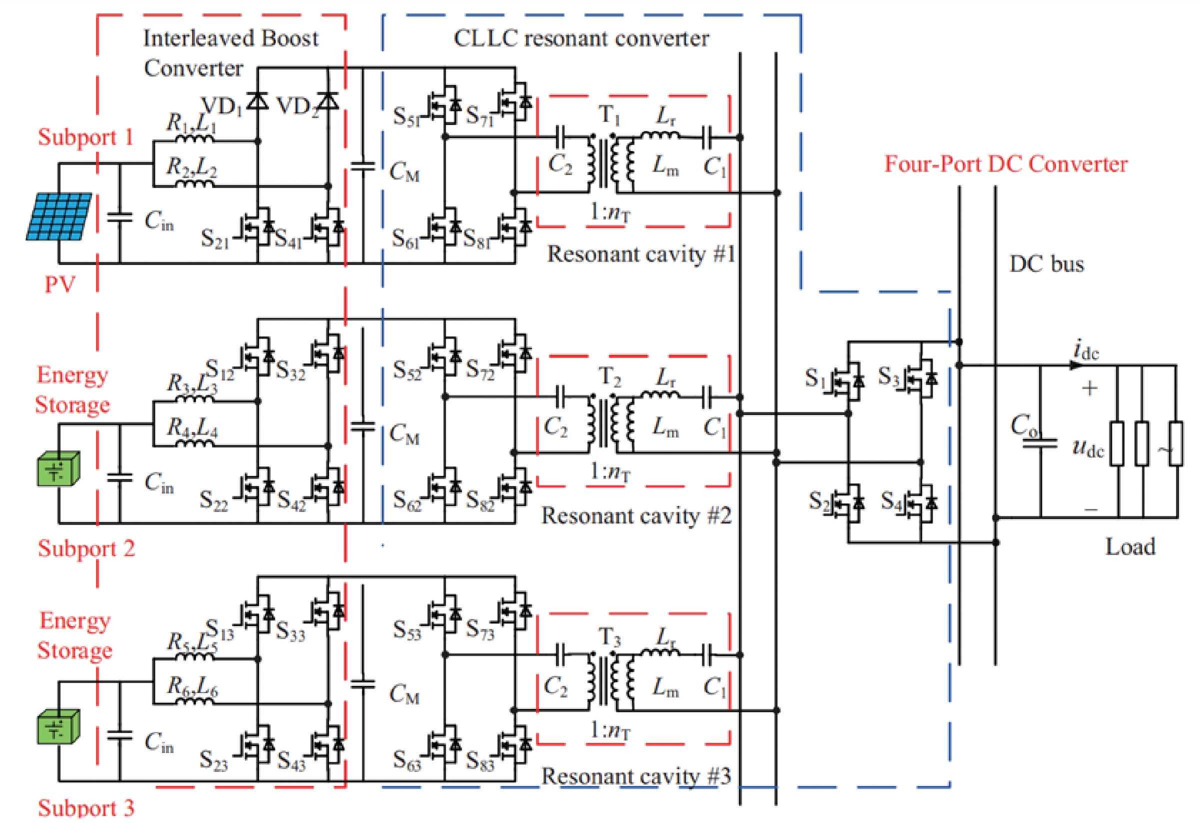

Fig. 15. DC micro-grid structure diagram of photovoltaic energy storage with FPIC (Liang et al., 2020). FPIC, Four-port isolated DC/DC converter.

The exact control method of this FPIS is as follows. Firstly, In the CLLC resonant circuit, a duty cycle of 50 percent is applied by the high-side full bridge and the two low-side full bridges to the switch tubes S_1, S_4, S_{5i}, *S8i (i = 1,2)*. Its switching frequency is the control signal of resonant frequency (in-phase). The other switching tubes S_{53} and S_{83} apply a complementary control signal. In terms of the post-stage interleaved Buck/Boost circuit, it is assumed that the photovoltaic converter has been working in the MPPT state and the energy storage converter (ESC) operates in improved virtual capacitor (IVC) mode. For the lower arm switch tubes S_{22} and S_{42}, Apply a driving signal with a phase difference between 180° and the same duty ratio. Besides, control the driving signals of the upper and lower arm switch tubes to be complementary.

Through the design of the virtual capacitor, the droop control of the ESC can simulate the charge and discharge characteristics and damping characteristics of the real capacitor so that the disturbance suppression ability of the DC bus voltage can be enhanced. The final equation of virtual capacitance corresponding to this IVC control is:

$$\begin{cases} C_{vir} = C_{v0}, \Delta_1 \le K \\ C_{vir} = C_{v0} + k_u S_2, \Delta_1 > K \text{ and } \Delta_2 > 0 \\ C_{vir} = C_{v0}, \Delta_1 > K \text{ and } \Delta_2 \le 0 \end{cases} \tag{6}$$

where C_{vir} is the virtual capacitance, C_{v0} is the initial virtual capacitance, k_u is the voltage tracking coefficient, K is the limited value of the voltage change, $\Delta_1 = |\Delta u_{dc}|$, $\Delta_2 = sgn\left(du_{dc}^* / dt\right)\Delta u_{dc}$, u_{dc}^* is the reference of DC bus voltage, S_2 is the on/off state value. If $\Delta_1 > K$ and $\Delta_2 > 0$, $S_2 = \Delta_2$ Liang et al. (2020).

To effectively manage and use energy storage devices in FPIC more efficiently, the multiple energy storage and coordinated control mainly includes IVC control, voltage and current dual-loop control and output current feed-forward control is also applied.

4.3.6. An energy hub with an energy router

An energy hub in Figure 16 is also able to supply various kinds of load instead of only electricity load (Almassalkhi and Hiskens, 2011). Figure 17 shows a schematic of an energy hub in which various kinds of electric power sources and gas supplies generate heat and power to satisfy the electricity load, cooling load and heat load (Li et al., 2020). Energy router has the advantages such as improved quality of power, a smaller size, tolerance of fault, and reactive power support feature (Syed et al., 2018). Figure 17 proposes a topology of energy hub which includes an energy router that realises the coordination of multiple energy sources and improves the efficiency of energy (Li et al., 2020).

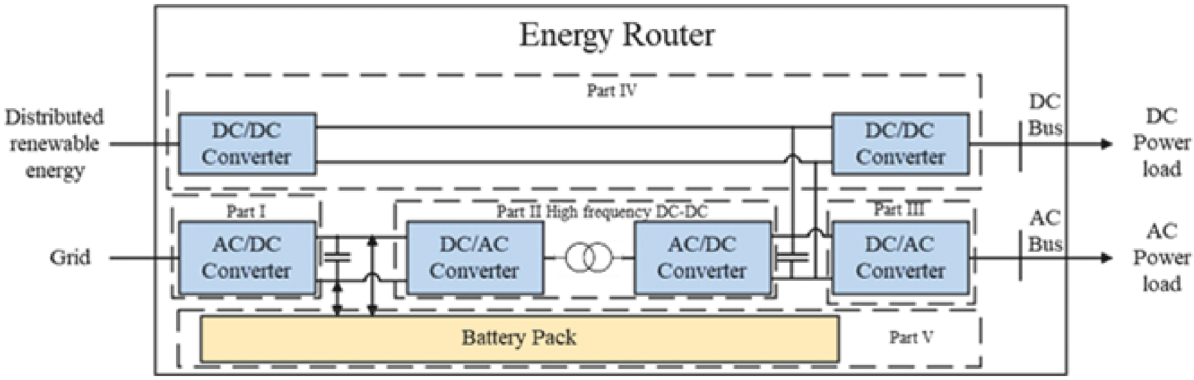

Fig. 16. The configuration of the energy hub Li et al. (2020).

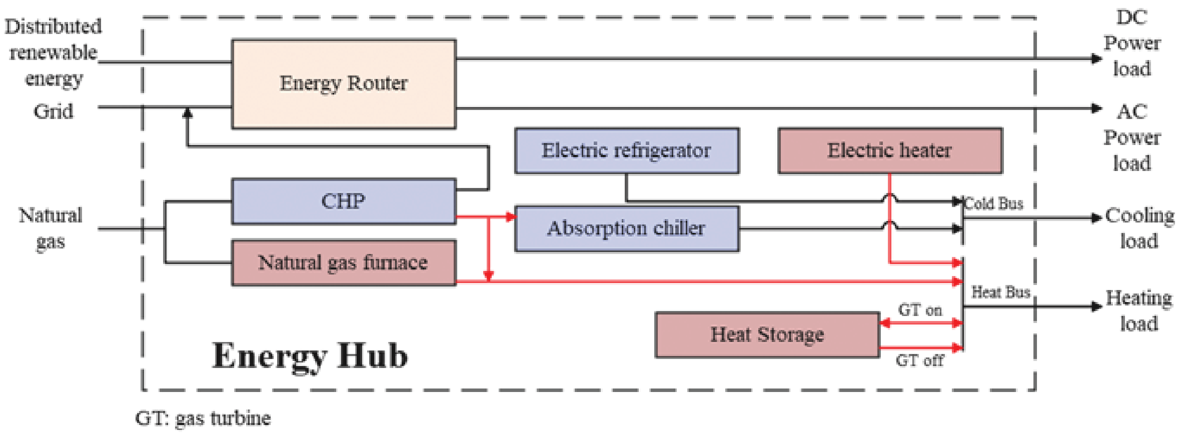

Fig. 17. The topology of an energy router Li et al. (2020).

The basic principle of this energy router is that it mainly uses distributed renewable energy to supply power to all loads and satisfy the charging demand of the battery pack. However, if the distributed renewable energy is unstable and unable to supply enough power, the power in the energy storage components (battery pack and Heat storage) will be used to generate power to satisfy the demands of the load. Besides, When the power supplied by the distributed renewable energy is still rest after satisfying the demands of all the load and battery pack, the rest power can be delivered to the power grid so that the rest power can be utilised by the load in other areas. The charging and discharging state of energy storage components can also be controlled (Li et al., 2020).

4.3.7. Discussion

Table 4 compares all the above energy routers from four of the most essential parts: import electric power source, export load, electronic power converter included, and energy storage function. In terms of the choice of emergency

	Import electric power source	Export load	Power electronic converter included	Energy storage function
Example 1	AC Power grid	AC load and DC load	AC/DC converter, DC/DC converter, and DC/AC converter	A power storage part which is charged by the AC power grid
Example 2	DC power grid and photovoltaic power	DC load	AC/DC converter, DC/DC converter, and DC/AC converter	Two energy storage modules charged by the DC power grid and photovoltaic power
Example 3	Various kinds of electric power sources	AC load	An ICBB	No energy storage function
Example 4	AC Power grid and renewable energy	AC Load and DC load	AC/DC converter, DC/DC converter, and DC/AC converter	One energy storage module charged by the AC power grid
Example 5	Photovoltaic power	DC Load	DC converter	Two energy storage modules charged by the photovoltaic power
Example 6	Renewable energy and AC Power grid	AC load and DC load	AC/DC converter, DC/DC converter, and DC/AC converter	One battery pack charged by the AC power grid

ICBB, integrated circuit building block.

Table 4. The comparison among energy routers.

power electric sources, connecting to the power grid could be greatly helpful to test if the power grid is normal. This is applied by the majority of energy routers. DC load and AC load can both be supplied by the energy routers as long as the correct and suitable power electronic converters are applied. Power electronic converters which are the most important parts of the energy router should be determined and selected according to the types of power electric sources and the types of load. The different design circuits of power electronic converters can easily lead to the difference between the function and power transmission performance of the energy routers. Besides, the energy storage function is an essential part of the energy router. It makes sure of power management and adjusting. It can supply power to the load when the power of electric power sources is not enough to satisfy the needs of the load. If the power of electric power sources is more than the needs of the load, the energy storage module will be charged by the extra power of electric power sources to improve the efficiency of the power transmission.

Example 1 MER has a lot of advantages such as the plug-and-play access of DERs and loads, various forms of electric energy, unified control and management of the MER-based energy subnet, high power supply reliability, fault isolation between the grid side and the users' side, etc. (Nikmehr et al., 2022). However, this kind of MER is only suitable for the low-voltage distribution network. Example 2 energy router realises flexible control and management of voltage and power, but it can only be used in the DC power grid. Example 3 introduces an ICBB design of emerging low-power, high-frequency multilevel and hybrid converter topologies operating at switching frequencies up to 10 MHz, however, with no power storage function and is only applicable for the AC power grid (McLaughlin et al., 2020). MER in example 4 utilises a free switching control strategy which can accurately transmit the required power and maintain the stability of the DC bus voltage. However, it can only be used in the distribution area with a high penetration rate of the new energy. The energy storage system of the energy router in example 5 can accurately distribute the output power according to the proportion of the remaining capacity of each energy storage unit to the total remaining capacity to ensure the safe and reliable operation, but the energy router has no connection with the power grid (Mahmood and Blaabjerg, 2022). The energy router in example 6 has relatively complete functions. however, it is designed for a part of the energy hub and renewable energy is the main source of energy instead of the power grid.

According to reviewed energy routers, the energy router is the most effective and potential distribution way that can be used in the emergency electric power supply in the future (Bulatov et al., 2021). Not only it can be set before the emergency occurs and store the power with a power-storage module, but also can connect multi kinds of different emergency electric power sources at the same time and utilise and combine them to generate stable and continuous power to the load which suffers from the unexcepted power failure. Thus, to better address the problem of a large-scale sudden power outage, developing a MER that can be connected to the power grid and other emergency electrical power sources is essential. This MER can detect if the power grid is working normally and combine the power of the power grid with the power of any other emergency electric power source to complete the power adjusting which can ensure to satisfy the needs of the load. The energy storage module in this kind of MER can also be charged by both the power grid and the emergency electrical power sources. Besides, it can supply power to the load when the power grid is paralysed, or the power supplied by the power sources cannot meet the needs of the load. With this kind of energy router, all kinds of emergency electrical power sources can relate to the power grid to supply power at the same time and minimise the loss caused by power failure.

5. Conclusion

The emergency power source is critical to deal with the unexcepted large-scale power failure of the power grid in the future. Discovering more efficient application schemes and more feasible new emergency power sources is the most important work to handle large-scale power failure and decrease economic loss and ensure safety of lives of people. At present, emergency power sources are various and can basically deal with many situations of sudden power failure. Therefore, it is extremely important to have a related complete, and excellent emergency power distribution scheme to supply emergency power to the areas in which occurs power failure. The allowable power failure time of the load and the site of the load are two of the most important factors when considering how to choose and use the appropriate emergency electric power source. In addition, to be more prepared to deal with sudden power failure, the battery of the electric vehicle is also a new and potential emergency electric power source considering that electric vehicles have been more and more popular. Besides, the energy router is the most potential device that can connect the emergency power sources to the load fast and is also set near the customers and easy to operate. A MER can also connect various kinds of different emergency electric power sources at the same time and adjust and store the output power of each emergency electric power source to meet the needs of the load. This means that the energy router can improve the efficiency of using emergency electric power sources and supply the load with a more stable voltage and current. Therefore, a MER that can connect the power grid with various kinds of emergency electric power sources with the function of storing power can be the most important and popular distribution way to explore and research the problems of large-scale unexcepted power failure in urban cities Besides, it also needs a lot of feasibility research to connect the battery of the electric vehicle to the energy router to realise bidirectional energy transmission.

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