Research on control strategy and dynamic test of multi-port electric energy router

Zaixin Yang1*, Xusheng Jian1 and Sitai Ya1

1 Inner Mongolia Enterprise Key Laboratory of Smart Grid Simulation of Electrical Power System, Inner Mongolia Power Research Institute, Hohhot, 010020, China

*Corresponding author’s e-mail: yangzaixin@impc.com.cn

Abstract. Researching an electric energy router and analyzing the control and operation characteristics are of significant importance for bi-high power system. In this study, a multi-modal two-level coordinated control strategy of multi-port electric energy router is proposed to achieve fast and flexible regulation of power flow. A prototype of multi-port energy router is trial-produced with an energy storage system, a sending-end power grid and a receiving-end power grid. Furthermore, a comprehensive dynamic test for the prototype of multi-port energy router is completed. The results show that the dynamic performance of the multi-port energy router in power step test is found to conform to the test standard. The charging and discharging modes of the energy storage unit under multi-modal control strategy are switched correctly. During the energy exchange process, multi-port AC/DC voltage operates stably. It can be applied to multi-port, multi-cascade, multi-flow distribution network.

1. Introduction

Around the new power system required by the bi-carbon (carbon emission peak and carbon neutralization) goal, the construction of the energy internet is accelerating. At the same time, it is increasingly important to ensure the coordinated control and operation of the bi-high power system (high-penetration power electronic equipment and high-penetration renewable energy). Based on power electronics, electrical energy router can provide multiple types of electric interfaces for loads and renewable generation sources, and achieve active power flow control [1].

In recent years, domestic and foreign researchers have carried out research on the electrical energy router in physical topology, control strategy, communication, equipment development, energy management and other aspects. In detail, the development process for the physical topology of the energy router goes through five stages, namely: high-frequency electronic transformer, fully electronic transformation, intelligent high-frequency electronic transformer, high-voltage with high-frequency transformer and multi-port electric energy router [2]. In 2011, the United States proposed intelligent energy management (IEM) based on the FREEDM system (future renewable electric energy delivery and management) to realize the system interconnection for AC and DC power grid and the flexible control of power flow [3]. Japanese scholars use the concept of the internet to construct a digital grid, decompose the large power grid into asynchronous and autonomous interconnected power local area networks, and use a digital grid router (DGR) for energy allocation and network interconnection [4]. On the other hand, the high-profile active distribution network (ADN) at the 2014 International Big Grid Conference [5] proposed to design a more flexible power supply and distribution structure to increase the multi-directionality of energy flow and the flexibility of control. Although China's energy Internet...
started late, it has developed rapidly in recent years. The application of power routers based on power electronic conversion to the energy Internet can achieve efficient access and utilization of energy [6].

The electric energy router integrates information technology and power electronic conversion technology. It has the ability of accurate, continuous, rapid and flexible regulation, can realize the efficient use and transmission of distributed energy, and can provide flexible and standardized power electronic interface for "generation, grid, load and storage". At present, according to different technical implementations, there are three representative power routers as follows: Solid State Transformer (SST), Multi-port Converter (MPC) and Power Line Communication (PLC) [7-8]. Drawing lessons from the protocol structure of network routers, power routers are divided into physical layer, link layer and network layer in [9]. The power router structure of the AC/DC hybrid microgrid is designed and the operation mode of the microgrid is analysed in [10]. A novel modular-based energy router [11] is proposed to extend the functions of energy router. A Lyapunov optimization-based energy management strategy for the energy hub with an energy router is applied to integrated energy system (IES) in smart grid [12].

In this paper, multi-port electric energy router is studied by referring to the control strategy of power electronic converters and the hierarchical design idea of energy routing. The paper is organized as follows: In Section 2, a multi-modal two-level coordinated control strategy of multi-port electric energy router is presented. In Section 3, a prototype of multi-port energy router including an energy storage system, a sending-end power grid and a receiving-end power grid is trial-produced. In Section 4, a comprehensive dynamic test for the prototype of multi-port energy router is given. Finally, the conclusions with multi-port electric energy router are presented in Section 5.

2. Multi-modal two-level coordinated control method of multi-port electric energy router

The basis of the multi-port electric energy router is to rely on power electronic devices for energy conversion and transmission. It is responsible for connecting different AC and DC ports to realize the directional and quantitative flow of active power and reactive power, and at the same time provide different electrical form interfaces for various types of electrical equipment. In this way, multi-source complementarity and coordination and optimization of "generation, grid, load and storage" can be realized, and real-time interaction between the main network and distribution network can be realized to enhance the flexibility of the power grid and the initiative of the user side.

The topology of the multi-port electric energy router includes single input-multiple output, multiple input-single output, multiple input-multiple output. Correspondingly, the access forms include AC side single-ended access, ring network access, and DC side parallel access. As a core control method of the energy router, it is mainly aimed at the electric parameters control of each port and the overall energy distribution method. Therefore, we propose the multi-modal two-level coordinated control method.

2.1. Top-level multi-modal strategy

The multi-modal two-level coordinated control method is composed of top-level multi-modal strategy and low-level coordinated control strategy. The purpose of the top-level multi-modal strategy is energy management and distribution flexibly. It has the functions of power flow adjustment, reactive power compensation, and flexible energy storage for multiple ports. Taking a three-port electric energy router as an example, the design of the multi-modal for multi-port electric energy router is shown in Figure 1. The input power of the sending-end power grid is $P_s$, the output power of the receiving-end power grid is $P_r$, and the output power of the energy storage is $P_e$.

Firstly, the top-level control center judges the state $SOC$ of the energy storage terminal to determine whether the power flow adjustment function of the energy storage output terminal is activated. The judgment method is as follows:

$$\begin{align*}
  SOC < S_{\text{min}} & \quad \text{low charge} \\
  S_{\text{min}} < SOC < S_{\text{max}} & \quad \text{power flow adjustment is activated} \\
  SOC > S_{\text{max}} & \quad \text{fully charge}
\end{align*}$$  \hspace{1cm} (1)
Figure 1. The multi-modal for multi-port electric energy router.

Modal 1: The receiving-end active power is less than the sending-end active power, at the same time, the SOC state value of the energy storage device is lower than the discharge limit. The control measure is that the sending-end power grid charges the energy storage device, and the power of the sending-end power grid to the receiving-end power grid is $P_s - P_e$.

Modal 2: The receiving-end power grid is a heavy load, and the sending-end power grid cannot perform charging operations for energy storage at this time. Energy storage terminal warn: low charge.

Modal 3: The SOC is between the upper and lower limits of charge and discharge, and the sending-end active power is greater than the receiving-end active power. The sending-end power grid not only charges the energy storage port, but also provides power for the receiving-end power grid.

Modal 4: When the receiving-end active power is insufficient, the energy storage device provides electrical energy support for the receiving-end power grid.

Modal 5: When the SOC is greater than the upper charge limit and the receiving-end power grid is lightly loaded, the energy storage device will warn that fully charge.

Modal 6: If $Pr > Ps$ and $SOC > S_{max}$, then the control measure is that both the sending-end grid and the energy storage send active power to the receiving-end grid.

2.2. Low-level coordinated control strategy

The low-level coordinated control strategy adopts the distributed control idea for the serial-in and parallel-out electric energy router composed of cascaded H-bridges. The dual-loop Control mode is used by each port. However, the control target of each port is different.

For the input stage as AC/DC sending-end power grid, the outer loop is voltage control, and the inner loop is current control. It is also necessary to consider the use of phase-shift angle control methods to ensure the constant voltage of the DC bus.

For the output stage as DC/AC receiving-end power grid, the PQ control method is adopted, that is, the outer loop is the power loop and the inner loop is the current loop. The PQ control principle of the AC/AC output-end electric energy router is shown in Figure 2. The dynamic phase angle is obtained by PLL and the d-axis and q-axis components are obtained according to dq reference frame transformation. Through the PI regulator to adjust the AC and DC axis current of the receiving-end electric energy router, the obtained $V_{d}^{*}$ and $V_{q}^{*}$ control equations are as follows.
\[ V_d^* = \left( k_p + \frac{k_i}{s} \right) (i_{d_{\text{ref}}} - i_d) - \omega L i_q + U_d \]  
\[ V_q^* = \left( k_p + \frac{k_i}{s} \right) (i_{q_{\text{ref}}} - i_q) - \omega L i_d + U_q \]

Figure 2. The PQ control principle of the AC/AC output-end electric energy router.

For the output stage as the DC/DC energy storage port, which is composed of a Buck/Boost type DC/DC converter. The outer loop adopts DC voltage control and the inner loop current control strategy to quickly stabilize the DC voltage.

3. Multi-port electric energy router prototype

The developed three-port electric energy router includes a grid-connected AC/DC converter, a DC/AC inverter and a three-phase DC/DC converter. The topology of the prototype is shown in Figure 3. The power of the sending-end grid can be regulated in real time according to the load of the receiving-end grid. The system can flexibly control the charging and discharging of the energy storage battery. The system judges the charge/discharge mode according to the SOC, can charge or discharge at a constant rate, and realize the regulation of the input power of the grid.

Figure 3. Topology of the three-terminal electric energy router prototype.

Design the system hardware and communication for the three-terminal electric energy router. The main parameters of the three-terminal electric energy router prototype are shown in Table 1. Among
them, the underlying hardware is mainly composed of a power supply module, an AD conversion module, a control strategy module, a communication module, and a system protection module. Control chips include DSP, FPGA, Flash, RAM, etc. DSP exchanges information with the outside through CAN communication. The system protection function is equipped with hardware temperature abnormality protection, IGBT overcurrent and overvoltage protection, and DC bus overvoltage protection.

### Table 1. Parameters of the three-terminal energy router prototype.

| Parameter                          | Value | Unit |
|------------------------------------|-------|------|
| System capacity                    | 30    | kW   |
| AC bus voltage                     | 380   | V    |
| DC bus voltage                     | 750   | V    |
| Lithium battery voltage            | 197   | V    |
| Lithium battery capacity           | 60    | Ah   |
| IGBT breaking frequency            | 12.5  | kHz  |
| IGBT ratio                         | 1200/150 | V/A |
| Lithium battery charge/discharge current | 10  | A    |
| DC side capacitor                  | 8000  | μF   |
| AC filter inductor                 | 500   | μH   |
| AC filter capacitor                | 10    | μF   |

### 4. Dynamic test for the prototype of multi-port electric energy router

In order to verify the validity and correctness of the three-port control strategy, and further verify the rationality and correctness of the cooperative control strategy of the energy router prototype running in multi-scenario mode, and conduct dynamic tests on it according to the standards “Functional specifications and technical requirements of energy router” and “The dynamic test of power system protective products” [13-15].

The test equipment is as follows: the sending-end grid is provided by a programmable AC power source, receiving-end grid is provided by a dynamic adjustable load device, high-precision waveform recorder (sampling accuracy is 200 kHz). The test items of the three-terminal energy router prototype are as follows: the start-stop test, the steady-state operation test, the grid-connected load test, and the dynamic adjustment test [16]. This paper mainly analyses the comprehensive performance of the three-terminal electric energy router prototype with two dynamic experiments.

#### 4.1. Power step test of the receiving-end power grid

This item tests the dynamic operation of the electric energy router under different load mutations of the DC/AC inverter. Continuously change the load of the receiving-end power grid from 3 kw to 10kw, and monitor the electrical quantity changes at each measuring point of the system during this process.

A recording chart of the power step test for the receiving-end power grid is shown in Figure 4. The figure shows the DC bus voltage, the output voltage and active power of the receiving-end grid, and the AC current and voltage of the sending-end grid. The adjustable load adopts the form of three consecutive adjustments of the load, that is, from 5 kW to 7 kW and then to 10 kW, and the time interval for each load increase is 1.5 s. It can be reflected from the figure that the active power reaches the target value through three-stage adjustment during the power rise process. The average time for each response and adjustment is 0.17 s. From the enlarged diagram of AC instantaneous value for the current sudden change, it can be concluded that the step overshoot of the current is less than 2%, which meets the standard requirements. At the same time, the energy transmission of the three ports is stable, and the AC voltage of the sending-end grid and DC bus voltage have no obvious fluctuations.
4.2. Electric energy routing function test

This item tests whether the prototype of three-port electric energy router can be used for power transmission distribution and path selection according to external instructions or actual operating condition. Furthermore, the power flow adjustment is used to verify whether the control strategy of the multi-port electric energy router is effective.

The test condition is that the prototype is connected to the grid with a 3 kw load, and the control mode 3 and mode 4 of this paper are used as examples to verify. Start the power flow adjustment function of the energy storage port, and actively adjust the power of the grid input port. The test result of electric energy routing function is shown in Figure 5.

The charging of the energy storage port is started at 30 s, and the electric energy routing function will switch to mode 3 operation. It can be seen from the figure that there is a transient inrush current of 11.7 A for 490 ms. Thereafter, the energy storage adjustment is started at 147 s, and the energy routing function is switched to mode 4 operation, and then the mode 3 operation is restored after 85 s. During the entire adjustment process, the energy storage port can actively adjust the input power of the sending-end power grid and maintain a constant output power of the receiving-end power grid. At the same time, the DC bus voltage fluctuation range is 739 V to 747 V, which meets the requirements of the standard and is not less than 90% of the rated voltage.

Figure 5. The test result of electric energy routing function.
5. Conclusions
Through the dynamic test of the three-port electric energy router prototype, it is verified that the device can have the corresponding rapid adjustment and control ability in the case of a sudden change in the system operation state, and the system has good robustness. The effectiveness of the control strategy for multi-port electric energy is verified. It can be applied to multi-port, multi-cascade, multi-flow distribution network.

References
[1] Zong, S., He, X., Wu, J., et al. (2015) Overview of power electronics based electrical energy router. Proceedings of the CSEE, 35: 4559-4570.
[2] Zhao, Z., Feng, G., Yuan, L., et al. (2017) The development and key technologies of electric energy router. Proceedings of the CSEE, 37: 3823-3834.
[3] Antipin, A.S., Frizen, V.E., Udintcev, V.N., et al. (2018) The energy router based on a solid-state high-frequency transformer. In: IEEE Conference of Russian. Russian. pp. 562-565.
[4] Deng, X. (2013) Digital electrical grid plan of Japan. World Science, 7: 9-19.
[5] Zhao, B., Wang, C., Zhou, J., et al. (2014) Present and future development trend of active distribution network. Automation of Electric Power Systems, 38: 125-135.
[6] Bie, Z., Wang, X., Yuan, H.U. (2017) Review and prospect of planning of energy internet. Proceedings of the CSEE, 37: 6445-6462.
[7] Wu, H., Zhang, J., Xing, Y. (2014) A family of multiport buck–boost converters based on dc-link-inductors (dlis). IEEE Transactions on Power Electronics, 30: 735-746.
[8] Tashiro, K., Takahashi, R., Hikihara, T. (2012) Feasibility of power packet dispatching at in-home DC distribution network. In: IEEE Third International Conference on Smart Grid Communications. Taiwan. pp. 401-405.
[9] Wang, R., Ding, S., Chen, J., et al. (2020) Design of a novel power/information integrated energy router for E-LAN. In: IEEE 9th International Power Electronics and Motion Control Conference. Asia. pp. 1640-1644.
[10] Loh, P.C., Li, D., Blaabjerg, F. (2011) Autonomous control of interlinking converters in hybrid AC-DC microgrids with energy storages. In: IEEE Energy Conversion Congress and Exposition. USA. pp. 652-658.
[11] Tu, C., Xiao, F., Lan, Z., et al. (2018) Analysis and control of a novel modular-based energy router for dc microgrid cluster. Emerging and Selected Topics in Power Electronics, IEEE Journal of Emerging and Selected Topics in Power Electronics, 7: 331-342.
[12] Li, P., Sheng, W., Duan, Q., et al. (2020) A lyapunov optimization-based energy management strategy for energy hub with energy router. IEEE Transactions on Smart Grid, 11: 4860-4870.
[13] Yang, Z., Xing, L., Yin, B., et al. (2019) Dynamic Test for DC Training Emulation System with Back-to-back MMC. In: IEEE Sustainable Power and Energy Conference (iSPEC). Beijing. pp. 2187-2191.
[14] China Electricity Council. (2021) GB/T 40097-2021 Functional specifications and technical requirements of energy router. Beijing: China Electric Power Press.
[15] China Electricity Council. (2011) GB/T 26864-2011 The dynamic test of the power system protective products. Beijing: China Electric Power Press.
[16] Yang, Z., Wang, Y., Xing, L., et al. (2019). Relay protection simulation and testing of online setting value modification based on RTDS. IEEE Access, 8: 4693-4699.