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Experimental evaluation of an energy storage system for medium voltage distribution grids enabling solid-state substation functionality MV solid-state substation with energy storage

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Abstract

"Smart grids" is a new concept of managing the power transfer in modern grids that will rely not only on the on-line processing of a variety of consumption and generation power data but will also need new hardware to facilitate a flexible and efficient conversion and storage of electrical power to maintain grid stability under fast changing operating conditions. This paper presents the results of the experimental evaluation of a 1.5MJ/25kW energy storage system connected directly to a medium voltage grid to provide fast and flexible grid control capabilities. The demonstrator consists of a supercapacitor stack connected to a low-voltage DC bus via interleaved converters whilst connection to the medium voltage grid is done either via a low voltage inverter and step-up 50Hz transformer or via a cascaded modular multilevel converter fed by dual active bridge converters isolated by medium frequency transformers. The experimental features demonstrated are fast power peak levelling, reactive current injection, grid fault ride through whilst maintaining a high round trip efficiency over a wide power range. The concept on which the demonstrator was designed facilitated the implementation of the solid-state substation with integrated energy storage concept that can further increase flexibility and reliability of future grids.

1 | INTRODUCTION

Energy storage systems (ESSs) [1] are seen as the solution to many problems caused by the integration of increasing levels of renewable power generation (wind/residential PV) into existent transmission and distribution grids or caused by the mismatch between highly dynamic power consumption that follows demand and the traditional flat power generation profile that aims at maximizing conversion efficiency and lowering the production cost.

Existing large-scale ESSs, such as pumped hydro or compressed air, rely on electromechanical conversion provided by large AC electrical machine operating both as a generator (discharging) and motor (charging), which means an additional conversion stage is needed to convert hydraulic or pneumatic power to mechanical, making the system more complex and less efficient. Variable speed operation of the mechanical actuators may be beneficial to maximize the conversion efficiency at reduced power loading but an additional AC (variable frequency)/DC/AC(fixed frequency) conversions stage is needed that adds extra cost and losses. For these reasons, medium- and large-scale ESSs have a very restricted power range capability which limits their usability. In applications where accurate power peak levelling is needed that will require an ESSwith wide power range capability, it may not be acceptable to disable the ESS when required power is small to maintain high efficiency; therefore, a more versatile ESS technology is needed relying on electrochemical energy storage connected to a medium voltage grid via power electronic converters that offer an extended high-efficiency operating range. This can be designed as a standalone unit to deliver all required power or be designed to work in conjunction with a bulk storage/large ESS having reduced energy storage but larger power range to increase the flexibility and overall efficiency, resulting in a hybrid ESS solution.

As more renewable power is generated at the point of consumption, mostly PV, exceeding the power consumed by local loads, a new challenge appears for distribution networks to enable the redistribution of excess renewable power to the potential consumers situated at a significant distance which may require the excess electrical power to travel upstream into the MV distribution or even the transmission grid. This feature is not fully supported by the existing power system/substation technologies. It is, however, envisaged that more power electronics will be installed in future power grids/substations to provide additional functionality such as accurate reactive power injection for more accurate voltage control, enhanced power quality by implementing active filtering, interphase power balancing etc. whilst the use of medium frequency in solid-state substations may enable significant size reductions which will support future needs for more power to be delivered to consumers in same substation footprint. By integrating energy storage in a distribution grid, the following benefits may be reached:

- To benefit from dynamic electricity pricing, by buying electricity cheap/off-peak (i.e. during night) to cover electricity consumed during peak time (i.e. during early morning before renewable/PV generation is fully available);
- To store locally the excess renewable power (rather than exporting it upstream the transmission grid) that can be consumed later during peak consumption;
- To delay the upgradation of the interconnection lines that are unable to deliver higher peak power requested by the loads, by performing peak shaving of load power;
- To operate the low-voltage (LV) distribution grid in an islanded mode, completely disconnected from the main grid. This option may be very useful in local distribution grids with sensitive loads (i.e. hospitals) when relatively long maintenance work on the interconnecting MV lines is required, or in case of grids affected frequently by short--term grid faults by implementing local grid fault ride-through capability.

Forty years ago, power electronics started to be used in power systems as a mean to improve the operation of tap changers in distribution transformers [2], followed by the proposal to control fast and accurately the active and reactive currents of grid-connected power converters [3] which was facilitated not only by the availability of faster power switches with controlled turn off capability, but also by the emergence of digital control. Only relatively recently the possibility to use low rated power electronic converters in power systems to increase controllability of power flow and flexibility was formulated [4]. The possibility to fx1fx18embed full solid-state substation was reported in [5-9]. Clare [5] reported the implementation of a 3-port power conversion system interconnected by modules consisting of AC/DC/high-frequency AC converter modules interconnected back-to-back via medium frequency transformers that enabled series connection on one low-frequency AC port, therefore facilitating direct connection to a medium voltage grid, whilst parallel connection of the other low-frequency AC port enables connection to LV distribution grids and therefore implementing solid-state substation functionality. Shah and Crow [6] focused on control aspects of a distribution system with solid-state transformer whilst modular design to facilitate a simpler and cheaper scaling up and voltage/power customisation was investigated in [7]. Klumpner et al. [8] investigated the substation functionality with the integration of energy storage. Wang et al. [9] investigated the improvement in the protection scheme for a distribution network powered by a solid-state transformer.

This study presents the experimental evaluation of a supercapacitor-based ESS suitable for direct connection to a medium voltage grid and its potential use as a platform to test the substation with embedded the energy storage concept. Two power electronic converter technologies that are able to interface ES with the medium voltage AC grids have been selected and their capabilities relevant for the power system operators, experimentally evaluated: (i) an industry-grade converter topology which is the LV two-level modular inverter structure using a 50 Hz step up transformer that can be easily scaled up by connecting identical LV modules in parallel and have also the possibility to achieve additional switching ripple cancelation by interleaving the switching of paralleled modules and (ii) a research-grade true cascaded multilevel inverter using dual active bridge (DAB) and medium frequency transformers to maintain isolation between the series connection of the inverter modules used to directly generate a high-quality medium-voltage multilevel waveform.

The structure of the energy storage subsystems will be first presented followed by the experimental evaluation which will contain an assessment of the waveform quality during steady-state operation and the ability to operate during fast step active and reactive power transients. Then, the round-trip evaluation will be analysed highlighting the implementation aspects that affected efficiency. More specific grid-related tests (ride through and power peak levelling) will show the full grid support capability that this ESS offers.

2 | ENERGY STORAGE SYSTEM TOPOLOGY

At the time the main design choices in this project have been done, the general perception was that wide band-gap (WBG) power semiconductors [10] are very expensive and not really suited for very high power (MW) systems. Therefore, although the prototyping of the experimental demonstrator has been done at reduced power level (tens kW), design principles related to high power converters design such as the design of magnetics would result in moderate/medium frequency transformers, the converters to be chosen, to be of modular design enabling easy scale up by paralleling or series connection of LV inverter modules. Also, the competing converters that were analysed were chosen as not high risk to facilitate an easier acceptance from the industry.

Two competing power electronics technologies to interconnect the ESS to a medium voltage (MV) grid have been implemented for a critical experimental evaluation of performance:

(i) An industrial-grade converter technology relying on low-voltage (LV) inverters and 50 Hz step-up transformer and
(ii) a research-grade multilevel modular converter using DAB bidirectional DC/DC converters to feed power to/from the cascaded modules. An additional conversion stage was needed to compensate for the variable voltage of the supercapacitor stack which is always dependent on its state of charge.

2.1 | DC/DC supercapacitor converter subsystem

An 8-channel interleaved DC/DC converter topology shown in Figure 1(a) using coupled inductors [11] was used to interface the variable supercapacitor voltage (200–350 V) to a constant 400 V DC-bus voltage. It is important to limit the minimum supercapacitor voltage to 200 V to make sure that the system can still deliver the 25 kW constant power with maximum converter channel current of 16 A. The interleaving operation in conjunction with the inductor coupling offers small size for the magnetics, a modular design for the power electronics which may result in smaller costs, a fast response and improved efficiency. The reason is that the virtual sampling frequency can be 8× higher than the channel switching frequency (10 kHz) which enables a very fast response time (70 µs) to a –60 A/+60 A current step change as shown in Figure 1(b). The physical implementation of this subsystem is shown in Figure 1c.

2.2 | LV interleaved modular inverter and 50-Hz transformer

A modular approach shown in Figure 2, which is widely used in industry and allows implementation of a wide range of powers by paralleling multiple units of a single subsystem design, was also used in the implementation of the LV inverter. To avoid the use of large grid side inductors which result in larger size/cost/losses, coupled inductors in conjunction with an interleaving operation of the paralleled channels were used [8], which is not widely employed by industry but straightforward to implement.

2.3 | MV cascaded multilevel converter

A cascaded structure of H-bridge inverters as shown in Figure 3(a), having an asymmetric set of 200 V/400 V and 800 V DC-link voltages, that can generate 31-voltage levels with minimum number of power semiconductors [12-15] switching with only 5 kHz, was adopted. A DAB consisting of a medium

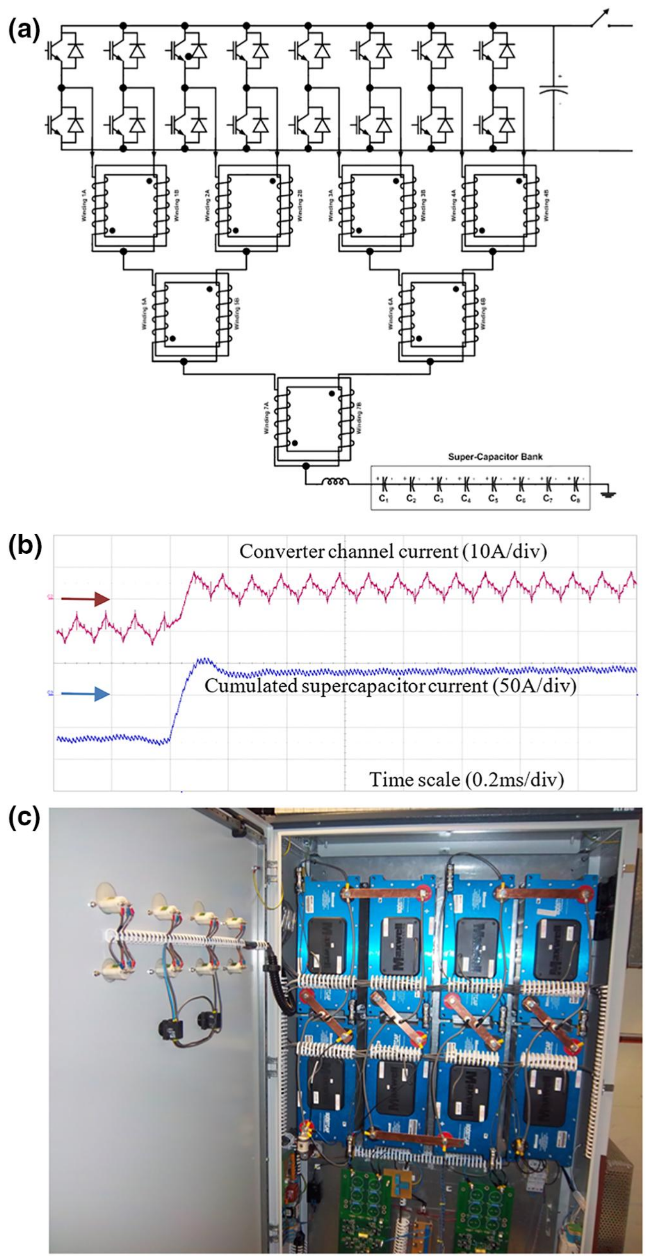

FIGURE 1 (a) DC/DC converter topology with 8-channel interleaved and multistage coupled inductors interfacing a 20 F/384 V supercapacitor stack to a 400 V constant DC bus; (b) –60 A/+40 A supercapacitor current step response; (c) the prototype implementation of the supercapacitor converter subsystem

frequency (5 kHz) transformer connected on each side to an H-bridge inverter to be able to provide isolation of each inverter cell in the cascaded multilevel converter (MLC) but also able to control accurately the power flow was used [16]. To minimize the design and manufacturing effort and to prove this concept is suitable for modular/high manufactured numbers, only two designs for the H-bridge inverters were produced: a high voltage one operating with 800 V in the DC-link used only with the MLC and a LV design operating at 400 V and 200 V DC-link voltage used in all the three

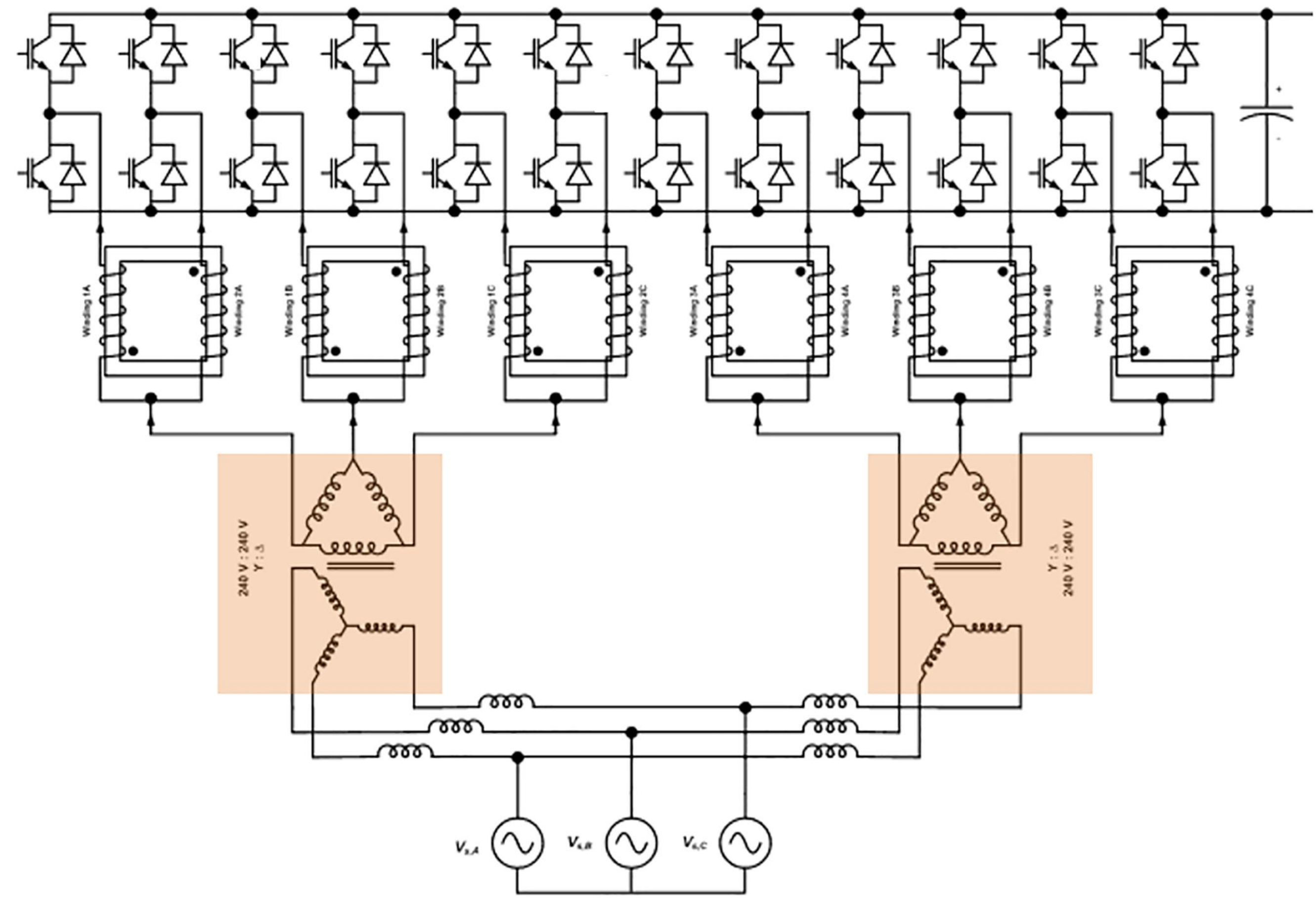

FIGURE 2 Modular topology of low voltage interleaved inverter with 50 Hz step-up transformer

subsystems. To minimize the potential isolation-related issues which were not the main focus of this research, the string structure was built in a mirrored arrangement, with the LV-rated bridges in the middle of the string and the high voltage-rated at the edges. This gives the flexibility to ground the midpoint of the string which means that at each of the string terminal the voltage potential is <1 kV rms (half of 1.9 kV rms, the phase voltage of a 3.3 kV system). In a three-phase arrangement, the succession of H-bridge inverters may need to be changed and the endpoint of the string where the LV H-bridges are connected has to become the neutral of the MV system.

3 | EXPERIMENTAL EVALUATION

The performance of the supercapacitor-based ESS connected to the AC grid via a LV inverter topology and 50 Hz step-up transformer will be compared to a true medium voltage cascaded multilevel inverter. The tests will contain the evaluation of waveform quality in steady-state condition as well as transient performance, including active and reactive power reversal and more specific tests such as right through operation and power peak levelling.

3.1 | MV multilevel inverter waveform quality

Figure 4 shows the voltage and the grid current produced by the multilevel inverter when operating in charging (Pac = 20.3 kW) and discharge (Pdc = 22.7 kW) modes. The typical multilevel voltage profile that follows a sinusoidal shape with small PWM ripple (fsw = 5 kHz) is clearly visible in both situations and this high-quality PWM waveform result is a very high-quality current.

3.2 | Active and reactive power reversals

Figure 5a shows the voltage and current waveforms of the MV multilevel converter at the MV AC input and Figure 5(b) shows the DC-bus voltage, current and power during a 17.5-kW power reversal. It can be noted that the DC-bus has a 100-Hz current/power ripple which is the typical result of single-phase AC/DC power conversion but this is expected to cancel out in a three-phase arrangement.

Figure 6 shows a full reactive power reversal. Since there is no active power change, there is no disturbance caused to the DC-link voltage controllers of the cascaded inverters. Also, due

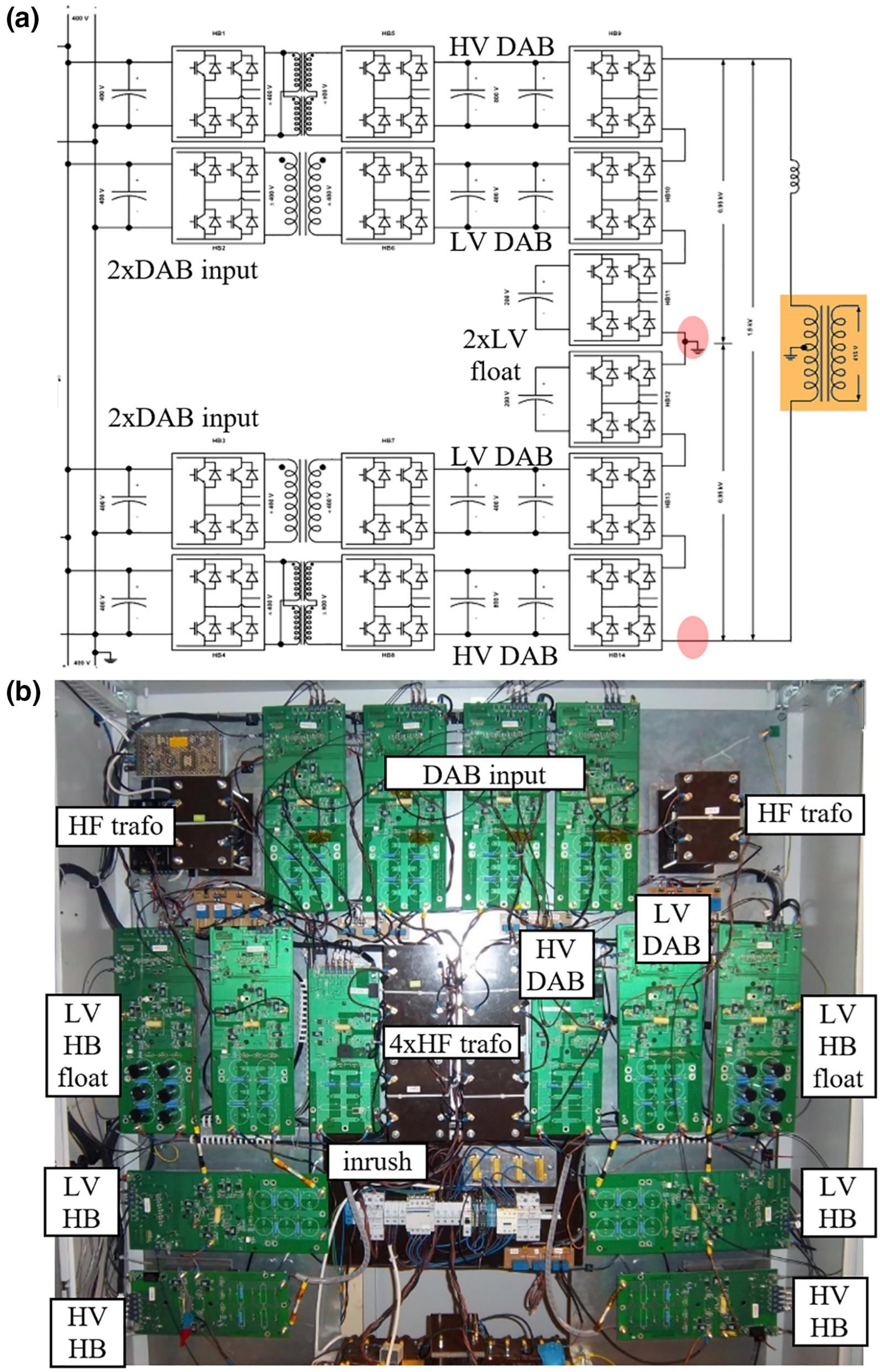

FIGURE 3 (a) The multilevel converter (MLC) topology using asymmetric H-bridges fed from a low voltage DC-bus DABs that use medium frequency transformers to provide isolation; (b) the practical implementation of the 25 kVA/1.9 kV rms prototype

to the very low AC side inductance needed to limit the current ripple in a MLC (voltage ripple is only 200 V for a 2.5 kV peak voltage generated), this fast change in reactive power injection can be done very fast because the dynamic of the grid current being limited only by the grid side inductance size which is much lower compared with the 50 Hz design.

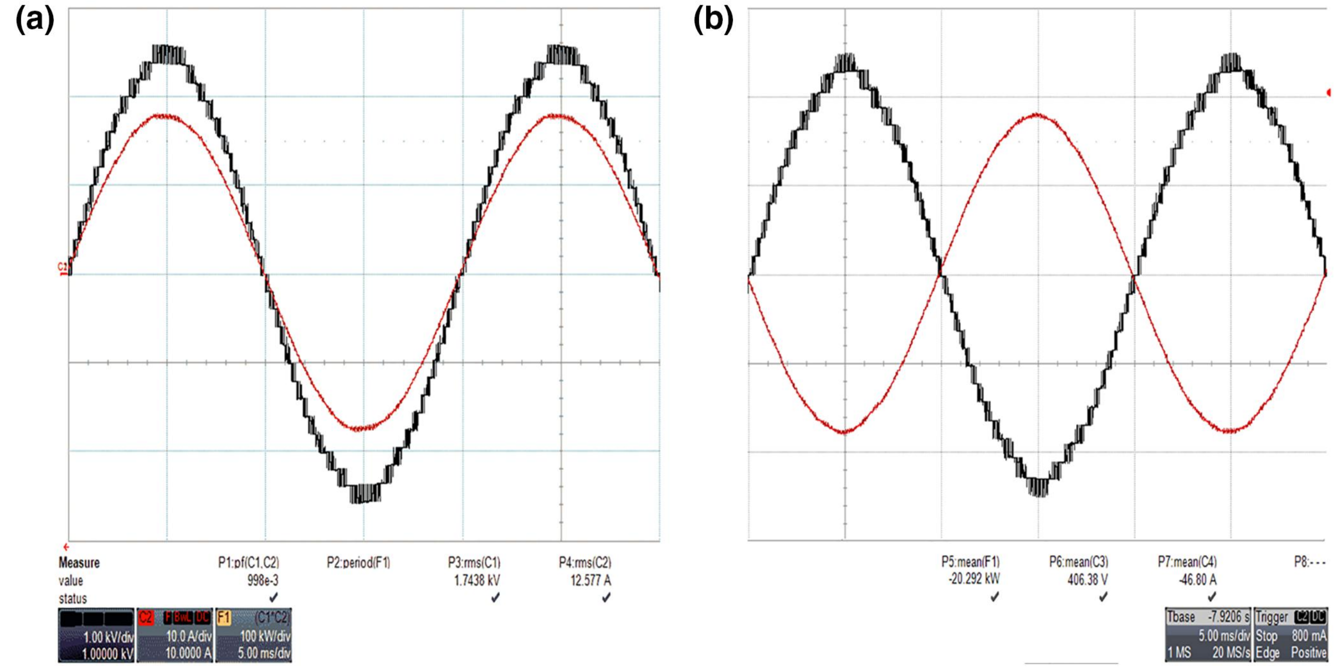

FIGURE 4 Steady-state performance of the MLC working in (a) rectifier mode and (b) inverter mode. Time scale: 20 ms/div

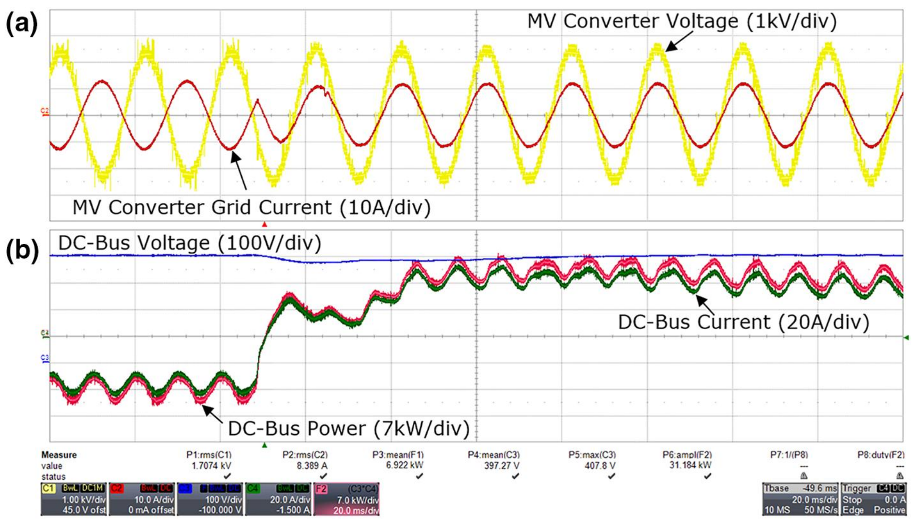

FIGURE 5 ±20 kW active power reversal tests on MV AC side: (a) waveforms of AC voltage and current and (b) DC-bus voltage current and power waveforms

3.3 | Round trip efficiency evaluation

The implementation of the experimental prototype was chosen so that it will be possible to exchange power between the supercapacitor stack and the grid via any of the two inverter types considered by only (dis)connection of the corresponding 400V DC bus positive terminals using separators. Therefore, it was straightforward to perform an experimental evaluation and comparison of the roundtrip efficiency of the ESS connected to a MV grid with each of the two competing converter technologies: LV inverter with the 50 Hz step-up transformer or a true MV inverter where the galvanic isolation is provided by the medium frequency transformers within the DABs.

Figure 7 shows the experimentally determined round-trip efficiency curves of the two converter solutions which consisted of running the setup on constant power charge/discharge cycles at the specified powers whilst the supercapacitor unit was experiencing charge/discharge within the specified voltage range (200–350 V). This means that the losses in the Supercap system are accounted in the round trip efficiency of both ES systems. The power loss measurements have been carried out using two separate methods and measurement equipment. The power and energy flow were measured with a 12-bit oscilloscope (LeCroy) and a Power analyser (PPA3530 from N4L). Several efficiency points were calculated using successive cycles to make sure the error of unequal cycle starting and ending voltage of Supercap system (and therefore

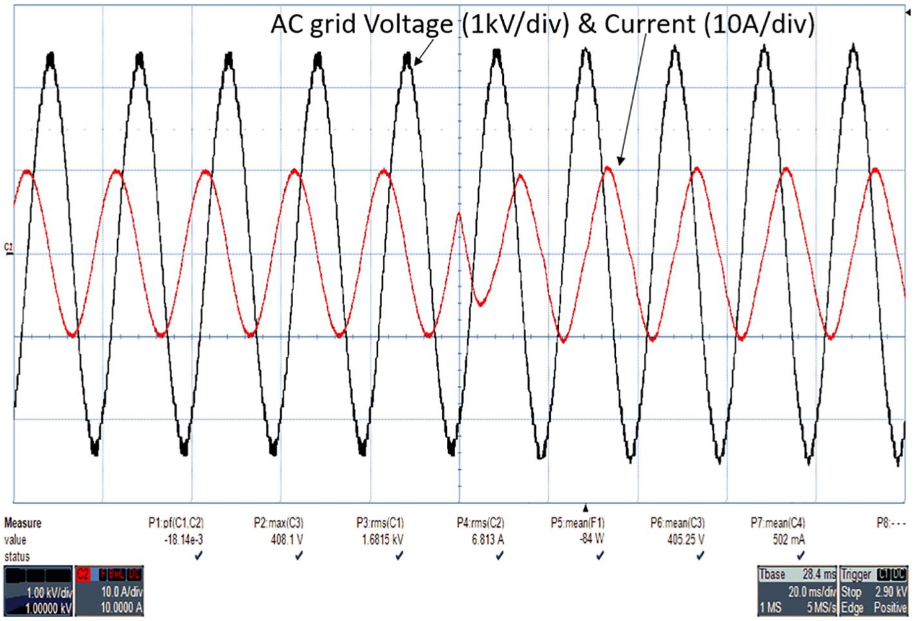

FIGURE 6 Leading/lagging reactive power reversal on MV AC side

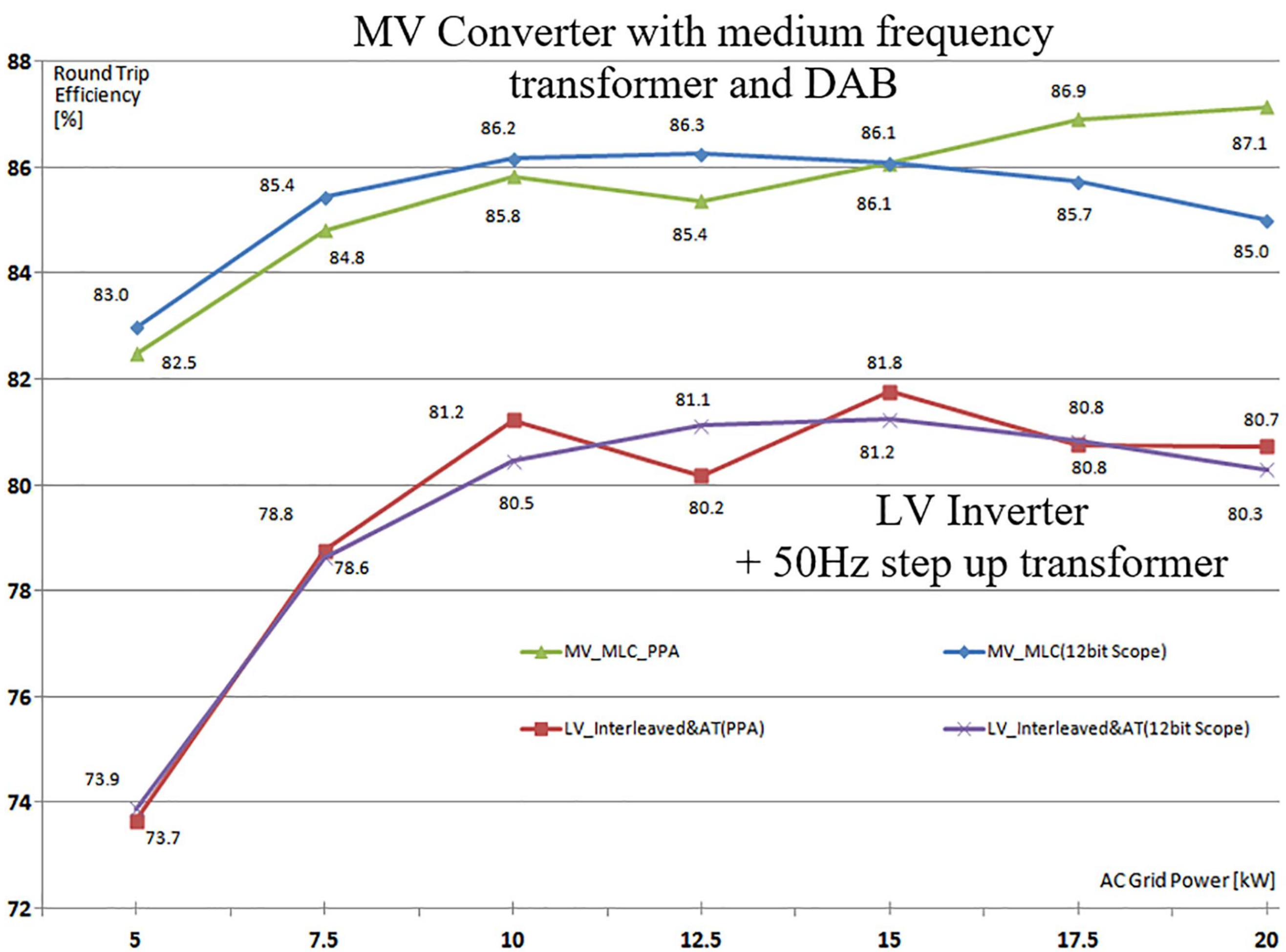

FIGURE 7 Comparison of experimentally evaluated round trip efficiency of the two converter solutions used to build the ESS interfacing the supercapacitor and its DC/DC converter to the MV grid via the cascaded converter connected directly to MV grid (top) and via low voltage interleaved inverter +50 Hz step-up transformer (bottom curves)

the mismatch in start and finish stored energy) was minimised and the fact that both methods resulted in relatively converged curves proves the efficiency measurement method was consistent.

The roundtrip efficiency of the ESS relying on the MV MLC exceeded 86% and was 5% higher than the efficiency of the LV inverter with 50 Hz step-up transformer. The cause for the significantly lower efficiency of the LV inverter +50 Hz transformers was that the 50 Hz step-up transformer had relatively large standby (iron) losses because it was procured following a commercial competitive process with no efficiency target imposed. It can be seen from the variation of efficiency with loading that the losses of the 50 Hz step-up transformer are significantly affecting the round trip efficiency especially at low loading, which is a region where typically, an ESS is supposed to operate a significant amount of time and although losses in absolute terms are not high, when multiplied with a longer operating time, can lead to large energy losses. It should be noted that the efficiency of the LV inverter could be improved by specifying the expected standby loss for the step-up transformer, which may be possible using Metglas cores but this will make them more expensive (volume/mass of the core is inverse proportional with operating frequency). On the other hand, due to the careful design of the medium frequency transformer used in DABs that was optimized for reduced core (standby) loss (but this affected slightly the efficiency at high power), the MV inverter provides a fairly flat efficiency curve exceeding 85% in a wide range of powers from 7.5 to 20+ kW.

4 | SOLID-STATE SUBSTATION WITH EMBEDDED STORAGE

It can be noted that test setup that consisted of having a LV and a medium voltage AC/DC conversion stages connected back to back for performance comparison purpose is in fact implementing the functionality of a solid-state substation that has bidirectional power flow capability as requested in future distribution grids where local LV grids

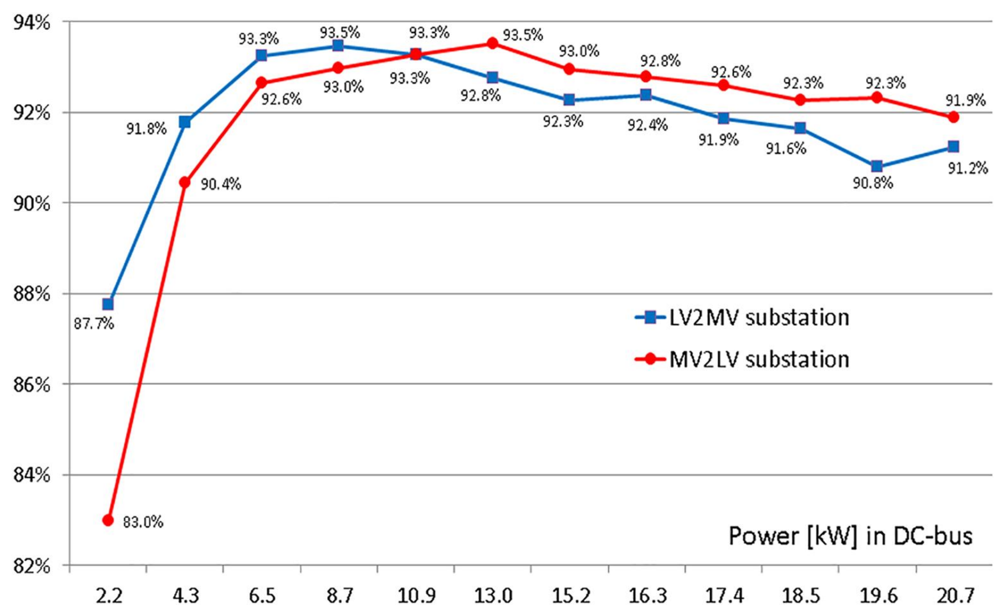

FIGURE 8 Efficiency curves of a solid-state substation for each direction of power flow

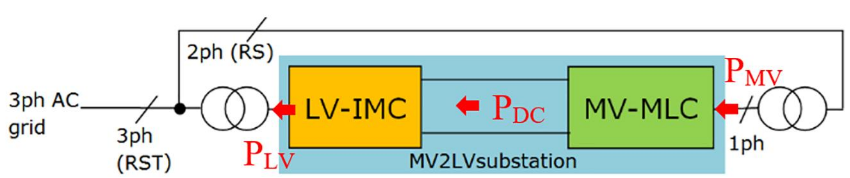

FIGURE 9 Block diagram of the test setup showing where the MV and LV powers have been measured for the efficiency calculations in substation mode. Direction of arrows indicated in the figure is for power flow direction from MV to LV ports giving:

$$\eta_{MV2LV} = P_{LV}/P_{DC} \cdot P_{DC}/P_{MV} = \eta_{MVrec} \cdot \eta_{LVinv} \tag{1}$$

with a significant amount of PV generation will require the power distribution to facilitate the export of PV power upstream. For this reason, determining the typical efficiency of operating in substation mode is important and Figure 8 shows the efficiency versus power loading for both directions of the power flow. Figure 9 depicts the block diagram of the test setup, indicating where the MV and LV powers have been measured. Since the LV converter performance is no longer affected by the standby losses of the 50 Hz transformer, the overall efficiency exceeds 90% in a very wide (10–100%) power range with peak efficiencies near 94% obtained at a relatively light loading (30%–50%). To determine the efficiency, the power losses of each conversion stage have been measured using a 3-phase power analyser (same as above) by measuring the AC power using the two-Wattmeter method on the AC side and the DC power on the 3rd phase. The slight discrepancy of the measured efficiencies is because of having a different current distribution through the IGBTs and their antiparallel diodes in the two-level and MLCs.

Integrating the super-capacitor subsystem in the LV DC bus of the M2L substation can increase offer all benefits of having an ESS demonstrated previously at both MV and LV distribution networks. In addition, it may increase the reliability of the LV distribution system by enabling repair work to be done on the MV network without the need to power off the LV consumers. In addition, energy storage may be used to control/restrain the upstream flow of renewable power until the MV grid is upgraded to safely handle it.

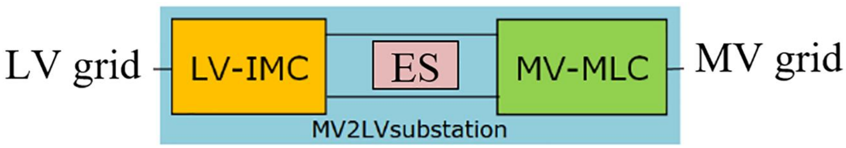

FIGURE 10 Test setup to evaluate the transient behaviour of the solid-state substation with embedded storage

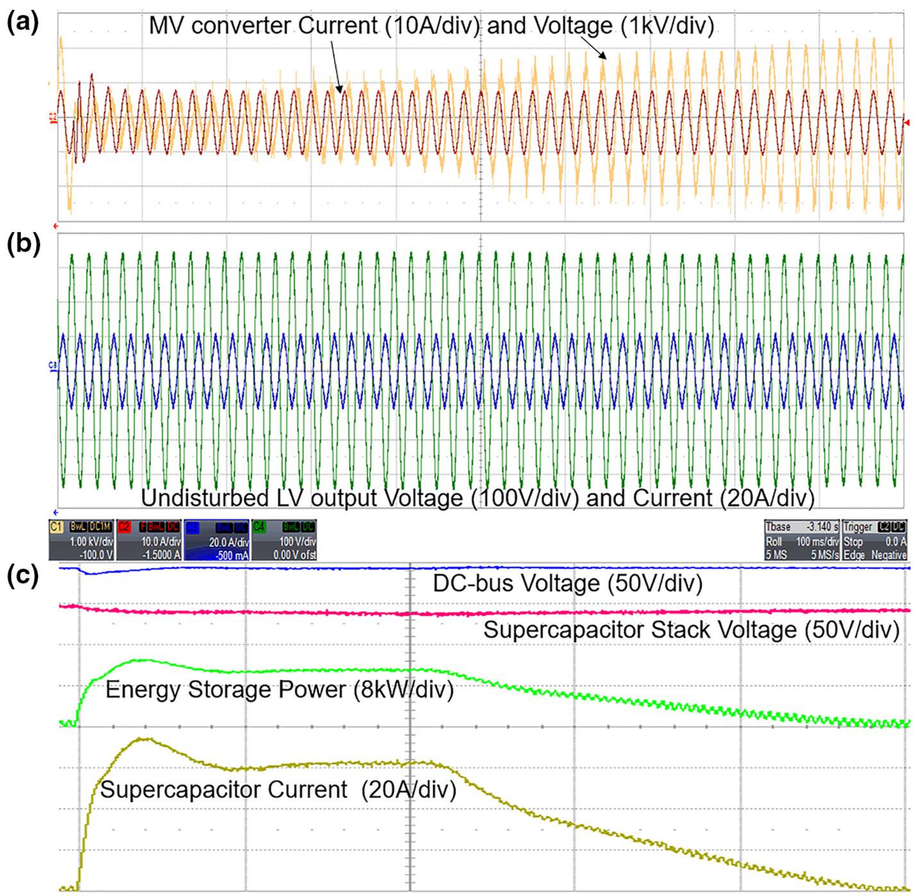

FIGURE 11 Operation during a standard grid fault profile demonstrating the capability of the 'Substation mode with embedded energy storage' concept to provide low voltage ride-through capability on the MV port as demonstrated by (a) MV voltage (1 kV/div) and current (10 A/div) waveforms, whilst the LV port connected loads remain undisturbed as shown by (b) LV voltage (100 V/div) and current (20A/div) waveforms; the power mismatch is effectively covered by the supercapacitor subsystem as shown by (c) waveforms of Supercap voltages, current and power (scales in captions). Overall operating time shown is 1 s

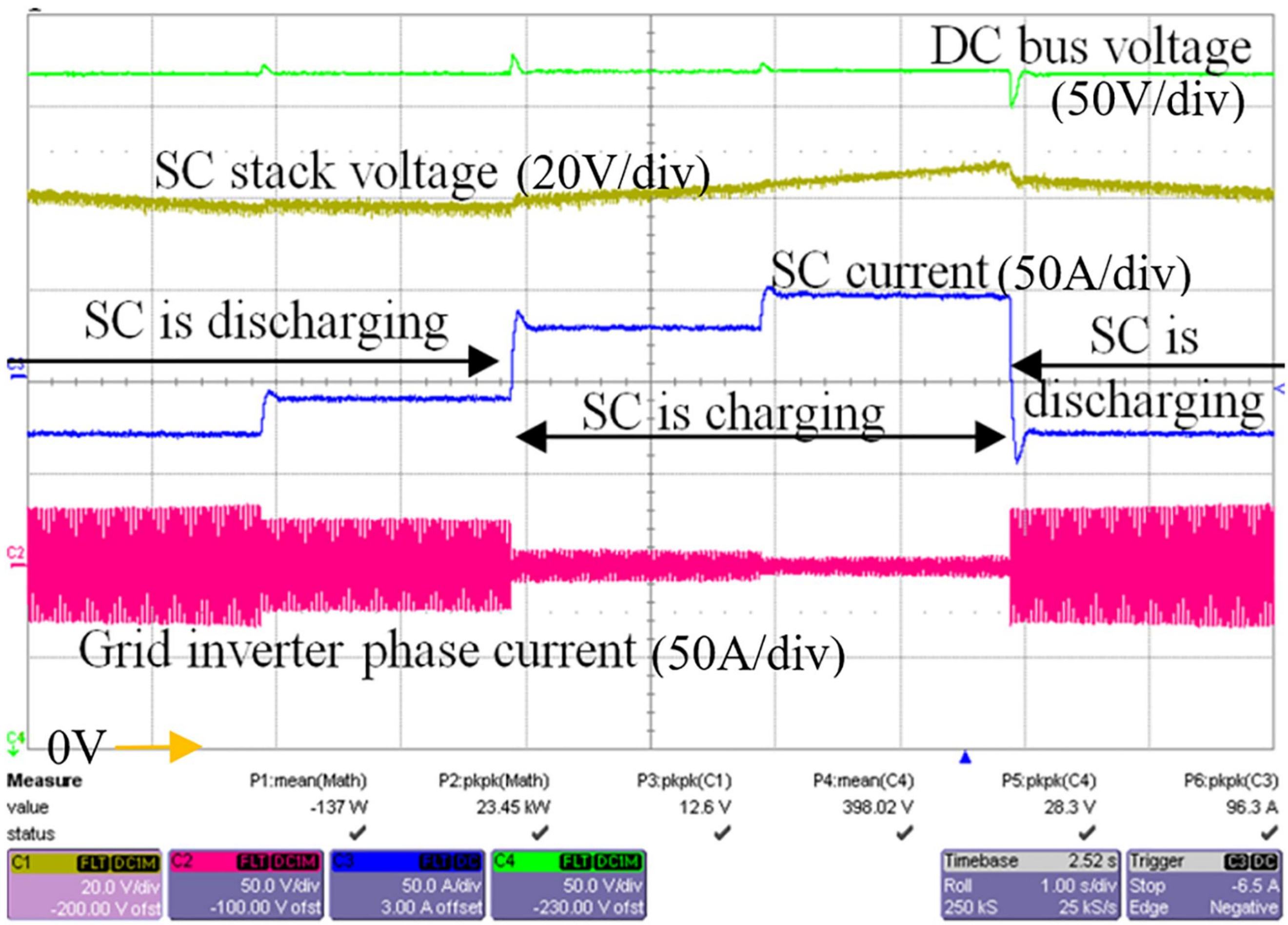

FIGURE 12 Operation of the energy storage system in power peak levelling mode on LV port showing only super-capacitor voltage and current (top) and LV inverter current waveforms

4.1 | Grid fault ride through operation

The operation of the ESS demonstrator configured in a substation mode with embedded energy storage was configured as suggested in Figure 10: the MV inverter was connected directly to an MV distribution network, whilst the 50 Hz step-up transformer is removed from the LV inverter, which feeds directly the LV consumers. The performance of this concept under a grid fault on the MV port that follows a standardised voltage profile was evaluated and the response is illustrated in Figure 11. The MLC initially operates with rated active power but when the drop of the supply voltage is sensed, the control of the MV converter switches to full reactive current injection as required by the distribution grid support mode. Figure 11(a) reveals that the MV port current is maintaining rated amplitude during the fault but the phase shift relative to the MV voltage increases to leading by 90 degrees, which means it injects full rated reactive current and in the grid and therefore wil not be able to supply any active power to the DC-bus/LV inverter/LV loads. It is the Supercap energy storage subsystem that is bridging the power/energy gap very quickly to make sure the LV loads are not disturbed by the grid fault as shown in Figure 11(b) where LV load voltage and current remain unchanged. The fast operation of the Supercap subsystem is seen by inspecting the DC-bus voltage, which experiences only a small voltage dip that is corrected immediately by the very fast Supercap energy storage control as seen in Figure 11(c). As the grid voltage on the MV port recovers, once it exceeds 50% of the rated level, the MLC converter is allowed to absorb also some active power (although injection of reactive current continues as requested by the grid codes) and this partial contribution of active power absorbed from MV grid is denoted by the reduction of the supercapacitor current and power which reduce linearly (from $t = 0.4$ s) as the MV voltage recovery continues.

4.1.1 | Power peak levelling operation

Another important test is the capability of the solid-state substation with embedded storage is to provide fast and accurate power peak smoothing capability on the LV AC distribution grid whilst the MV grid has a limited power capability (weak grid) well below the largest of the LV port load peaks. In this situation, as illustrated in Figure 12, the link with the weak MV power grid supplies the average power consumed by the LV loads (these waveforms are not shown since the MV currents were constant in amplitude) and the ripple power is supplied by the ESS. Whilst the LV grid inverter follows the AC power profile consumed by the loads resulting in a large transient in the DC-bus power absorbed from the DC-link capacitors, the DC-bus voltage of the ESS is very quickly controlled by the supercapacitor subsystem and this can be seen by the relatively small overshoots in the supercapacitor current that coincide with the DC-bus voltage overshoots caused by the sudden power steps produced by the grid side inverter.

5 | CONCLUSION

Excess renewable power generated at the consumer end in the LV distribution networks that cannot be consumed locally and may not be so easily absorbed in the medium voltage distribution network without significant upgrades may be handled relatively easier by embedding energy storage either as a separate unit or integrating it within a substation. ES interfaced via power electronics is also expected to offer grid fault ride-through operation or extended islanding operation during major distribution grid failures, in addition to better voltage regulation and improved power quality.

This article presents the results of evaluating two power electronics technologies used to connect a supercapacitor stack to a medium voltage grid: an industrial-grade technology relying on LV inverters and 50Hz step-up transformer and a research-grade multilevel modular converter that is using DAB bidirectional DC/DC converters to feed power to/from the cascaded modules. An additional conversion stage, however, was needed to compensate for the variable supercapacitor stack voltage which is always dependent on its state of charge but this may not be essential in case a battery storage solution with significantly more energy storage capacity would be needed.

A 1.5 MJ/25 kVA demonstrator has been built that is able to deliver 1.9 kV rms on the MV port and this level was chosen as it is the rated phase-to-neutral voltage level that corresponds to a 3.3-kV grid. The LV inverter topology is interfaced with the MV grid via a 50 Hz step-up transformer which is simpler. The experimental evaluation consisted of verifying the excellent AC side harmonic performance of the MV and LV inverters, the very fast response to step changes in active and reactive power requirements and the ability to provide ride-through the operation with full voltage and power availability at the consumer end whilst the MV grid is affected by a standardised grid fault.

In terms of round-trip efficiency, the operation of the two technologies results in 81–86% efficiency with higher and flatter efficiency levels achieved by the MLC. The LV converter technology that is connected to the MV grid via a 50-Hz step-up transformer has lower efficiency due to the poor efficiency profile of 50 Hz transformers as this was chosen solely based on the lowest cost and the higher core losses affect more the efficiency at reduced loading which is where an ESS is expected to operate for a significant amount of time. Efficiency improvements of the 50-Hz transformer are possible using lower current densities (winding losses) and lower magnetic flux level to reduce the core loss or by employing more expensive core materials such as Metglas but these will have an impact on increasing the transformer size and cost. This aspect highlights the need that a potential manufacturer or OEM of an ESS controls very tightly the quality of components received from the supply chain.

The use of WBG power semiconductors such as SiC and GaN can indeed maximize the efficiency and minimize the size of the magnetics but at a significant increase in cost. This technology is currently deployed in low and medium power converters (up to hundred kW) in niche applications such as aerospace where indeed low size/weight can induce significant system savings. Currently, efforts are made to develop commercially medium voltage WBG and increase the current ratings of the LV ones to enable implementing MW power converters in a similar way. However, faster switching causes additional EMI-related problems which require the use of additional filters; the development of passive components able to cope with the significantly higher frequencies such as ceramic capacitors and geometry of windings is currently investigated in the research study. In addition, large-sized (hundreds kW) transformers built with winding technologies typical for a 50-Hz power systems may be sensitive to the large dv/dt caused by WBG switches. All this means that the conclusions of this study for implementing a power converter scalable at high powers for integrating energy storage in a medium voltage grid remain relevant for the medium term.

In conclusion, this article demonstrated the features that a solid-state substation with embedded energy storage can bring to a distribution power system to enhance grid stability and resilience. These hardware features would complement smart grid features offered by online fast data processing capabilities.

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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

Author elects to not share data Research data are not shared.

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