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Design of GaN Energy Router to Reduce Household Energy Use

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As the total power consumption of family residences continues to increase, to promote green and low-carbon ideas and to reduce electricity costs, distributed power sources such as rooftop photovoltaic power generation systems and small wind turbines are gradually being introduced into family residences. In view of the low utilization efficiency of current distributed energy sources and the lack of effective energy management devices, a household energy management system based on energy routers is proposed. In this study, we designed a GaN power converter for use as an energy harvester that employs devices based on the third-generation, wide-bandgap semiconductor GaN with high switching frequency, low switching loss, good temperature characteristics, and low energy loss. Through effective energy scheduling strategies, control and adjustment can be made according to the energy output, the electricity costs of energy storage equipment, and the household load.

1. Introduction

With the excessive consumption of traditional fossil fuels, climate and environmental problems have become increasingly serious, along with the continuous growth of global energy demand. On the other hand, the development and utilization of renewable energy have rapidly progressed under the impetus of these factors, which has also undergone comprehensive and profound changes.(1) Using renewable energy to generate electricity has advantages of abundant availability and low environmental impact, but its randomness and intermittent characteristics will reduce the quality of the power supply. For households equipped with distributed power generation devices, this will undoubtedly increase the instability of their energy supply.(2) The number of households with renewable energy power generation equipment and the capacity of battery energy storage are gradually increasing. Therefore, the research and design of household electric energy routers are a basis for future electric energy utilization and energy interconnection. A household energy router integrates energy, capital, and information flows, and realizes functions such as community power trading, grid power trading, and household electricity scheme design. It connects household smart loads, distributed energy storage equipment, distributed power generation equipment, and power grids through the use of plug-

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and-play devices. The household energy router is the basic unit of the household energy management system.[3–8]

The converter as the core of the energy routing can be adapted in power electronic equipment. Schulze *et al*. proposed the concept of the solid-state transformer (SST), which essentially uses power electronic transformers to convert between AC and DC electrical energy.[3] Rosa *et al*. proposed some key technologies of existing photovoltaic power generation, such as output forecasting based on a weather index, grid-connected photovoltaic technology, and a household photovoltaic model.[5] With the promotion of clean energy, the penetration rate of household photovoltaics is increasing. Liao and Ruan proposed an energy management scheme for household photovoltaic power generation systems, and mainly focused on the coordinated charging and discharging of photovoltaic power generation and energy storage batteries.[9] At present, household photovoltaic energy management systems do not yet involve the overall scheduling of household power consumption. Research is being carried out on energy routers to make up for this shortcoming. Liu *et al.* proposed a household energy router and energy management strategy suitable for AC/DC hybrid power supplies and household loads. By using a distributed hierarchical energy management system (HEMS), energy routers can achieve different functions, such as peak shifting, power planning tracking, and so forth.[10] However, the HEMS in their study is both cumbersome and impractical. Uno and Sugiyama proposed the main loop structure of a typical energy router based on a multiport power converter (MPC), which controls multiple subsystems through a multiport bidirectional power converter to achieve a balanced energy supply.[11] Chen *et al.* proposed a method based on the DC bus voltage signal to switch the working conditions of an energy router, but this method requires a wide bus voltage working range to ensure reliable working conditions.[12] Liu *et al*. proposed a seamless switching method between different working conditions, but it only involves switching between off-grid and on-grid states.[13] By analyzing the topology of these energy routers, power converters can play an important role in reducing household energy consumption. Therefore, the selection of switching devices of these power converters will directly affect the efficiency of the energy router. The improvement of semiconductor technology and the application of new semiconductor materials, such as SiC and GaN, have pushed the development of power converters into an era of high frequency and large capacity. Esposto *et al*. proposed an analytical model for a GaN power converter.[14] Shenai *et al*. compared the applications of Si and GaN in DC–DC power converters, and preliminarily demonstrated the superiority of power converters based on GaN power devices.[15]

In this study, we further investigate power converters based on GaN devices, concentrating on their advantages such as low on-resistance, high switching frequency, and high breakdown voltage. Through a detailed analysis of the characteristics of GaN devices, a more efficient power converter is designed. This GaN-based power converter improves the efficiency of household energy routers. In addition, an operation control strategy is designed, which can take full advantage of the characteristics of energy routers based on GaN power devices. The proposed hierarchical unified coordinated control strategy can realize the seamless switching of energy routers between different working conditions.

2. Household Energy Management System Architecture Based on Energy Router

To respond to the diversity of modern household energy structures and solve the problems caused by the integration of photovoltaic, wind, and other renewable energy into the household energy system, a HEMS based on energy routers is designed.[16] The grid, renewable energy system, energy storage, and load are connected through an energy router. Compared with existing research results, the HEMS proposed in this paper has the following characteristics: 1) It can manage distributed energy and load through energy routers and provide plug-and-play ports. 2) It can optimally dynamically control the load according to the user's comfort, energy consumption, and load characteristics. 3) It can improve the local consumption rate of renewable energy. 4) It can automatically adjust the control strategy according to the optimization target set by the user.

2.1 Energy router framework for household energy management

A household energy router can be divided into the physical, transmission, and application layers to analyze the hierarchical characteristics of its energy flow and information flow transmission. The physical layer represents the basic physical composition, connection interface, and connection object of the energy router. The transmission layer represents the transmission mode and control structure of energy and information. The application layer represents the basic functions of the energy router and human–computer interaction.

Figure 1 shows a schematic diagram of the structure of a household medium- or low-power energy router. The core of the internal electric energy conversion of the household energy router is made of power converters with various functions. They not only control the flow of energy, but also have powerful functions such as fault isolation and protection. They play an important role in power quality adjustment and reactive power compensation. In this paper, we propose a power converter based on GaN power devices considering its important role in energy routers and the frequent status changes of the sockets of household energy routers. This power converter makes full use of the high-frequency and high-energy-density characteristics of GaN power devices to reduce the volume and power loss of the household power router and to improve the switching speed of a power router between different operating states.[17]

As shown in Fig. 1, the DC bus is the conversion center of the energy router, which is connected to the AC access socket on the distribution network side, the DC access socket on the distribution network side, the photovoltaic access socket, the AC load socket, the DC load socket, and the energy storage equipment socket. Each socket is connected to a switch, and the control system can select the on-off status of the corresponding switch according to its requirements and relevant rules and policies. When electric energy enters and leaves the DC bus, it passes through the power measurement unit, and the real-time power consumption is fed back to the control system so that the control system can make appropriate decisions. All the power measurement units and switches can realize wired communication with the control system. All the smart electrical equipment, energy storage devices, and photovoltaic devices can use the household power local area network and control system to achieve wireless communication. The system

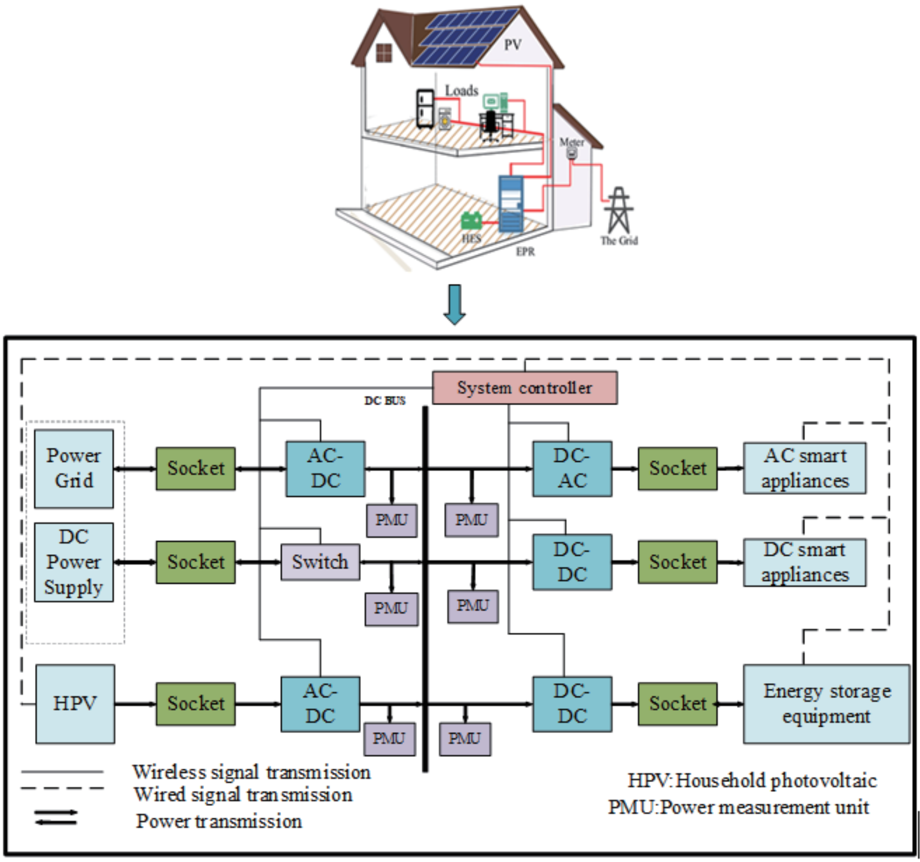

Fig. 1. (Color online) Topology of energy router.

manager realizes the unified management of household electricity and power generation equipment by collecting the status information of all the equipment and devices.

2.2 Function design of power router

The functions of the electric energy router mainly include the two-way billing transaction function and the design of the electricity usage plan. The two-way billing transaction is centered on the household using the energy router, and the transaction objects are the electric power companies and other household users. Among them, the real-time on-grid electricity price is used as the unit price for transactions between household users and grid companies. When trading with other household users, the bidding mode of the community energy pool is used.

As shown in Fig. 2, users can obtain the current electricity price information, the electricity bill list, and the electricity usage plan given by the energy router through an interactive interface. Users can select a trading strategy based on their own electricity demand. After being processed by the energy router, the user information and response strategy are fed back to the community energy management platform to complete the energy transaction, and at the same time, the electricity price information and electricity bill list are collected for the next stage. The energy

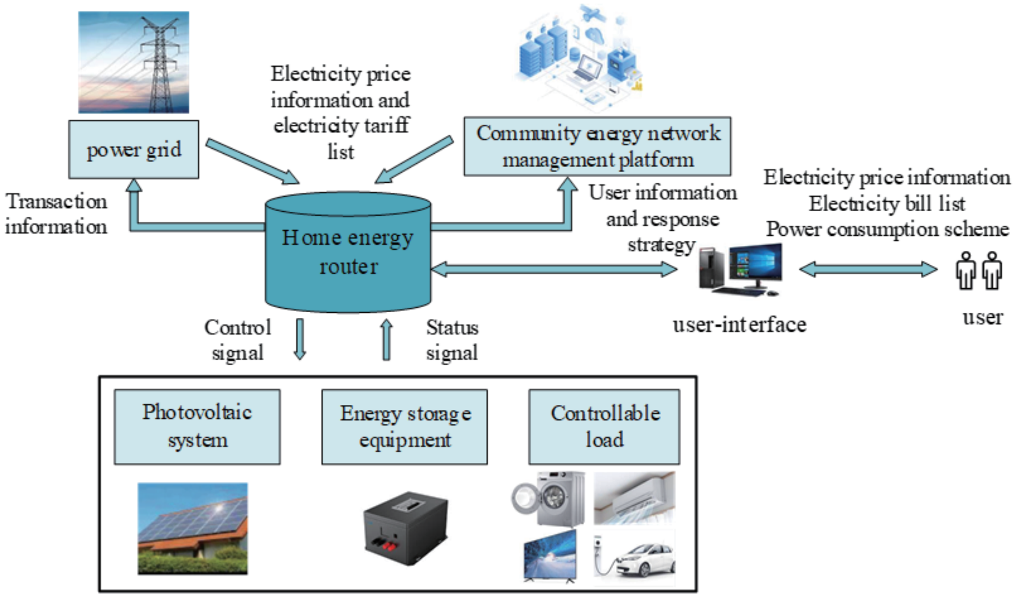

Fig. 2. (Color online) Information flow diagram of two-way billing mode.

router provides different power consumption schemes according to different transaction strategies of users and controls various devices in the household power system.

3. Power Converter Based on GaN Devices

GaN high-electron-mobility transistors (HEMTs) have the characteristics of a wide-band-gap semiconductor and heterostructure, showing excellent low on-resistance, high breakdown voltage, and high operating frequency. The operating characteristics of GaN HEMT devices are similar to those of Si metal oxide semiconductor field-effect transistor (Si MOSFET) devices, both of which exhibit low resistance during forward conduction, and the current and voltage levels of the two types of devices are relatively similar. Therefore, GaN HEMT devices can be used in power converters instead of Si MOSFET devices to increase the operating frequency of the converter and reduce the switching loss. Because the status of the socket interface of a household energy router changes frequently, the application of a GaN-device-based power converter to the energy router will greatly improve the work efficiency of the household energy router. In this section, the characteristics of GaN power devices will be introduced, and a power converter based on GaN devices will be modeled and analyzed.

3.1 Characteristics and modeling of GaN power devices

Figure 3 shows a comparison of the characteristics of Si, SiC, and GaN. Among the characteristics, the forbidden band width and temperature coefficient determine the breakdown voltage and maximum operating temperature of a device, and the electron mobility and saturation drift rate determine the switching speed of the device. A GaN-based device can have

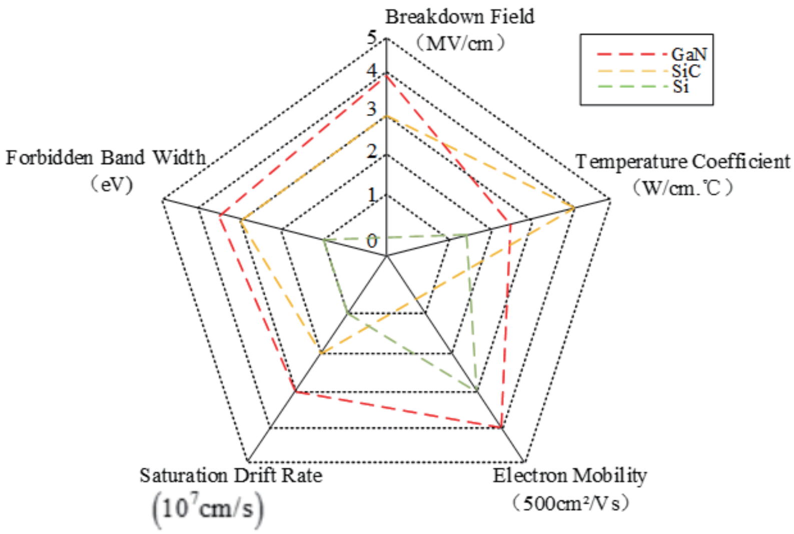

Fig. 3. (Color online) Comparison of characteristics of Si, SiC, and GaN.

a higher breakdown voltage than a Si-based device with the same bare chip volume owing to the wider band gap of GaN than of Si, which is conducive to the miniaturization of devices. The parasitic capacitance of the GaN device will be smaller, which is helpful for improving the switching speed and reducing the switching loss. The higher carrier migration rate reduces the on-resistance of the device, which helps to reduce its on-state loss. Therefore, GaN devices are very suitable for high-frequency operation.

It can be seen from the lateral structure of the GaN HEMT in Fig. 4 that, unlike the channel conduction mode of Si-based power devices based on PN junctions, a two-dimensional electron gas (2DEG) is a product of the physical characteristics of GaN/AlGaN heterojunctions in GaN devices. Since GaN and AlGaN have different band gaps, a heterojunction will be formed at their contact surface. The sudden change in Fermi level at the contact surface leads to electron transfer from AlGaN to the GaN semiconductor and a change in electric field at the contact surface. The GaN material with a lower band gap will drive holes to bind with electrons owing to its low electron potential energy, resulting in the formation of a 2D potential well region with many free electrons on the GaN semiconductor side of the heterojunction. The free electrons in it are a 2DEG. The free electrons leaving AlGaN and entering the GaN semiconductor will no longer be affected by the scattering of ionized impurities and thus have high electron mobility.[14,15] The free electrons with high mobility move at high speed on the heterojunction to form the conductive channel of the GaN power device. Therefore, this type of GaN device is also called a GaN HEMT.

Since the source and drain of the GaN HEMT are connected through a 2DEG channel, they are essentially depletion-type normally-on devices. However, it is necessary to use enhanced normally-off devices in power electronic converters. Cascode technology is used here to package the high-voltage depleted GaN HEMT and low-voltage enhanced Si MOSFET in the manner of common gate and source to form a normally-off cascode GaN HEMT, as shown in Fig. 5.

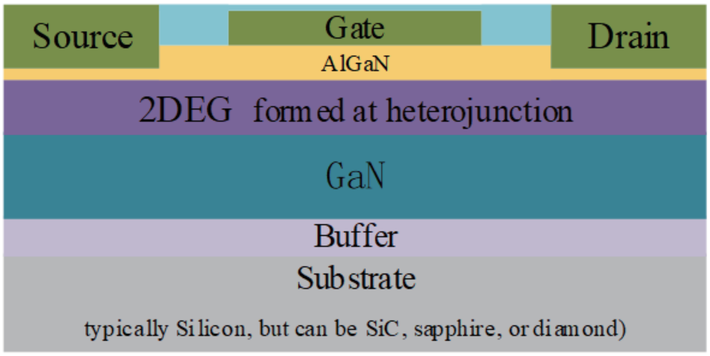

Fig. 4. (Color online) Vertical cross section of GaN HEMT.

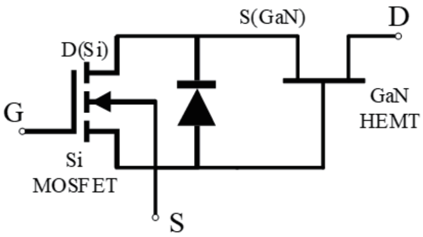

Fig. 5. Cascode GaN structure.

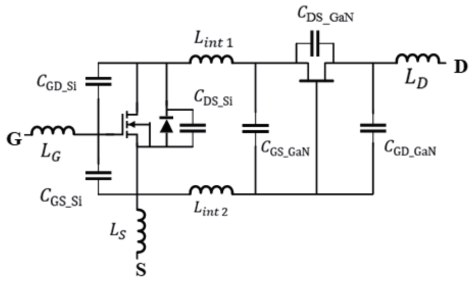

Fig. 6. Equivalent cascode GaN transistor considering parasitic inductors and capacitors.

In Fig. 6, the low-voltage Si MOSFET drives the high-voltage GaN HEMT, and the turn-on and turn-off of the low-voltage Si MOSFET respectively control the turn-on and turn-off of the high-voltage GaN HEMT. To ensure the accuracy of the model, the parasitic capacitance and lead parasitic inductance of the low-voltage Si MOSFET and high-voltage GaN HEMT must be considered. Figure 6 shows the equivalent circuit of the cascode structure considering these parasitic parameters, where L_G, L_S, and L_D represent the parasitic inductances of the gate, drain, and source pins of the device, respectively, and L_{int1} and L_{int2} represent the parasitic inductances of the internal leads of the device. There are three types of parasitic capacitances in both Si MOSFET and GaN HEMT devices, which are the gate capacitance (C_{GS_Si}, C_{GS_GaN}), drain capacitance (C_{GD_Si}, C_{GD_GaN}), and source capacitance (C_{DS_Si}, C_{DS_GaN}). When the device is turned on, since the charge on capacitor C_{DS_GaN} is larger than that on capacitor C_{DS_Si}, the junction capacitance of the GaN transistor cannot be completely discharged during zero-voltage switching (ZVS), namely, the true ZVS turn-on cannot be achieved.

When the GaN transistor is turned on, capacitors C_{DS_Si}, C_{GS_GaN}, and C_{DS_GaN} are discharged, as shown in Fig. 7(a). When the voltage V_{SG_GaN} drops to the turn-on voltage of the depletion-mode GaN transistor, the depletion-mode GaN transistor is turned on, but the capacitor C_{DS_GaN} has not been completely discharged at this time. If $V_{DS\_GaN} = V_x$ at this time, an energy of $C_{DS\_GaN}V_x^2 / 2$ will be consumed by the channel resistance of the GaN, which is emitted in the form of heat, as shown in Fig. 7(b). When V_{DS_GaN} drops to 0, C_{DS_Si} and C_{GS_GaN} continue to

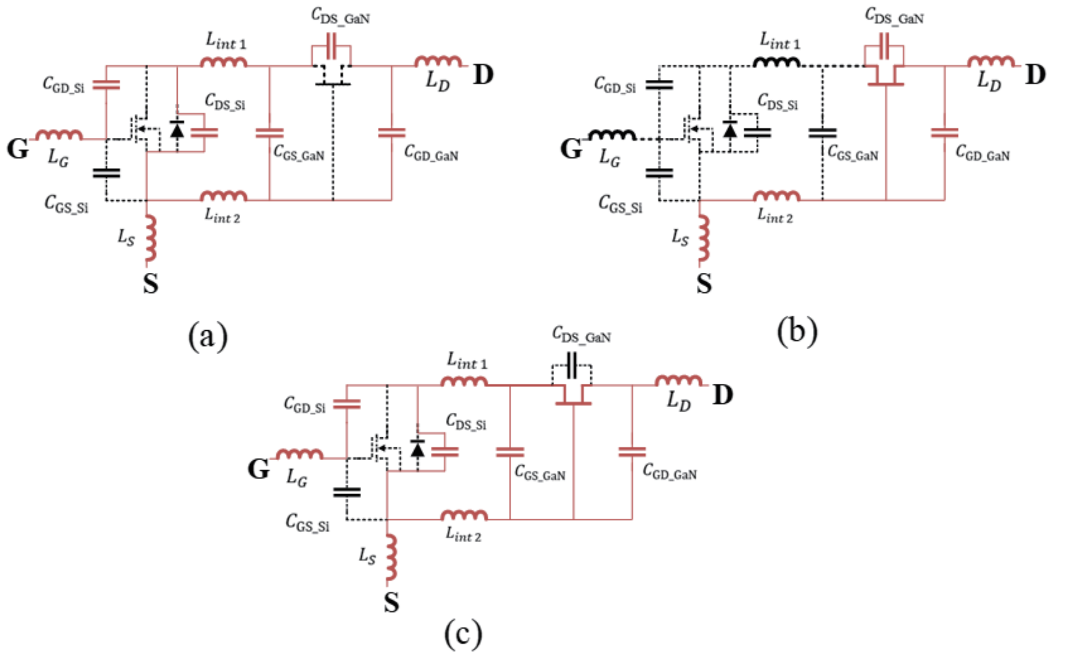

Fig. 7. (Color online) ZVS turn-on equivalent circuit: (a) GaN transistor, (b) emission in form of heat, and (c) discharge phase.

discharge until their voltage drops to 0, as shown in Fig. 7(c). In summary, during the turn-on process of the cascode-type GaN HEMT, the voltage measured from the outside is zero before driving. Although it appears that the ZVS turn-on has been achieved, part of the internal energy is consumed by the channel resistance, which means that the ZVS turn-on is not completely achieved. These parasitic parameters have a direct impact on the operating characteristics of the GaN device. By establishing the analytical model in Fig. 6, the parasitic parameters can be simulated and analyzed and the switching characteristics of the device can be tested, and therefore the switching loss can be calculated.

3.2 Characteristic analysis of power converters based on GaN devices

The use of clean energy in household energy routers depends on photovoltaic power generation systems and energy storage batteries. A photovoltaic power generation system is connected to the DC bus through a power converter, and the energy storage battery and the DC bus conduct a bidirectional energy flow. Therefore, the study of bidirectional DC–DC power converters is very important to improve the efficiency of household power routers. Reducing the switching loss, eliminating the circulating energy, and expanding the soft switching range are requirements for new isolated bidirectional DC–DC converters. The logical link control (LLC) resonant converter uses a resonant cavity to resonate, so that both the primary and secondary sides can achieve soft switching characteristics, meeting the requirements of new isolated bidirectional DC–DC converters. However, in view of the high efficiency, miniaturization, and frequent changes in the socket status of household energy routers, this places higher requirements on the switching device. Here, a GaN router is combined with a full-bridge LLC resonant converter to further improve the efficiency and power density of the LLC resonant converter. The main circuit structure of the two-way full-bridge LLC resonant converter designed in this study is shown in Fig. 8. The switching device is a cascode GaN HEMT device, making it necessary to pay attention to its scalability when realizing ZVS opening.

The primary and secondary sides of the transformer in the main circuit adopt a full-bridge structure, with the high-voltage side on the left and the low-voltage side on the right. The transformer turns ratio is N : 1. The resonant network module is composed of resonant inductance L_r, excitation inductance L_{m1}, and resonant capacitor C_r. Through the setting of the switching frequency, frequency matching can be achieved with the resonant frequency f_r [Eq. (1)] at which the resonant capacitor and resonant inductance resonate and the resonant frequency f_m [Eq. (2)] that makes the resonant capacitor, resonant inductance, and magnetizing inductance resonate together, thereby reducing loss and improving efficiency.

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

$$f_m = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \tag{2}$$

We define the forward operation as the transfer of energy from the high-pressure side to the low-pressure side, and the reverse operation as the opposite. The principle of this circuit is the same as that of a traditional unidirectional LLC converter during the forward operation. L_{m2} does not participate in resonance and only plays a role in helping the inverter to achieve ZVS. During the reverse operation, L_{m1} does not participate in resonance, and the values of L_{m1} and L_{m2} are equal; thus, the symmetry of the forward and reverse operations can be realized. When energy is forwarded, Q1–Q4 act as inverter tubes and Q5–Q8 act as rectifier tubes. In reverse transmission, Q1–Q4 act as rectifier tubes and Q5–Q8 act as inverter tubes. The output voltage can be adjusted by changing the switching frequency. The quality factor and DC output gain are defined as follows.

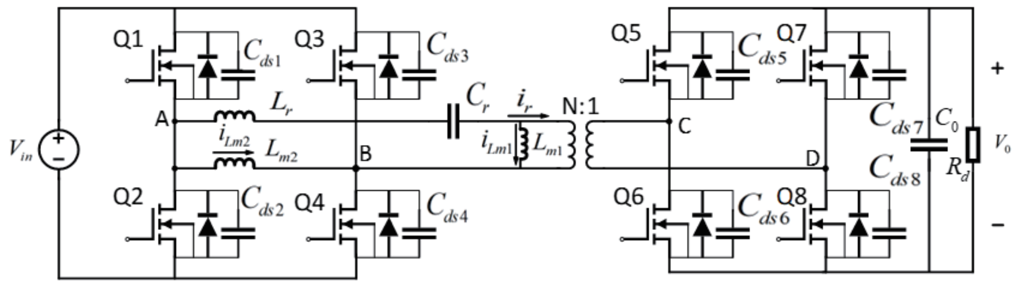

Fig. 8. Main circuit structure of LLC resonant converter.

Quality factor:

$$Q=\frac{Z_0}{R_{ac}}=\frac{2\pi^3 f_r L_r}{8n^2 R_L} \tag{3}$$

DC output gain:

$$\mathrm{Gain}\left(f_n,Q,K\right)=\frac{1}{\sqrt{\left[1+\frac{1}{K}\left(1-\frac{1}{h^2}\right)\right]^2+Q\left(h-\frac{1}{h}\right)^2}} \tag{4}$$

Here, $K = L_m / L_r$ is used to normalize the inductance, $h = f_s / f_r$ is used to normalize the frequency, and f_s is the switching frequency.

Using the expression for the DC output gain, taking h as the abscissa and the open-loop gain of the full-bridge LLC resonant converter as the ordinate, the relationship curves of the open-loop gain with f_n and Q when K = 4 and 6 are obtained. On the basis of the pure resistive curve, the resonant ring on the left is capacitive, and the switch tube on the secondary side of the transformer realizes zero-current switching (ZCS). The resonant ring on the right is inductive, and the primary switch tube of the converter can achieve ZVS. When h = 1, the total impedance of the resonant inductor and capacitor is 0, and the efficiency of the converter is maximized. Therefore, the LLC resonant converter can be divided into three working areas.

As shown in Fig. 9, working area 1 is where $f_s > f_r l$; in this area, the primary-side switch tube can realize ZVS, but the secondary-side switch tube cannot realize ZCS. Working area 2 is where $f_r \geq f_s > f_m$; in this area, the primary-side switch tube can realize ZVS and the secondary-side switch tube can also realize ZCS. Working area 3 is where $f_s < f_m$; in this area, the primary-

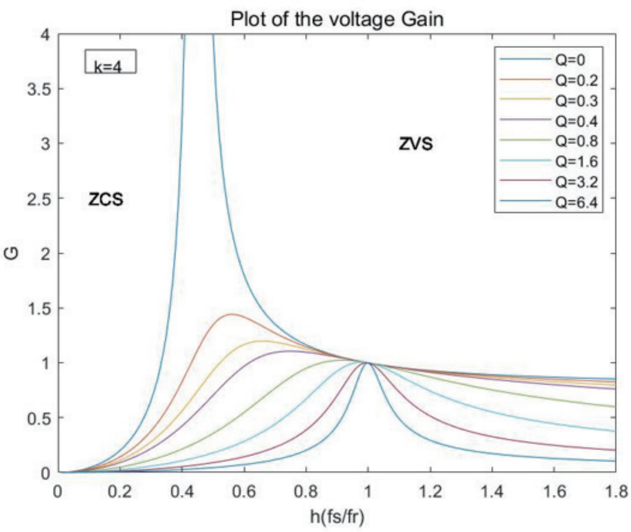

Fig. 9. (Color online) Relationship curves between open-loop gain and normalized frequency.

side switch tube cannot realize ZVS, but the secondary side switch tube can realize ZCS. Therefore, to achieve soft switching on both the primary and secondary sides of the LLC resonant converter, the parameter design should be done in working area 2.

4. Control Strategy of Household Energy Router Based on GaN Power Device

The control strategy of the household energy router is based on the design of the household electricity scheme. The household electricity scheme includes household load forecasting, the power control of controllable loads, and the interactive control of distributed energy and power grids. Figure 10 shows the design process of the household electricity scheme.

According to the optimization objective, different power consumption schemes of the household energy router can be designed. The optimization goal can be set according to the user's needs, such as the minimization of the cost, the maximum use of renewable energy, and the stable operation of the power grid. Household load forecasting can be realized by analyzing historical electricity consumption data and establishing a neural network model. The output of photovoltaic power generation can be predicted from the weather conditions of the day. The remaining power consumption of energy storage equipment can be obtained through the battery management system.

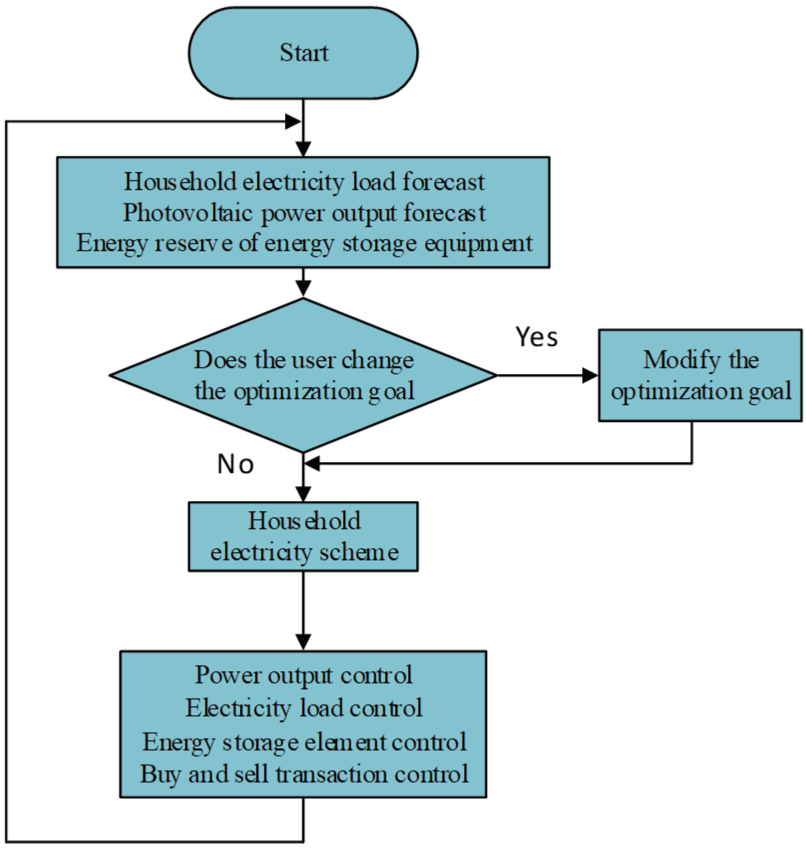

Fig. 10. (Color online) Flow chart of electricity scheme for household electric energy router.

4.1 Switching control of home energy router

According to different trigger signals, energy routers can be divided into the grid-connected operation, off-grid operation, grid-dispatching power absorption, grid-dispatching power feeding, battery protection, and system shutdown modes. These six basic working modes are switched as shown in Fig. 11. On the basis of the user's optimization goal, the energy router combines trigger signals such as grid connection, grid dispatch, energy storage state of charge (SoC), and DC bus voltage signals to form a set of current states in order to choose a basic operation mode.

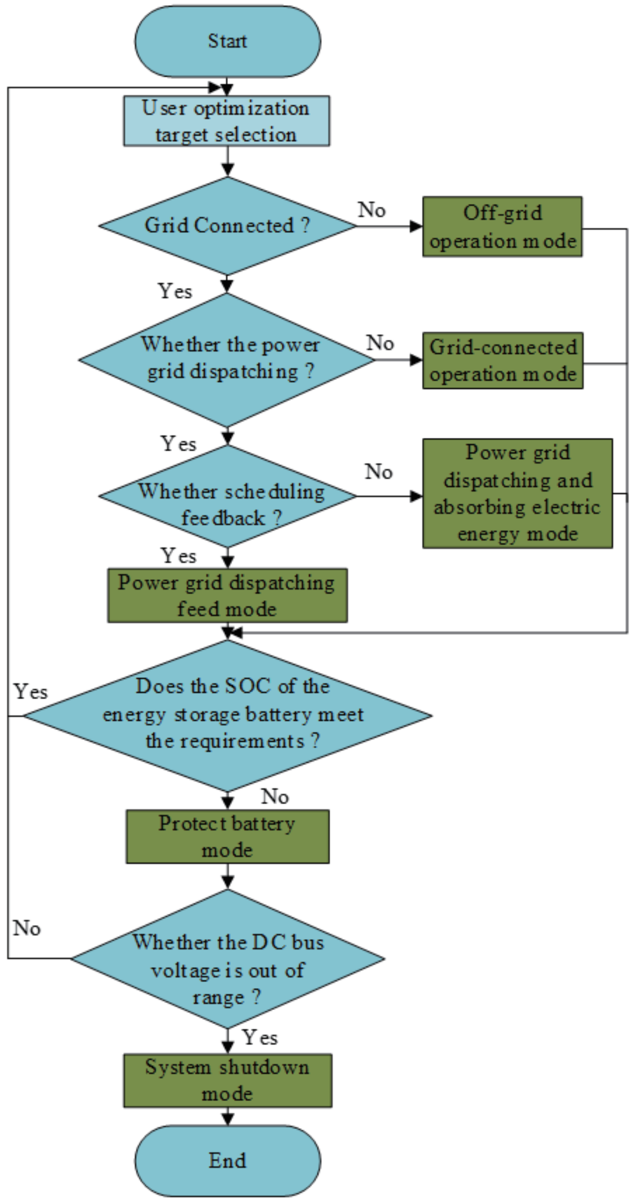

Fig. 11. (Color online) Flow chart of switching control between basic operation modes.

(1) Grid-connected operation mode:

The grid-connected operation mode is the basic operation mode when the household energy router is connected to the grid and there is no dispatch. A photoelectric device continuously operates in the maximum power point tracking (MPPT) mode. When the SoC of energy storage is high, the photovoltaic power will ensure a household power supply and energy storage for backup. When the SoC of energy storage is low, the photovoltaic power contributes to ensuring a household power supply, power grid backup, and energy storage charging. If the user's optimization goal is to minimize cost, the control strategy of energy storage and the grid can also be adjusted according to the real-time electricity price.

(2) Grid-dispatching power feeding mode:

In the grid-dispatching power feeding mode, the grid voltage or frequency drops and the overall grid energy is insufficient, and the grid-dispatching layer dispatches the energy router to feed the grid. The photovoltaic power operates in the MPPT mode. By regulating and controlling household appliances, when the basic operation is satisfied, energy storage and photovoltaic power feeding occur together to support the grid.

(3) Grid-dispatching power absorption mode:

In the grid-dispatching power absorption mode, the overall load of the grid is small and the grid voltage or frequency is on the high side. Currently, the grid dispatches each household energy router to absorb excess energy. The energy router rationally absorbs the excess power on the grid side according to its situation.

(4) Off-grid operation mode:

In the off-grid operation mode, the grid side or grid access socket fails, and the energy router works in the off-grid operation mode. The photovoltaic power operates in the MPPT mode with energy storage for backup, and the power of the system is completely balanced by the energy router itself to maintain the stability of the DC bus voltage. When necessary, the photovoltaic power can also be adjusted through the community energy interface.

(5) Battery protection mode:

In the battery protection mode, the energy storage battery is protected when it reaches the critical SoC of overcharge or over-discharge. When the SoC of the energy storage battery reaches the upper limit, the energy storage can only be discharged or not work, and when the SoC of the energy storage battery reaches the lower limit, the energy storage can only be charged or not work.

(6) System shutdown mode:

In the system shutdown mode, all the above operating modes are running stably or are seamlessly connected and the DC bus voltage is maintained at the rated value. However, when the photovoltaic power is off-grid, the photovoltaic power is available when the energy storage reaches the maximum, the power cannot be traded with the community, and the power in the system cannot be balanced, which will inevitably cause the DC bus voltage to exceed the limit and the system to enter the shutdown mode and lock the switch tube.

4.2 Control strategy

The energy router has a variety of working modes according to the user's optimization goal and various trigger signals. Therefore, a coordinated control strategy is needed to achieve the seamless switching of working conditions to achieve system energy balance and DC bus voltage stability.

The photovoltaic power adopts the MPPT control strategy based on voltage disturbance. The converter of the grid interface adopts the traditional d-q axis decoupling voltage and current double closed-loop control to realize unit power factor operation on the grid side. Energy storage uses a combination of droop control and current control. As shown in Fig. 12, a current loop is first used to control the input current I from the DC bus to the energy storage converter to track the given reference value I_{ref}. The difference between these two values is adjusted by a proportional–integral (PI) controller. The latter value is sent to a low-pass filter (LPF) to filter out high-frequency ripple and then multiplied by the DC bus voltage U_{dc} to obtain the reference power value U_{ref}. To carry on the secondary correction of the DC bus voltage to prevent the DC bus voltage from deviating from the rated value owing to power changes when using droop control, after obtaining the reference voltage value, an amount of secondary voltage compensation δ_u given by Eq. (5) is added. The corrected voltage is subtracted from the actual value U_{dc} of the DC bus voltage, and the phase shift angle of the energy storage power converter is obtained through the double closed-loop control of the voltage and current and the phase shift control.

The new droop control based on current tracking can precisely control the current through the current tracking loop and the voltage through the secondary voltage compensation of the droop control, and finally, it can precisely control the transmission power. When it is necessary to put the PI controller in the energy storage, it only needs to act when its reference current is zero.

$$\delta_u = \frac{1}{T_s s+1}\left(k_p + \frac{k_i}{s}\right)\left(U_{rat} - U_{dc}\right) \tag{5}$$

Here, U_{rat} is the rated voltage of the DC bus, and U_{rat} and k_i are the proportional and integral coefficients of the PI controller, respectively.

The system uses a combination of centralized control and distributed control to achieve unified coordinated control. The centralized controller of the energy router operates under a

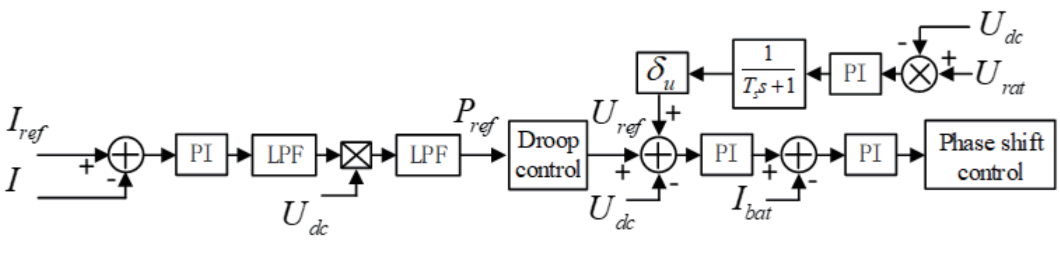

Fig. 12. Energy storage converter control strategy.

specific working condition according to the current trigger command to maintain the power balance and voltage stability in the system. During the transition of working condition switching, the unbalanced energy flowing into the DC bus can be completely absorbed by the capacitance of the DC bus. The fluctuation of the bus voltage depends on the magnitude of the unbalanced energy as follows:

$$\left(P_{grid}+P_{PV}+P_{bat}+P_L\right)\Delta t=0.5c\left(u_{c2}^2-u_{c1}^2\right). \tag{6}$$

Here, P_{grid}, P_{PV}, P_{bat}, and P_L are the power flowing into the DC bus from the grid, the photovoltaic power, the energy storage load, and the household load, respectively. Moreover, c is the DC bus capacitance, u_{c1} and u_{c2} are the DC bus voltages before and after the operating conditions are switched, respectively, and Δt is the period.

The coordinated control strategy ensures the real-time balance of the power of each socket in the conversion process under different working conditions. Therefore, the bus voltage fluctuation is very small, which effectively avoids the bus voltage jump resulting from the energy mismatch caused by the changes in power during the working condition conversion process, thus realizing seamless switching between different working conditions. This provides a basis for realizing the optimization target set by the user.

5. Case Analysis

To verify the unified control strategy of the household electric energy router discussed in the paper, a simulation-based analysis of the switching of various working conditions was carried out. The feasibility and efficiency of the home electric energy router with the power converter based on GaN power devices were also verified (Table 1).

To verify that the household electric energy router can switch between all working conditions in the design, the switching between various basic modes was investigated. Figure 13 shows the simulated waveforms of switching between operating conditions in different basic operating modes. Before 0.5 s, the system was in the steady state of the previous working condition, and the photovoltaic output and DC bus voltage were maintained at the rated values, as shown in Fig. 13(a). At 1 s, in response to grid dispatch, the system enters the grid dispatching energy

Table 1
Simulation parameters of energy routers.

Parameter	Numerical value
DC bus rated voltage	750 V
Phase C voltage	220 V
DC bus capacitor	2 mF
Rated voltage of energy storage	500 V
Inertial delay link T_s	0.05 s
Transformer transformation ratio of energy storage power converter	150 : 225

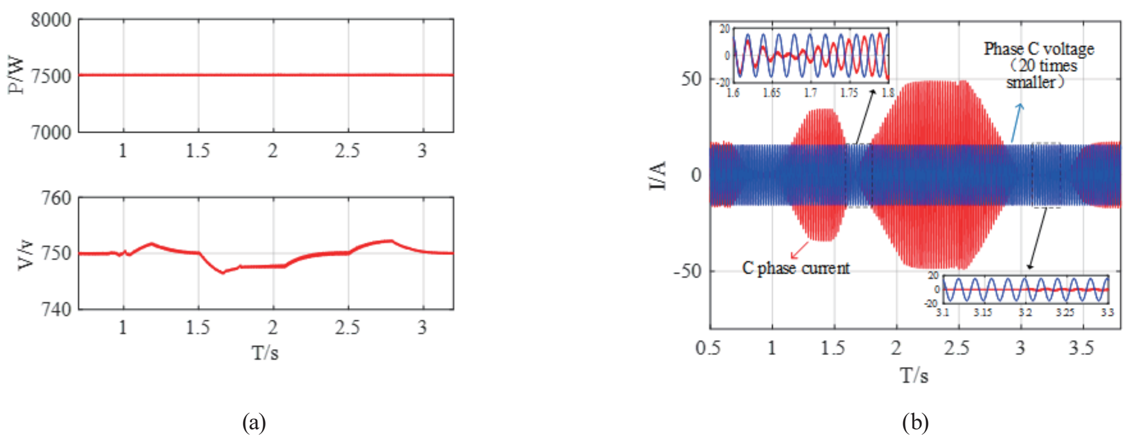

Fig. 13. (Color online) Simulation waveforms of switching between various working conditions under different basic operating modes. (a) Photovoltaic output power and DC bus voltage. (b) C-phase voltage and current waveform.

absorption mode, and the energy storage starts to charge until it enters the off-grid operation mode. At 1.5 s, the system operates in the grid dispatching feed mode. Limited by the capacity of the grid connected to the socket, the energy storage charging current drops to zero. The rectified current of the grid interface converter gradually decreases, and finally, the rectification mode is automatically switched to the inverter mode, as shown in the partial enlarged view in Fig. 13(b). At 2.4 s, when an off-grid instruction is received, the energy storage discharge and photovoltaic output supply power to the DC bus, and the current of the power converter at the grid interface gradually decrease. When the system reaches a steady state at about 3 s, the energy router realizes the energy balance in the system and has completed the seamless switch from being grid-connected to off-grid. At 3.2 s, it is necessary to connect to the grid; the energy storage discharge is reduced at this time and the system is converted to the standby mode. It can be seen from the partial enlarged view of 3.1–3.2 s in Fig. 13(b) that the power converter of the grid interface is connected when the transmission power is zero. In the whole simulation process of seamless grid connection, the DC bus voltage changes stably with little fluctuation while switching between different basic modes. This clearly demonstrates that household energy routers based on GaN device power converters can achieve the seamless switching of various working conditions under a unified and coordinated control strategy.

To investigate the performance of power converters based on GaN devices, the 24 h power curve shown in Fig. 14 was obtained by comparing the use of traditional power converters in the same working mode of the household energy router.[13] As shown in Fig. 14, the router socket is frequently used from 9 am to 10 pm, and the power loss of the household power router based on GaN power devices is significantly less than that of the power router using traditional switching devices under the same power consumption. Through calculation, it is concluded that the household power router based on GaN power devices has 12.66% higher efficiency than traditional power routers.

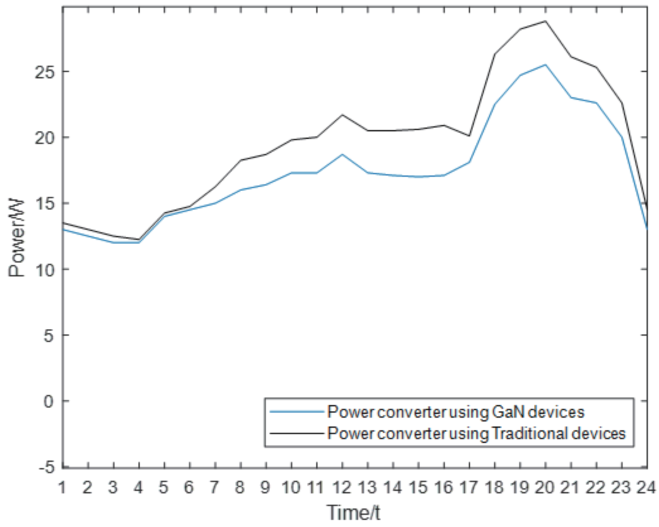

Fig. 14. (Color online) Performance of power converters based on GaN devices.

6. Conclusions

We designed a HEMS based on an energy router, which connects the grid, renewable energy systems, energy storage, and loads through the energy router. The frame structure of the household energy router was analyzed in detail, and its function was analyzed and designed. Because the status of the socket interface of the household energy router changes frequently, the energy router based on the traditional power converter has problems of large loss and poor switching performance. We proposed an energy router based on GaN power converters. GaN power devices, with advantages of low on-resistance, high breakdown voltage, and high operating frequency, are applied to power converters, and we designed LLC resonant converters based on GaN devices. Through the design of the working status of the household energy router and the switching control of different working conditions, a combination of centralized control and distributed control was proposed to achieve unified and coordinated control. The coordinated control strategy ensures the real-time balance of the power of each socket in switching between different working conditions to achieve seamless switching between them. On this basis, users can select and convert the working conditions of the household electric energy router according to their optimization goals and operating data. We verified the feasibility and efficiency of GaN power converters in household power routers through simulation.

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