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Hybrid AC/DC microgrid architecture with comprehensive control strategy for energy management of smart building

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ABSTRACT

The permeability of distributed generations (DGs) is affected because of their uncertainty and randomness, and the traditional architecture of microgrid with conventional power transformer is unsuitable for smart building due to its uncontrollability and vulnerability to interference. In this article, a hybrid ac/dc microgrid architecture for smart building is proposed to increase the penetration of DGs and to isolate the interference to the grid. Thus, the system safety and stability can be ensured in a changeable and complicated grid environment. The advantages of this architecture include (1) the full use of the controllability of the modular multilevel converter based solid state transformer (MMC-SST), (2) the complementary characteristic of time and space of DGs, (3) and the peak shaving capacity of energy storage systems (ESSs). The characteristics of typical operating modes, i.e. grid-connected mode and off-grid mode are analyzed, and the comprehensive control strategy combining with the characteristic of each mode is designed. Finally, the effectiveness of the proposed architecture and the comprehensive control strategy is validated by a simulation platform.

1. Introduction

Microgrid is a flexible and effective approach to connect DGs to the grid, and it is an emerging developing trend for the smart building. Microgrid generally consists of power electronics converters, DGs, ESSs and a variety of dispersed loads (DLs) [1]. It can provide high-quality electricity to DLs and realize coordinated control of DGs.

There are ac, dc, and hybrid ac/dc microgrid. However, the single form of dc or ac microgrid cannot realize the efficient utilization of DGs and cannot meet the diversified demand. Therefore, the hybrid ac/dc microgrid architecture is of more value for smart building than single ac or dc forms [2].

In the traditional microgrid, conventional power transformers are utilized and DGs are connected to network via power inverters, which would lead to inefficient control, complex structure and high cost. As compared with the conventional power transformer, the solid state transformer (SST) is relatively small, highly controllable and it has both dc and ac interfaces [3,4]. It can implement various functions such as voltage transformation, electrical isolation and power quality management [5]. Hence, the SST would replace the conventional power transformer to connect various DGs and DLs in the future microgrid for smart building.

In recent years, researches of the SST mainly focus on how to enlarge their capacity and improve their voltage level. In this regard, many works have devoted to the topology design of the input stage, i.e. the MMC cascade topology [6–8] and the H bridge cascade topology [3,9,10]. Comparing with the H bridge cascade topology, the MMC based topology can significantly reduce the amount of switch devices and improve the dc output voltage quality. MMC-SST combines the advantages of the SST and the MMC topology, and thus has a larger power density and a better operating ability. The MMC-SST based microgrid is more suitable for smart building and future energy Internet than the traditional one [11].

At present, there are many researches about the control design of the SST, which mainly include the proportional integral (PI) control [12,13] and the proportional resonance (PR) control [14]. Although the PI control has good response performance, it is sensitive to parameters and its calculation is complex. The PR control is relatively simple without *dq* decoupling calculation, but it has a poor robustness when facing with non-fundamental frequency interference. Recently, the internal model control (IMC) is employed in this area. Comparing with above strategies, IMC shows superior characteristics with more simple control structure, faster response speed and stronger robustness [15]. Up until now, the studies about the coordination control of the SST in microgrid is still limited [16–18], especially in the hybrid ac/dc microgrid of MV distribution network and LV residential environment.

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The main highlights of this article are summarized as follows.

(1) A MMC-SST based hybrid ac/dc microgrid architecture is proposed for energy management of smart building. The proposed architecture with high power quality, flexible controllability, reduced volume and superior fault tolerance would be a good option for the future microgrid of smart building.
(2) A hybrid power droop control is presented to realize a reasonable energy distribution between the ac microgrid and the dc microgrid automatically in the off-grid mode. In this strategy, the power transmitting between the ac microgrid and dc microgrid is codetermined by both frequency variation of ac microgrid and voltage fluctuation of dc microgrid. The references of active power demand of the ac microgrid and the dc microgrid are obtainable for timely operating detection and control.
(3) The IMC strategy is adapted in the proposed architecture of smart building, which has simpler control structure, faster response speed and stronger robustness comparing with existing PI and PR control strategies.
(4) The dynamic reactive power compensation capacity of MMC-SST in off-grid mode is indicated. The MMC-SST can work as a STATCOM device alone even when it is disconnected from the dc microgrid. This function can help maintain the voltage of ac bus and ensure the system stability when the reactive power demand in ac microgrid increases significantly.

2. Hybrid AC/DC microgrid architecture based on MMC-SST for smart building

Fig. 1 shows the proposed MMC-SST based hybrid ac/dc microgrid structure for smart building in this article. The ac microgrid and the dc microgrid are linked to MMC-SST by intelligent bypass switches IBS_{ac} and IBS_{dc} at ac interface and dc interface, respectively. The MMC-SST connects to a common coupling point of 10 kV distribution network via IBS_g. The system mainly includes MMC-SST, ac microgrid, dc microgrid and DLs in smart building, in which the ac microgrid and the dc microgrid can be considered as a whole, i.e. the hybrid ac/dc microgrid.

(1) The SST is comprised of three stages, i.e. the input stage, the isolation stage and the output stage. The input stage is a MMC with high withstand voltage level, low output harmonics and high redundancy degree. Meanwhile, the input stage can realize unit power factor operation under a proper control. The isolation stage consists of several dual active bridges (DABs). The DABs are connected in series at input terminals and are connected in parallel at output terminals, i.e. in Input Series Output Parallel (ISOP) connection form [15]. The isolation stage can obtain the function of voltage and current transformation, electric isolation and dual energy flow control. The output stage is formed of a three-phase inverter and some filter branches, and this stage plays different role under different operating mode.
(2) The hybrid ac/dc microgrid. The output stage of the MMC-SST can be regarded as an interlinking converter (IC) between ac microgrid and dc microgrid. The ac bus and the dc bus are connected to the ac interface and the dc interface at this stage, respectively. In this hybrid ac/dc microgrid, both dc access and ac access are available, an optimal assess form of each DG can be selected after considering various factors, e.g. economy effectiveness, operating efficiency and characteristics of DGs. In Fig. 1, DGs such as wind power generation and photovoltaic device can be integrated by both ac and dc lines, and they are simplified as the symbol ‘G’ in ac microgrid in Fig. 1. The building facilities like elevator, EV charging post and ESSs are dc access. The high power loads (washing machines, refrigerators, etc.) and low power loads (lights, electronic devices, etc.) in private apartment are ac assess.
(3) The DLs in smart building contains ac load and dc load. The ac load links to ac bus and requires high-quality three-phase ac power. The dc load connects to dc bus and obtains stable dc power from it.

3. Operating modes of hybrid AC/DC microgrid for smart building

The MMC-SST is like a power router which implements coordinated management in hybrid ac/dc microgrid for smart building. Facing the changes of operating conditions, the proposed microgrid configuration can operate in grid-connected mode and off-grid mode by changing the control strategy of MMC-SST.

On the basis of the direction of energy flow, the hybrid ac/dc microgrid can be classified into two operating states in the grid-connected mode and can be divided into five states in the off-grid mode. When the operating condition changes, e.g. a grid fault or a control failure happens, the controllable devices at each level change automatically and the system will operate in another mode which adapts to the new operating condition. The states of the hybrid ac/dc microgrid for smart building are listed in Table 1. In Table 1, the symbol “–” means none. The corresponding relationships between IBSs and operating modes is shown in Fig. 2.

3.1. Grid-connected operating mode

Fig. 3 shows the diagram of grid-connected mode of the hybrid ac/dc microgrid for smart building. In the grid-connected mode, the ac microgrid and the dc microgrid are connected to the medium voltage distribution network via the MMC-SST. In this mode, the ac microgrid and dc microgrid are considered as a whole, i.e. the hybrid ac/dc microgrid. Hence, only the energy flow between the medium voltage distribution network and the hybrid ac/dc microgrid are considered. Energy control between the ac microgrid and the dc microgrid are similar to that in the off-grid mode, therefore this part will not be repeated here. The grid-connected mode can be divided into two states, i.e. state 1: power consumption state, and state 2: power feedback state.

State 1: When DGs in the hybrid ac/dc microgrid cannot satisfy the power demand of load, the power shortage is filled up by the distribution network via MMC-SST. The entire hybrid ac/dc microgrid can be regarded as a load if seen from distribution network. This state is called power consumption state.

State 2: When DGs in the hybrid ac/dc microgrid produce more electricity than the demand of load, the surplus power will be fed back to the distribution network via the MMC-SST. The hybrid ac/dc microgrid can be seen as a power source to the distribution network, so this state is called power feedback state.

If the power loss is ignored, the power equations of grid-connected mode are

$$\begin{cases} P_{ac}^{*} = P_{ac,DG} + P_{ac,ESSs} - P_{ac,DL} \\ P_{dc}^{*} = P_{dc,DG} + P_{dc,ESSs} - P_{dc,DL} \end{cases} \tag{1}$$

where P^{*}_{ac}, P^{*}_{dc} are power flow from the ac microgrid and the dc microgrid to the distribution network, respectively. If they are positive, the power directions are in line with the reference direction, i.e. from the microgrid to distribution network, otherwise the power is injected into distribution network. $P_{ac,\,DG}$, $P_{ac,\,ESSs}$, $P_{ac,\,DL}$, $P_{dc,\,DG}$, $P_{dc,\,ESSs}$ and $P_{dc,\,DL}$ represent the power of DGs, ESSs and DLs in the ac microgrid and the dc microgrid, respectively.

3.2. Off-grid operating mode

Fig. 4 is the diagram of the off-grid mode of the hybrid ac/dc microgrid for smart building. In this mode, the hybrid ac/dc microgrid and the distribution network are disconnected, and the output stage of MMC-SST operates as an IC between the ac microgrid and the dc microgrid. Using the proposed hybrid power droop control strategy, a reasonable power allocation between the ac microgrid and the dc