Design and Application of Standardized Power and Communication Module for Energy Router

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***Abstract*—Energy Internet (EI) is a cyber-physical system. In order to improve the scalability of equipment in EI, a standardized power module (SPM) is designed in this paper. The SPM is based on a power electronic structure through which rectifying, inverting and chopping can be realized. With SPMs, a variety of distributed energy or load can be interconnected. Besides, the authors design a standardized communication module (SCM) to integrate the communication units such as RS485, RS232, Ethernet, CAN and optical fiber, and to coordinate with the SPM. The new energy router (ER) structure based on SPM and SCM can realize power exchange and optimization control. Aiming at power quality control and lifting voltage level, SPM and SCM can work as modular multilevel converter (MMC) and active power filter (APF). This article provides scheme and simulation verification.**

Keywords*—energy Internet, energy router, standardized power module, standardized communication module

I. INTRODUCTION

Since the twenty-first century, the human society has developed rapidly, and the demand for energy has become more and more intense [1]. However, excessive reliance on fossil fuels has caused global warming and a decline in air quality. For this reason, research has been focused on finding alternative energy sources [2], [3]. Research on distributed energy and energy storage has made great achievements in recent years. As a product of the highly integration of new communication technology and new energy technology, the energy Internet (EI) provides a basic platform for the access, control and transmission of all kinds of distributed energy, energy storage equipment and loads [4]-[6]. Inspired from the design of switching equipment in the Internet, the concept of energy router (ER) is put forward by researchers in the field of EI in order to realize interconnection, scheduling and control of energy network.

ERs can be utilized for energy forwarding, caching and trading. Besides, power quality can be guaranteed by ERs. According to the characteristics of distributed energy, high scalability of ER is required to achieve open, interconnected, equal and sharing in EI. The concept of ER was firstly proposed by the FREEDM center [7]. The power electronic architecture of the FREEDM model is based on solid-state transformers, including multiple cascaded full bridge rectifier parts, an isolated DC-DC transform part and a voltage source inverter part. The FREEDM model can control the power quality, including harmonics management, reactive power compensation and voltage support. The concept of electric energy switch is advanced in reference [8]. The core module in [8] consists of two power electronic converters and a high frequency transformer. Compared to the solid-state transformer structure, it has high voltage direct current and low voltage direct current interface. The ER structure studied in [9] is similar to the typical AC microgrid (MG) architecture. Distributed energy resources and loads are interconnected via AC bus through a proprietary AC-AC or DC-AC converter. The AC bus is connected with the power grid through the grid connected converter. A variety of research focus on the control and scheduling of ERs are based on MG model [10], [11]. Although model and control technologies in MG are mature, the architecture of MG is very different from the idea of plug and play (PNP) and extensibility of ERs [12]. The above requirements can be achieved by SPM.

The development of the power sector relies on the deployment of a wide range of expensive infrastructures. Disruptive innovation will be costly and time consuming. The existing infrastructure needs to be fully utilized when design the communication network architecture of the EI [13]. The commonly used communications modules in power system include RS485, RS232, Ethernet, CAN and optical fiber. RS232 is one of the main serial communication interfaces [14]. It is mainly used for the transmission of signals between two short range devices. RS485 can be used for half duplex communication and multiple devices communication is supported. Ethernet communication contains carrier-multi-access and collision detection mechanism. Data transmission rate reaches 1Gbit/s, which can meet the requirements of non-persistent network data transmission. Ethernet is widely applied in various computer networks, and is currently one of the most commonly used network standards. The optical fiber communication system has been developing rapidly in the past decades. With wide transmission bandwidth, high anti-interference and small signal attenuation, optical fiber has become the main transmission way in communication.

In [15], it is proposed that ERs have functions such as power energy exchange, coordinated optimization control and power quality control. At present, STATCOM, SVC, APF, UPFC, UPQC is commonly used to adjust the power quality in the power system. The modular multilevel converter (MMC) [16], by connecting the sub-modules in series to form a converter valve. MMC has greatly improved the voltage level as well as reduced the harmonic distortion and the switching loss without reducing the pressure of the switch tube. MMC is widely applied to HVDC transmission system. Active power filter (APF) is highly controllable and respond to the current change quickly. APF is utilized to compensate harmonics, suppress flicker and compensate reactive power. Its filtering characteristics are independent of the variance of system impedance such that the changing harmonics are auto-tracked and compensated [17]. APF plays an important role in power systems.

In this paper, A standardized power module (SPM) based on diode clamped three level inverter architecture is designed, realizing rectifier, inverter and DC chopper without changing the main body of power circuit. The effect of SPM power transformation is verified by simulation. This paper also proposes a standardized communication module (SCM) to access variety of communication units, coordinate with SPM. The fusion of cyber-physical and the extensibility of the system are realized through the combination of SPMs and SCMs. Finally, the application of SPM and SCM in building ERs, regulating power quality and improving voltage level is presented, and advanced functions such as power quality management and energy optimization management are realized.

The contribution of this paper can be outlined as follows:

1) *Standardized* power and communication module are designed to replace varied types of converters and communication units.
2) The effectiveness and superiority of SPM and SCM is confirmed by simulating in MATLAB/Simulink.
3) Applications of using SPMs and SCMs to solve problems including establishing ER, APF and MMC are proposed.

The rest of the paper is organized as follows: Section II introduces the Design of SPM. The design of SCM is introduced in Section III. In Section IV, applications of SPM and SCM are illustrated. Finally, Section V concludes the paper.

II. Design of SPM

The SPM topology is a diode clamped three level converter [18], as is shown in Fig. 1. The DC side is connected with two identical voltage dividers in series. Each phase is composed of four series switch tubes. Two fast recovery diodes are connected in parallel with two switches in the middle. The middle point of the clamping diode is connected with the neutral point of the voltage divider capacitor to realize the clamping function. Since the switch voltage is only half of the DC voltage input, the voltage of the system has been improved. SPM can be applied to high voltage and high-power occasions. The AC-DC transform and DC-AC transform can be realized through the proper control of the twelve switch switches, and the related control methods are already mature [19]. Under this state, the SPM works in the rectifier-inverter mode thus has the DC input/output side and the AC input/output side.

DC sources and loads also need to be connected to the power system. The SPM has the function of bidirectional DC-DC transformation, and it can work in DC chopper mode. Buck-Boost converter is the most widely adopted bidirectional DC-DC converter. By controlling the IGBT turn on and off, step-up or step-down function can be realized. However, the DC ripple of buck-boost converter is too large, and the withstand voltage and current of switches lead to limitations in high-voltage and high-power applications.

Through the power switch, the three-phase circuit of the AC side is interconnected and connected to the voltage regulator, and the module is converted into a DC chopper mode, as is shown in Fig. 1. A three level buck-boost structure is formed when three-phase output is connected in parallel after the inductance filter. In the DC chopper mode, two switches on each half bridge arm are turned on or off at the same time, thus the output characteristic of single-phase circuit is the same as that of buck-boost converter. The driving signal of the three phase switch tube is different from the 1/3 cycle, and the output signal is added to the waveform after the DC conversion. Under this state, the system input and output of are both DC power, with high voltage side and low voltage side. The theoretical derivation of ripple analysis is given in [20].

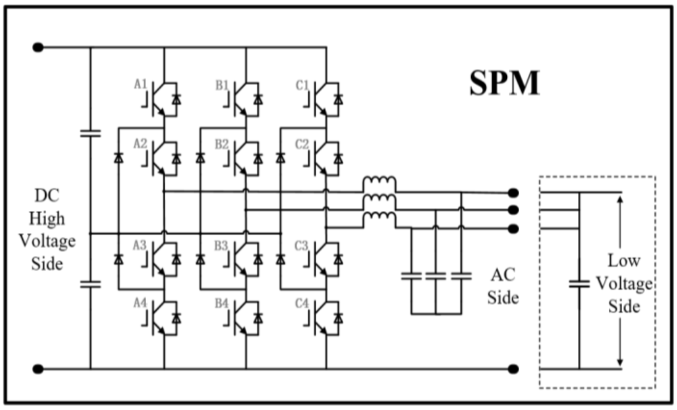

Fig. 1. Structure of SPM

When SPM works in DC chopper mode, it has many advantages compared with the basic buck-boost structure:

- Current in single phase bridge arm of SPM is 1/3 of that in the common structure, the capacity of the system can be increased.
- The harmonic ripple and the inductor current is reduced.
- The fault tolerance of the system is improved. If one bridge arm failures, the system can still operate normally.
- IGBT switching frequency is improved, thus the dynamic characteristics are improved.

III. Design of SCM

SCM is utilized to transform data from different communication units into a unified form of communication. Standardization includes protocol standardization and interface standardization. Considering the diversity of sources or loads that may be accessed in the power system, SCM is designed in this paper. The structure of SCM is shown in Fig. 2.

The interface of the SCM mainly includes the external port side interface and the upper controller side interface. The port side interface communicates with the converter and the external device, including RS485, RS232, Ethernet, CAN, optical fiber communication unit, and the reserved expansion interface for other types of communication unit access. The baud rate of the RS485 communication chip utilized in SCM is above 512Kbps. RS485 interface adopts the MODBUS-RTU communication protocol and the communication isolation scheme. The RS232 communication chip selected in SCM has a baud rate at least 1 Mbps, and the other configuration is the same as that of the RS385 unit. The CAN unit adopts the standard CAN2.0 communication interface, and the communication rate can reach 1Mbps. Data frames, remote frames and error frames can be realized. The Ethernet unit adopts the standard RJ45 isolation network port. The network interface chip supports the 10M/100M communication based on the Modbus-RTU protocol. The optical fiber communication unit on the interface side communicates with the converter controller. The HFBR2521 and HFBR1521 chips are used. The controller sends the current, voltage and power information to the ARM chip through the input optical fiber port. Information displays on the LCD screen. The upper controller side interface communicates with the upper controller and the upper computer, including the standardized optical fiber unit and the GPRS unit. A UART interface is reused between the optical fiber unit and the ARM chip, and the GPRS is reserved for the SIM card slot. In order to supply power for the whole system, the SCM also has a power module and an AC power input interface.

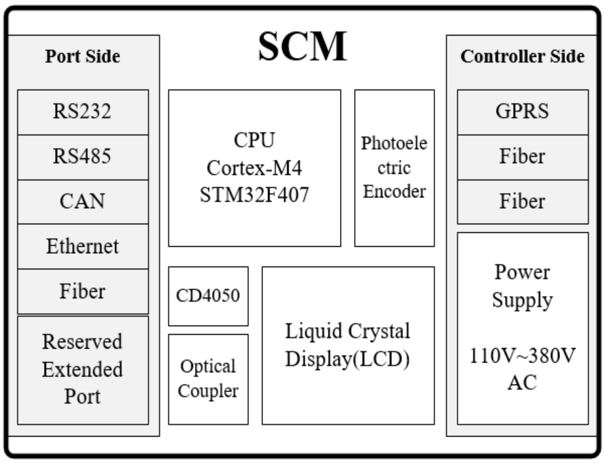

Fig. 2. Structure of SCM

In addition to the above interface, a number of functional modules are integrated on SCM. In order to access the wind power, the SCM is integrated with the photoelectric encoder to pick up the data of the rotor speed or position of the paddle control system and the doubly fed generator. The photoelectric encoder helps to realize the precise positioning and reset control of the blade in the varying propeller system, and improves the power generation efficiency and the power quality of the wind power generation interface. In addition, CD4050 and optical coupler module are used to buffer and isolate signals. LCD displays real-time electrical parameters such as current and voltage in converter, which is convenient for engineering personnel to monitor. SCM controller adopts ARM Cortex-M4 processor STM32F407 series which are compatible with STM32F2 series products. The feature helps users to maintain hardware compatibility and scalability. The controller of the SCM and SPM is directly connected by a physical line.

IV. The Application of SPM and ACM

In actual engineering, SPM and SCM are always used together. In this section, applications of SPM and SCM are illustrated.

A. Energy Router

Consider the structure of the ER as is shown in Fig. 3. ER includes six ports: photovoltaic units (PV), wind turbine generator (WTG), battery energy storage devices (BES), power grid (PG) , DC loads and AC loads. The SCM of each interface is coordinated with SPM. The initial state of SPM is the rectifier inverter state. The DC side is connected by the DC bus. The ER side interface of SCM communicates with the ER controller. The port side interface communicates with PV, WTG, BES, PG and loads. Take PV interface as an example, before accessing, photovoltaic cells first communicate with SCM. PV information is received and SPM control the power switch to operate in DC chopper mode, and then access PV units. After ER starts working, the ER controller processes the data transmitted from all interfaces SCM, and sends instructions to each port controller. The working mode of the corresponding ports is controlled by the port controller.

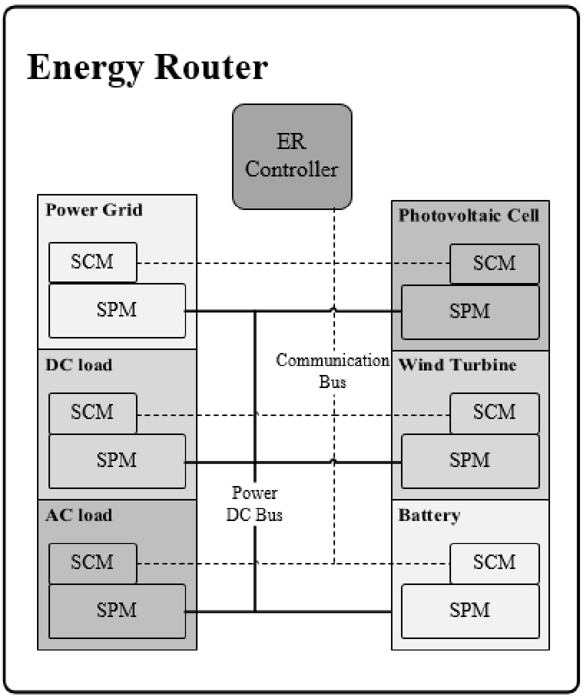

Fig. 3. The scenario of a typical ER

The requirements for communication of different types of ports vary greatly. In order to make the ER shown in Figure 3 work properly, a standardized requirement parameter is given for a common type port, as is shown in Table 1. Based on these parameters, the controller can receive enough information and the ER can operate normally.

TABLE I. ER Port Paramaters

Port Type	Communication Requirement Parameters		
	Physical Parameters	***Electrical Parameters***	***Status information***
Power Grid		Voltage; Current; Frequency; Active power; Reactive power.	Failure or not; Working mode.
Photo-voltaic	Light intensity; Temperature; Power characteristics.	Voltage; Current; Actual power.	Failure or not; Working mode.
Wind Power	Wind speed; Leaf tip speed ratio; Pitch angle.	Current; Voltage; Speed; Torque; Power rating of the generator.	Failure or not; Working mode.
Battery Energy Storage	Battery temperature; Battery capacity.	Maximum charge/ discharge number; Voltage; Current; Maximum charge/ discharge current; Maximum charge/ discharge voltage; SOC	Failure or not; Working mode.
Load	Temperature.	Rated voltage; Rated power; Power; Voltage; Maximum / minimum power; Maximum / minimum voltage; Resistance; Anti time protection parameters; Soft start time.	Failure or not; Working mode.

B. Power Quality Control

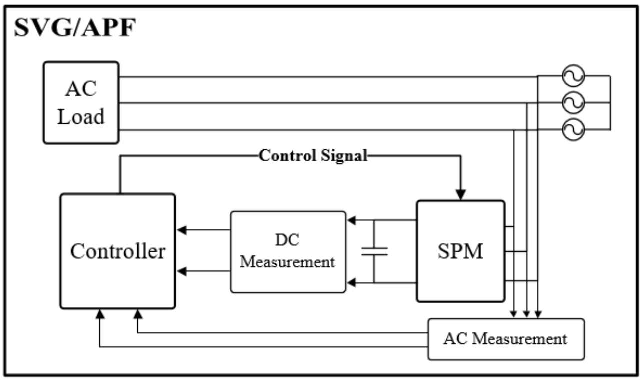

Fig. 4. The scenario of SPM work as SVD/APF

SPM and SCM can be applied to SVG and APF. SVG is mainly used for reactive power compensation, the purpose is to improve the power factor and stabilize the grid voltage, and also reduce voltage flicker, reduce overvoltage and improve the stability of power system. SPM works in the rectifying and inverting mode, the form of access and the principle of control as is shown in the use of SVG. The electrical parameters of the AC side and the DC side of the power grid and SPM are collected, and the amplitude and phase of the AC side current of the SPM are adjusted by PWM technology to compensate the reactive power. The structure of SPM has four quadrant operating characteristics, which can achieve non harmonic and continuous dynamic reactive power compensation.

When SPM is applied to APF, the access mode is the same as when it is applied to SVG. It also adopts real-time compensation technology to improve the power supply quality of the power grid. The function of APF and SVG can be realized simultaneously by customized software. The application of SPM to APF needs to have current source characteristics, injecting compensation current into the power grid, counteracting harmonic currents generated by harmonics, and making the current of the grid as a sine wave [21]. Mainly has the following advantages:

- Change the frequency and size of harmonics and the change of reactive power compensation, and a fast response to changes in the object of compensation.
- While compensating harmonic and reactive power, continuous reactive power compensation.
- Collect a small grid impedance effect not easy to resonate with the grid.
- Can track the change of power grid frequency, impact compensation performance is not affected by the change of grid frequency.
- Multiple harmonics and reactive power sources can be compensated centrally.

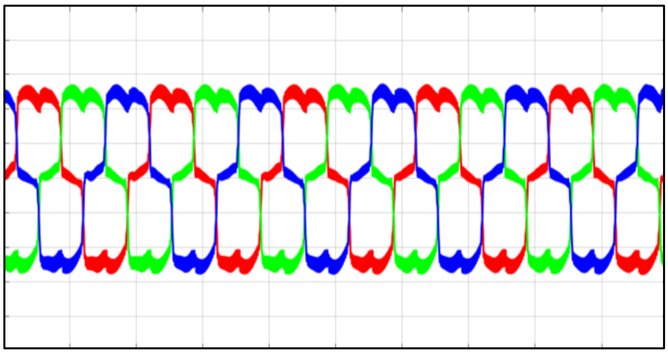

Fig. 5. Current waveform of the three-phase circuit without SPM work

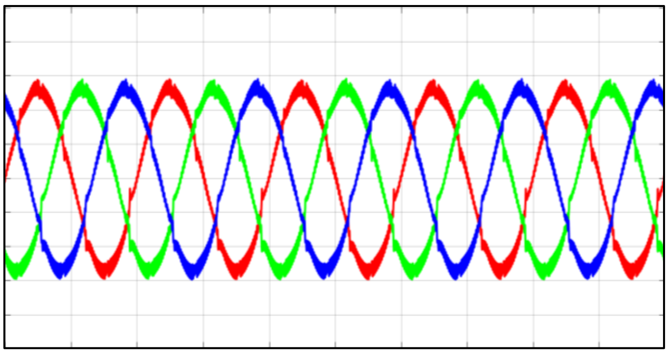

Fig. 6. Current waveform of the three-phase circuit with SPM work

The effectiveness of the SPM active power filter is verified by the simulation in MATLAB/Simulink. The three phase uncontrolled rectifier bridge is used to simulate the harmonic source. The current waveform of the three-phase circuit without and with SPM work are shown in Fig. 5. and Fig. 6., respectively. SPM can effectively compensate the active power.

C. *Voltage Level Lifting*

MMC is mainly used in high voltage and high-power scenes, with high modularization, which can greatly reduce the harmonic distortion and switching loss. The topology of the MMC consisting of SPM is shown in Fig. 7.. Several (n) SPMs are made up of a group, which is connected in series to form a half bridge arm. The output of AC power is connected to the midpoint of the upper and lower half of the bridge arm to form a phase access, and the output of three phase channels is connected to output high voltage direct current. The 2n SPMs of each bridge arm are used in combination with the sinusoidal AC voltage, and the number of sub modules at any time is n to keep the DC voltage constant. In the modular design, the rated values of each module are the same, and the reactance values of the six bridge arms are equal, and the DC current in the steady state is distributed evenly in the three-phase.

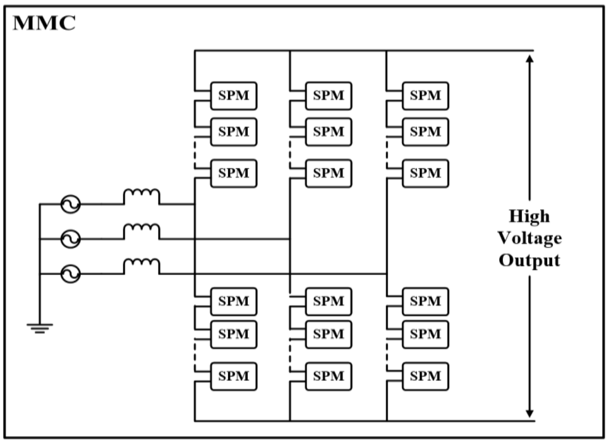

Fig. 7. Topology of MMC made up of SPMs

The topology of each sub module of MMC is shown in Fig. 8. The SPM at this time has a slight difference from the DC chopper mode described in the previous article. There is no need for input or output on the high side of the high voltage side. The voltage stable capacitor at the low voltage side is cut off through the power switch. The two ends of the lower half bridge arm are respectively used as the output and input of the sub module. The SPM module has three working state:

1) Locking state: The switch tubes in the two zones are turned off at this time, usually when the system starts or fails.

2) Accessing state: At this time, the switch tube of the zone 1 is turned on, and the switch tube of the zone 2 is turned off.

3) Cut off state: At this time, the zone 1 switch tube is turned off, and the zone 2 switch tube is turned on.

The input and cut out of the control SPM sub module can superpose the multilevel step signal and simulate the sinusoidal AC signal.

The traditional MMC sub module is single-phase structure, and the three-phase structure of SPM sub module greatly improves the fault tolerance of the system to a single switch tube, and improves the range of single module's changeable voltage. Summarize the advantages of MMC SPM as a sub module are as follows:

- The required voltage is low, and the uniformity of the device is low.
- Multiple voltage levels greatly reduce harmonics; The switching frequency is low, while the switching loss is small and system utilization is high.
- It is easy to realize back to back structure, so that the energy flow in two way MMC.
- No transformer is needed on the output side, which greatly reduces the quality and volume of the device, reduces the loss and saves the cost.
- The modular structure makes the capacity expansion and redundancy design easier.

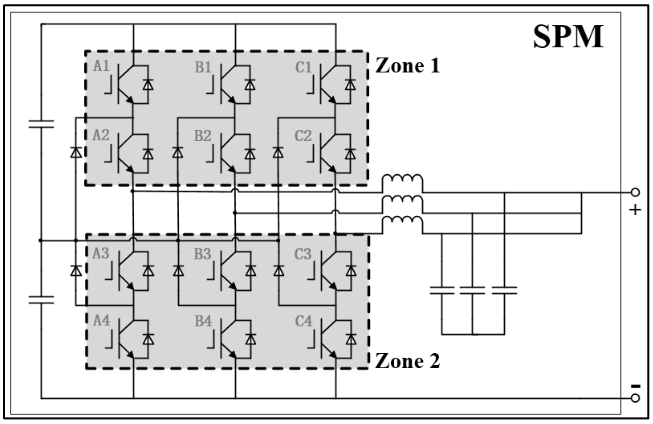

Fig. 8. Topology of sub module of MMC

A four voltage-level MMC structure model was built in MATLAB / Simulink to verify the function of SPM. The voltage and current waveform are shown in Fig. 9. and Fig. 10., respectively. The result shows SPM can lift voltage level with good performance.

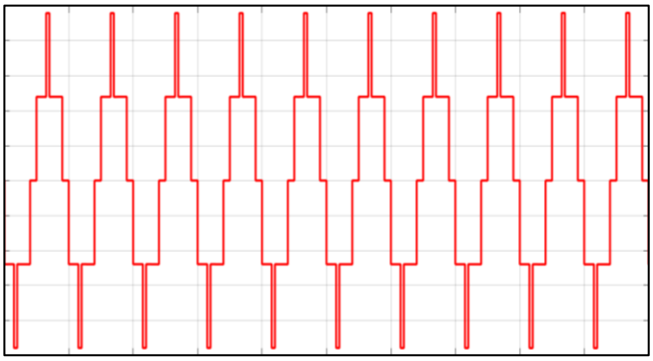

Fig. 9. Voltage waveform of a four voltage-level MMC

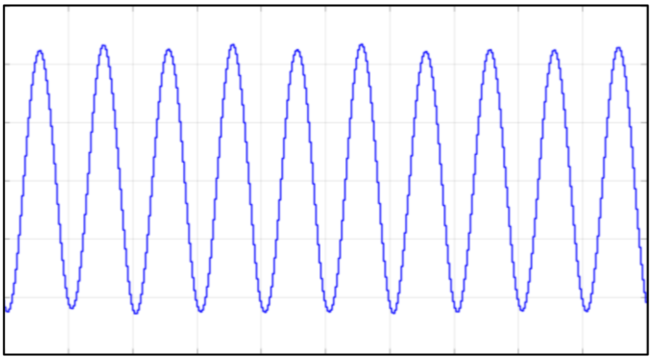

Fig. 10. Current waveform of a four voltage-level MMC

V. Conclusion

In this paper, SPM is designed, and the power conversion, such as rectifier, inverter and DC chopper, can be realized without changing the main structure. A standard communication module with standard power module used is also presented, which is based on the Modbus protocol, support by RS485, RS232, Ethernet, CAN and fiber form and peripheral interface in a unified form of communication, fiber and PC or the upper control module realizes the communication, communication protocol and communication interface standard. Finally, we give examples of the application of SPM and SCM in the design of ERs, power quality control of power grid and upgrading of voltage level. The design of hardware standardization and software customization is in line with the concept of "Open, Interconnected, Peer to peer, Sharing" in the energy Internet.

Acknowledgment

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References

[1] C. Hernandez-Aramburo, T. Green, and N. Mugniot, “Fuel consumption minimization of a microgrid,” *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 673–681, May-Jun. 2005.

[2] S. Bilgen, K. Kaygusuz, and A. Sari, “Renewable energy for a clean and sustainable future,” *Energy Sources*, vol. 26, no. 12, pp. 1119-1129, 2004.

[3] R. H. Lasseter and P. Paigi, “Microgrid: A conceptual solution,” *in Proc. IEEE 35th Annual Power Electron. Specialists Conf.*, Aachen, Germany, Nov. 2004, pp. 4285-4290.

[4] J. Rifkin, “The third industrial revolution: how lateral power is transforming energy, the economy, and the world,” *Palgrave Macmillan*, New York, pp. 31–46, 2013.

[5] J. Cao and M. Yang, “Energy Internet - towards smart grid 2.0,” *Fourth Int. Conf. Networking & Distributed Computing*, Los Angeles, USA, Dec. 2013, pp. 105–110.

[6] L. H. Tsoukalas and R. Gao, “From smart grids to an energy Internet - assumptions, architectures and requirements,” *Smart Grid and Renewable Energy*, vol. 1, pp. 18–22, Sept. 2009.

[7] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The future renewable electric energy delivery and management (FREEDM) system: The energy internet," *in Proc. IEEE*, vol. 99, no. 1, pp. 133-148, Jan. 2011.

[8] W. Sheng, Q. Duan, and L. Ying, "Research of Power Distribution and Application Grid Structure and Equipment for Future Energy Internet," *in Proc. Csee*, 2015, 35(15):3760-3769.

[9] B. Huang, Y. Li, H. Zhang, and Q. Sun, "Distributed optimal co-multi-microgrids energy management for energy Internet," *IEEE/CAA J. Autom. Sinica*, vol. 3, pp. 357-364, Oct. 2016.

[10] Y. Xu, J. Zhang, W. Wang, A. Juneja, S. Bhattacharya, "Energy router: Architectures and functionalities toward energy internet," *in Proc. IEEE 2nd Int. Conf. SmartGridComm*, pp. 31-36, Oct. 2011.

[11] J. Zhang, W. Wang, and S. Bhattacharya, “Architecture of solid state transformer-based energy router and models of energy traffic,” *in Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES*, Jan. 2012, pp. 1 - 8.

[12] M. Pan, N. Shen, and G. Yang, "A general framework to design operation modes of DC microgrids without communication links," *Power Electronics Conference. IEEE*, 2014:582-586.

[13] J. Wang, K. Meng, and J. Cao, "Information Technology for Energy Internet: A Survey," *Journal of Computer Research & Development*, 2015.

[14] W. Willinger, "Self-Similarity through High-Variability: Statistical Analysis of Ethernet LAN Traffic at the Source Level", *Proc. ACM SIGCOMM '95*, pp. 100-113.

[15] J. Wang,L. I. Yang, and L. U. Zhaoming, "Research on Local-area Energy Internet Control Technology Based on Energy Switches and Energy Routers," *in Proc. of the Csee*, 2016.

[16] A. Lesnicar, R. Marquardt, "An innovative modular multilevel converter topology suitable for a wide power range", *Proc. IEEE PowerTech Conf.*, pp. 1-6, 2003.

[17] M. Aredes, J. Häfner, K. Heumann, "Three-Phase Four-Wire Shunt Active Filter Control Strategies", *IEEE Trans. on Power Electronics*, vol. 12, no. 2, March 1997.

[18] I. T. A. Nabae, H. Akagi, "A new neutral-point-clamped PWM inverter", *IEEE Trans. Ind. Appl.*, vol. IA-17, no. 5, pp. 518-523, Oct. 1981.

[19] H. J. Kim, H.-D. Lee, S.-K. Sul, "A new strategy for common-mode voltage reduction in neutral point-clamped inverter-fed ac motor drives", *IEEE Trans. Ind. Appl.*, vol. 37, no. 6, pp. 1840-1845, Nov. 2001.

[20] C. Chang, "Current ripple bounds in interleaved dc–dc power converters", *Proc. Int. Conf. Power Electron. Drives*, pp. 738-743, 1995.

[21] N.-Y. Dai, M.-C. Wong, Y.-D. Han, "Application of a three-level NPC inverter as a 3-phase 4-wire power quality compensator by generalized 3-DSVM", *IEEE Trans. Power Electron.*, vol. 21, no. 2, pp. 440-449, Mar. 2006.