A Novel Full Soft-switching Resonant Power Converter for Mid-feeder Voltage Regulation of Low Voltage Distribution Network

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Abstract

This paper presents a novel resonant based, high power density power electronics converter solution for mid-feeder voltage regulation of a low voltage (LV) distribution network. Owing to the use of high switching frequency operation and a full soft-switching control strategy, the proposed converter is capable of superimposing LV compensation into the feeder voltage, to achieve a significant system effect with a compact system volume and correspondingly smaller absolute power loss.

Introduction

The largely increasing use of electric vehicles, domestic PVs and electric heating [1] brings a voltage constraint issue to low voltage (LV) networks of many European Distribution Network Operators. The increase in electrical load stress will push the feeder voltage over the standard limit, i.e. ±10% of 400V supply. Network reinforcements, such as increasing cable current rating to limit line voltage drop/rise, can solve the problem. However, it causes significant power disruption to local community, and thus is very expensive and time consuming to obtain permission.

It has been realised that, in many cases, the current LV network does have spare capability, since the line voltage limit is exceeded before the thermal limit is reached. This implies that, if the line voltage profile can be corrected, the network is still capable of serving. To take full use of current carrying capacity of the existing distribution network, mid-feeder voltage regulation is considered to be an effective solution. By injecting a compensating component into the feeder voltage, the spare line capability can be released for constant power load requirement. A converter candidate for this application would need to be installed close to the voltage regulation point and thus have a stringent system volume requirement.

Several techniques, such as unified power flow controllers [2], unified power quality conditioners [3], and dynamic voltage restorers [4] have been extensively studied to increase the downstream voltage by using a small amount of line power. But they were not considered to be appropriate for this particular application, mainly due to the bulky system volume caused by line frequency transformers. To meet the strict system volume demand, several high frequency AC link based converter topologies were investigated in [5-8]. However, the inherent commutation issue of the cyclo-converter introduced by transformer leakage inductance strongly limits the converter design and operation [6, 8], and thereby compromises its performance and efficiency to be a less attractive candidate.

A novel resonant based, high frequency, high power density power electronic converter solution is proposed in this work to meet the stringent needs of the mid-feeder voltage regulation. The use of the high switching frequency ensures that the compact system volume requirement is achievable, while the introduction of the resonant stage mitigates the commutation problem and allows full zero-current switching (ZCS) operation of the high frequency AC stage. Consequently, the proposed converter is capable of superimposing LV compensation into the feeder voltage, to achieve a significant system effect with a compact system volume and correspondingly smaller absolute power loss. A single phase, 8kVA, prototype converter is developed, and experimental results confirm the effectiveness of the proposed converter concept and modulation strategy.

Converter topology

Figure 1 shows a block diagram of the proposed converter solution for the LV mid-feeder voltage regulation. Supplied by local full line voltage, a four-wire active front end (AFE) converter is applied to create a constant DC-link source. Three single-phase, SiC based, H-bridge inverters are employed to produce a high frequency square wave voltage set. Three series resonant series loaded (SRSL) resonant tanks and associated high frequency step-down transformers are utilised to scale the voltage down. Three LV, MOSFET based, cyclo-converters are used to reconstruct the waveform and inject the compensating output into the feeder network.

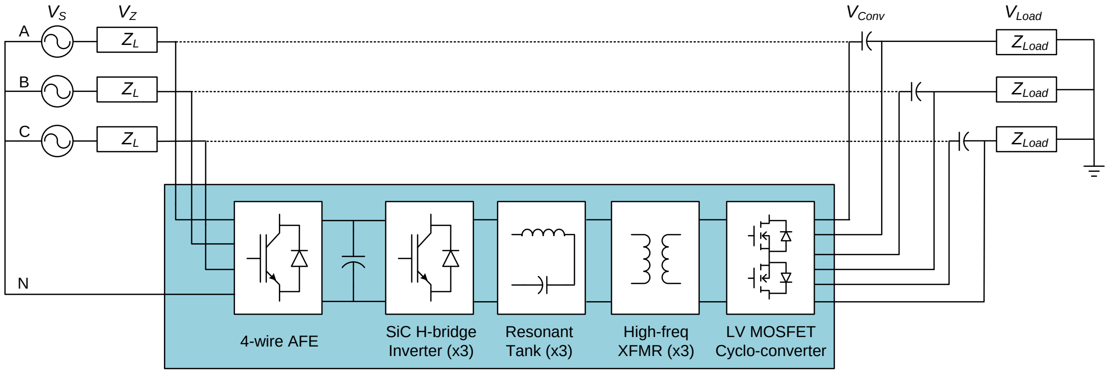

Fig. 1: Block diagram of the proposed converter solution

The SRSL tank approach has been adopted as it is particularly suitable for this application: first, two tank elements, including resonant inductor and capacitor appears in a symmetrical manner, which makes the analysis and management of bidirectional power flow straightforward; second, the leakage inductance of the transformer can be incorporated into the tank inductance, and so its influence on the tank circuit and the restrictions on the cyclo-converter commutation can be both avoided naturally.

It should be noted that each conversion stage, i.e. from the AFE to cyclo-converter, has bidirectional power flow capability. This implies that each phase of the converter is capable of operating at any of the four quadrant modes. Also, due to the 4-wire topology configuration, it is possible to shift power between the input three phases for compensation purposes under imbalanced supply conditions.

Design and modulation

Figure 2 shows the detailed circuit arrangement (one phase) of the proposed converter system, where the 4-wire AFE is replaced by a constant DC voltage source of V_{dc} for simplicity; L_{res} and C_{res} represent the inductance and capacitance of the SRSL resonant tank; $L_{leakage}$ and C_{filter} represent the lumped leakage inductance referred to the transformer secondary winding and output filter capacitance. *XMFR* and Z_{load} are the high frequency step-down transformer unit and load impedance, respectively. *T1* to *T4* are the SiC switching modules of the H-bridge inverter, while *S5* to *S8* are the bidirectional LV MOSFET modules of the cyclo-converter.

The design of the resonant tank is considered as a trade-off between the system energy storage and the output voltage ripple level. Using a high tank quality factor can relieve the filtering requirement on the cyclo-converter output. However, the energy stored in passive components is increased proportionally, and the corresponding high voltage/current stress makes the design of the tank elements challenging. In this work, the value of the tank quality factor is chosen to be 1.5, and the resonant frequency is selected at 50kHz.

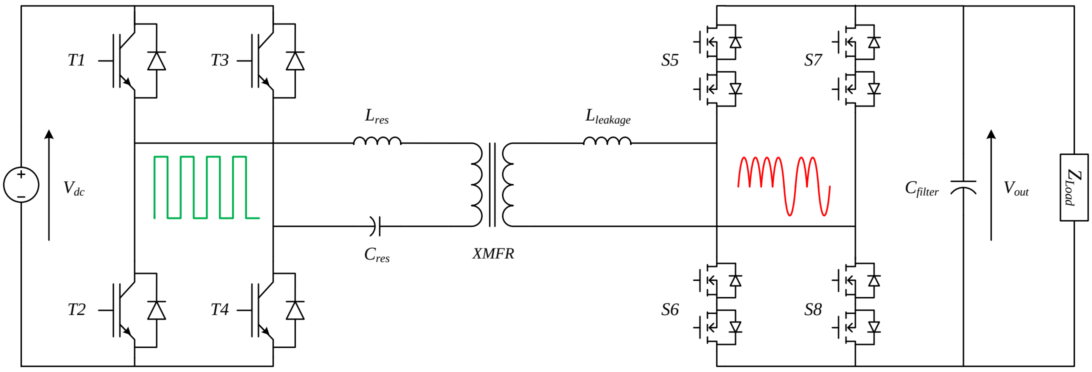

Fig. 2: Detailed circuit arrangement (one phase) of the proposed converter

Placing the proposed converter system part way along an LV distribution network allows the feeder voltage to be adjusted and thus corrected back inside constraints. Considering the European standard voltage of 230V and a compensation capability of ±12%, the peak operating voltage of the converter output would be 40V per phase.

When the switching frequency is reasonably close to the resonant frequency, the loaded SRSL tank behaves like a sinusoidal current source and the maximum voltage gain is 1. Based on the nominal DC-link voltage level of 700V and peak output voltage of 40V, the turns ratio, N, of the step-down transformer can be obtained. For each phase, the full apparent power rating is chosen to be 8kVA, which allows a large system effect to be achieved on the mid-feeder network. Table I lists the complete system specification and design result for a three-phase 400V, 24kVA converter system.

Table I: System specification and design result

Symbol	Description	Value
P_{each}	Full apparent power per phase	8kVA
V_{dc}	DC-link voltage level	700V
f_s	Switching frequency	50kHz
V_{out_pk}	Peak output voltage	40V
N	Transformer turns ratio	17.5:1
L_{res}	Resonant inductance	180µH
C_{res}	Resonant capacitance	63nF

In order to construct a 50Hz sinusoidal wave from the cyclo-converter output, a pulse density modulation (PDM) strategy is adopted for this work. The SiC H-bridge inverter is switched at the resonant frequency of 50kHz to produce a series of square wave voltage. Meanwhile, during each switching cycle, the output voltage, V_{out}, is compared with the instantaneous value of the 50Hz voltage reference, to determine the corresponding switching state of the cyclo-converter. This allows a positive current pulse, negative current pulse or zero to be passed through, in order to charge up/down the filter capacitor and thus to create the desired voltage output.

Since all the devices are switched only at the zero-crossing point of the tank current, the inherent commutation problem of the cyclo-converter can be overcome and high conversion efficiency can be obtained. Furthermore, due to the large frequency ratio between the switching and the output, a relatively smooth output voltage can be achieved for the four quadrant operating modes.

Experimental verification

With the aim of verifying the proposed converter concept and modulation approach, a single phase prototype converter rated at 8kVA was constructed. To avoid unnecessary laboratory cost, the 4-wire AFE was replaced by a constant DC power supply to charge the DC-link capacitor. A DSP/FPGA based digital control platform is employed to provide the analog-to-digital (A2D) conversion, control calculation, PDM modulation, hardware trip protection, and user interface. Figure 3 shows a photograph of the experimental prototype converter. A high power resistive load bank and two high current inductors are configured to represent different load conditions.

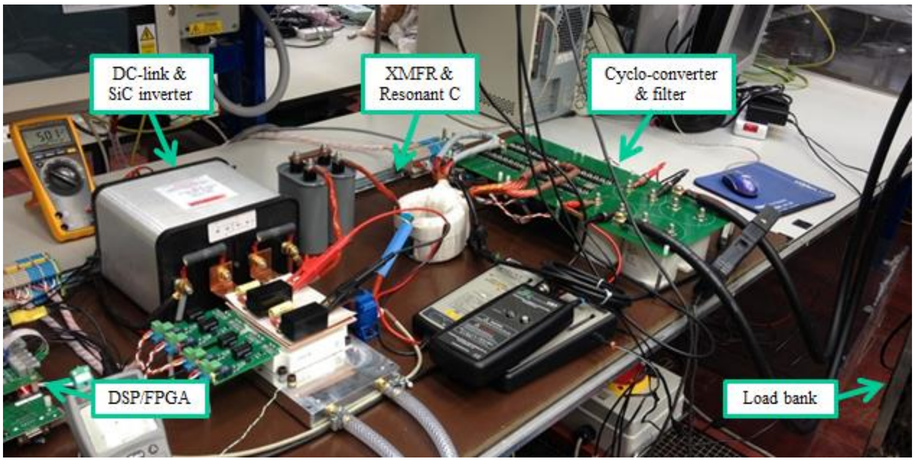

Fig. 3: Photograph of the experimental prototype converter

Figure 4 presents the simulation and experimental results for the output voltage generated by the prototype converter, where the reference voltage amplitude was set to be 25V, 50Hz and the load bank was configured as a resistive load of 150mΩ. The mean output power was 2kW. Figure 5 highlights the zoomed-in detail of Figure 4 at the time point of 25ms, i.e. where the voltage reaches its peak value. Clearly, the simulation and experiment results show a very good match between each other, therefore validating the proposed converter concept.

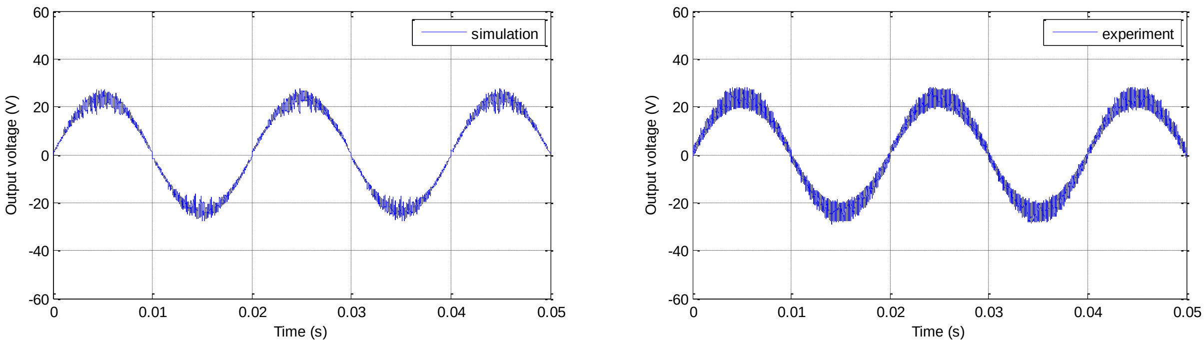

Fig. 4: Converter output voltage with amplitude of 25V (left: simulation; right: experimental)

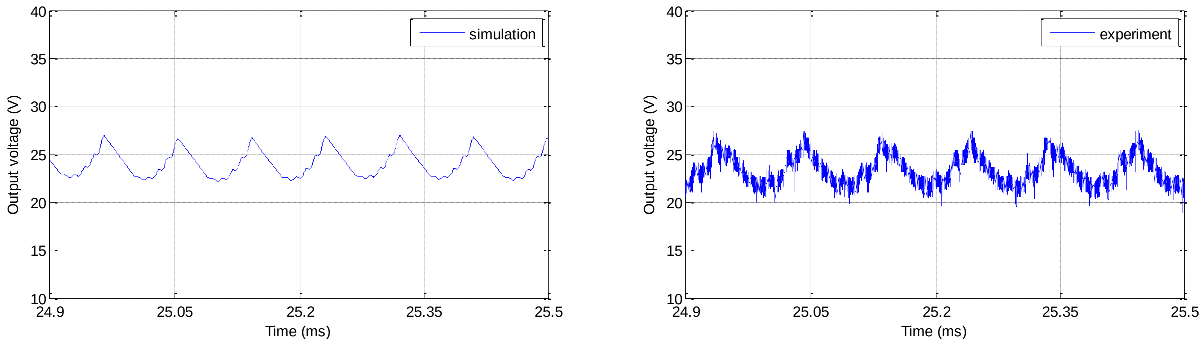

Fig. 5: Zoomed-in detail of Fig. 4 (left: simulation; right: experimental)

In order to examine the converter switching transitions, the tank input voltage and the current flowing through the transformer secondary winding are plotted in Figure 6. It can be seen that, the converter is only switched at each instant when the current goes across zero. Consequently, the ZCS can be always guaranteed, resulting in a high efficiency for the conversion system.

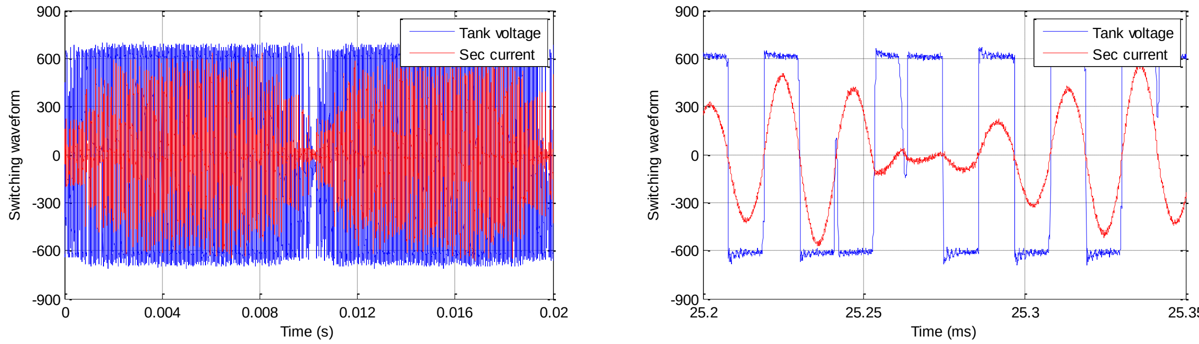

Fig. 6: Tank input voltage and transformer secondary winding current (left: overall; right: zoomed-in)

Figure 7 presents the experimental results for the output voltage and current, where the reference voltage amplitude was set to be 40V and the load bank was configured as a resistive load of 100mΩ. The mean output power was 8kW. Compared with the light load condition, a higher peak-to-peak ripple level can be observed from the top/bottom part of the output voltage, which is caused by the high instantaneous power demand and the nature of the PDM modulation utilised.

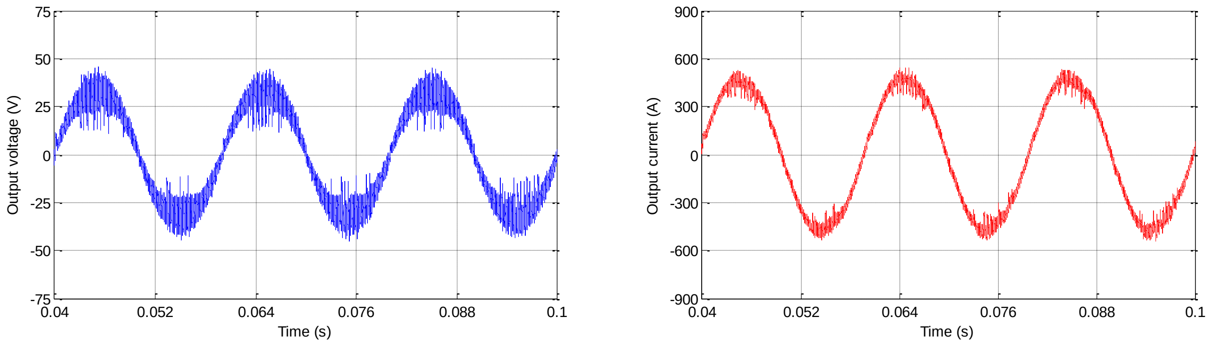

Fig. 7: Converter output with voltage amplitude of 40V and load power of 8kW (left: voltage; right: current)

Figure 8 examines the zoomed-in detail of the output voltage and the corresponding tank input voltage and transformer secondary winding current, at the time point of 85ms where the voltage reaches its peak value. Every time when the output voltage reaches the reference of 40V, a zero state is set on the cyclo-converter and the H-bridge is switched off to flow the tank energy back to the DC-link. The high instantaneous power demand, i.e. up to 16 kW, reduces the output voltage quickly, and a few pulsing cycles are required to bring it back to the reference level.

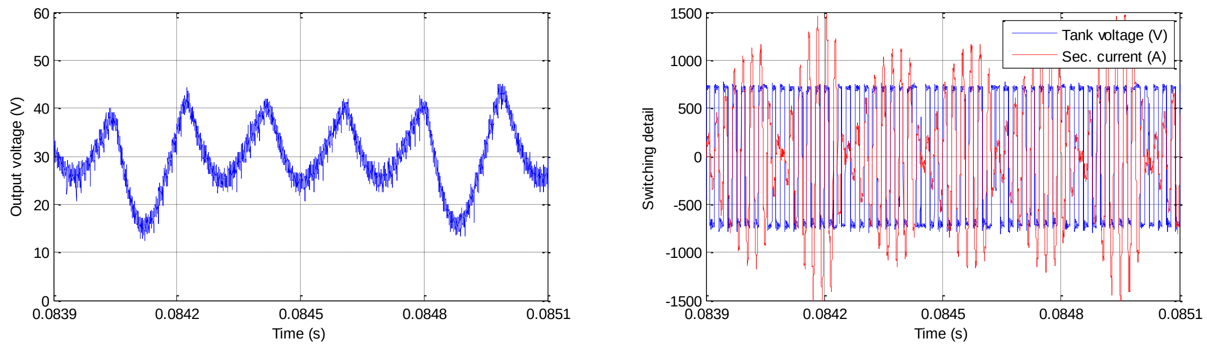

Fig. 8: Zoomed-in detail of Fig.7 and corresponding tank input voltage and transformer secondary winding current

Figure 9 shows the experimental results for the output voltage and current, where the reference voltage amplitude was set to be 40V and the load bank was configured as an inductive load of 150mΩ+300μH. The apparent power was 3.5kVA. Clearly, the proposed converter system and modulation strategy works soundly under inductive load condition.

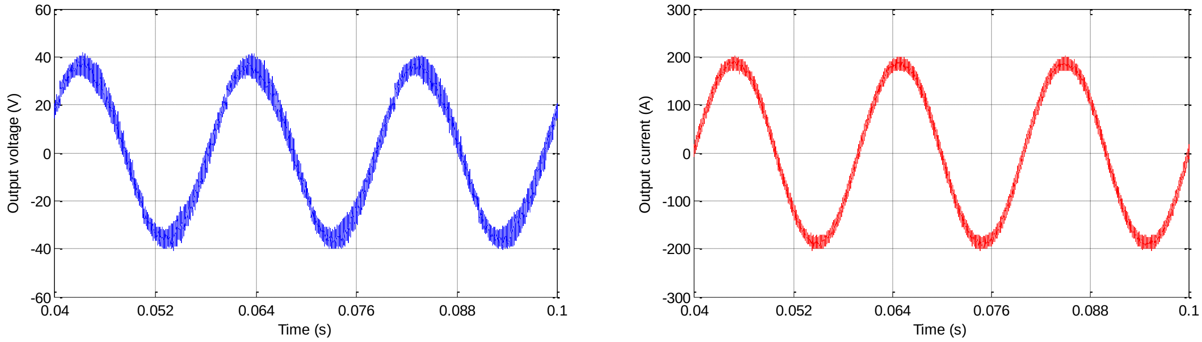

Fig. 9: Converter output with voltage amplitude of 40V and apparent power of 3.5kVA (left: voltage; right: current)

Conclusion

This paper proposed a competitive converter solution to defer or even avoid network reinforcement and allow penetration and growth in load without excess network costs. By superimposing a LV compensation component into the feeder voltage, a significant system effect can be achieved by using a much smaller converter with correspondingly smaller absolute power loss. A single phase, 8kVA, prototype converter was developed, and the experimental results successfully proved the proposed concept.

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