Prototype of Smart Energy Router for Distribution DC Grid

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Keywords

Abstract

Smart energy router (SER), also called as power electronics transformer (PET) or solid state transformer (SST), will serve as a critical component in the next-generation electric power system. Taking advantage of modular multilevel converter (MMC) and input series output parallel (ISOP) topologies, new type of smart energy router has been developed. Presented architecture using two stages with AC/DC conversion in the medium-voltage (MV) side, and ISOP type DC/DC conversion in the low-voltage (LV) side, thus allows interaction with DC grid and local renewable sources, etc. Compared to existing topologies, proposed SER uses less power switches and high-frequency transformers. The details related to the 2-MVA SER prototype, including the electrical design of the circuits and control system is presented in this paper. Simulation and experimental results on this prototype with distribution DC grid show validity of this SER.

I. Introduction

In recent years, the increasing concern with renewable energy resources and intelligent energy management has prompted developing overall upgrade of the legacy electric power systems in energy management. In this revolutionary energy system, which has been regarded as the future power grid: Energy Internet[1], is now capturing worldwide attention.

The traditional 50/60 Hz distribution transformers are key components in today’s electric power systems for providing different voltage level link. The transformer is widely adopted for integrating renewable energy units with DC/AC converters and interfacing the FACTs devices[2]. However, it has several limitations in the energy internet such as large size/weight, equal input and output operation frequency and active/reactive power.

The SER has garnered a great deal of attention and has been extensively investigated for smart grid[1-4] and traction application[6-7]. As has been noted by FREEDM and UNIFLEX[8], the SER is combined of power transmissions and information exchanges and is expected to manage efficiently the transmission...
and distribution of electricity in the energy internet. It is observed that the SER can functionally replace the traditional 50/60 Hz distribution transformers and some power electronics converters, thus showing a potentially more integrated and compact system.

In the published literature, numerous converter structures of SER are suit for integrating the medium-voltage (MV) ac grid and low voltage (LV) dc link. Depending on the number of stages and the output voltage type, previous features on the SER architecture can be included as: a) three-stage power conversion with medium voltage (MV) and Low voltage (LV) DC link[8]; b) two-stage scheme with LV DC Link[8]; c) two-stage scheme with MV DC Link[8]; d) direct or indirect matrix-type topologies[9]. According to the realization of three-phase conversion, reported SER structure contain[10-11]: a) direct three-phase converter; b) three-phase connected by single-phase systems; c) hybrid combinations.

Modular design, low switching frequency, excellent output voltage quality are the advantages of modular multilevel converter (MMC) [2]. Taking advantage of MMC, proposed three-phase SER can enlarge its applications to meet the requirement of high-power transmission and to provide the interface for MV- DC link.

II. Proposed SER Topology

Fig.1 shows the schematic diagram of SER prototype which is comprised of MMC and DC-DC converter. This SER prototype includes DC-link in MV- and LV- sides and adopts two stages of conversion (MMC applied as AC/DC in front-end MV-side, medium-frequency (MF) isolated DC/DC conversion).

![Fig. 1: Basic topology of proposed SER](image)

In front-end AC side, MMC can make the overall system robust and fault-tolerant with the redundant cells[2]. What is more, the series connection structure of sub-modules makes the extension of different voltage level application can be feasible. Unlike the single phase converters should bear the problem related to the power pulsation at twice the grid frequency[10], the common MVDC-link makes the access of MVDC transmission easily.

In the intermediate stage, the dual active bridge series resonant converter (DABSRC) can allow bidirectional power flow and zero-current-switching (ZCS)[12]. This topology consists of two active bridges connected through a MF transformer in series with a resonant tank. Usually, the magnetization
The inductance of the MF transformer is much greater than its leakage inductance\(^{(1)}\). Therefore, the resonant inductor \(L_r\) can be integrated in the leakage inductance to achieve a compact design.

The ISOP linked DABSRC play key roles. At first, they provide galvanic isolation between the MV DC and the LVDC side. Second, this structure provides suitable voltage adaptation between the 16-kV intermediate dc-link voltage level and the 750 V DC voltage. Their third key function is to enable the IGBT modules to work in the soft-switching mode, by that positively increasing the overall efficiency of the SER. As the fourth key functionality, they allow for bidirectional energy flow.

### III. Main Circuit Design and Implementation

The complete SER prototype contains mainly the MV- side MMC, the ISOP DC-DC converter. It has been assembled compactly and is shown in Fig. 2. Design and control methods for the two converters are considered independently.

#### A. MMC Circuit

To offer a good trade-off between the efficiency, economic, electrical requirement and power density, 12 modules including 2 redundant modules are used as an arm of MMC for series connection. Each module uses half bridge structure including two 3.3kV/200A IGBTs. Therefore, the developed SER prototype has 72 sub-modules in MMC, with this AC-DC stage rated for 2 MVA. The details of these compactly designed modules can be seen in Fig. 3.
B. The ISOP Linked DABSRC Circuit

The ISOP linked DABSRC usually operated in series resonant mode. And the resonant frequency is 8.3 kHz. To achieve the 16kV DC voltage of MVDC, 16 cells have to be connected in series, taking over-voltage into account. Considering a total power of 1MW, each cell needs to transfer 70kW. Part of ISOP-DABSRC contains MV- side and LV- side converters and the MF transformer is shown in Fig.3.

C. Control Strategy of MMC

The mathematical model analysis and control method has been studied in several papers. The control strategy for the MMC can be designed as the three-phase grid-connected converter. Fig. 4 shows a grid-oriented double-loop structure for the MMC. The outer loop is the DC voltage control loop. Both the MVDC and LVDC can be chosen for the voltage control loop with different characteristics.

D. Control Strategy of ISOP DABSRC

Usually, the DABSRC operates in which the switching frequency of power device of the two H-bridges are the same as the resonant frequency. What is more, the duty ratios of them are both of 50% (the dead time in the power switch gating signals is ignored) and the phases of the two voltages are also identical.

IV. Simulation and Experimental Results

In order to verify the proposed SER topology in this paper, both simulations and experiments on a 10kVAC-750VDC SER prototype have been carried out. The parameters of this prototype are listed in TABLE I.

<table>
<thead>
<tr>
<th>MMC Parameters</th>
<th>Value</th>
<th>DABSRC Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC grid voltage</td>
<td>10kV, 50Hz</td>
<td>Cell MF transformer frequency</td>
<td>8.3kHz</td>
</tr>
<tr>
<td>MV DC-link Voltage</td>
<td>16kV</td>
<td>Cell MF transformer turns ratio</td>
<td>4:3</td>
</tr>
<tr>
<td>LV DC-link voltage</td>
<td>750V</td>
<td>Cell MV Resonant (leakage) inductance</td>
<td>$L_r=35\mu H$</td>
</tr>
<tr>
<td>Arm filter inductors</td>
<td>$L_{arm}=8$ mH</td>
<td>Cell MV/LV resonant capacitor</td>
<td>20μF/1200V</td>
</tr>
<tr>
<td>Cell MMC</td>
<td>$C_{sm}=1.2\mu$F</td>
<td>Cell MV/LV</td>
<td>800μF/1200V</td>
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</tbody>
</table>
Capacitor capacitance

<table>
<thead>
<tr>
<th>Cell MMC Voltage</th>
<th>Cell MV devices</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{sn}=1600V$</td>
<td>300A/1700V IGBT(FF300R17ME4)</td>
<td>1600V Cell MV devices 300A/1700V IGBT(FF300R17ME4)</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>MMC sampling frequency</th>
<th>Cell LV devices</th>
<th>Voltage</th>
</tr>
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<tr>
<td>5kHz</td>
<td>300A/1200V IGBT(FF300R12ME4)</td>
<td>1600V Cell LV devices 300A/1200V IGBT(FF300R12ME4)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell MMC devices</th>
<th>Cell MV/LV voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>150A/1700V IGBT(FF200R33KF2C)</td>
<td>1000V/750V</td>
</tr>
</tbody>
</table>

A. Simulation Results

In the simulation, a resistive load change from 1.2MW to 2MW at the LVDC side is imposed on the SER when $t \geq 0.05s$. Simulation results are shown in Fig.5-Fig.7. As shown in Fig.5, the DC voltages on LV- and MV- side ($u_{dcL}$ and $u_{dcH}$) almost have the same voltage sag and recovery dynamic process when the SER is loaded with active power suddenly. The steady state average value of $u_{dcL}$ is about 737V, i.e. about 1.7% error to its nominal value.

![Graph showing simulation results](image)

Fig. 5: Simulation: the three-phase grid currents on the 10kV AC side, and the MV-, LV- side DC voltage $u_{dcM}$, $u_{dcL}$.

Fig.6 shows the three-phase voltages and currents of the AC grid side. Obviously, the power factor on the grid side is almost unity. Besides, good power quality is obtained with the proposed prototype.
Fig. 6: Simulation: the three-phase grid currents and voltages on the 10kV AC side.

Fig. 7 displays the simulation results of the voltages and currents on the primary and secondary side of a MF transformer. It is clear that the ZCS is achieved because the power devices switch at the zero current crossing instants in each switching period.

Fig. 7: Simulation: the voltages and currents on the primary and secondary side of a MF transformer in one DABSRC

B. Experimental results

The SER prototype has operated for directly interfacing the 10kV AC grid to a 750V distribution DC grid. Fig. 8 shows the test environment of the prototype and the grid equipment. Restricted to the experimental facilities, the 10kV AC grid is transformed from the 380V power system. The distributed DC grid contains three parts: the energy storage system including the lithium/lead-acid cell and super-capacitors, the PV and wind hybrid system and other DC loads, such as resistors and DC/AC converters.
The operation of DABSRC was performed and the current and voltage waveforms on the two sides of MF transformer for power flowing from LV to MV are shown in Fig. 9. The phase shift of both sides have been adjusted to achieve ZCS for bidirectional power flow. The waveforms of grid voltage and arm currents of the MMC are depicted in Fig. 10. High quality AC voltage is achieved with MMC. Over the power transmission cycle, LVDC voltage is shown in Fig. 11. It can be seen that the DC voltage is smooth and steady.

Fig. 9 Experimental results of primary and secondary sides of the MF transformer in one stage of the DC-DC converter
Fig. 10 Experimental results of grid voltage and arm currents when MMC connects to the AC grid

Fig. 11 Experimental results of LVDC voltage in the entire process
V. Conclusion
Taking advantage of the modular multilevel converter, a new type of SER topology has been developed. Propose SER provide the MV- and LV- interfaces and can be directly connected to HVDC system and LV renewable energy system including photovoltaic and wind hybrid system, energy storage system etc. Simulation and experiment results testify the effectiveness of the presented SER.

References
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