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EVALUATION AND EXPERIMENTAL VALIDATION OF POWER CONVERTER TOPOLOGIES FOR A BIDIRECTIONAL GRID-CONNECTED BATTERY ENERGY STORAGE SYSTEM

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Resume

In this research is described the topology assessment, design, simulation, and experimental verification of bidirectional grid connected BESS. Several converter topologies were assessed based on the efficiency, power quality, bidirectional capability, electromagnetic compatibility, and ease of implementation. A bridgeless totem-pole PFC converter, together with bidirectional CLLC resonant DC/DC converter, was chosen and implemented in 2 kW lab prototype. Experimental tests in both grid-to-battery and battery-to-grid modes yielded maximum power of 2.28 kW, a power factor of 1.0, total current harmonics of 1.43%, and maximum efficiency of around 96%. These results show the suitability of the architecture chosen for bidirectional energy storage systems and grid connected energy management, renewable energy integration, and electric vehicle charging and V2G applications.

Article info

Received 12 June 2026

Accepted 31 August 2026

Online 24 September 2026

Keywords:

active compensation system
battery storage system
bidirectional power flow
grid connected system

Available online: <https://doi.org/10.26552/com.C.2026.055>

ISSN 1335-4205 (print version)

ISSN 2585-7878 (online version)

1 Introduction

Active compensation systems (ACS) represent a modern approach to optimizing the electricity consumption, as they can play a key role in this process. These systems help to reduce harmonic distortions in electrical networks, losses in distribution networks, and increase a power system efficiency. Implementing these technologies allows not only to reduce costs but to stabilize electricity supplies, as well [1-3].

An important key element in saving electricity is energy storage, which allows the accumulation of energy in periods of excess and, conversely, its use when the energy demand is higher. In this way, it is also possible to contribute to stabilizing energy networks and support using renewable energy sources. These energy storages can be based on different technologies (mechanical, thermal, electrochemical, etc.). The current trend is

storage based on batteries (especially lithium or lead) [4-5].

Another important aspect is the reuse and second-life utilization of battery systems or components, especially battery recycling (especially the possibility of using batteries from electric cars and the like) [6-8]. This attitude would primarily contribute to reducing the environmental impact by reducing waste and emissions created [9-11].

Active compensation systems (ACS) can be used in industrial facilities, commercial buildings, and even homes, helping to reduce operating costs. Another great benefit of these ACS systems is the possibility of connecting them with systems of renewable energy sources such as solar, wind, geothermal, or others [12-14].

Another area of use of ACS is residential urban and local areas. Current trends also indicate that the

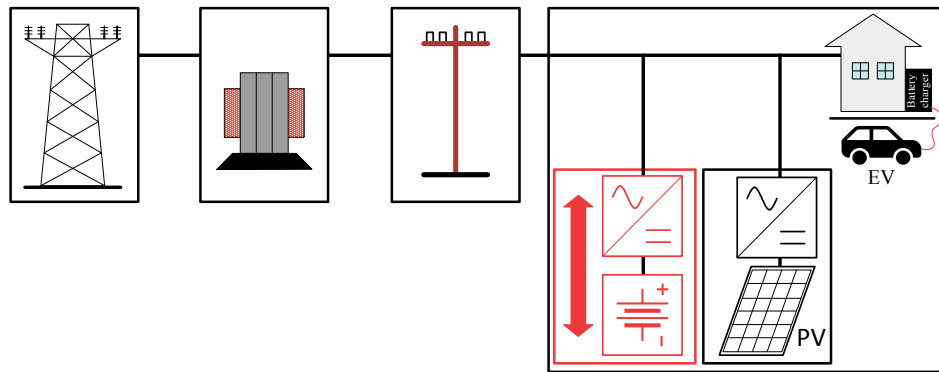


Figure 1 Configuration of ACS for combined applications

Table 1 Main contributions of the paper

Contribution	Description
Topology evaluation	Comparison of BLTP-PFC, DAB and CLLLC solutions
Experimental validation	Verification on 2 kW laboratory prototype
Bidirectional operation	Charging and discharging modes verified
Power quality analysis	$PF = 1$ and $THD_i = 1.43 \%$
Transport applicability	Suitability for EV charging and V2G operation

importance of using the ACS systems is significantly more complex, as they enable applications in Grid-to-Vehicle (G2V) or Vehicle-to-Grid (V2G) modes and support applications with renewable energy sources, Figure 1, [12, 15-19].

In the presented article are compared converter topologies suitable for implementing an ACS system for electrical energy compensation consisting of several parts and presents its initial implementation and verification, Table 1.

Unlike many previously published ACS and BESS solutions that focus either on converter design or on simulation-based evaluation, the presented work provides a comprehensive comparison of bidirectional converter topologies and experimentally validates a complete ACS architecture combining a bridgeless totem-pole PFC (BLTP-PFC) stage and a bidirectional resonant converter (CLLLC).

The proposed architecture achieves high power quality ($PF = 1$, $THD_i = 1.43 \%$) together with bidirectional operation and high efficiency, which makes it suitable for future smart-grid and transport-energy applications.

The ACS prototype uses two operating modes for basic verification of the principle of operation:

1. Mode - accumulation of energy from the grid to the batteries (accumulation mode),
2. Mode - supply of energy from the batteries to the grid (generative mode).

Based on the test results of the ACS system prototype, further stages will continue, focused on active compensation of negative phenomena in the electrical grid and the possibilities of their optimization.

2 ACS components

Active compensation systems (ACS) using electrical energy storage systems represent very complex devices, especially in terms of technical implementation and equipment, measurement of necessary quantities and corresponding control algorithms. From the point of view of safe and correct operation of the electrical network, the development of ACS systems and the development of necessary control algorithms to control these complex systems to achieve the required properties is important [12].

From the point of view of the power electronic part, they can be generally divided into three basic parts, Figure 2. All used parts of the system must operate in bidirectional operation to achieve the highest possible efficiency, stability, safety and dynamics.

The first part of the ACS system consists of the input-output system, which forms the interface between the electrical network and the energy storage. These are suitable bidirectional PFC converters, or Four-Quadrant Converter (4QC) [20]. The converter operates as a controlled rectifier in Mode 1 (accumulation mode), and as an inverter in Mode 2 (generative mode).

The second part of the ACS system deals with the optimal transfer of DC energy to and from the battery storage, i.e., suitable DC/DC converters. As suitable DC/DC converters can be considered bidirectional CLLLC [21-23] or DAB converter [24-27]. The converter operates in BUCK mode in Mode 1 (accumulation mode), and in BOOST mode in Mode 2 (generative mode).

The last part of the ACS system concerns the

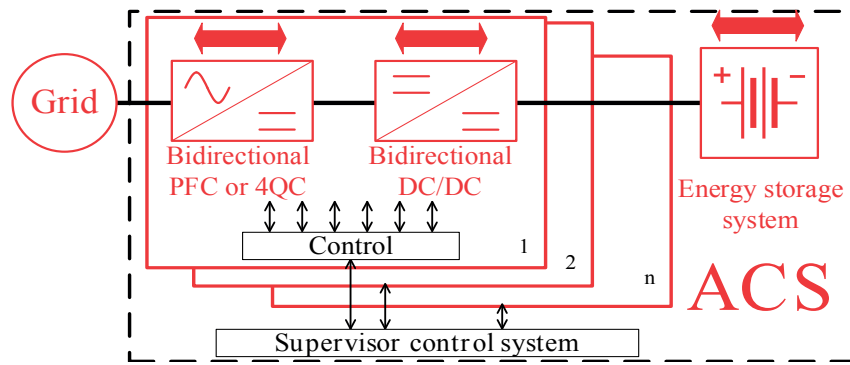


Figure 2 Block configuration of the ACS system

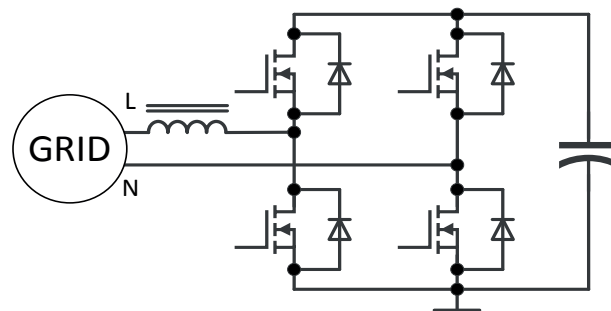


Figure 3 Bridgeless totem-pole PFC

battery storage systems themselves. Many professional and scientific articles are devoted to this issue [28-32].

2.1 PFC selection

As mentioned above, the first part of the ACS system consists of an input-output converter, which forms the interface between the electrical network and the energy storage. This converter operates as a controlled rectifier in Mode 1 (accumulation mode) and as an inverter in Mode 2 (generative mode). Based on these requirements, it is possible to choose a bidirectional PFC or 4QC topology for the first stage. Considering the nominal power, complexity, and overall requirements for the implemented system, the bidirectional PFC topology was chosen.

Within the used PFC converter topologies, one of the significant sources of power losses is the input bridge rectifier, which converts the AC input current into the high-voltage DC current required for the power factor correction (PFC) circuit. At lower AC voltages, high powers and at full load, the bridge rectifier can be responsible for 2% to 3% of the total output power loss due to line inefficiency [33-34].

For this reason, the bridgeless boost PFC topology has become popular. It has gained attention as a more efficient alternative because it eliminates the need for an input rectifier bridge, thereby reducing conduction losses [35-36].

The selection of a PFC converter topology for the DC power flow is usually a question of the need to achieve

the required level of transmitted power. It is possible to choose from the following topologies: classic boost PFC, double boost PFC, or one of the latest totem-pole PFC topologies. However, the selection of a PFC topology suitable for bidirectional power flow and for application in ACS is not so difficult nowadays. The Bridgeless Totem-Pole Power Factor Corrector (*BLTP-PFC*), Figure 3, is a topology with the smallest number of switching elements, which allows for bidirectional power flow, which is essential for ACS systems, and at the same time provides high efficiency. However, to achieve the desired properties, it is necessary to properly design and select the PFC inductance, semiconductor switches, output filter capacitors and control circuit of the entire PFC system. Semiconductor switches can be further divided into slow (MOSFETs, switching with the frequency of the power grid) and fast (GaN, switching the detailed current waveform). Another important part is the circuit for measuring the mains voltages and currents that the converter draws from or supplies to the power grid.

2.2 DC/DC converter selection

The bidirectional DC/DC power stage works as a battery charger in one direction - accumulation mode (*BUCK mode - Mode 1*) and as a constant voltage converter when operating in the opposite direction - generative mode (*BOOST mode - Mode 2*). The battery voltage level depends upon the system power level. In addition to the necessity of bidirectional energy flow, high inverter efficiency is also an important feature. For

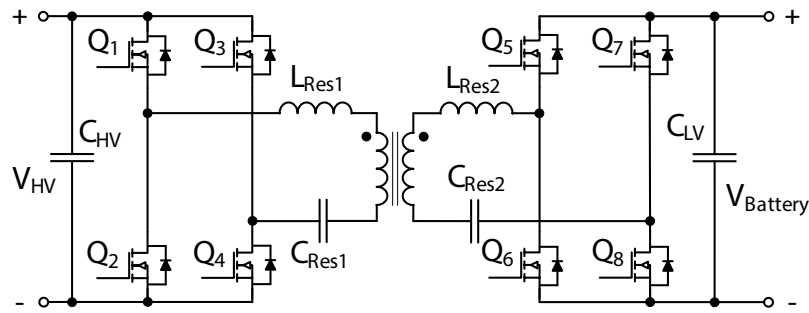


Figure 4 CLLC resonant topology

isolated bidirectional power stages, resonant CLLC converter and Dual Active Bridge (DAB) topologies are commonly used, providing suitable properties for ACS systems.

2.2.1 CLLC resonant topology

The CLLC resonant topology is a highly efficient, symmetric bidirectional DC-DC converter architecture widely used in modern power electronics. CLLC, Figure 4, is derived from popular LLC and uses all its advantages. One major advantage is using the secondary switches to obtain bidirectional power transfer which is most important for ACS system applications. This topology can be used for power levels up to 10 kW.

The resonant tank must be symmetrical (symmetrical design will ensure similar behavior during both charge and discharge cycles). This topology achieves Zero-Voltage Switching (ZVS) on the primary bridge and Zero-Current/Zero-Voltage Switching (ZCS/ZVS) on the secondary bridge, which drastically lowers the switching losses and enables high-frequency operation. Capacitors used in the resonant tank naturally prevent the saturation of the transformer core. The integration of minimalized resonant components combined with high operating frequencies (often 500 kHz up to 1 MHz) minimizes the overall volume of the converter. Due to soft-switching characteristics, superior Electromagnetic Interference (EMI) performance is achieved. This topology uses identical transmission characteristics for both power flow directions, simplifying the control system. Frequency-pulse modulation is a standard control technique for CLLC converters [21-23].

2.2.2 Dual Active Bridge (DAB) topology

Among different topologies, the Dual Active Bridge (DAB) converter, Figure 5, is increasingly popular for its isolation, natural bidirectional operation, high power density, and ability to perform soft switching. The DAB converter is well-suited for efficient bidirectional energy conversion with high power density, making it appropriate for applications where the power needs to be transferred over a wide voltage range, especially

in low-voltage energy storage. The operation of the DAB converter relies on the phase difference between the primary and secondary bridge voltages and on the interaction of two active full bridges via the high-frequency transformer and the energy-transfer inductance. By controlling the power transfer through the phase difference, the conditions for soft-switching and for minimizing switching losses are achieved, leading to high efficiency.

Numerous publications were focused on the design of DAB converters for medium- and high-power applications, such as EV charging, energy storage systems, and the integration of renewable energy sources. They addressed issues related to the modulation scheme, efficiency, wide voltage regulation range, and the use of digital controllers. Low-power isolated DC-DC converters are discussed much less frequently and detailed guidelines for design, testing, and implementation are lacking [24-26].

At the same time, there are specific challenges associated with DAB converter design, including transformer optimization, leakage inductance selection, semiconductor switching loss reduction, control system stability, and cooling. The topology can operate with a wide range of battery voltages. However, it exhibits a high circulating current, which contributes significantly to reduction in efficiency. Another disadvantage of the topology is the loss of ZVS at low load. These disadvantages can be eliminated by using further modulation modes (Dual phase shift and triple phase shift), which increases the complexity of the system control [27].

Finally, based on the comparison in Table 2, based on the application requirements for low EMI and high efficiency, the CLLC topology was selected for its superior performance in high-power applications where efficiency, low EMI, and thermal management are critical. The resonant design of the CLLC enables the zero-voltage switching (ZVS) and zero-current switching (ZCS), significantly reducing switching losses and improving efficiency over a wide load range. In addition, its EMI suppression makes it suitable for noise-sensitive applications. Although it requires more complex control and potentially a larger number of passive components, the benefits in reliability, efficiency, and reduced cooling requirements justify these tradeoffs. This makes the

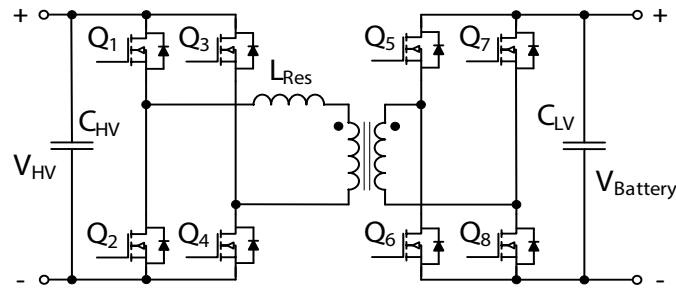


Figure 5 Dual Active Bridge (DAB) topology

Table 2 DC/DC converters comparison

Parameter	CLLLC	DAB
Soft switching	Excellent	Moderate
EMI	Low	Medium
Control complexity	Medium	High
Circulating current	Low	High
Efficiency	High	Medium-High
ACS suitability	Excellent	Good

CLLLC topology optimal for achieving high performance in demanding, high-power environments.

The resulting topology of the ACS system was a combination of bridgeless totem PFC (BLTP-PFC) and bidirectional CLLLC converter, which was subjected to simulation and experimental verification of operation.

2.2.3 Energy Storage Systems

The Energy storage systems (ESS) absorb electrical energy from the energy sources - such as solar panels, wind turbines or the electrical grid and store it. When needed, this energy can then be used for power generation. They play a key role in balancing supply and demand in the grid, mitigating the intermittency of renewable energy supplies and providing reliable backup power.

The Energy Storage Systems (ESS) can be implemented as purely battery-based (Battery Energy Storage Systems - BSS) or as hybrid (Hybrid Energy Storage Systems - HESS).

Battery energy systems (BSS) are a key pillar of modern energy transformation, grid stability and renewable energy integration (RES).

With the increasing share of solar and wind power plants, whose production is unstable and dependent on the weather, a backup (system) is needed to balance the mismatch between electricity production and consumption. BESS systems can absorb excess energy during times of overproduction and feed it back into the grid during times of deficit or peak. In addition to supporting RES, they serve to provide support services (frequency and voltage stabilization), optimize costs through charging during times of low tariffs

(arbitrage), reduce reserved capacity (peak reduction), and ensure uninterrupted power supply (UPS) for critical infrastructure [28-32].

For the ACS system, a battery storage system was designed consisting of LiFePO₄ batteries LFP48150U5E, V_{NOM} 48V, 150Ah, 7200Wh, capacity according to requirements (according to the number of battery modules), maximum 96kWh [37].

2.2.4 Final structure of ASC and control architecture

As mentioned in the previous sections, the final topology of the ACS system consists of an input EMI filter, BLTP-PFC and CLLLC converter and battery storage, Figure 6.

The ACS control system is very complex and intricate and its description is not the primary subject of this article. This issue will be addressed in detail in further research and the results will be published in detail.

The ACS control system must process a large amount of data in real time, for example: sensing of quantities - grid voltage and current, battery voltage and current, inverter and battery temperatures, relay control, BLTP-PFC and CLLLC converter control, CAN communication, sensing data from the superior system and defining the magnitudes and directions of power flows, parallelization, HW and SW protection, and many others.

The control architecture of the proposed ACS consists of two independently controlled power conversion stages (BLTP-PFC and CLLLC) interconnected by a common DC-link capacitor. The first stage (BLTP-PFC) is

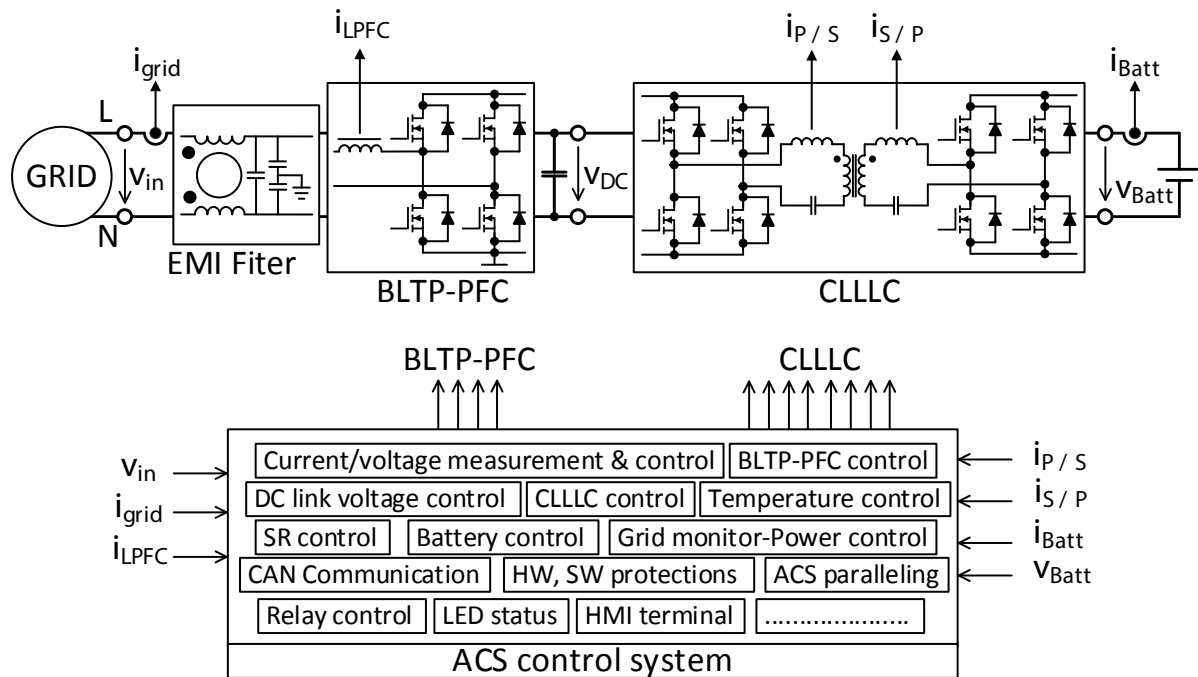


Figure 6 Final structure of ASC system

responsible for the grid interface, whereas the second stage (CLLLC) is responsible for battery charging and discharging. The overall control strategy follows a hierarchical structure. The BLTP-PFC converter controls the power exchange with the utility grid, while maintaining a regulated DC-link voltage. The CLLC converter independently controls the battery current or battery voltage according to the selected operating mode. The DC-link capacitor therefore acts as an energy buffer separating the dynamics of the grid-side converter from the battery-side converter.

The complete control architecture consists of three principal control loops:

1. Grid synchronization and current control (BLTP-PFC),
2. DC-link voltage regulation,
3. Battery charging/discharging control (CLLLC converter).

This hierarchical arrangement allows both converters to operate independently while maintaining stable bidirectional power transfer.

The BLTP-PFC converter operates as a current-controlled voltage-source converter synchronized with the supply grid; switching frequency is 70 kHz. The grid voltage is continuously measured and processed using a Phase-Locked Loop (PLL), which generates the instantaneous phase angle required for current synchronization. The outer (slower) voltage-control loop regulates the DC-link voltage by comparing the measured DC-link voltage with its reference value. The resulting controller output defines the required active current reference. The inner (fast) current-control loop regulates the converter input current so that it accurately follows the sinusoidal reference synchronized with the grid

voltage. Consequently, the converter achieves nearly unity power factor and very low harmonic current distortion. Depending on the operating mode, the sign of the reference current determines the direction of power flow. During the battery charging, the converter behaves as an active rectifier drawing sinusoidal current from the grid. During the battery discharging, the current reference is reversed, allowing the converter to inject active power back into the utility grid while maintaining synchronized operation.

The DC-link capacitor principally electrically decouples the grid-side converter from the battery-side converter and represents the main intermediate energy storage element. The DC-link voltage is continuously monitored and regulated to a constant reference value of approximately 415 V. A cascaded control structure is used. The outer voltage controller determines the required active power transferred through the BLTP-PFC converter, while the fast inner current controller ensures rapid dynamic current response.

The second stage (CLLLC) transmits power controlled by changing the switching frequency around the resonant frequency (140 kHz) of the resonant tank. During the battery charging, the converter operates in BUCK mode. The battery charging current is regulated according to the charging profile while maintaining stable DC-link operation. During the battery discharging, the converter operates in BOOST mode. The switching frequency is automatically adjusted to maintain the required DC-link power under varying battery voltage conditions. For battery voltages below the nominal value, the switching frequency decreases below the resonant frequency in order to increase the converter voltage gain. Conversely, operation above resonance

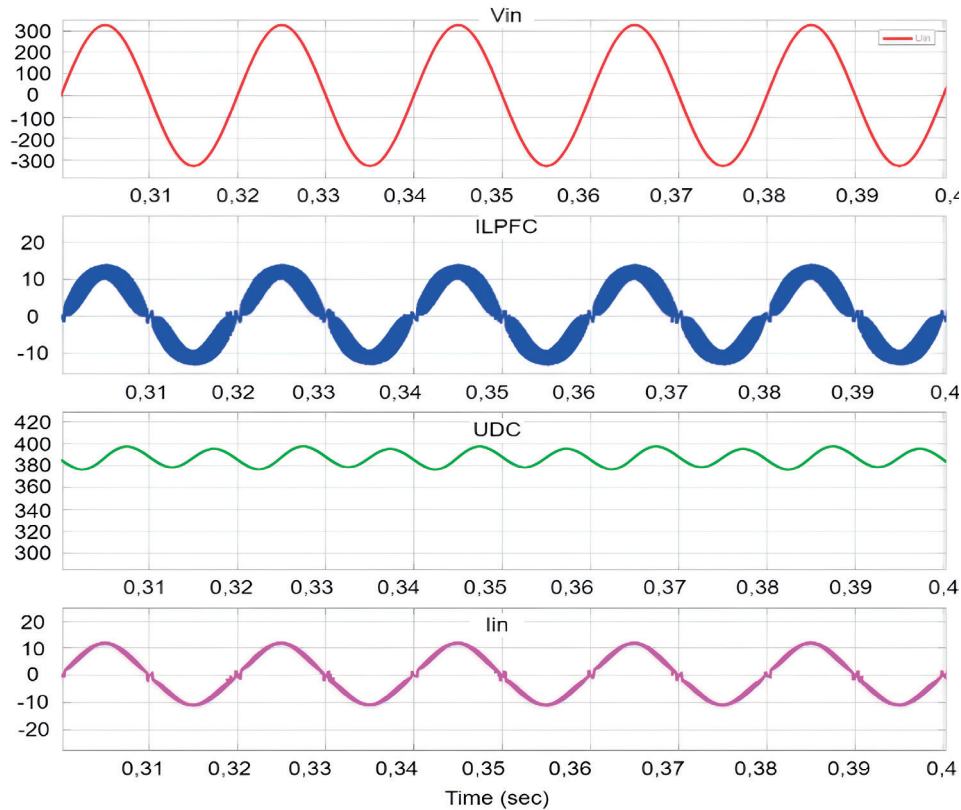


Figure 7 Simulated BLTP-PFC waveforms, rectifier mode at full power

reduces the voltage gain while preserving soft-switching conditions.

The frequency-control strategy enables Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS) over a wide operating range, contributing to the high efficiency experimentally verified in this work (what is an advantage of this topology).

The advantage of this topology is that the switching frequency control strategy allows zero voltage switching (ZVS) and zero current switching (ZCS) over a wide operating range, which contributes to high efficiency, which is also verified in this paper.

3 Simulation verification

Simulation tests were performed to verify the correct function of the proposed solutions for individual inverter topologies of the ACS system. As a part of the simulation testing, models of the bidirectional BLTP-PFC and bidirectional CLLLC inverter were verified in both operating modes: Mode 1 (accumulation mode, battery charging) and Mode 2 (generative mode, inverter).

3.1 BLTP-PFC simulation

A BLTP-PFC simulation model was created to verify the PFC converter's functionality and features.

This converter was tested in both work modes - in Mode 1 (accumulation mode, operates as a controlled rectifier) and in Mode 2 (generative mode, operates as an inverter). These waveforms show the input voltage v_{IN} (red), the i_{LPFC} inductor current (blue), the DC bus voltage v_{DC} (green), and the input current i_{IN} (magenta).

At the input, the inverter is connected to the grid, so it is important to focus on the shape of the input current i_{IN} , which is directly related to THD_i. Another quantity worth noting is the current through the main inductor of the i_{LPFC} .

The first waveforms represent the valid results for a total output power of 2 kW in the rectifier mode of the BLTP-PFC converter, Figure 7. Similar waveforms represent the results in the inverter mode at the same power 2 kW, Figure 8. In this case the BLTP-PFC works as a VSI inverter and transfers energy from DC bus back to the main grid. In this mode of operation, it is necessary to achieve the desired current shape, as well which directly determines the THD.

3.2 The CLLLC simulation

The resonant CLLLC converter was simulated in two modes of operation depending on the direction of the energy flow. In Mode 1 for the direction of energy flow to the battery, the DC/DC converter is in BUCK mode, Figure 9. This Figure shows the transformer primary current i_p (green) and the transformer secondary current

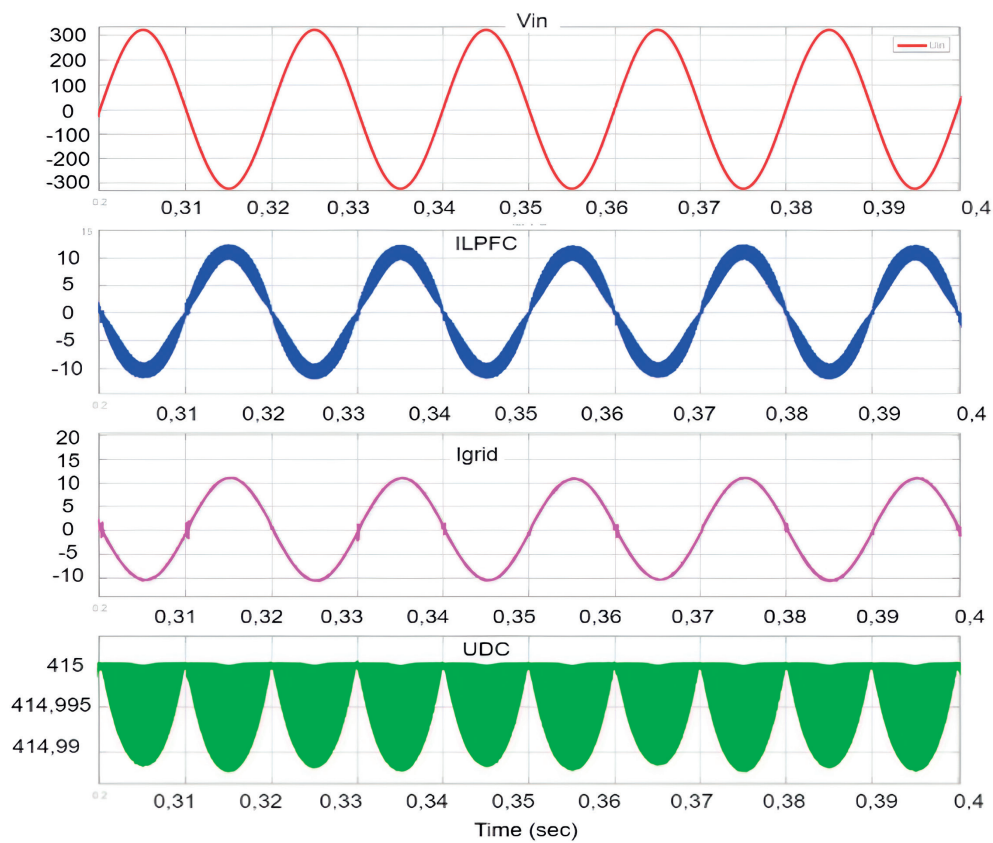


Figure 8 Simulated BLTP-PFC waveforms, inverter mode at full power

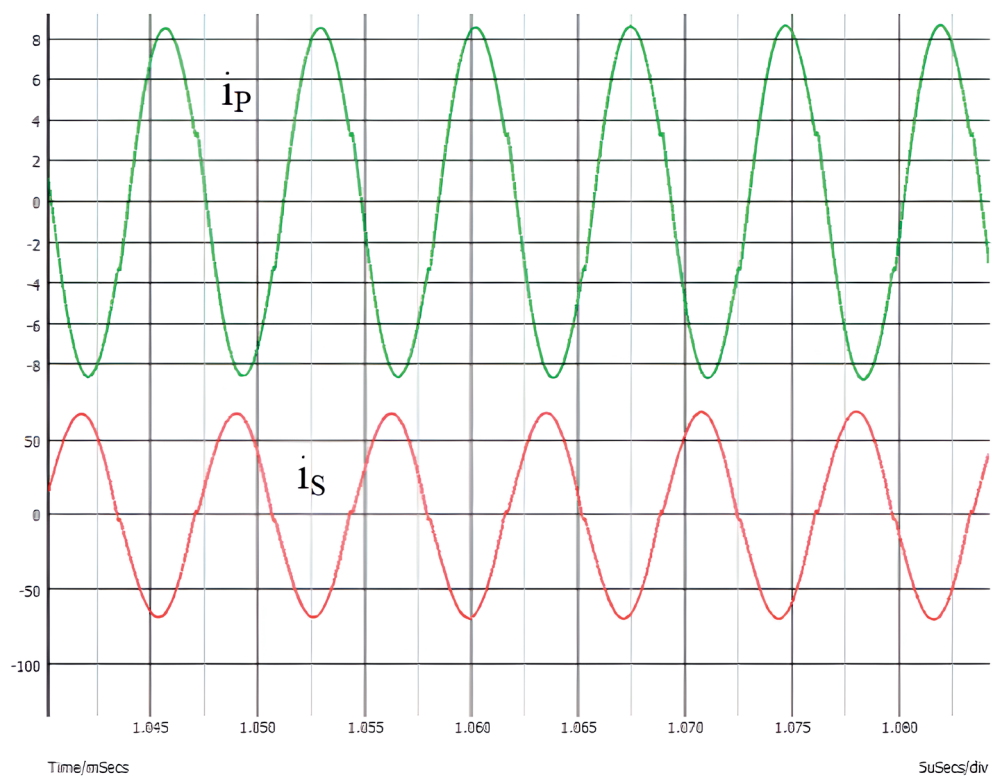


Figure 9 The CLLC converter BUCK mode

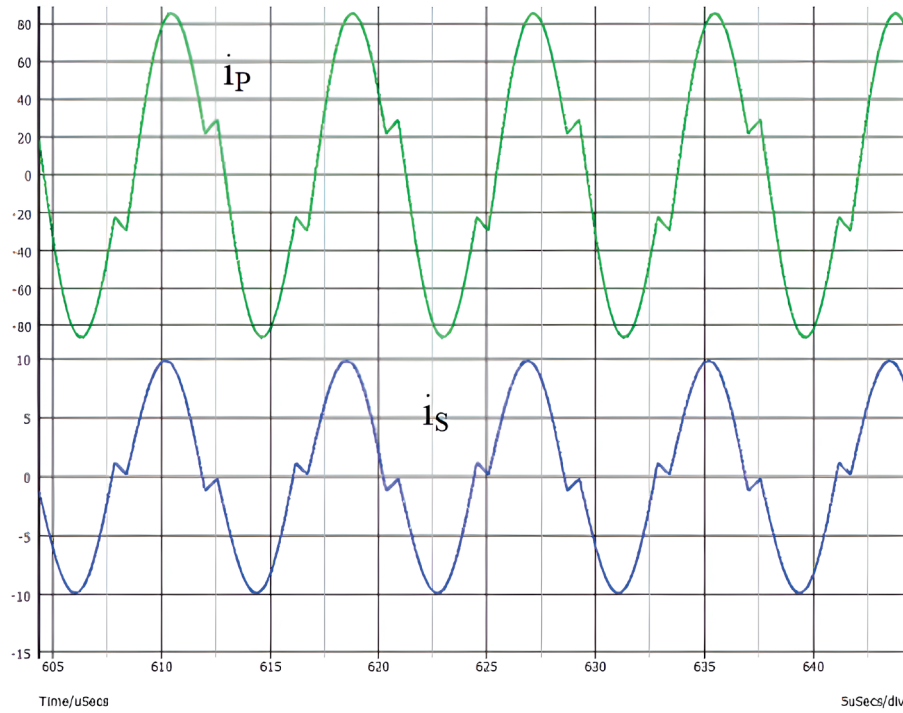


Figure 10 The CLLC converter BOOST mode

Table 3 Designed ACS prototype specification

Parameter	Value
Nominal power [kW]	2
Nominal input voltage [V]	230
Nominal interlink capacitor voltage [V]	415
Switching frequency BLTP-PFC [kHz]	70
Switching frequency CLLC [kHz]	140
Battery nominal voltage [V]	48
Battery capacity [Ah]	150

i_s (red) - battery charging current. Conversely, in Mode 2, the direction of energy flow is from the battery to the grid, which represents BOOST mode of converter. Figure 10 also shows the transformer primary current i_p (green) and the transformer secondary current i_s (blue) - battery discharging current (see Figure 4.)

From a control perspective, this condition in Mode 2 was simulated for the specific case where the converter is operating below the rated input voltage (below 48 V). In order for the control loop to provide the required power transfer at a lower input voltage, the switching frequency f_{sw} had to be reduced below the resonant frequency f_{res} of the resonant circuit and thus the magnetizing component of the current is significantly more visible.

4 Experimental verification

Table 3 shows the parameters of the designed ASC system prototype. As described above, the experimental

prototype of the ACS system consisted of a bidirectional BLTP-PFC and a bidirectional resonant CLLC DC/DC converter. A LiFePo4 battery LFP48150U5E was used as an energy storage. To verify the correct operation, both converters were first independently verified and tested in laboratory conditions.

4.1 The BLTP-PFC verification

The BLTP-PFC converter was tested in both operating modes. The first measurement, Mode 1 - rectifier mode, was carried out at a nominal output power of 2 kW. Figure 11 shows the waveforms of the input voltage, which is also the grid voltage, i.e., $v_{IN} = V_{GRID}$ (magenta) and input current i_{IN} (yellow). The input voltage and current are in phase, so the inverter draws the necessary power from the grid (active power). The waveform of the consumed current shows a low content of higher harmonic components and almost zero phase shift.

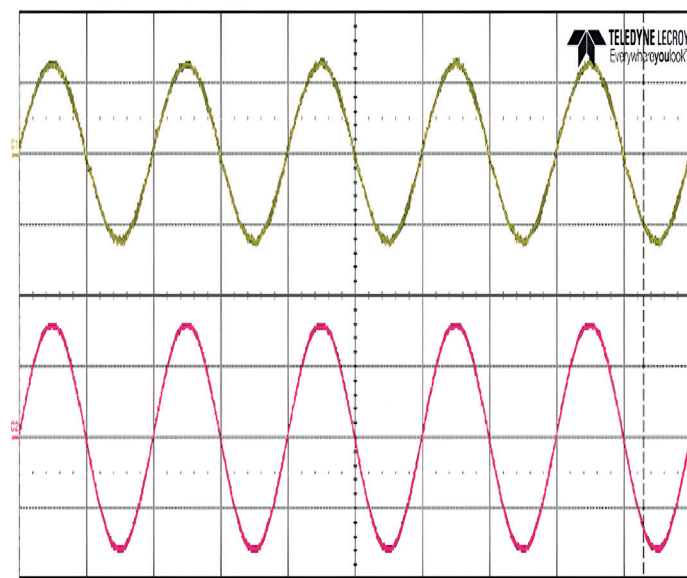


Figure 11 Measured i_{IN} and v_{IN} in rectifier mode, output power 2 kW

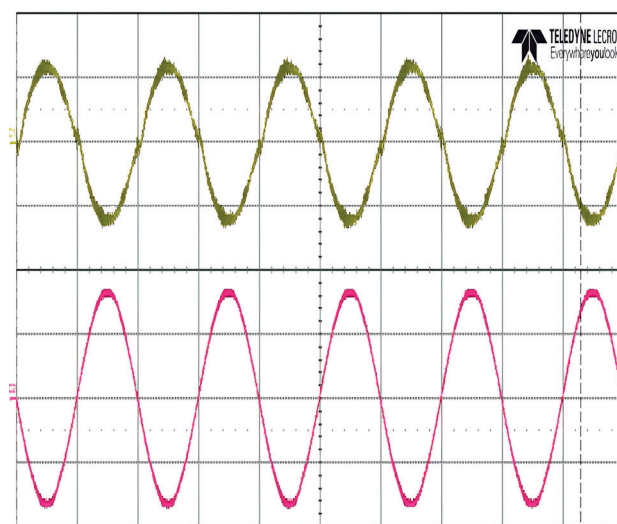


Figure 12 Measured i_{OUT} and v_{GRID} in inverter mode, output power 2 kW

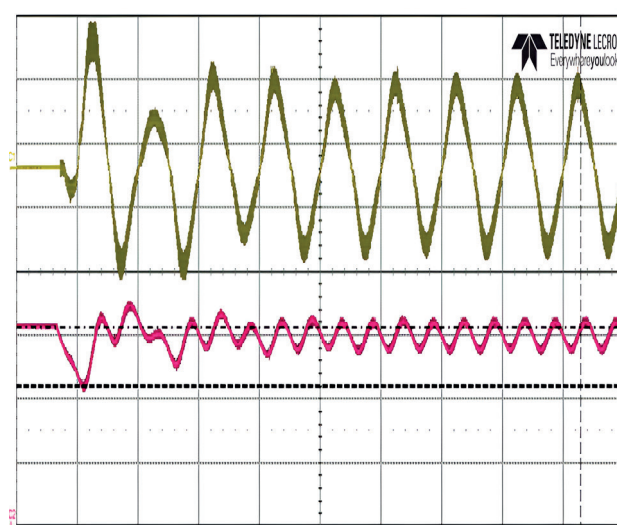


Figure 13 Measured dynamic response during a step change in load power

The second measurement, Mode 2 - inverter mode, was carried out similarly at a nominal power of 2 kW. Figure 12 shows the output voltage waveform, which in this case also represents the grid voltage $v_{OUT} = v_{GRID}$ (magenta) and the current supplied to the grid $i_{OUT} = i_{GRID}$ (yellow). The current supplied to the grid is in the opposite phase of the grid voltage so that the required power is provided to the grid (negative power). Again, the waveform of the consumed current shows a low content of higher harmonic components and almost 180° phase shift, which corresponds to the delivery of active power to the grid.

Within the BLTP-PFC operation, a mode based on synchronous switching of transistors has also been tested and is used. This mode replaces the classic diodes in the BLTP-PFC converter with actively controlled transistors (most often SiC MOSFETs or GaN HEMTs), which significantly reduces power losses and increases the overall efficiency of the device. During the conventional rectification, a high voltage drop occurs on the diodes, which generates significant heat at high currents. For this reason, it is more advantageous to switch on transistors with a significantly lower voltage drop and therefore lower losses.

The BLTP-PFC converter consists of two main branches (half-bridges): The High-Frequency Leg: Switches at a high frequency (tens to hundreds of kHz) and ensures the shaping of the current into a sinusoidal waveform. Synchronous switching here means that when the main transistor opens, the current flows through the parasitic diode of the opposite transistor. The control system immediately turns on this opposing transistor, redirecting the current through its low-resistance channel. The Low-Frequency Leg: Switches at the mains frequency (50 Hz) and serves to rectify the polarity (replaces the mains diode bridge). Controlled MOSFETs completely eliminate the losses of classic diodes here.

Main advantages: increased efficiency, bidirectional

energy flow (key for the operating modes used), synchronous switching allows a smooth transition from Mode 1 (rectifier - grid consumption) to Mode 2 (inverter - grid supply), better thermal management (less losses = less heat produced = smaller heat sinks = higher power density).

The proposed BLTP-PFC converter was also tested in dynamic mode, Figure 13, with a step change in load. During this measurement, the power changed from 0 to P_{MAX} (2 kW). In Figure 13, the current i_{IN} (yellow) can be seen, and the V_{DC} voltage (magenta) drops by only 50 V. This is because a fast V_{DC} regulator is used in the control. When using a standard (slow) V_{DC} regulator, the voltage drop was more than 120 V.

4.2 The CLLC verification

The CLLC converter was also tested in both operating modes - Mode 1 - BUCK and Mode 2 - BOOST. Both modes were tested at a nominal power of 2 kW.

In the first measurement, the direction of energy flow is to the battery, i.e., the converter operates in mode - BUCK. Figure 14. shows the primary current of the transformer i_p (yellow) and the secondary current i_s (green).

In the second measurement, the direction of current flow is reversed; i.e. the current flows from the battery and the converter operates in mode - BOOST, Figure 15. Again, the Figure shows the primary current of the transformer i_p (green) and the secondary current i_s (yellow).

4.3 Complete ACS system verification

Further experimental measurements were performed on the complete unit of the designed ACS system with parameters according to Table 3. During

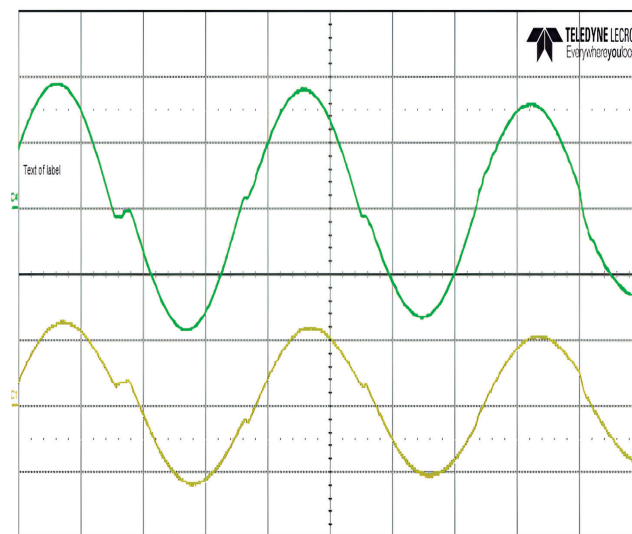


Figure 14 The CLLC converter in BUCK mode

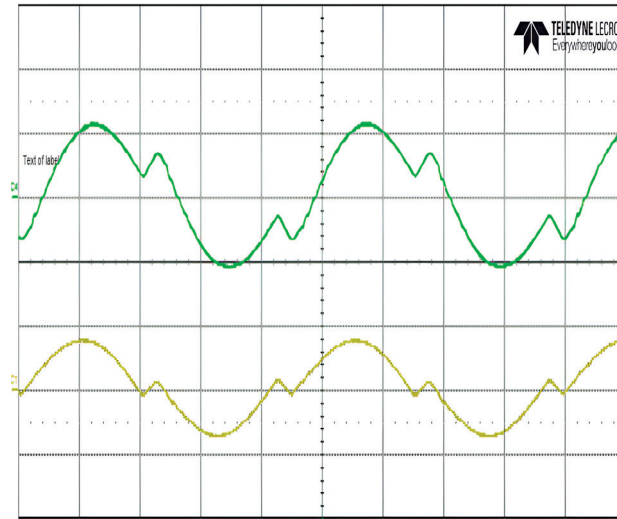


Figure 15 The CLLC converter in BOOST mode

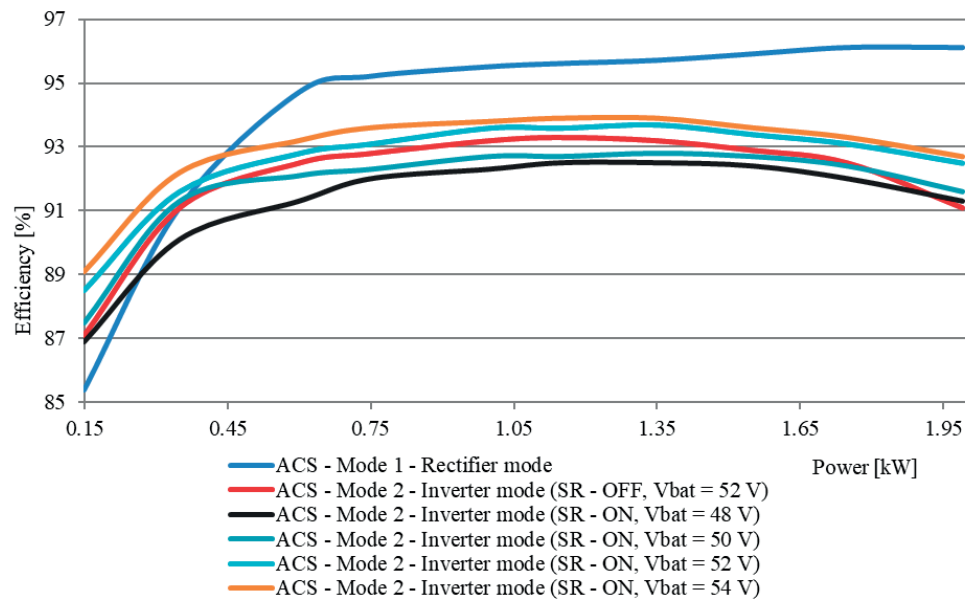


Figure 16 Efficiency waveforms of the complete ACS system

Table 4 Complete ACS system harmonic analysis.

Parameter	Value
Standard	EN 61000-3-2:2014
Frequency	50 [Hz]
Voltage	230.59 [V _{RMS}]
Current	9.892 [A _{RMS}]
Power Factor	1.000
Apparent power	2281.0 [VA]
Fundamental power component:	P1 = 2279.9 [W]
Fundamental harmonic factor:	cos φ1 = 1,000
Total voltage harmonic distortion	0.90 %
Total current harmonic distortion	1.43 %
Total harmonic voltage	0.047 [V]
Total harmonic currents	0.142 [A]
Partial harmonic voltage	0.014 [V]
Partial harmonic currents	0.079 [A]
Weighted voltage harmonic distortion	0.04 %
Weighted current harmonic distortion	5.66 %

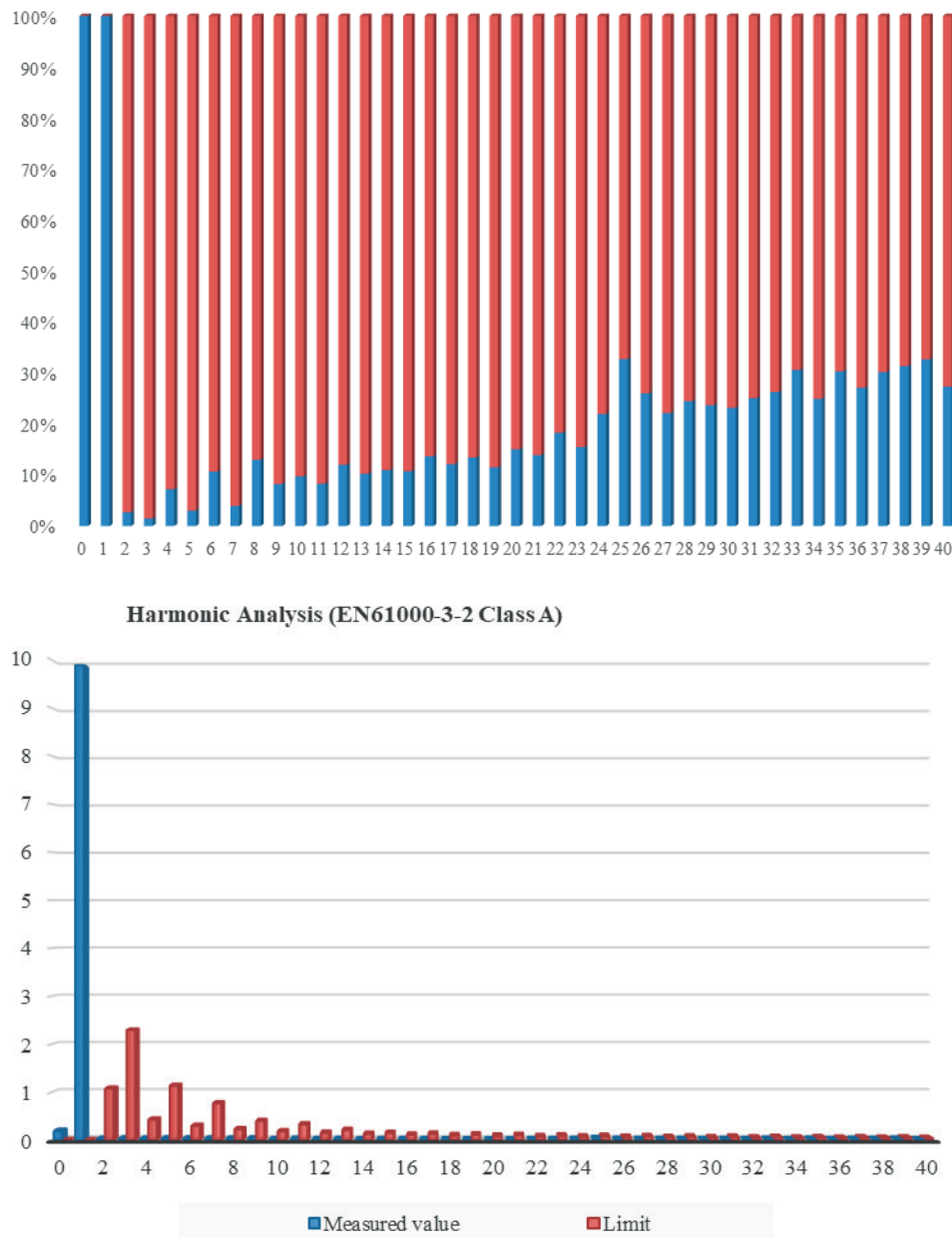


Figure 17 Complete ACS system current harmonic analysis

the measurements at the maximum achieved power $P_{\text{MAX}} = 2180 \text{ W}$ (apparent power $S = 2181 \text{ VA}$), the values $\text{PF} = 1$, $\cos \varphi = 1$, $\text{THD}_i = 1.43\%$ and $\text{THD}_u = 0.90\%$ were determined.

Figure 16 shows the results of measurements of efficiency of the entire ACS system in different operating modes. ACS operates in rectifier mode, in inverter mode - but without using the synchronous rectifier mode at a battery module voltage of $U_{\text{BAT}} = 52 \text{ V}$ and finally in the inverter mode by using the synchronous rectifier mode with the following battery module voltage values $U_{\text{BAT}} = 48 \text{ V}$, 50 V , 52 V and 54 V .

The ACS system was also subjected to harmonic analysis tests in a certified laboratory based on the EN 61000-3-2:2014 standard. The EMC test results

are shown in Table 4. A graphical interpretation of the harmonic analysis results is shown in Figure 17, where the blue columns represent the measured component and the red columns represent the limit of a given harmonic component for a given order of the harmonic component.

Final result of the harmonic analysis tests: The tested inverter achieved very low harmonic current distortion ($\text{THD}_i = 1.43\%$) at a power of approximately 2.28 kW and meets the requirements of the EN 61000-3-2:2014 standard, class A, with a significant margin against all harmonic current limits. The power factor reached a value of 1.000, which indicates practically ideal grid consumption.

4.4 Relevance of ACS for transport electrification

The proposed ACS architecture is directly applicable to transportation electrification systems, especially in bidirectional electric vehicle (EV) charging infrastructure. Modern charging stations require high efficiency, low harmonic distortion, and bidirectional power transfer capability to support Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) services [38-40].

The selected combination of BLTP-PFC and CLLLC converter provides several advantages for transport applications:

- unity power factor operation,
- low current harmonic distortion,
- galvanic isolation between the battery and a grid,
- bidirectional energy transfer,
- compatibility with second-life EV battery systems.

These features make the proposed ACS concept suitable for implementation in smart charging stations, electric bus depots, fleet charging hubs, railway auxiliary energy systems, and future smart transportation infrastructure.

5 Conclusion

In this paper are presented the design, simulation verification, and experimental validation of an Active Compensation System (ACS) prototype intended for bidirectional energy exchange between the electrical grid and battery storage. Based on a comparison of available converter topologies, the combination of a bridgeless totem-pole PFC (BLTP-PFC) converter and a bidirectional CLLLC resonant DC/DC converter was selected and implemented in the experimental prototype.

Simulation results confirmed the correct operation of both converter stages in accumulation and generative modes. The simulated waveforms demonstrated stable power transfer, proper current shaping, and expected converter behavior in both directions of energy flow. Experimental measurements showed a very good agreement with simulation predictions. The measured current and voltage waveforms corresponded closely to the simulated results, confirming the validity of the developed models and the selected control strategies.

The experimental verification demonstrated that the proposed ACS topology is capable of achieving high power quality and satisfactory efficiency. The BLTP-PFC converter maintained nearly unity power factor and

low harmonic distortion in both rectifier and inverter operating modes. The complete ACS system achieved a maximum measured power of approximately 2.28 [kW] while maintaining $PF = 1$, $\cos \varphi = 1$, $THD_i = 1.43 \%$, and $THD_u = 0.90 \%$. Harmonic analysis performed according to EN 61000-3-2:2014 confirmed full compliance with the standard and significant reserve against all prescribed harmonic limits.

Efficiency measurements revealed that the highest efficiency was achieved in rectifier mode, reaching approximately 96 %. In inverter operation, the efficiency ranged between 91 % and 94 % depending on battery voltage and operating conditions. The results further confirmed the positive impact of synchronous rectification, which improved converter efficiency, especially at higher battery voltages. The best measured efficiency in inverter mode reached approximately 93.9 % at a battery voltage of 54 [V].

Overall, the obtained simulation and experimental results confirm that the proposed ACS topology represents a promising solution for future smart-grid applications requiring bidirectional power flow, energy storage integration, and active power quality management. Besides the stationary battery energy storage applications, the proposed ACS architecture can also be directly utilized in bidirectional EV charging stations, V2G infrastructures, electric public transport charging hubs, and transport-oriented microgrids. The obtained results confirm that the selected topology provides the power quality and efficiency required for the future transportation electrification systems.

Acknowledgements

This research was funded by APVV-22-0330 "Research of a system for active and optimal management of electrical energy using battery storage system" and Vega 1/0314/24 "Research of a system for active management of electrical energy using battery storage system."

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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