A New Topology Pattern for AC-DC Mixed Microgrid

Peng Yu, Yong Zhang, Xing-Hua Liu, Peng Zhao, Sun Li, Rui-Qi Wang, Shu-Min Sun, Guang-Lei Li, Yu-Yao Qu, and Lin Li

Abstract—In order to realize the modular design of the microgrid, this paper proposed a new modular topology for the AC-DC mixed microgrid. In that topology, the AC microgrid unit and the DC microgrid unit were packaged together by the back-to-back converter. The battery-supercapacitor hybrid energy storage system was connected to the DC bus of back-to-back converter. By the reasonable design on the battery-supercapacitor hybrid system, the energy storage system could supply the rapid power and energy support for the microgrid spontaneously. The mathematical model and the control algorithm of that microgrid topology were studied. By the simulation analysis, it can be concluded that AC-DC mixed modular microgrid topology could operate steadily on both the grid-connected mode and the isolated mode. Furthermore, we can conclude by the simulation that the designed modular microgrid could operate uninterruptedly when the microgrid topology switched from the grid-connected mode to the isolated mode. The seamless switching became the natural property for the modular microgrid. As a result, the modular microgrid topology can be considered as a usual power/load module to realize the friendly power interaction with the power grid.

Index Terms—Microgrid, topology, energy storage, mode switching, operation mode.

1. Introduction

The microgrid is considered a new pattern power network which can be incorporated into the public power grid. At the same time, it can operate isolated when some electrical faults occur in the public power grid. The microgrid can resolve a series of negative impacts brought by the distributed generation, such as harmonic pollution, voltage flicker and so on[1][3]. However, the incorporation of the microgrid will influence the power/energy balance control and the operation dispatch of public power grid[4][5]. The plug and play technology is regarded as one of the most effective methods to realize the coordinated control between the microgrid and the public power grid[6].

In general, the realization of the plug and play technology is related with the topology structure of microgrid. The optimum design on the topology of microgrid will bring plenty of convenience for the operation control of microgrid. References [7] and [8] proposed the AC microgrid topology, the DC microgrid topology and the AC-DC mixed microgrid topology. All the above topologies follow the networking method developed by CERTS. By that method, the power load, the energy storage system and the distributed generation are connected into the bus as the current source in parallel. As a result, the transient oscillation of bus voltage will be hard to restrain when the microgrid switches from the grid-connected mode to the isolated mode. References [9] and [10] carried out an optimum design on the networking method and the operation mode of microgrid. However, the proposed topology can be also considered as the typical topology of CERTS in essence. The energy storage system which is considered as the power/energy buffer plays an important role in the operation control of microgrid. In [11], the energy storage system was regarded as the energy transformation buffer to eliminate the voltage fluctuation brought by the power fluctuation of the distributed generation. At the same time, the method cannot resolve the problem of seamless switching between the grid-connected mode and the isolated mode.

By packaging different kinds of distributed power sources and the power load through the back-to-back converter, this paper develops an AC-DC mixed modular microgrid topology based on the battery-supercapacitor hybrid energy storage system. Also, we handle an optimum design on the topology of battery-supercapacitor hybrid system to make full use of the energy storage merits of battery and supercapacitor. The mathematical model and control algorithm of the proposed microgrid topology are discussed. At the end of this paper, we carry out a simulation analysis on the operation of the proposed AC-DC mixed modular microgrid.
2. Modular Microgrid Topology Based on Hybrid Energy Storage System

In this paper, we develop the modular microgrid topology as shown in Fig. 1.

That modular microgrid topology is composed of the filter circuit, the back-to-back converter, DC bus, the hybrid energy storage system, the DC microgrid unit, and the AC microgrid unit. The back-to-back converter consists of the grid-side converter and the microgrid-side converter. The grid-side converter is connected to the public grid by the filter circuit and the transformer. The AC output of the microgrid-side converter serves as the AC bus for the AC microgrid unit. The AC distributed power sources and the AC loads in the AC microgrid unit are connected to the AC bus. The DC distributed power sources and power loads are incorporated into the DC bus to constitute the DC microgrid unit. As discussed above, this kind of microgrid topology packages the AC microgrid unit and the DC microgrid unit together by the back-to-back converter. In that topology, the grid-side converter is employed to make the microgrid quit or access the public grid. At the same time, the power/energy exchange between the microgrid and the public grid is controlled by the grid-side converter.

As for the hybrid energy storage system, it is composed of the battery, supercapacitor, and the bidirectional DC/DC chopper. The battery is connected to the low voltage side of the DC/DC chopper. Meanwhile, the supercapacitor which is connected to the high voltage side of the DC/DC chopper is regarded as the output interface of the hybrid energy storage system. As the supercapacitor is connected into the DC bus directly, the supercapacitor is able to fully develop the merits of high power density, long cycle life and fast charging-discharging response to supply the rapid power/energy supporting for the DC bus. The battery whose charging-discharging process is controlled by the DC/DC chopper offers the backup energy supporting to the supercapacitor. Therefore, the battery can fully develop its energy storage merit of high energy density.

The voltage stabilization of the DC bus is the key to the stable operation of the AC-DC mixed modular microgrid. When the modular microgrid withdraws from the public grid, the supercapacitor could offer the power/energy supporting spontaneously to the DC bus to ensure the stable operation of the DC microgrid unit and the AC microgrid unit. During that process, no more extra control algorithm is needed. Therefore, the seamless switching between the grid-connected mode and the isolated mode becomes the natural property for the modular microgrid.

3. Model Analysis on Modular Microgrid Topology

3.1 Model Analysis on the Back-to-Back Converter

The grid-side converter and the microgrid-side converter employ the pulse-width modulation (PWM) voltage source inverter topology.

A. Model Analysis on Grid-Side Converter

The AC output of the grid-side converter is connected to the public grid to handle the power/energy exchange between the microgrid and the public grid. The circuit model of the grid-side converter is shown in Fig. 2.

The three-phase voltage of the AC side is represented by \( e_a, e_b \) and \( e_c \). At the same time, \( i_a, i_b \), and \( i_c \) represent the inductor current. According to the Kirchhoff’s voltage law, we can obtain the mathematical model as follows:

\[
\begin{align*}
C \frac{dU_{dc}}{dt} &= \sum_{k=a,b,c} i_k S_k \\
L \frac{dI_k}{dt} &= e_k - U_{dc} (S_k - \frac{1}{3} \sum_{j=a,b,c} S_j), \quad k = a, b, c
\end{align*}
\]

(1)

where \( S_k \) and \( S_j \) serve as the switching function. By (1), we can conclude that the inductor current can be controlled precisely by adjusting the duty cycle of the power transistors in that topology. Correspondingly, the active and reactive power exchange between the public grid and the grid-side converter can be managed precisely.

B. Model Analysis on Microgrid-Side Converter

The microgrid-side converter operates on the voltage/frequency (V/F) mode to supply the stable three-phase AC voltage for the AC microgrid unit. The topology of microgrid-side converter is illustrated by Fig. 3.
According to the Kirchhoff’s law, we can deduce the mathematical model of microgrid-side converter as follows:

\[
\begin{align*}
    \frac{dL_i}{dt} &= U_a - U_b - U_c, \\
    \frac{dU_{ab}}{dt} &= U_a - U_b - U_c, \\
    \frac{dU_{bc}}{dt} &= U_a - U_b - U_c.
\end{align*}
\]  

(2)

where \( U_a, U_b, \) and \( U_c \) can be obtained by

\[
\begin{align*}
    U_a &= \frac{2S_a - S_b - S_c}{3} U_{dc} \\
    U_b &= \frac{2S_a - S_b - S_c}{3} U_{dc} \\
    U_c &= \frac{2S_a - S_b - S_c}{3} U_{dc}
\end{align*}
\]  

(3)

where \( S_a, S_b, \) and \( S_c \) represent the switching function.

By (2) and (3), we can conclude that the output voltage of microgrid-side converter can be controlled precisely by adjusting the duty cycle of power transistors to ensure the stable operation of the AC microgrid unit.

### 3.2 Model Analysis on Hybrid Energy Storage System

According to the circuit model of the DC/DC chopper, battery and supercapacitor, we can obtain the model of hybrid energy storage system as shown in Fig. 4.

As for the circuit model in Fig. 4, we define the \( X=[I_L, V_{cc}, V_{ch}]^T \) as the state phasor. \( V_{cc} \) stands for the electromotive force of the supercapacitor. \( V_{ch} \) represents the internal overpotencial of battery. The input phasor is defined as \( U=[V_a, V_b]^T \). By utilizing the state-space averaging method, we obtain the state-space averaging equation as follows:

\[
\frac{dX}{dt} = AX + BU
\]  

(4)

where

\[
A = \begin{bmatrix}
    -\frac{R_a(1-d)}{L} & -\frac{1-d}{L} & 0 \\
    0 & -\frac{(1-d)(1+R_{ac}/R_{sp})}{C_R c_{cc}} & 0 \\
    \frac{1}{C_b} & 0 & -\frac{1}{R_{bp} C_b}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
    \frac{1}{L} & 0 \\
    0 & \frac{1-d}{C_b c_{cc}} \\
    0 & 0
\end{bmatrix}
\]

According to (4), we can deduce the stationary solution as follows:

\[
X = -A^{-1}BU
\]

(5)

By the expression of \( I_L \), we can conclude that the \( I_L \) can be controlled precisely by adjusting the duty cycle of power transistors. Therefore, the charging-discharging power of battery can be controlled precisely.

### 4. Design on Control Algorithm of Modular Microgrid Topology

Under the grid-connected state, the grid-side converter operates on the P/Q mode to keep the voltage of DC bus constant. The control algorithm of the grid-side converter is illustrated in Fig. 5.

In Fig. 4, \( R_{es} \) represents the equivalent internal resistance. \( R_{es} \) and \( R_{sp} \) are utilized to represent the equivalent resistance and the self-discharging of supercapacitor. \( R_{sp} \) and \( C_b \) describe the overpotential of battery.
control algorithm which is composed of the external voltage loop and the internal current loop. By that method, the power/energy fluctuation can be transferred to the public grid. As the result, the voltage of DC bus can be maintained constant to make sure that the DC microgrid unit works steadily. In order to realize the stable operation of the AC microgrid unit, the microgrid-side converter operates on the V/F mode to supply the constant AC voltage for the AC microgrid unit. The control algorithm of the microgrid-side converter is shown in Fig. 6.

When the modular microgrid operates on the grid-connected mode, the battery in the hybrid energy storage system is charged under the control of DC/DC chopper. The control algorithm for the DC/DC chopper is shown in Fig. 7.

When the grid-side converter stops working, the modular microgrid will be disconnected from the public grid. Then, the modular microgrid converts to the isolated mode. Under the control of the DC/DC chopper, the hybrid energy storage system is responsible for holding the voltage of the DC bus constant. The double closed-loop control algorithm is adopted as shown in Fig. 8.

Under the isolated mode, the microgrid-side converter still employs the control algorithm shown in Fig. 6 to offer the constant AC voltage to the AC microgrid unit.

When the operation mode of the modular microgrid transfers from the grid-connected mode to the isolated mode, the supercapacitor will supply the transient power/energy supporting spontaneously to the DC bus. As a result, the voltage bus can be held relatively constant to ensure the stable operation of the DC microgrid unit and the AC microgrid unit. Then the DC/DC chopper begins to apply the control algorithm shown in Fig. 8 to keep the DC bus voltage constant. Under the isolated mode, the AC microgrid unit and the DC microgrid unit can keep on working steadily because of the stable DC bus. During that process, the power/energy supply from the supercapacitor needs no more control logic. The back-to-back converter and different kinds of distributed generation need not participate in that process. Because of the optimum design on the topology, the AC-DC mixed modular microgrid could be of the ability of the seamless switching between the grid-connected mode and the isolated mode in nature.

5. Simulation Analysis on the Modular Microgrid Topology

According to Fig. 1, we build the simulation model in MATLAB/SIMULINK. In this simulation, the effective value of the line voltage of the public grid is set to be 380 V. The voltage control target of the DC bus is supposed to be $U_{dc_{\text{ref}}}=550$ V. The capacity of the supercapacitor is 0.5 C. The withstand voltage and the initial voltage of supercapacitor are set as 900 V and 550 V separately. The battery unit is 300 V/1000 Ah. The rated charging-discharging current of the battery is 500 A. In the DC microgrid unit, the power is induced by the DC distributed generation and the power load ranges from −60 kW to 60 kW. The fluctuation cycle is 0.8 s. In the AC microgrid unit, the active power is induced by the AC distributed generation and the power load ranges from −10 kW to 10 kW, with the fluctuation cycle of 0.5 s.

During the period of 0 s to 6 s, the modular microgrid is supposed to operate on the grid-connected mode. The battery is controlled to discharge as the constant current $I_{\text{bat_{ref}}}=100$ A. At 6 s, the grid-side converter is made to
stop operating. During the period of 6 s to 10 s, the modular microgrid works on the isolated mode. As for the above operation process, the simulation curves are shown in Fig. 9 to Fig. 13.

Fig. 9 indicates that the grid-side converter could make the DC bus voltage tack the target vale \( U_{dc\text{ ref}} = 550 \) V by implementing the control algorithm shown in Fig. 5. Therefore, the AC microgrid unit and the DC microgrid unit can be made to operate steadily.

Under the grid-connected mode (0 s to 6 s), the battery can be made to discharge as the target value \( I_{bat} = 100 \) A under the control of DC/DC chopper, as shown in Fig. 10.

Fig. 9. Curve of dc bus voltage.

Fig. 10. Curve of charging-discharging current of battery.

By utilizing the control algorithm illustrated in Fig. 6, the microgrid-side converter could supply the steady AC voltage to ensure the stable operation of AC microgrid unit, as shown in Fig. 11. The microgrid-side converter transfers the internal power inside the AC microgrid unit to the DC bus to hold AC bus voltage of AC microgrid unit constant. As the active power induced by the AC distributed generation and the power load ranges from \(-10\) kW to 10 kW, the interface power of the AC microgrid unit fluctuates as shown in Fig. 12.

As the internal power of the AC microgrid unit and the DC microgrid unit fluctuate, the DC bus power will be fluctuant. The grid-side converter transfers the fluctuant power of the DC bus to the public grid to keep the DC bus voltage under the grid-connected mode. Therefore, the interface active power of the modular microgrid fluctuates as shown in Fig. 13 (0 s to 6 s). At the same time, the interface reactive power of the modular microgrid is controlled as zero by the grid-side converter as shown in Fig. 13 (0 s to 6 s). By that method, the reactive power impact induced by the modular microgrid can be avoided.

At 6 s, the modular microgrid transfers to the isolated mode. During that transferring process, the supercapacitor supplies the power/energy supporting for the DC microgrid unit and the AC microgrid unit. As a result, the DC bus voltage only drops 15 V, as shown in Fig. 9. That sight voltage drop can not destroy the stable operation of the AC microgrid unit and the DC microgrid unit. The back-to-back converter and all kinds of distributed generations need not participate in that process. Under the isolated mode, the hybrid energy storage can be made to keep the DC bus voltage constant by utilizing the control algorithm in Fig. 8, as shown in Fig. 9.

During the period of 0 s to 6 s, the modular microgrid operates on the isolated mode. By the control algorithm illustrated in Fig. 8, the DC/DC chopper in the hybrid energy storage system is able to manage the DC bus constant as shown in Fig. 9, with the voltage fluctuation of \( \pm 1\% \). As shown in Fig. 11 and Fig. 12, the microgrid-side converter could transfer the active power inside the AC microgrid unit to the DC bus to hold the AC bus voltage steady under the isolated mode.

When the modular microgrid operates at the isolated mode (6 s to 10 s), the hybrid energy storage system compensates for the power difference between the DC...
microgrid unit and the AC microgrid unit under the control of DC/DC chopper. As a result, the charging-discharging current of battery fluctuates randomly as shown in Fig. 10.

By the above simulation analysis, we can conclude that the designed modular microgrid could operate steadily on both the grid-connected mode and the isolated mode. At the same time, the modular microgrid is of the ability of the seamless switching between the grid-connected mode and the isolated mode in nature.

6. Conclusions

This paper developed a new pattern modular microgrid topology in which the DC microgrid unit, AC microgrid unit, and battery-supercapacitor energy storage system are assembled as a module by the back-to-back converter. At the same time, the mathematical model and the control algorithm of the proposed modular microgrid were well investigated. By the simulation analysis, it can be concluded that the modular microgrid can operate steadily on both the grid-connected mode and the isolated mode. As for the modular microgrid, the seamless switching between the grid-connected mode and the isolated mode can be achieved in nature without the participation of back-to-back converter and different kinds of distributed generation. By utilizing the research findings in this paper, the microgrid can be of the abilities of fast networking, plug and play, and seamless switching.

References


Peng Yu was born in Shandong Province, China in 1982. He received the M.S. and Ph.D. degrees from the Dalian University of Technology, Dalian in 2007 and 2012, both in electrical engineering. He is currently working with the State Grid Shandong Electric Power Research Institute. His research interests include renewable energy generation, energy storage techniques, and the applications of energy storage systems on the power quality conditioning of renewable energy generation.

The other authors’ photographs and biographies are not available at the time of publication.