An Open Energy Routing Network for Low-voltage Distribution Power Grid

Xinyang Han, Fang Yang, Cuifen Bai, Guanglong Xie,
State Grid Energy Research Institute,
Beijing, P. R. China

Junwei Cao, Guang Ren, Haochen Hua,
Research Institute of Information Technology,
Tsinghua University,
Beijing, P. R. China
renguang@ tsinghua.edu.cn

***Abstract*—Focusing on the issues of access management and consuming in energy routing network within the low-voltage distribution grid, this article studies the energy management mechanism from the perspective of routing topology, and the routing matrix is proposed to realize such mechanism. Firstly, we design a type of low-voltage ER (ER), in which the new energy and 380v distribution grid are adopted as energy resources, and energy storage devices are used to compensate the DC bus, such that the ER could manage all accessed devices. Secondly, we propose two types of energy routing topologies, i.e., series-shaped and star-shaped energy routing network, implementing the networking energy management in a low-voltage distribution grid. Furthermore, we put forward the energy routing matrix which describes the real-time operation status when the power devices are accessed with other routers, and the interacted change of such matrix is adapted to the open networking management. The simulation experiments show that the utilization of the single ER, the series-shaped and star-shaped routing network could implement the open access of power devices and network interactive management within the low-voltage distribution grid. Meanwhile, the balance of power in the local network is achieved.**

***Keywords*—EI, ER, Routing topology;**

I. INTRODUCTION

Since human beings have reached a consensus that green and low carbon energy consumption, currently many countries, especially advanced countries are trying to reduce carbon emission and improve energy efficiency. It is the EI (EI) that is regarded as the most effective approach to realizing such target. Rifkin analyzed the prospect of EI in *The Third Industrial Revolution* [1], there EI is supposed to bring people with new ideas, such as green energy, low carbon, high efficiency and energy sharing.

Regarded as the next generation energy management equipment, EI is believed to be the core of EI at an advanced development stage, see, e.g., [2]. The investigation of ER has drawn many researchers' attention in the past few years, among which, the concept of EI was first proposed in a project funded by American National Science in 2008, namely, "the Future Renewable Electric Energy Delivery and Management (FREEDM) system" [3,4]. It proposes that EI can be viewed as one type of novel grid structure based on renewable power generation as well as distributed energy storage devices. In this project, inspired by the core router of information technology, the definition of ER was proposed, and a prototype was implementated [5]. Within the same year, the research group of Swiss Federal Institute of Technology developed "Energy Hub" [6-9], which is originated from the concept of hub in computer science, also known as the energy control center. In 2013, researchers in Japan presented the concept of "Power Router", which is also known as the digital power grid router. This particular router could manage the power within a certain range of area and dispatch regional power [10]. Besides, focusing on the energy management between power usage and demand in the smart grid, some researchers in North Carolina State University studied the infrastructure and communication performance of ER, including power electronics, communication and grid intelligence [2]. In China, a variety of research works in the field of ER are also carried out, with theoretical exploration and experimental prototype obtained, see, e.g., [11-13].

In 2015, the research about EI has been widely carried out in China within the field of both academia and industry, with lots of research institutions and industry alliances established. For example, the EI Innovation Research Institute of Tsinghua University was set up in city Beijing on April 14th, 2015; the China EI Industry Technology Alliance was set up in Zhongguancun in Beijing city on June 16th, 2015, etc. These organizations aim at promoting the development of EI in China. Meanwhile, the year 2015 is also remarkable for the EI industrial demonstration projects in China, due to the appearance of a number of large-scaled engineering projects of EI in the whole country. Aiming at various applications, the modes of these projects include cogeneration of heat and power, wind-solar-storage complementation, autonomous industrial park, etc., all of which need suitable ERs for the regional energy management.

According to the requirement of the above engineering projects, this article studies the ER's structure, router network and access management of power equipment. The issues of new energy access and distribution would be complicated due to the existence of massive distributed rooftop PV within the low-voltage grid. In this article, a medium scaled energy autonomous system is designed, where we propose a low-voltage ER with networking routing system, such that the access management and autonomy of new energy are implemented within the scope of 380-volt distribution grid.

II. THE IMPLEMENTATION METHOD OF LOW-VOLTAGE ENERGY ROUTING NETWORK

A. The Structure and Functional Analysis of a Single ER

(1) The Structure of ER

Focusing on the access and consumption of the distributed new energy, a new type of low-voltage ER is designed, with its structure shown in Fig1. We assume that the ER is connected to the 380v AC power grid and two categories of local equipment devices, i.e., new energy power generation stations and power loads. The bus voltage of ER is LVDC, and all the local power devices are connected to the bus by some standard interfaces. In the same way, the intelligent energy storage device is interposed by a standard interface, and its main function is restraining the fluctuation and flick of the DC bus voltage.

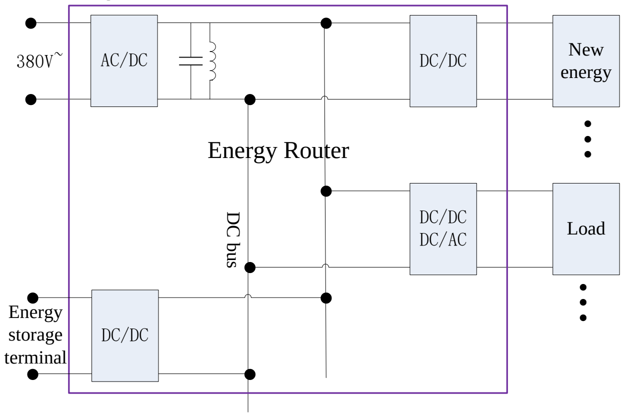


Fig. 1 Low-voltage ER' structure

(2) The Access Management of the Distributed New Energy

There are two types of energy sources in the router, namely the 380v distribution grid and the distributed PV stations, and the system has the following characteristics:

1) The ER has a rated power, which is the summation of the power from new energy and the 380v grid. The maximum accessing power of the new energy is the rated power.

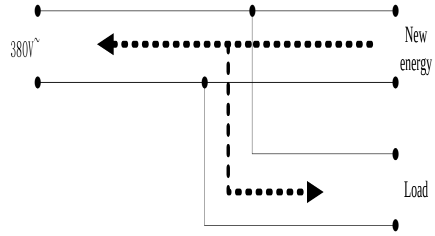
2) These standard interfaces of new energy devices are plug-and-play, which meets the requirement of openness of EI. In this case, the installation of ER is convenient.

3) The total number of accessible new energy is limited. The total number of the controlled output channels of PWM is also limited. Besides, since the voltage of the bus is low and the line loss is relatively large, bus length of the bus line should be typically small.

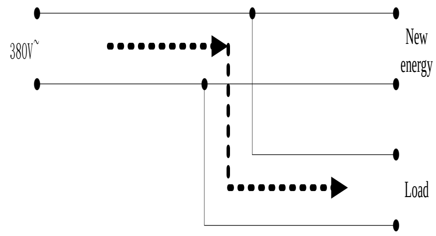
4) Functional boundary of ER is distinct. The physical part of the ER only refers to the framing content in Fig1. Specifically, the ER includes the following: the left side AD/DC module, the low-voltage DC bus, the right side DC/DC module and DC/AC module, and all the other standard interfaces. The energy storage device does not belong to ER, and it should be connected externally when it is applied.

(3) Analysis of power flow

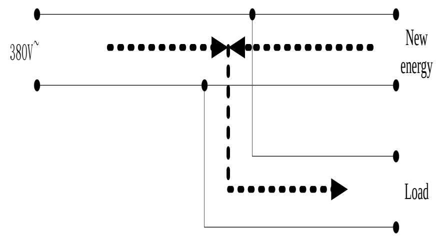
The power is supplied by the energy power station and the 380v distribution grid when the ER functions normally. There are three types of scenarios for the power flow, the new energy supply, the distribution network power supply and the hybrid power supply, which are illustrated in Fig2, respectively.



(a)New energy supplying



(b)Distribution grid supplying



(c) Hybrid power supply

Fig. 2 These power flow situations when ER is running

The power generated by the new energy stations is supplied to the load directly, when the weather condition is appropriate. When power supply is abundant, the surplus power is delivered to the 380v distribution grid, shown in Fig.2(a). During the time period in which the new energy station doesn't work, the distribution grid should be regarded as the only power supplier, shown in Fig.2(b). When the power generated by the new energy is insufficient, the ER would be operated in the hybrid power supply mode, shown in Fig.2(c).

B. Networking Energy Routing System

(1) Application Scenarios of Energy Routing Network

In generally, ER could be located in different physical layers of EI, such as the wide area network layer, the local area micro-grid layer and the low-voltage terminal network which is a small-scale region within the micro-grid. An ER application scenario is shown in Fig.3. Apparently, the ER appears in the layer of low-voltage terminal network.

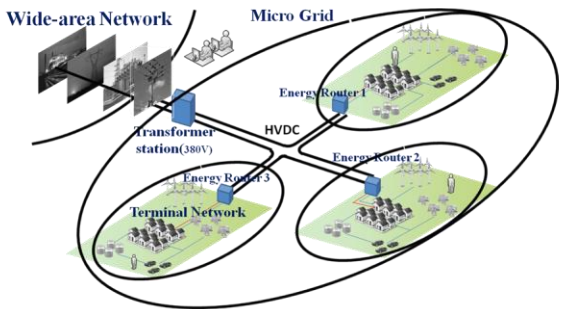
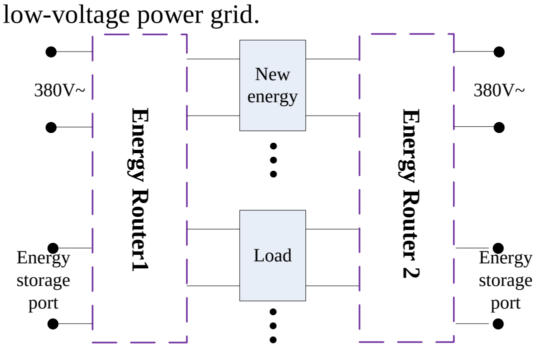


Fig. 3 The application scene of ER in the low-voltage power grid

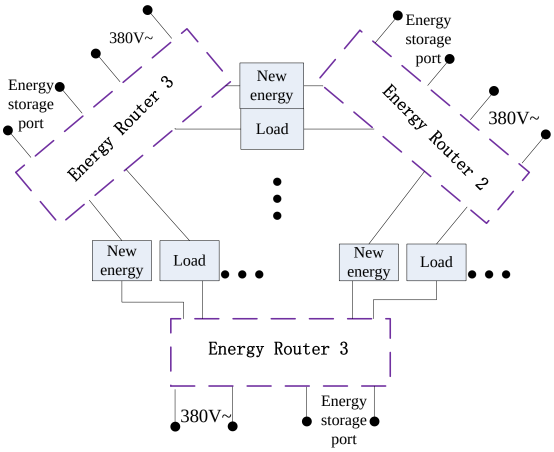
The ER studied in this paper is marked in Fig.3, where three ERs are located in three low-voltage power grids, respectively. These three ERs form a cooperative routing network, and such routing network constitutes a micro-grid routing system. When the micro-grid is connected to an external wide-area grid, a new wide-area ER is needed.

(2) The Operation of Energy Routing Network

When the ER is located in the low-voltage power grid, it could be operated within the environment of both EI and the traditional 380v distribution grid. When ER is connected to EI micro-grid and wide-area EI, it could transfer power to the micro-grid and the wide-area network in the next step. When ER is connected to the traditional distribution grid, power could be transferred to 380v grid but couldn't be further transferred to high-voltage grid due to the unidirectional flow of the traditional power grid. Therefore, the management of power should be carried out only within the 380v distribution grid. The energy routing network structure is shown in Fig.4 for the low-voltage power grid.



(a) Series-shaped energy routing network



(b)Star-shaped energy routing network

Fig. 4 The structures of two types of energy routing network

A class of series-shaped structure energy routing network is shown in Fig.4(a), where every new energy station or load is physically connected to two ERs in both left and right sides. Thus, for the new energy station it could optionally transfer power to either the left ER or the right one according to the requirement of the power balance. Similarly, the load could also obtain power from either the left ER or the right one.

It is notable that under such circumstances ER could manage the energy from both the left and the right side coordinately, selecting a suitable as well as required power input. Meanwhile, it considers the requirement of load from both the left and the right side, such that a better energy distribution is achieved. In this sense, the series-shaped energy routing network enhances its capability to manage the energy.

The other type of energy routing network is denoted as the star-shaped structure, shown in Fig4(b). Based on the series-shaped structure, a closed loop structure is formed by three ERs and three groups of power devices. Compared with series-shaped energy routing network, the star-shaped energy routing network could be connected to six groups of power devices, each of which has an angle of 60 degrees. Thus, the ER's ability of interconnection and the power distribution is enhanced under such structure. Besides, since power flow bi-directionally, the energy routing network could even manage a farther new energy station indirectly.

C. *Routing Mechanism*

(1) Access Management for the Single ER

There are six kinds of functioning modes when the single ER is operating, i.e., startup mode, operation mode, new energy joining mode, new energy dropping mode, load joining mode and load dropping mode. A routing matrix is proposed to describe the access to all devices as follows:

$$A_{6\times n}=\begin{bmatrix} a_{11},a_{12}......a_{1n} \\ a_{21},a_{22}......b_{2n} \\ a_{31},a_{32}......a_{3n} \\ a_{41},a_{42}......a_{4n} \\ a_{51},a_{52}......a_{5n} \\ a_{61},a_{62}......a_{6n} \end{bmatrix} \quad (1)$$

where n means the number of the devices which are physically connected to the ER. Each line of the above matrix refers to one of the six modes. The value of each element in the matrix $A_{6\times n}$ is either 1 or 0. Here, 1 indicates access to the ER, whereas 0 indicates separation from the ER. In the matrix $A_{6\times n}$ a_{11} stands for the value of the first device in the startup mode; correspondingly a_{21} represents the value of the first device in operation mode; a_{22} is the value of the second device in operation mode, etc. Hence, the matrix $A_{6\times n}$

completes the management of all devices, with its elements determining the operation state of ER.

(2) Series-Shaped Network Routing Mechanism

The routing matrix could also be applied to manage power for the series-shaped energy routing network in Fig4(a). Since each ER connects to two other ERs, then each ER has two routing matrices, e.g., $A_1 = A_{6\times n_1}$ and $A_2 = A_{6\times n_2}$, where n_1 and n_2 represent the number of the left device and the right one, respectively.

Compared with the single ER, series-shaped energy routing network has more types of routing mechanisms for the power coordination between these adjacent routers. Since the values of the elements of the matrices vary frequently, Fig.5 illustrates the coordination relationship of series-shaped routing network, where the ER 1 has two matrices A_1 and A_2; the ER 2 has two matrices B_1 and B_2.

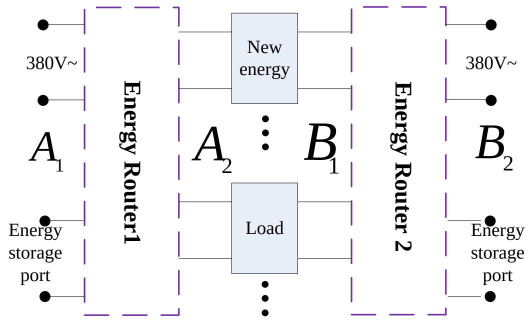


Fig. 5 The bidirectional coordination of routing matrix

The ER 1 and ER 2 have a direct power coordination via the matrices A_2 and B_1. Once the values of A_2 and B_1 change, instructions would be generated by two ERs to the corresponding electronic switches. This type of coordination has the following characteristics: 1) Both A_2 and B_1 has the same matrix structure, which means they have the same connection physically. 2) The corresponding elements at the same position of matrices A_2 and B_1 shouldn't be 1 synchronously. In other words, every device could be accessed with only one ER. 3) The values of A_2 and B_1 would affect that of A_1 and B_2 according to the requirements of power coordination.

Different with the single ER, the series-shaped energy routing network realizes the routing function due to the energy coordination features mentioned above.

(3) Star-shaped Network Routing Mechanism

A star-shaped energy routing network is shown in Fig.6, in which the matrices are used to manage access of power devices. Each ER has six routing matrices corresponding to six groups of power devices which are severally connected to the ER. The star-shaped routing network has more routing selections than the series-shaped routing network. The schematic diagram of matrix connection is shown in Fig.6.

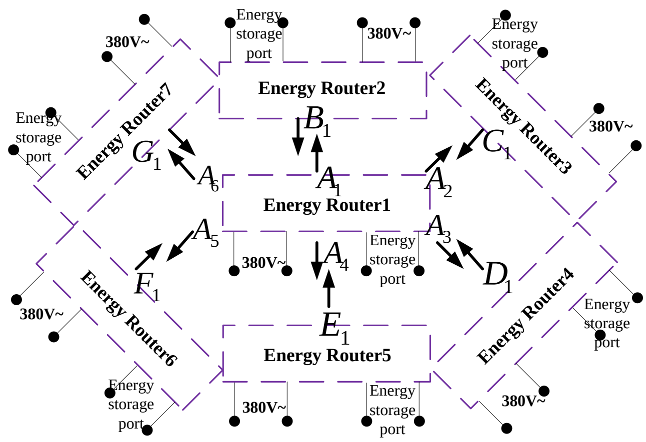


Fig. 6 Star-shaped routing matrix diagram

In Fig.6, the matrix A_1 of ER 1 has direct energy coordination with the matrix B_1 of ER 2, and the matrix A_2 of ER 1 has direct energy coordination with the matrix C_1 of ER 3, etc. The connection relationships of the matrices indicate that every ER has direct energy coordination with the peripheral routers (the maximum number of the peripheral routers is six). To summary, since the star-shaped energy routing network is highly interconnected, it has more powerful routing functions.

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III. Simulation Experiments

For the energy routing networks mentioned above, the following three aspects should be verified, 1) the openness of ER, which could ensure the access and exit of power devices in order; 2) the linkage mechanism of series-shaped energy routing network; 3) the networking linkage mechanism of star-shaped energy routing network.

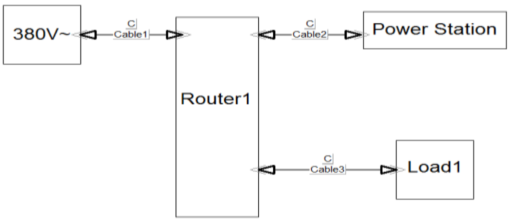
A. *The Single ER*

It is designed that the acessed parts include a 380v power grid; a photovoltaic new energy and loads. The DC bus volt is 700V. The detailed parameters are shown as in Tab.1.

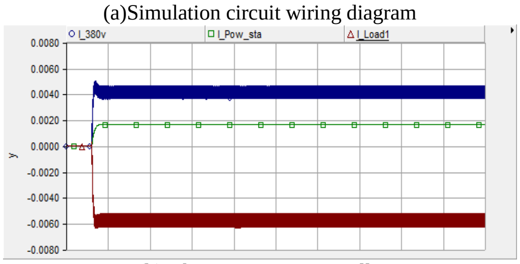
Table1. The accessed devices and parameters

Bus voltage	200volt
Maximum power of new energy	5KW
Maximum power of load	4KW
Maximum power of 380volt grid	limited by router's rated power
Testing points of currents	closed to bus side
Quantity of new energy	1
Quantity of load	1

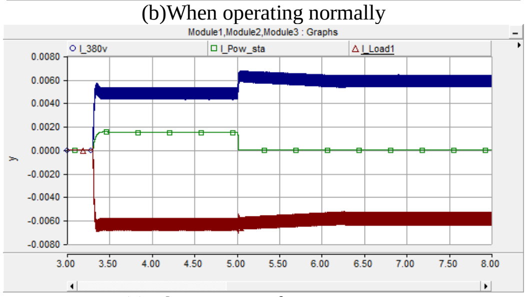
The single ER could implement the switch freely and power adjustment quickly. The effectiveness of power balance for all accessed devices when switching is shown in Fig.7, with the blue, green and red wires denoting the current of the 380V grid, the new energy and the loads, respectively.



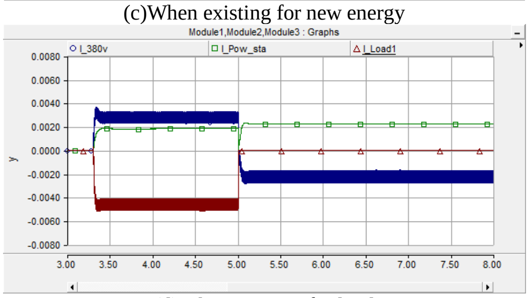
(a)Simulation circuit wiring diagram



(b)When operating normally



(c)When existing for new energy



(d)When existing for load

Fig.7 The access management of the single ER

For the circuit diagram of Fig.7(a), its normal operating matrix is:

$$A=\begin{bmatrix}1,1\\0,0\end{bmatrix} \tag{2}$$

The current curves of photovoltaic, load and 380V grid are shown in Fig7(b). When one group of photovoltaic exits the ER at the moment of the fifth second, the matrix becomes the following:

$$A=\begin{bmatrix}1,1\\0,0\end{bmatrix}\Rightarrow\begin{bmatrix}0,1\\0,0\end{bmatrix} \tag{3}$$

The current curves for this moment are shown in Fig7(c). It could be seen that the 380V grid's current increases rapidly once the current of new energy station disappears, so that the power requirement of the loads can still be satisfied.

When a group of loads exit from the router, the change of the routing matrices is similar to equation (3), and current curves are shown in Fig7(d).

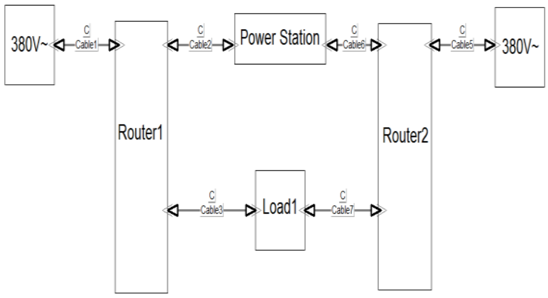
B. *Series-Shaped Routing Network*

We introduce the linkage mechanisms in the series-shaped routing network. Every new energy or load could be accessed into either the left router or the right one according to the requirements of cooperative power supply. The circuit wiring diagram is shown in Fig.8(a). When the system is operating normally, the routing matrix is:

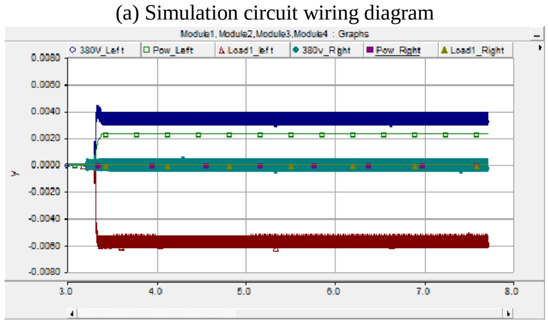
$$A_2=\begin{bmatrix}1,1\\0,0\end{bmatrix};\quad B_1=\begin{bmatrix}0,0\\1,1\end{bmatrix}$$

(4)

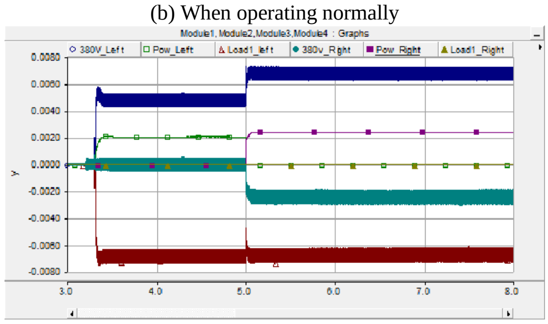
At this moment, all the current curves are shown in Fig8(b).



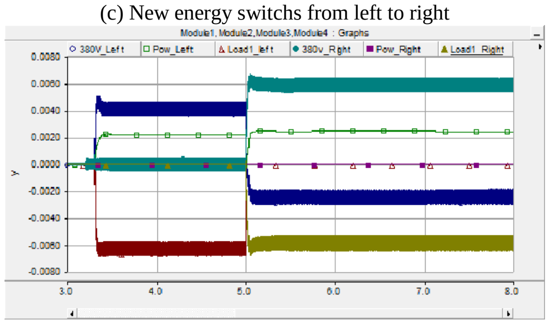
(a) Simulation circuit wiring diagram



(b) When operating normally



(c) New energy switchs from left to right



(d) Load switchs from left to right

Fig. 8 The linkage mechanisms of series-shaped ER

When a group of new energy devices exist from router 1 and are accessed into router 2, the routing matrices would change into the following:

$$A_2 = \begin{bmatrix} 0,1 \\ 0,0 \end{bmatrix}; \quad B_1 = \begin{bmatrix} 1,0 \\ 1,1 \end{bmatrix}$$

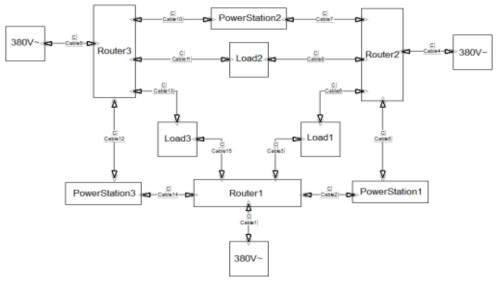
(5)

Correspondingly, the current curves of all kinds of accessed devices are shown in Fig8(c). It could be seen that some correlated changes happen between A_2 and B_1, and the power distribution of router 1 and router 2 changes synchronously. In this case, the adjustment of current is adapted timely to the change of device, which makes the power balanced.

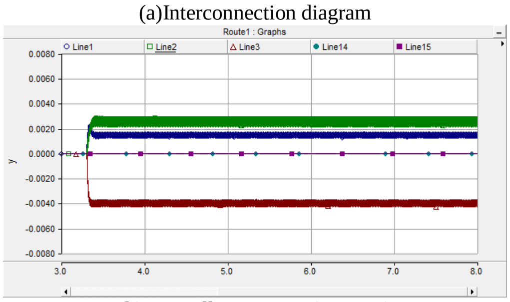
Similar to the change of equation (5), the matrix would change when one group of loads exit from router 1 and is accessed to router 2, and the current curves are shown in Fig.8(d).

C. Star-Shaped Routing Network

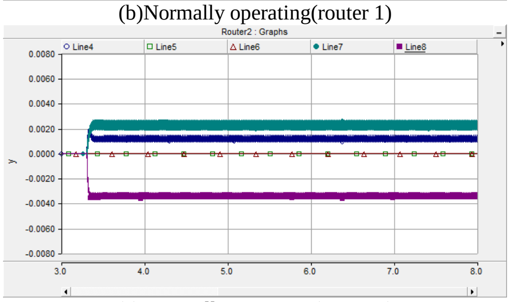
The star-shaped network, which includes three routers, has a stronger linkage as its powerful feature, so that it could promote the power's distribution flexibly in the network. The following figures show the star-shaped network's operation in detail. The normal operation is shown in Fig.9; the switching of the new power supply is shown in Fig.10; the load's switching is shown in Fig.11. There are totally 15 testing wires for three routers in Fig.9(a). In each picture below, five testing points of each router are plotted for clear demonstrations.



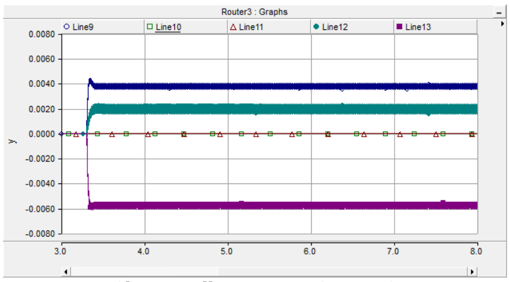
(a)Interconnection diagram



(b)Normally operating(router 1)



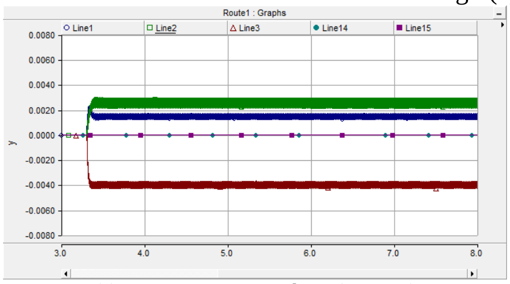
(c) Normally operating(router 2)



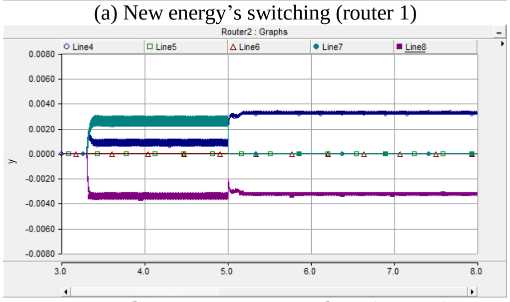
(d) Normally operating (router 3)

Fig. 9 Star-shaped interconnection and its operation normally

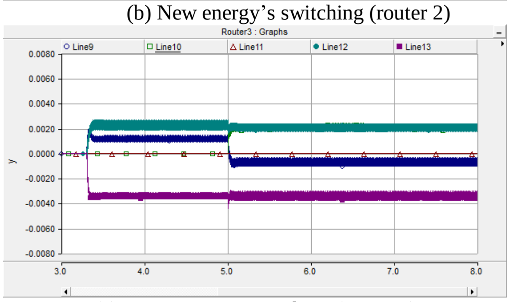
In the fifth second, the new energy 2 existed from router 2, and is connected to router3, and the total 15 testing point's changes, which is shown in Fig.10. The ER 1 doesn't have any change, but the router 2 and 3 have a series of adjustment for device access. We can see the wire's number in Fig.9(a).



(a) New energy's switching (router 1)



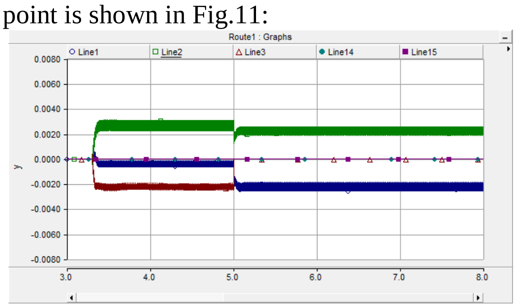
(b) New energy's switching (router 2)



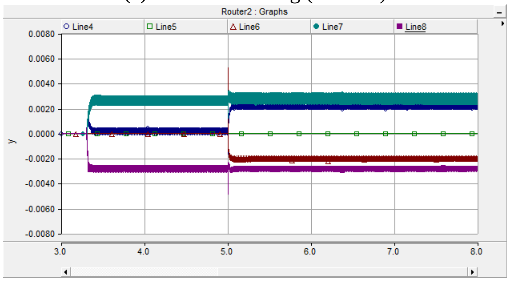
(c) New energy's switching (router 3)

Fig. 10 The new energy 2 switchs from router 2 to router 3 at the fifth second

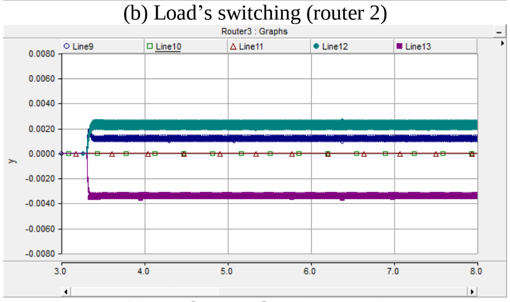
In the fifth second, the loads exist from router 1 and are switched to router 2. At this moment, the change of the 15 testing point is shown in Fig.11:



(a) Load's switching (router 1)



(b) Load's switching (router 2)



(c) Load's switching (router 3)

Fig. 11The load switches from router 1 to router 2

The simulations show that the ER 3 doesn't have any change, but the router 1 and 2 have some change for device access. In this case, the device's switching between two routers could rebuild the balance of power.

IV. Conclusions

Focusing on the issues of new energy' assess and consuming, we propose the ER' structure and its function design in this article. Furthermore, we have designed two kinds of routing network topology for low-volt distribution grid by the ERs' interconnection. We highlight the importance of this work by presenting and investigating the single ER, series-shaped and star-shaped energy routing networks, with which power management is achieved. In this sense, this article can be regarded as a foundation to the routing algorithm for a low-voltage energy routing system. The other main contribution is the establishment of the routing matrices and their applications, which realizes the management for the accessed devices.

In this study we apply the energy routing theory into the low-voltage distribution grid, such that implementation approaches of energy routing are realized. Meanwhile, it brings a series of new issues, which need to be further studied urgently. For example, although we have proposed the routing mechanism in power management, a precise control problem shall be investigated in future research. Secondly, when the routing matrix is applied to the series-shaped and star-shaped network, the effecting mechanisms between two adjacent matrices should be considered. Besides, since the energy storage device is only used to compensate the DC bus voltage, so compensation algorithm should be studied in detail for the stability of DC voltage.

Acknowledgment

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