SmartGYsum Research Outcomes

ESR05: Mohammadreza Azizi

Energy Router for Hybrid Microgrids for Efficient and Robust Energy and Power Management

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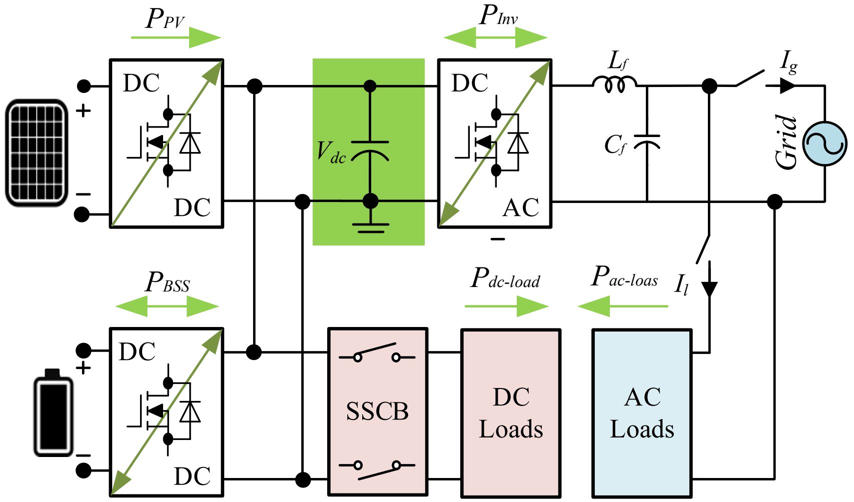
SmartGY
SUM

- This research objective includes the following tasks:

- 1. Design the 5 kW multiport converter which includes single-phase ac input, single-phase ac output, input for solar panels, input for battery storage and isolated output dc grid terminals.
- 2.Study of the reliability and protection enhancement of the proposed solution.
- 3. Improve the control system for dynamic conditions and enhance the reliability level of the multiport energy router.



How to reach these objectives:

1. Review & Analysis:

- Evaluated existing ER structures, performance, and safety.
- Compared isolated dc-dc converters for low-power ERs.
- Studied NZEB connection scenarios to the ac grid.

2. Modeling & Simulation

- Developed PLECS simulation models (open-loop, closed-loop, multi-level control).
- Modeled common-ground ER structures for improved safety.
- **Simulated dc leakage** in isolated ER-ac connections.

3. Control Development

- Applied modulation techniques for inverter operation (boost, buck, buck-boost).
- **Designed and tuned FBC-based control** for fast and robust response.

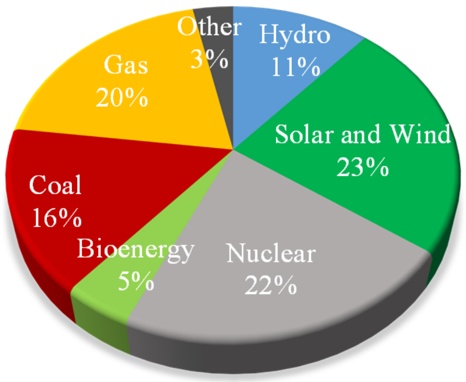
4. Experimental Work

- Assembled experimental setup for ER system.
- Tested dc-mode, grid-forming, grid-following, and **dynamic load change.**

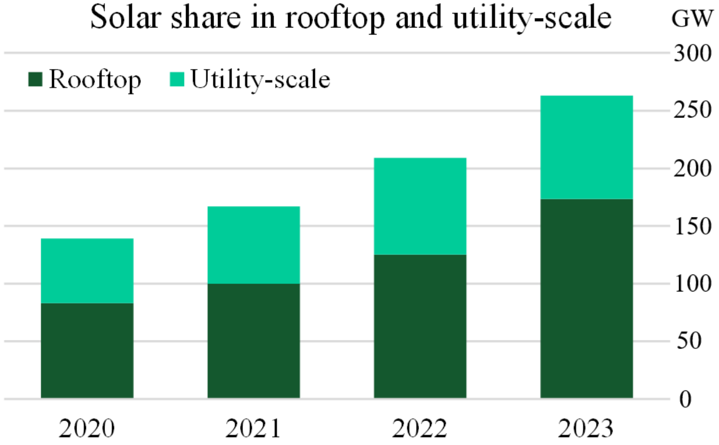
Introduction

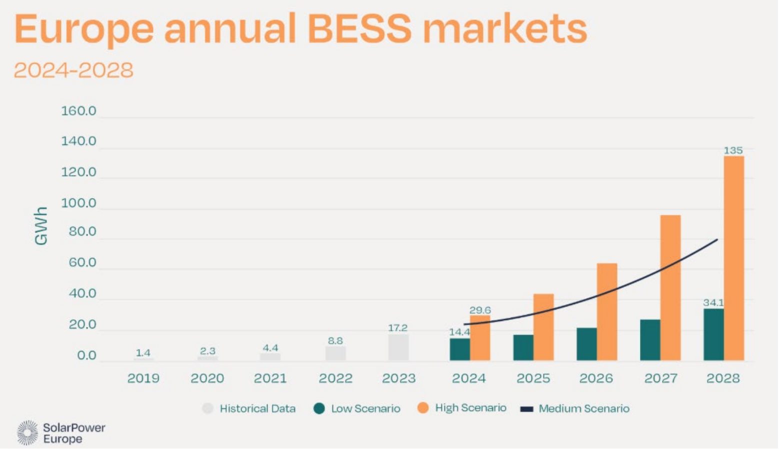
- Solar and battery storage systems are increasing, and the NZEB concept is developing.

Energy production share in EU



Solar share in rooftop and utility-scale





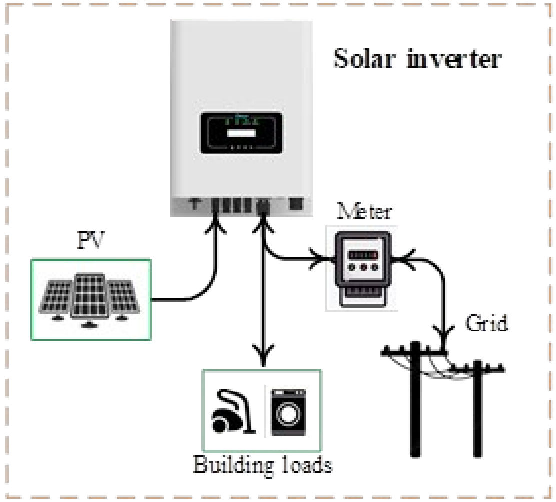
Residential and industrial units equipped with PV and storage systems help in improving power generation, ensuring a continuous supply, and offering economic benefits, supporting NZEB/ZEB concepts.

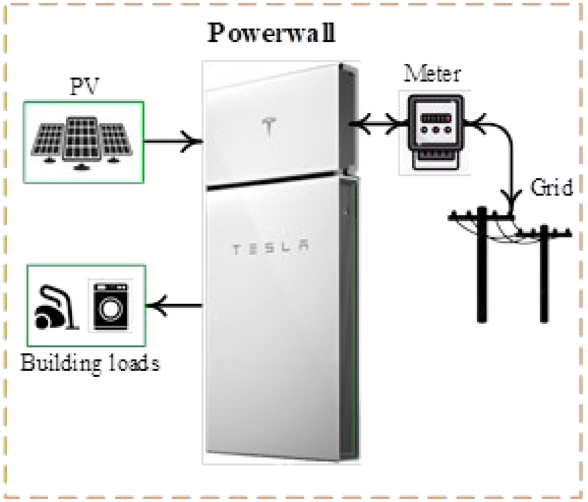
Due to the dc nature of PV and BSS, moving toward **dc and hybrid systems** leads to **higher efficiency**.

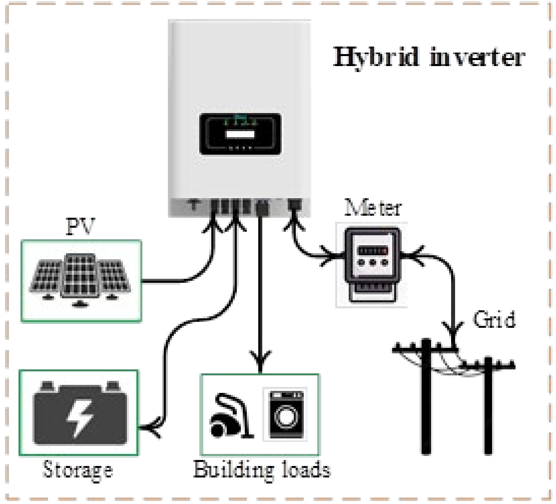
However, due to the dominance of ac system, future distribution systems will face a **hybrid** structure.

Therefore, the development of interface converters and the move towards a hybrid system are crucial.

Latest technology for residential buildings equipped with PV and storage systems:







- All these cases are designed for ac buildings.
- Solar inverter is suitable for a limit budget.
- Powerwalls have a fixed storage capacity.
- Powerwall is user-friendly and can be easily controlled and monitored.

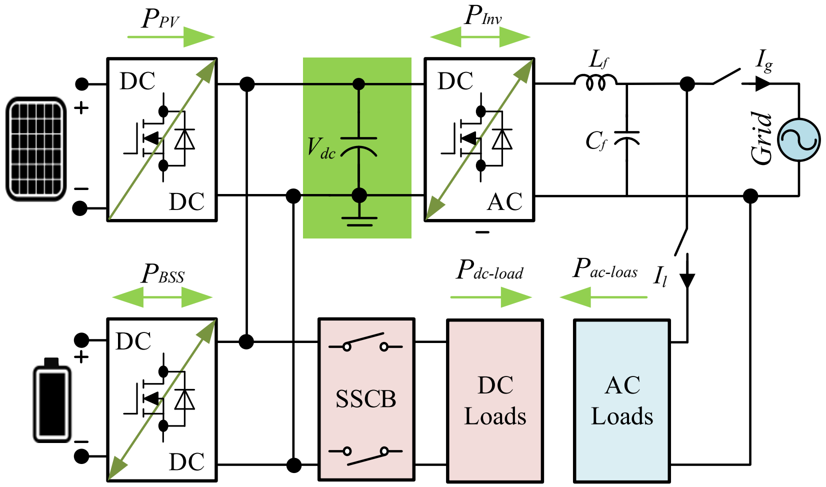
What are the problems?

1. Available devices are **designed for ac buildings**.
2. Even in isolated structures, **issues related to leakage current and grounding still pose challenges**
3. Struggle to **supply dc loads** while **ensuring safety at both sides of the dc–ac interface**.
4. **Lack of sufficient standards** and guidelines on the dc side regarding **protection, grounding and leakage currents.**
5. Creating 3-ph **grid imbalance for existing single-phase structures.**
6. Conventional interlink systems **face challenges** in handling multiple sources, loads, and **dynamic conditions**.
7. Previous structures **lack effective and flexible energy management**.

M. Azizi, O. Husev, R. Mbayed, E. Monmasson, J. Martins and O. Veligorskyi, "**Energy Router: A Sustainable Solution for Future Residential Buildings**," in IEEE Power Electronics Magazine, vol. 12, no. 1, pp. 75-86, March 2025.

Therefore, my objective was defined as:

- Develop an Energy Router (ER) for hybrid nanogrids that **overcomes the limitations of previous structres**

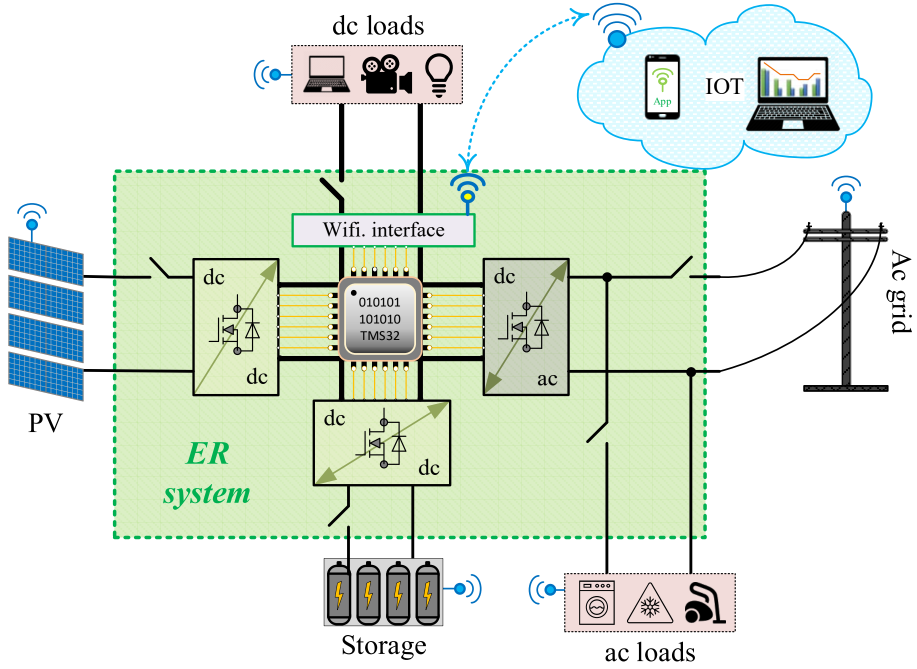


- ➢ **Supplies dc loads efficiently**
- ➢ **Ensures the safety** of personnel and equipment on both ac and dc sides
- ➢ **Single-phase but with the ability to interact with all three phases** of the grid
- ➢ Provides **robust control under dynamic conditions**
- ➢ Capable of implementing an optimized and reliable Energy Management System (EMS)

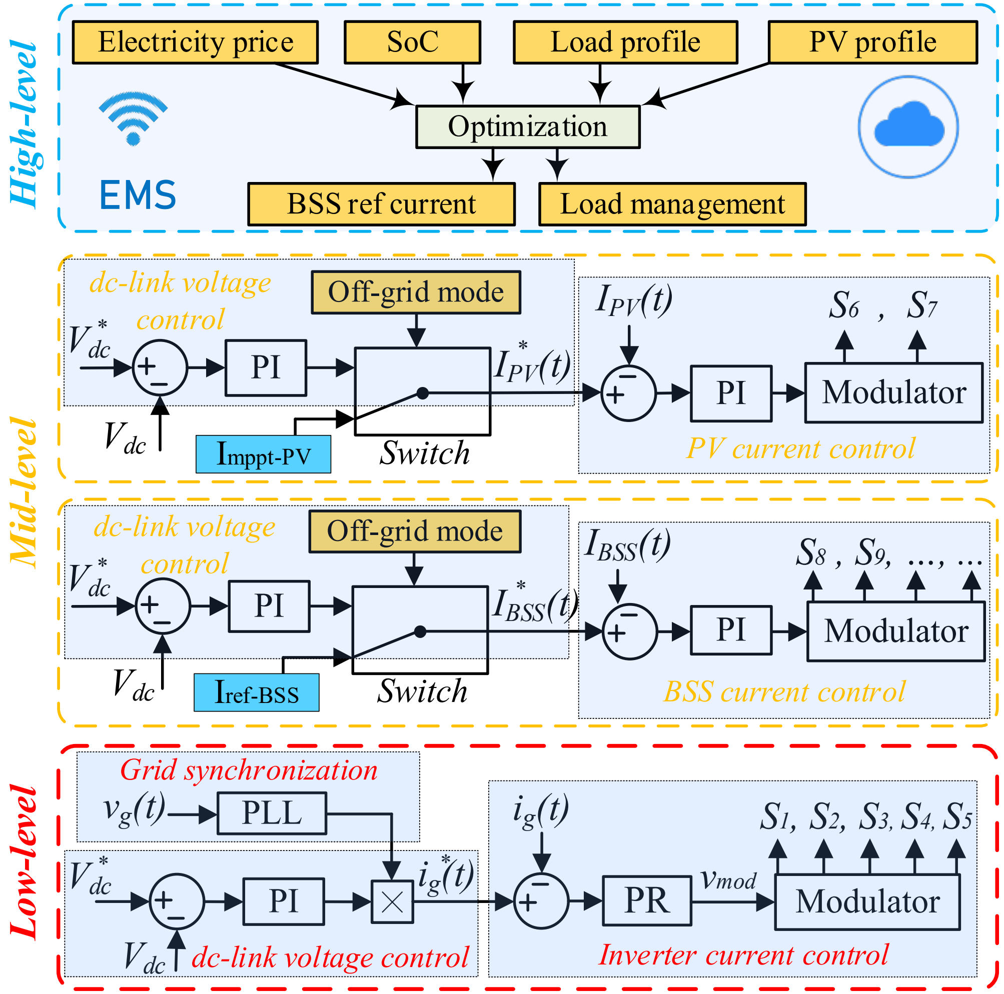
Ultimate Goal:
Higher reliability, efficiency, and protection

What is an Energy router (ER)?

What is an ER?

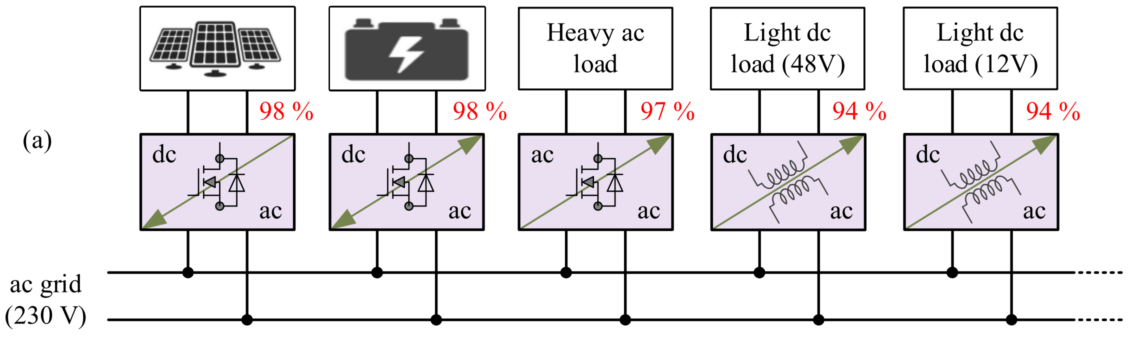


Control levels in ER

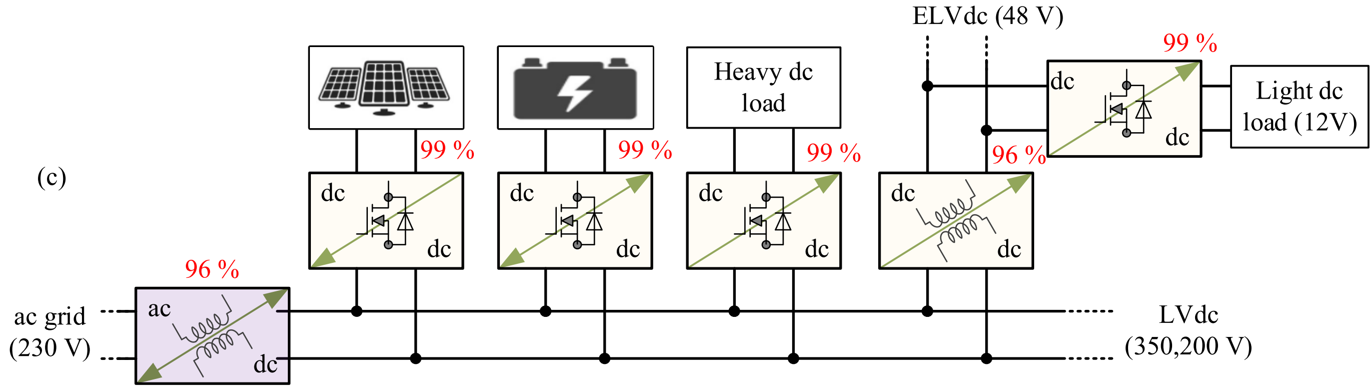


- **ER** is an **advanced power electronic interface.**
- **Converts power** from different parts and **manages energy flow** among sources, storage, and loads.
- Compared to PV/Hybrid inverters, it goes beyond conversion; **enables coordination and optimization**.
- Acts as a **central hub for intelligent**, **efficient energy distribution** in modern systems.

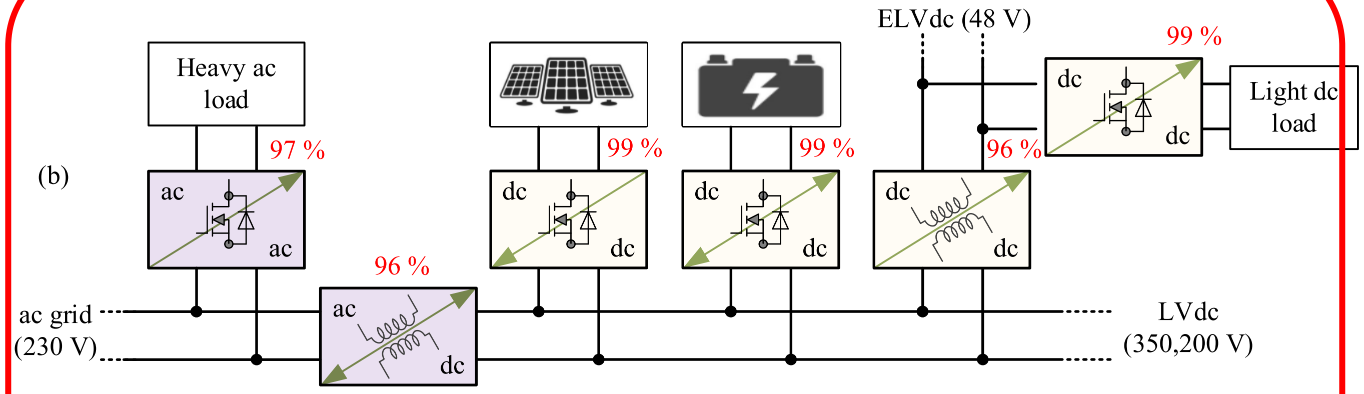
How to integrate dc system in ER



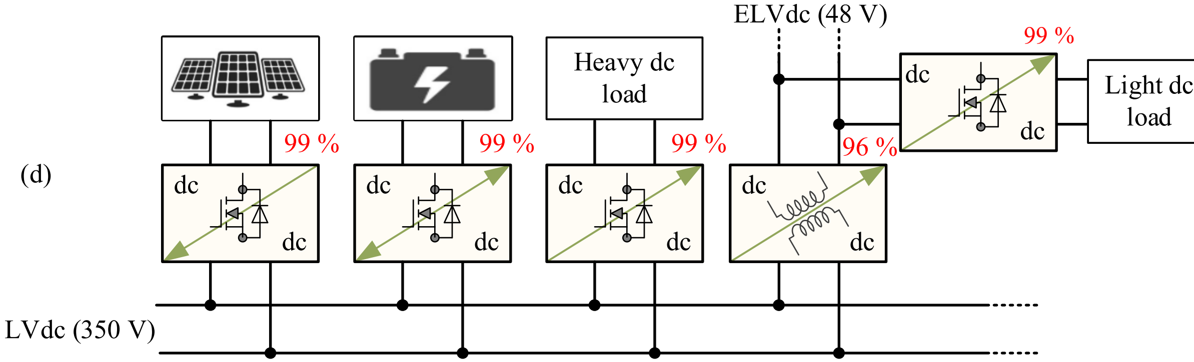
Classical non-effective and non-efficient system (ac)



“Pure” dc system connected to ac grid (dc/ac)



Hybrid dc/ac system

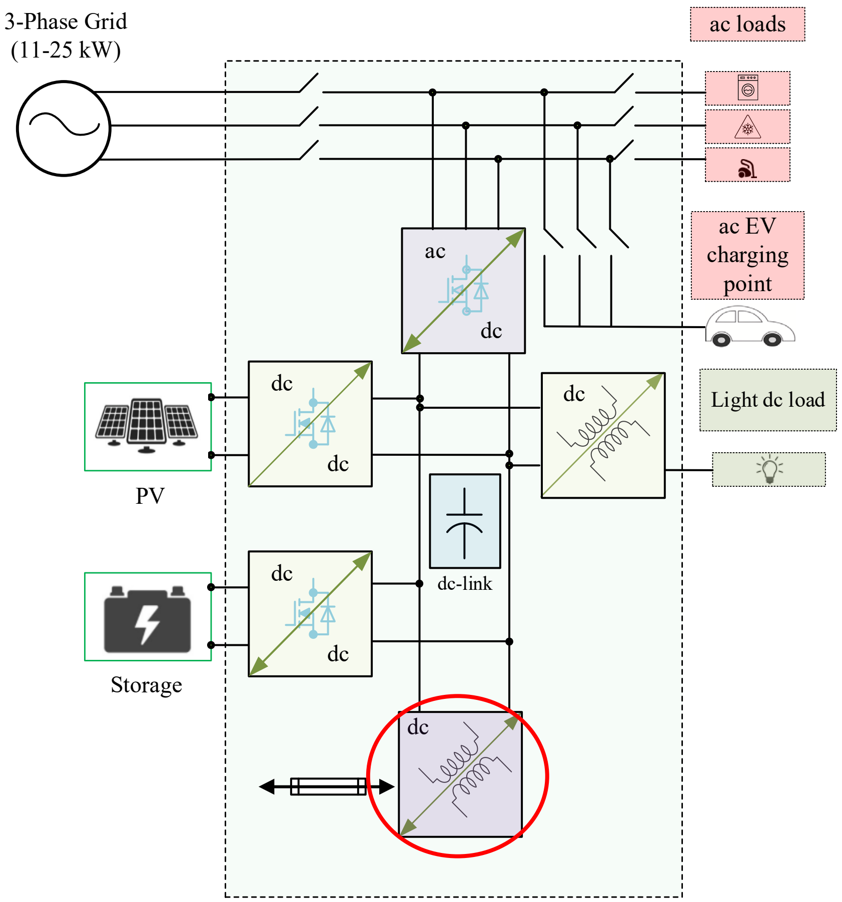


Pure dc system connected to dc grid (dc)

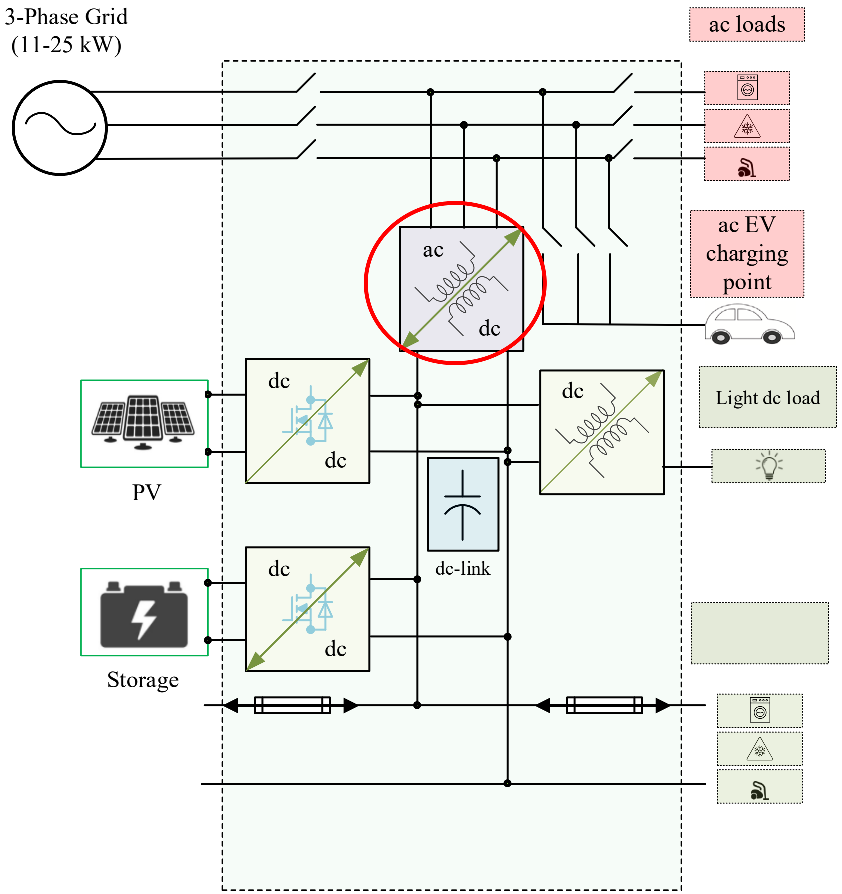
M. Azizi, O. Husev, R. Mbayed, E. Monmasson, J. Martins and O. Veligorskyi, "**Energy Router: A Sustainable Solution for Future Residential Buildings**," in IEEE Power Electronics Magazine, vol. 12, no. 1, pp. 75-86, March 2025.

Different configuration for the ER system with dc system

Based on the standard, isolation between ac grid and the dc microgrid is mandatory.



ER structure in case of **ac domination**



ER structure in case of **dc domination**

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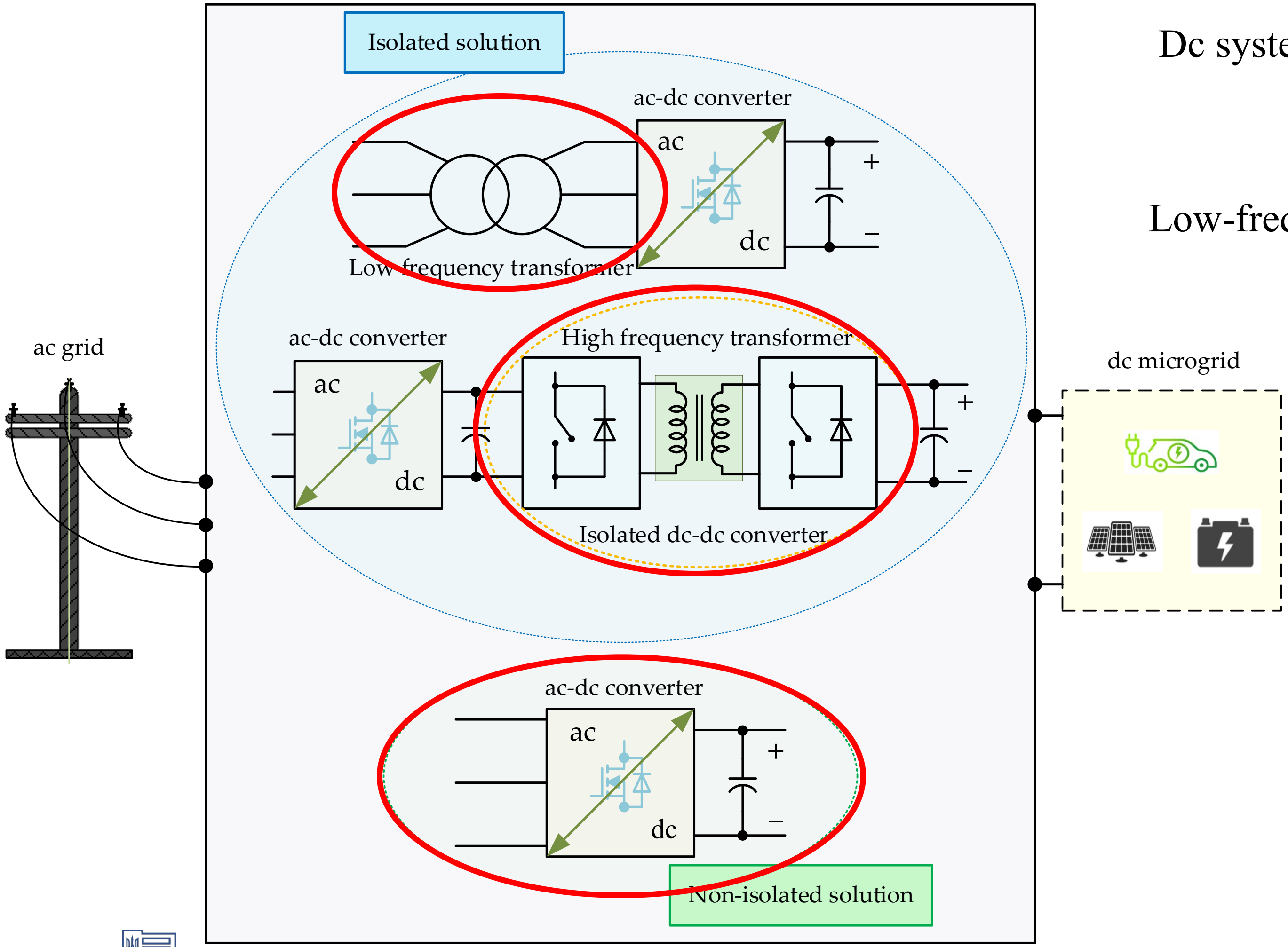
Different solutions for connecting a dc microgrid to an ac grid:



Dc system can be connected to ac system through an **isolated** or a **non-isolated** solution

Low-frequency isolation is a reliable option, but at a high cost, weight and volume.

Although high-frequency isolation is expanding for many applications,

Non-isolation method is still an option

When isolation is not necessary.

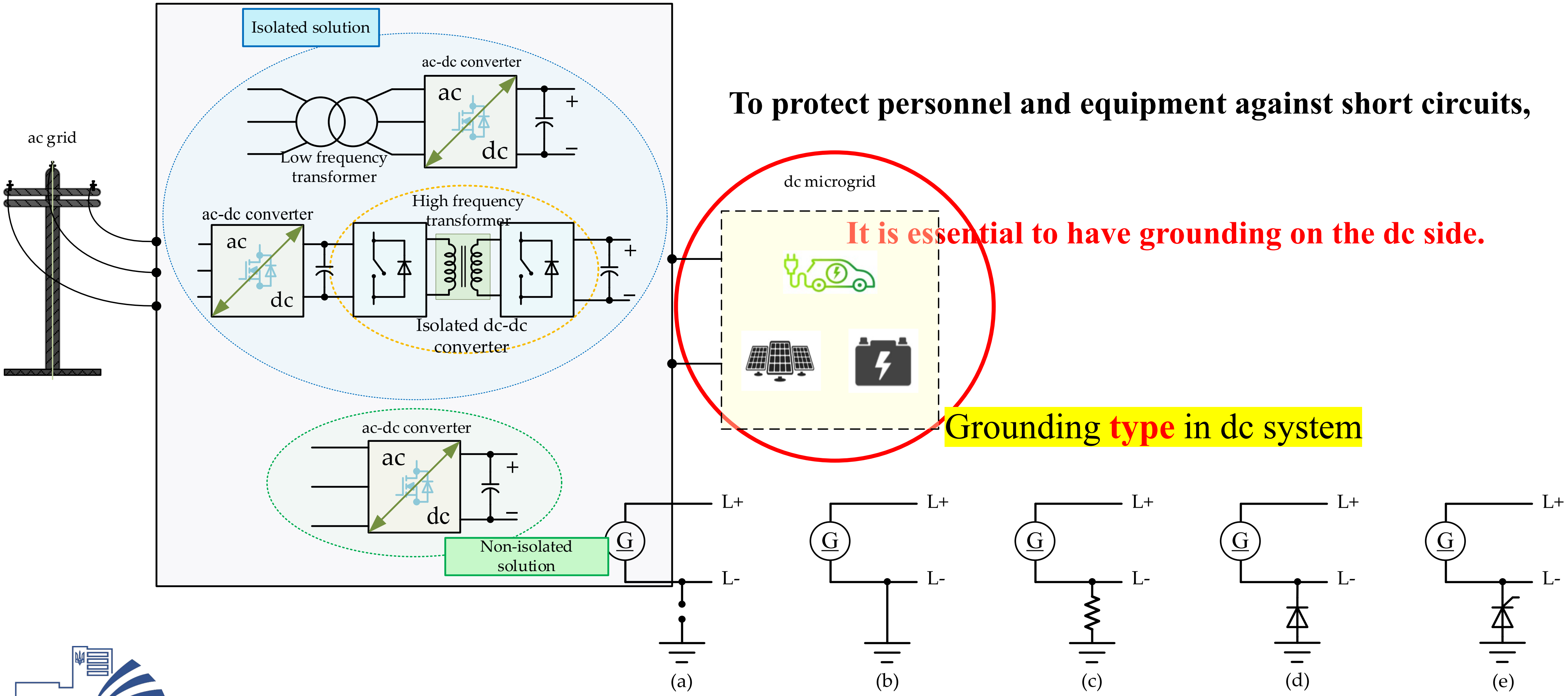
Grounding and safety in dc nano/microgrid

Having a dc micro/nano grid including PV, BSS, and various dc loads.

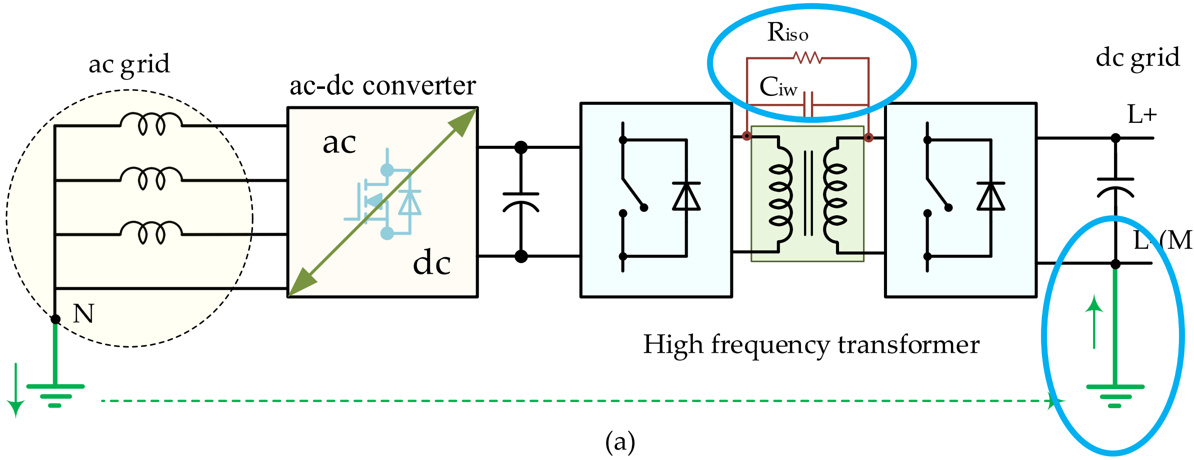
To protect personnel and equipment against short circuits,

It is essential to have grounding on the dc side.

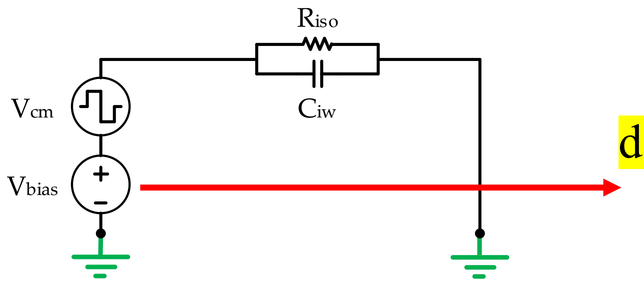
Grounding **type** in dc system



In isolated cases, dc leakage current can be created based on grounding and insulation resistance

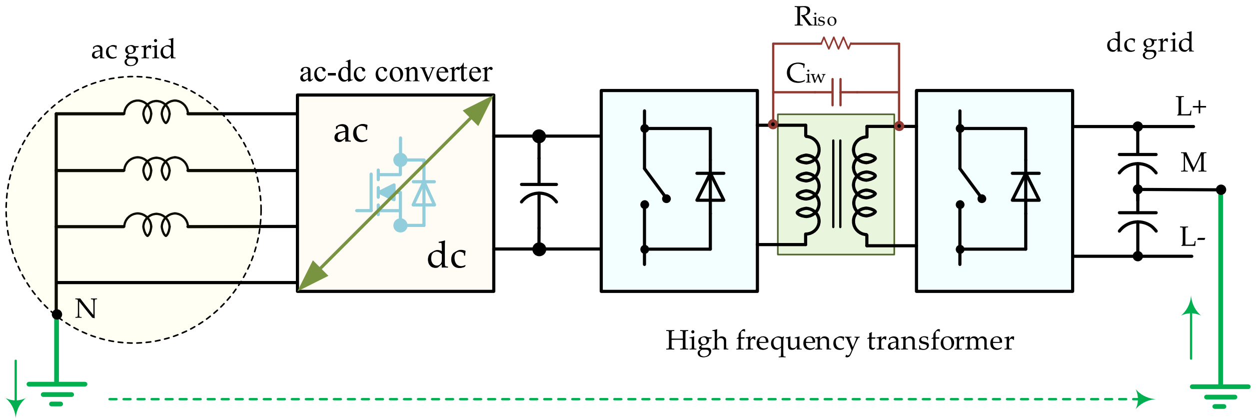


(a)

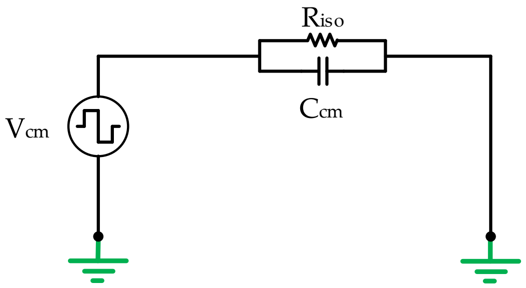


(b)

dc bias create dc leakge



(a)



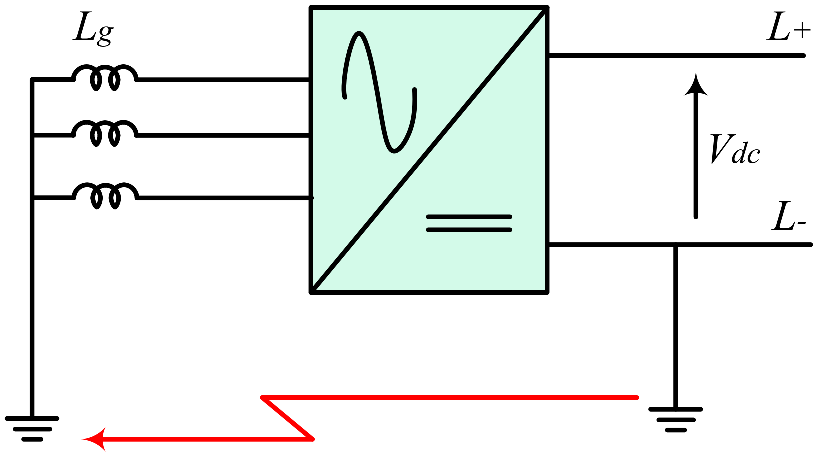
(b)

In a high-frequency isolated case, the middle point should be grounded to eliminate dc bias.

M. Azizi, O. Husev, O. Veligorskyi, M. Turzvński and R. Strzelecki, "**Dc Leakage Current in Isolated Grid-Connected dc Nanogrid - Origins and Elimination Methods**," 2024 IEEE 18th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Gdynia, Poland, 2024, pp. 1-6.

Non-isolated cases

In a non-isolated case, due to the direct current path, both ac side and dc side can not have grounding



Therefore

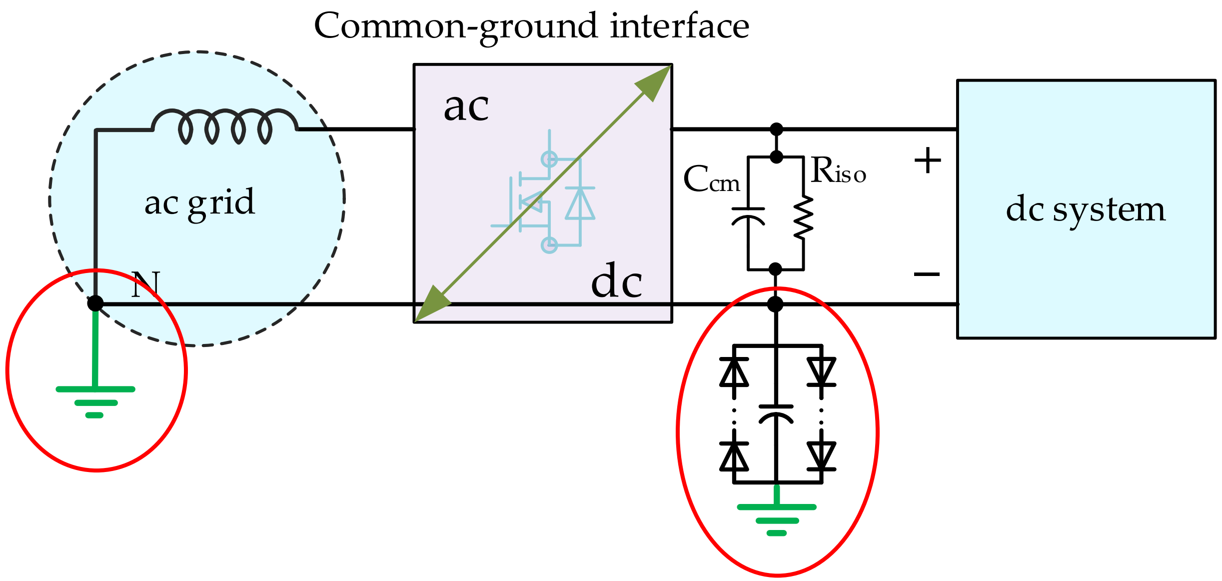
Different solutions for grounding at the connection point.

ac GND / dc GND	TN (any kind)	TT	IT
Negative point grounded	Forbidden	Forbidden	Possible
Middle point grounded	Forbidden	Forbidden	Possible
Ungrounded	Possible	Possible	Possible

What is the solution?

Common-ground inverters

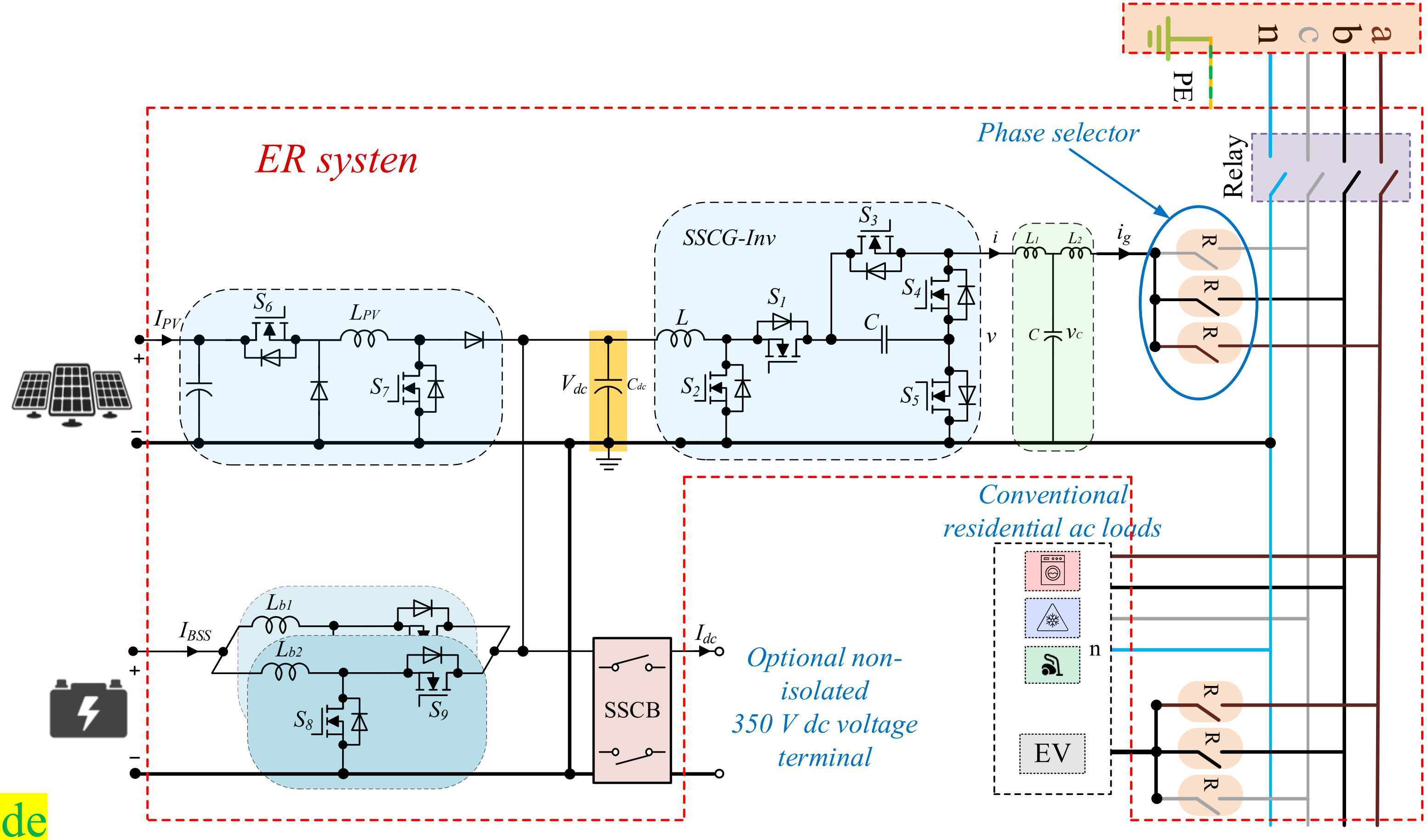
- ✓ No need for isolation
- ✓ Eliminating the leakage current path
- ✓ Providing grounding and safety on both sides
- ✓ No path for dc leakage current



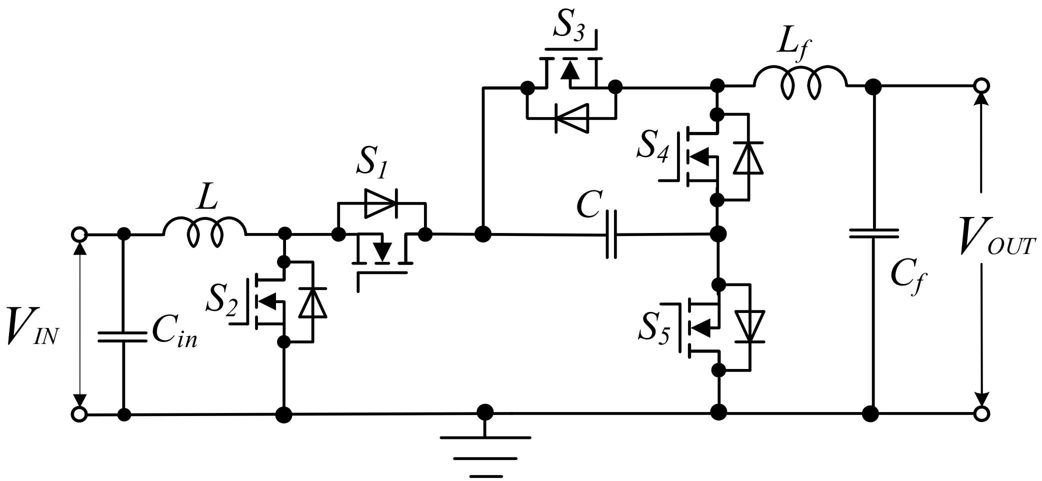
Azizi, M.; Husev, O.; Veligorskyi, O.; Rahimpour, S.; Roncero-Clemente, C. **Grounding and Isolation Requirements in DC Microgrids: Overview and Critical Analysis**. ***Energies*** **2023**, *16*, 7747. https://doi.org/10.3390/en16237747

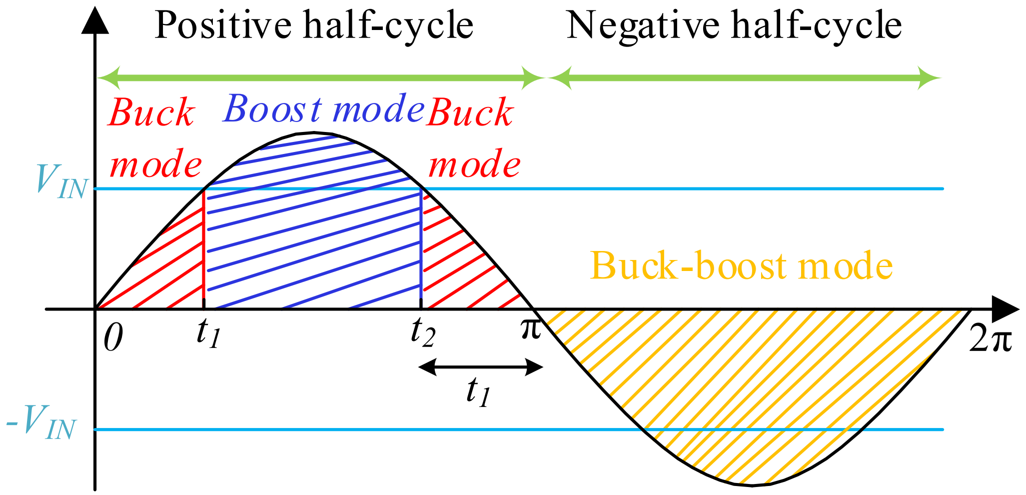
Proposed ER structure

- ✓ Single-cell three-phase topology
- ✓ Common-ground structure
- ✓ Single-stage inverter
- ✓ Supplying dc and ac loads
- ✓ Solid-state circuit breaker for dc side



Inverter modulation strategy

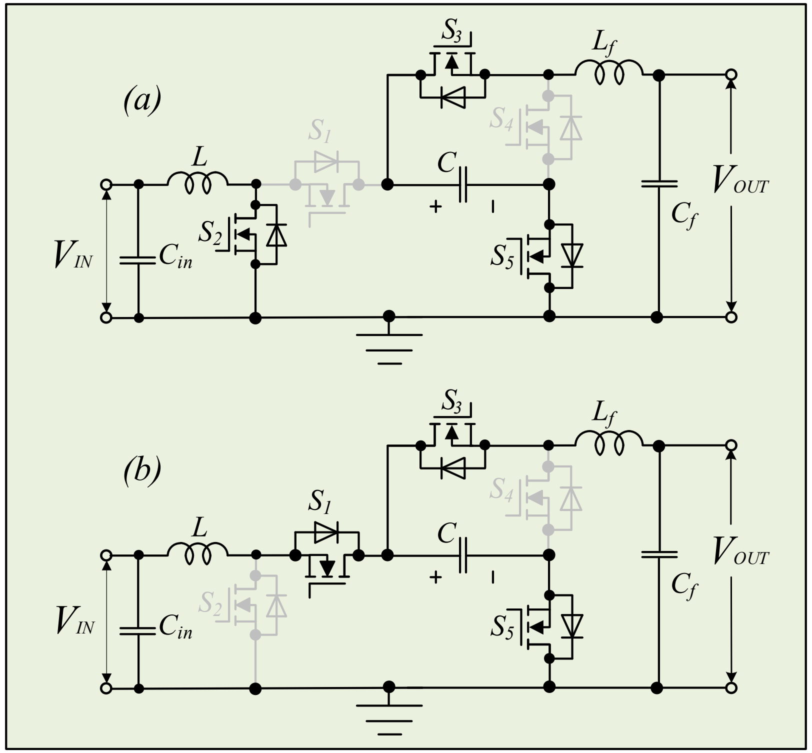




- Common-ground single-stage inverter: five switches, one inductor, and one capacitor.
- Works in three modes: buck and boost (positive half-wave), buck-boost (negative).

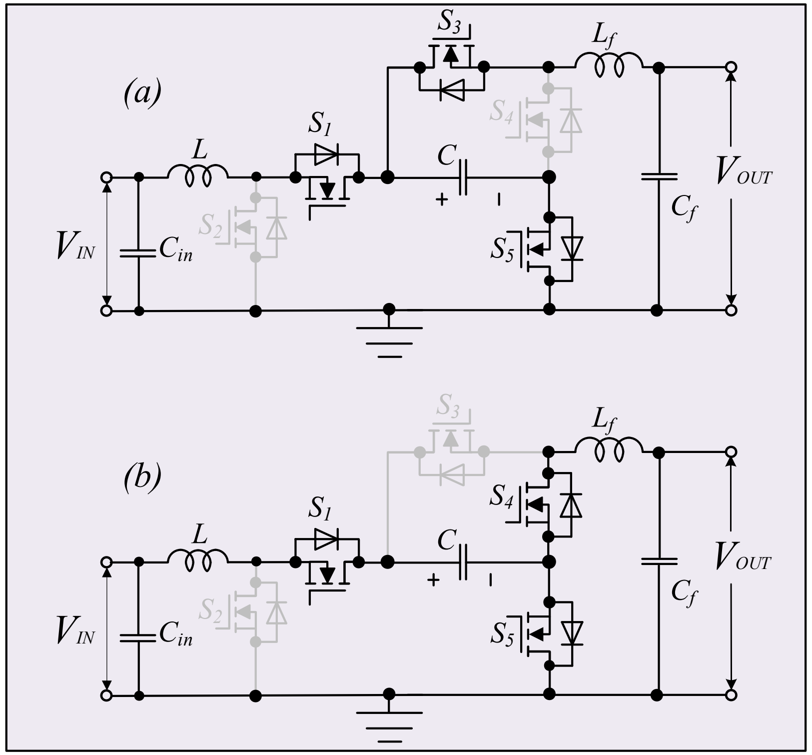
S. S. Lee, C. Shen Lim, Y. P. Siwakoti and K. -B. Lee, "Single-Stage Common-Ground Boost Inverter (S2CGBI) for Solar Photovoltaic Systems," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 4229-4233.

Different operation modes in the common-ground inverter



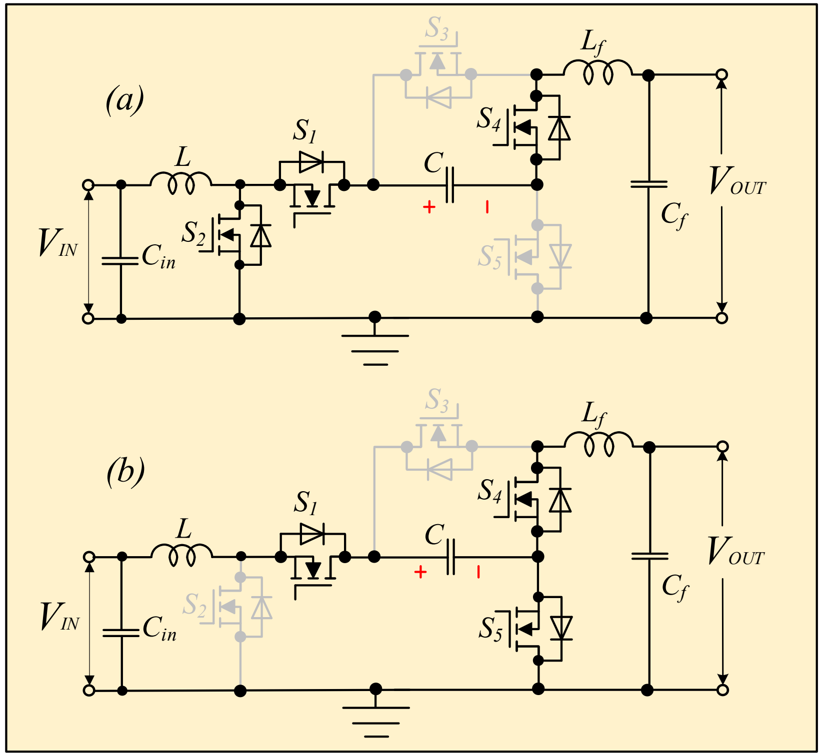
Boost mode

S1 and S2 work in complementary mode



Buck mode

S3 and S4 work in complementary mode



Buck-boost mode

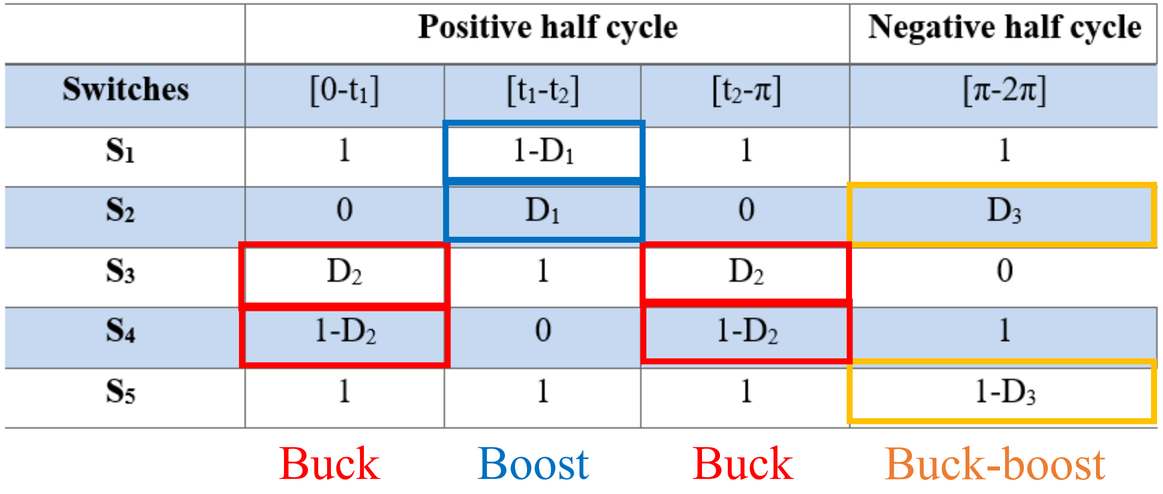
S2 and S5 work in complementary mode

Different operation modes in the common-ground inverter

- In each mode, two switches work in a complementary manner.

- In boost and buck-boost mode, a higher duty cycle increases voltage stress on the switches.

Inverter switching pattern.

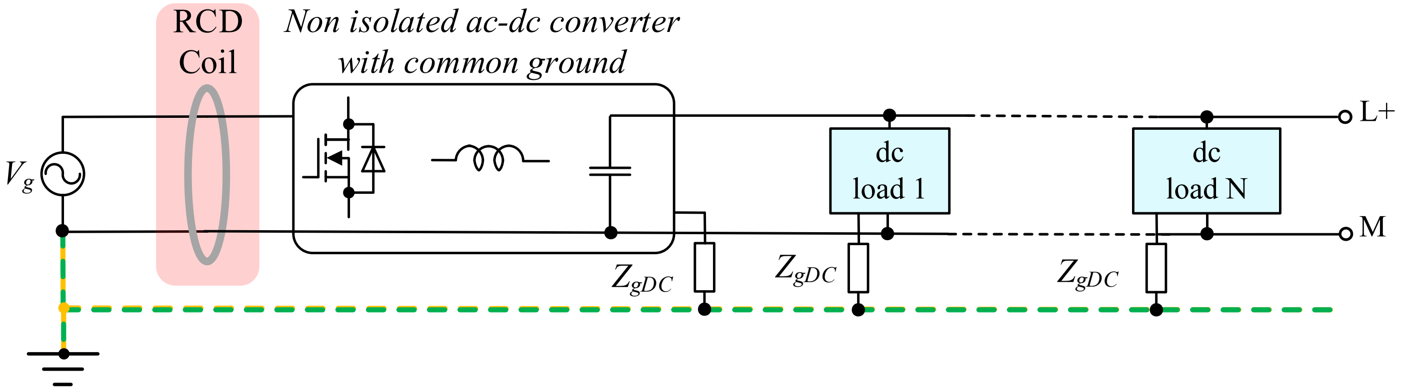


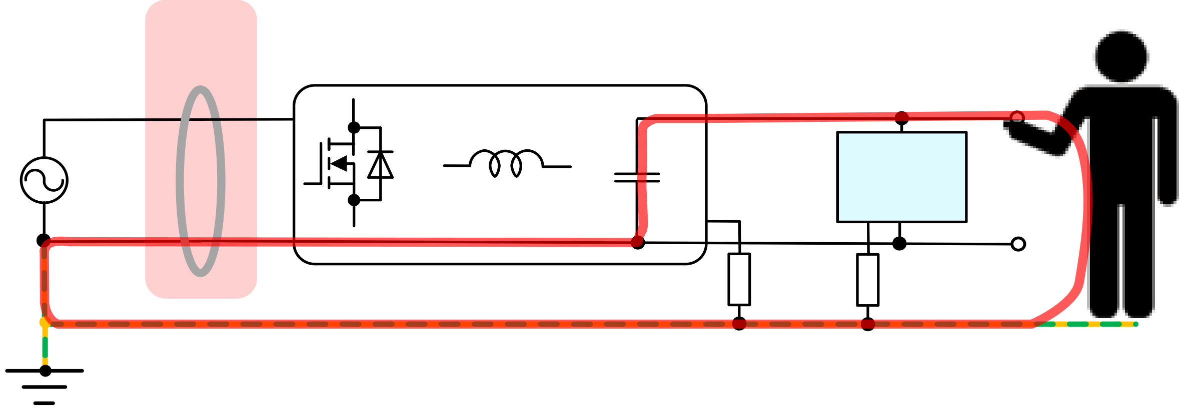
	Positive half cycle			Negative half cycle
Switches	$[0-t_1]$	$[t_1-t_2]$	$[t_2-\pi]$	$[\pi-2\pi]$
S_1	1	$1-D_1$	1	1
S_2	0	D_1	0	D_3
S_3	D_2	1	D_2	0
S_4	$1-D_2$	0	$1-D_2$	1
S_5	1	1	1	$1-D_3$
	Buck	Boost	Buck	Buck-boost

Inverter voltage stress.

Mode	S_1	S_2	S_3	S_4	S_5	**Capacitor**
Buck	0	V_{IN}	V_{IN}	V_{IN}	0	V_{IN}
Boost	$V_{IN}/(1-D_1)$	$V_{IN}/(1-D_1)$	0	$V_{IN}/(1-D_1)$	0	$V_{IN}/(1-D_1)$
Buck-boost	0	$V_{IN}/(1-D_3)$	$V_{IN}/(1-D_3)$	0	$V_{IN}/(1-D_3)$	$V_{IN}/(1-D_3)$

Safety and protection





In case **a person touches the hot line** (L+), the **residual current will pass through the capacitors** in the inverter structure and the neutral wire of ac side.

Therefore, the **RCD will trip** and disconnect the grid.

Flatness-based control (FBC) theory to improve control behavior

Introduced by M. Fliess as a **fast and reliable control method for nonlinear systems**.

Uses algebraic relations instead of solving optimization problems → lower computational burden than MPC.

In the proposed Energy Router, FBC regulates dc-link voltage and grid-side current using a dual-loop cascade structure.

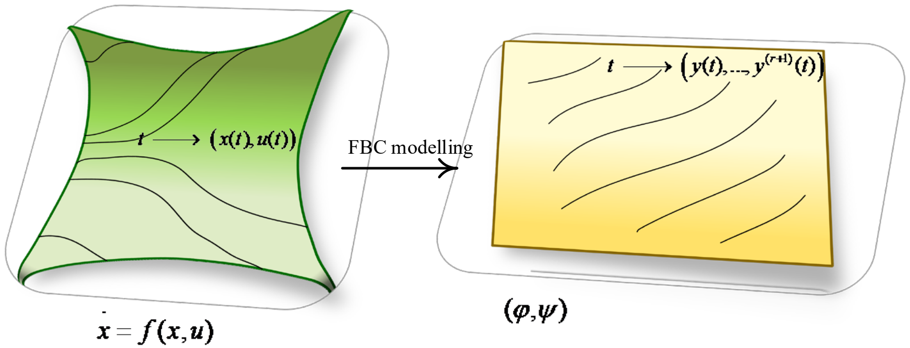
Mathematical definition of FBC

If the system $\dot{x} = f(x,u)$ has a state $x \in R^n$, and an input $u \in R^m$, then the system is differentially flat if an output $y \in R^m$, can be found in the form:

$$y = \phi\left(x, u, \dot{u}, \dots, u^{(l)}\right), \tag{1}$$

When, $$x = \varphi\left(y, \dot{y}, \dots, y^{(r)}\right), \tag{2}$$

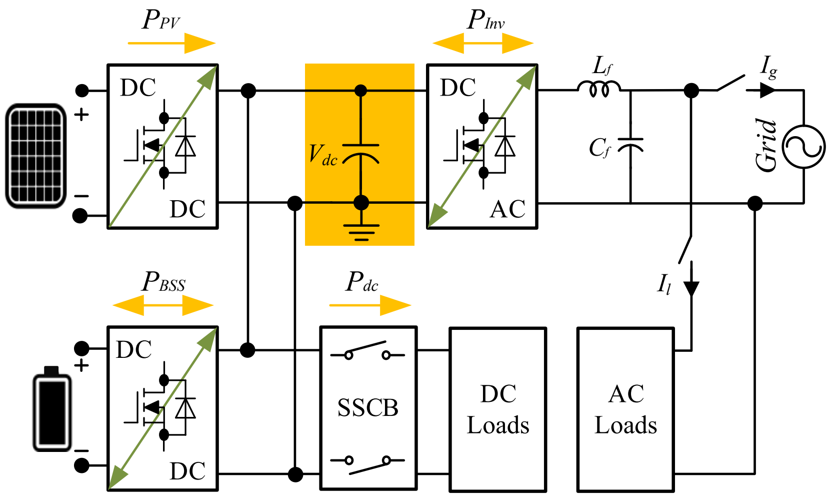
And, $$u = \psi\left(y, \dot{y}, \dots, y^{(r+1)}\right). \tag{3}$$



A non-linear flat system is equivalent to a linear controllable system.

Implementation of FBC on ER

A. dc-link voltage control using FBC:



Energy in dc link: $e_{dc} = \frac{1}{2} C_{dc} V_{dc}^2,$ (4)

Power in dc link: $\dot{e}_{dc} = P_{PV} \pm P_{Bat} - P_{dc} \pm P_{Inv},$ (5)

Assumptions: $\begin{cases} y = e_{dc} \\ x = V_{dc} \\ u = P_{Inv} \end{cases},$ (6)

Rewriting (4) to obtain V_{dc}: $V_{dc} = \sqrt{\frac{2e_{dc}}{C_{dc}}} \Rightarrow x = \varphi(y).$ (7)

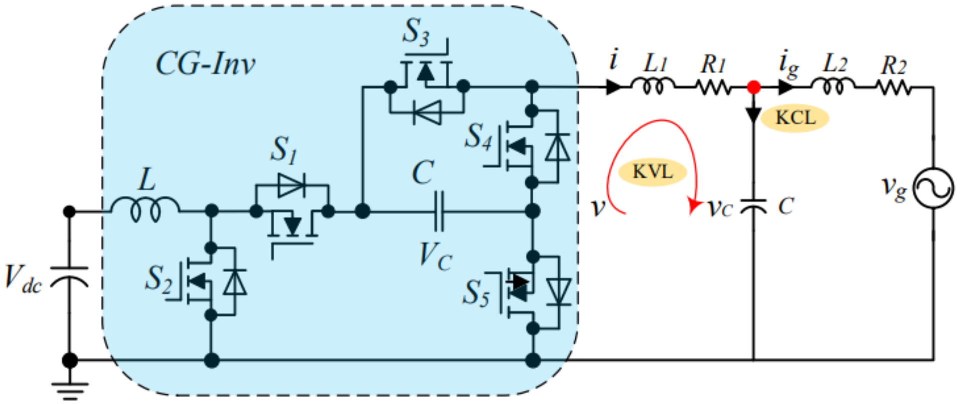
From (5), and rewriting P_{dc} in terms of V_{dc}:

$$P_{Inv} = P_{PV} + P_{Bat} - \frac{V_{dc}^2}{R_{dc}} - \dot{e}_{dc} = P_{PV} + P_{Bat} - \frac{2e_{dc}}{C_{dc} R_{dc}} - \dot{e}_{dc} \quad \Rightarrow \quad u = \psi(y, \dot{y}), \qquad \textbf{(8)}$$

Therefore, the considered system is differentially flat.

Implementation of FBC on ER

- **B. Inverter control using FBC**



Applying KVL:

$$\frac{di_d}{dt} = \frac{1}{L_f}\left(v_d - v_{Cd} - R_f i_d\right) + \omega i_q, \qquad (9)$$

$$\frac{di_q}{dt} = \frac{1}{L_f}\left(v_q - v_{Cq} - R_f i_q\right) - \omega i_d, \qquad (10)$$

Assumptions: $y = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, \quad x = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, \quad u = \begin{bmatrix} v_d \\ v_q \end{bmatrix}.$ (11) $\Rightarrow x = y$, and then

$x = \varphi(y)$

Rewriting (9) : $u_1 = L_f \dot{i}_d + R_f i_d - \omega L_f i_q + V_{Cd},$ **(12)** $\Rightarrow u_1 = \psi(y_1, \dot{y}_1, y_2)$

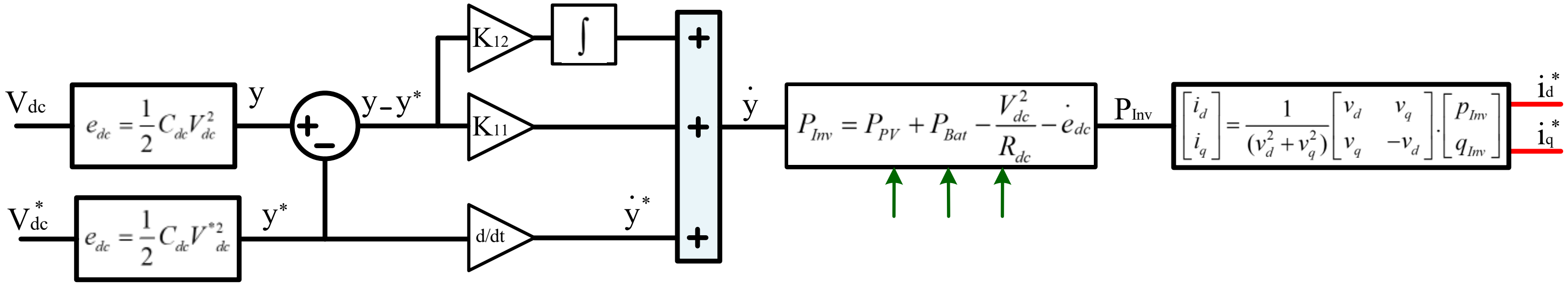
Rewriting (10): $u_2 = L_f \dot{i}_q + R_f i_q i + \omega L_f i_d + V_{Cq},$ **(13)** $\Rightarrow u_2 = \psi(y_2, \dot{y}_2, y_1)$

Therefore, the considered system is differentially flat.

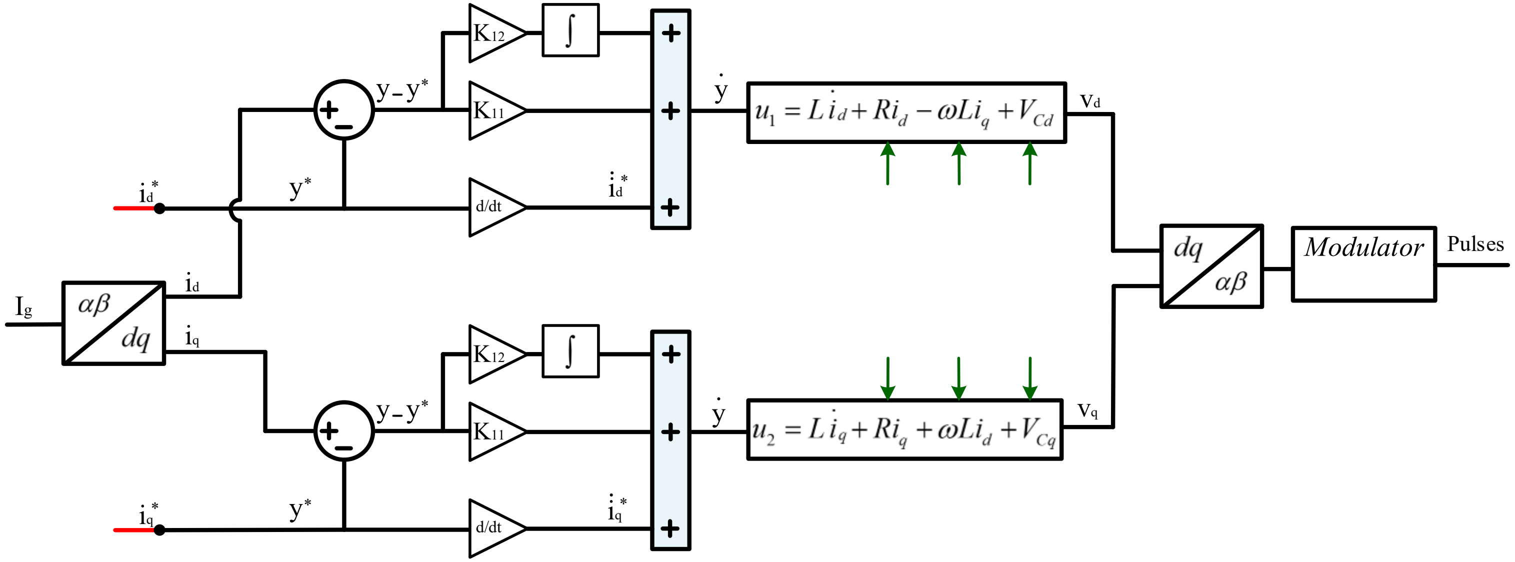
FBC Design

- **Control system is in cascade form as:**

1. The outer control loop controls the dc-link voltage by producing the inverter reference current.



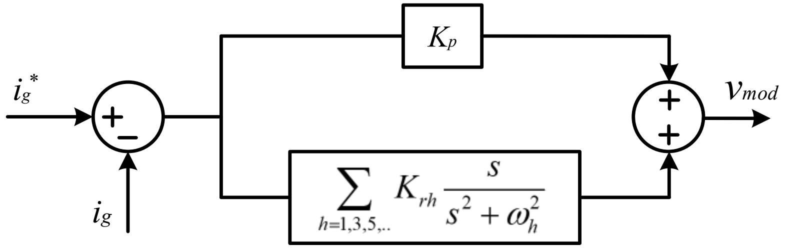
2. The inner control loop controls the grid current by producing the reference voltage for modulation.



M. Azizi, O. Husev, C. Roncero-Clemente, O. Veligorskyi and R. Strzelecki, "**Fast and Robust Energy Router Control in Dynamic Conditions Using Flatness-Based Control Theory**," 2025 IEEE 19th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Antalya, Turkey, 2025, pp. 1-6

Proportional Resonance (PR) controller as an **alternative for grid current controller**:

The proportional gain K_p **improves transient performance and stabilizes the system**, while the **resonant term introduces infinite gain at the fundamental grid frequency** ω_0, ensuring zero steady-state error for sinusoidal references.

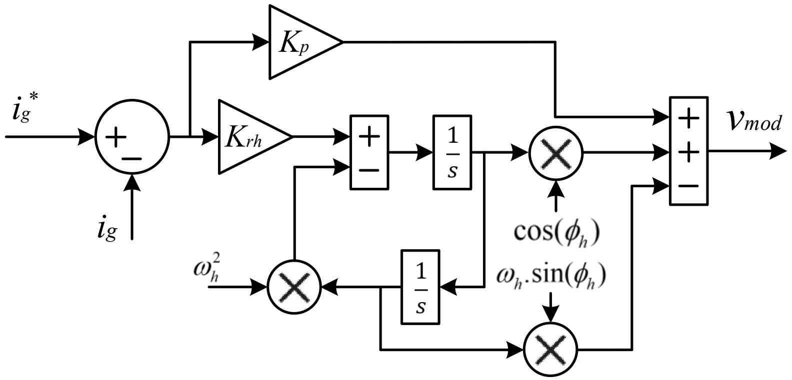


In practice, a PR controller often employs **a finite gain, which helps minimize steady-state error** and **extend the controller's bandwidth by properly selecting the cutoff frequency ωc**.

$$G_{PR}^{id}(s) = K_p + \sum_{h=1,3,5,..} K_{rh} \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega_h^2}$$

The phase-compensation method to reduce the effect of processing delays

$$G_{PR}^{id}(s) = K_p + \sum_{h=1,3,5,..} K_{rh} \frac{s.\cos(\phi_h) - \omega_h.\sin(\phi_h)}{s^2 + \omega_h^2}.$$



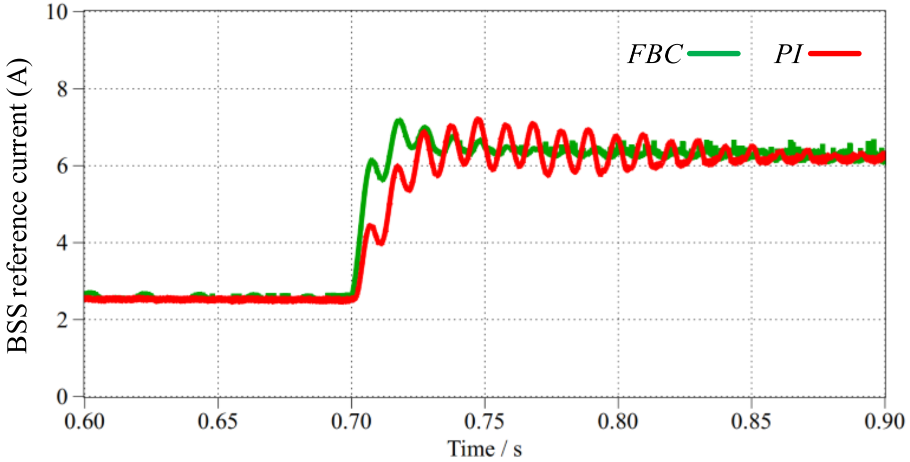
O. Husev, C. Roncero-Clemente, E. Makovenko, S. P. Pimentel, D. Vinnikov and J. Martins, "**Optimization and Implementation of the Proportional-Resonant Controller for Grid-Connected Inverter With Significant Computation Delay**," in IEEE Transactions on Industrial Electronics, vol. 67, no. 2, pp. 1201-1211, Feb. 2020.

Simulation and experimental verification

Simulation results of FBC in dc-link for a step change in ac load (grid-forming):

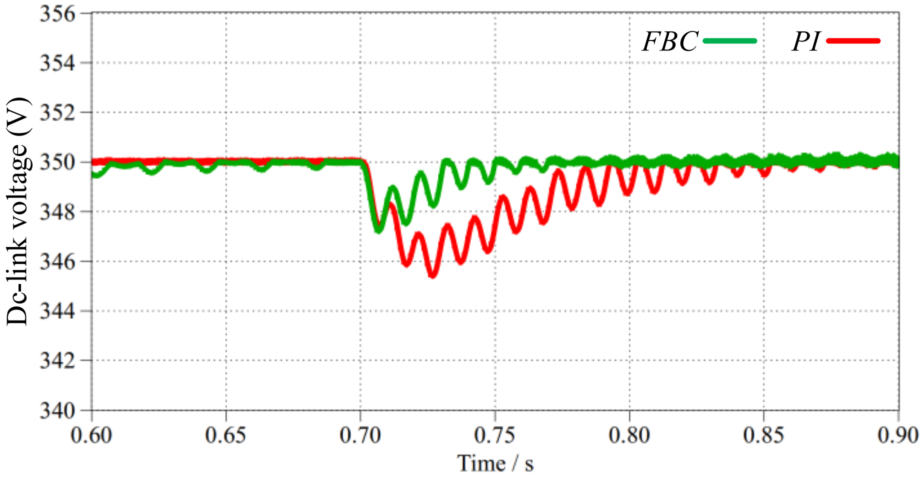
The BSS is discharging and feeding a dc load with a power of 630 W, while PV is not connected.

At t = 0.7 s, a **resistive ac load (59 Ω) is added** to the output side of the inverter.



BSS reference current

FBC response is faster

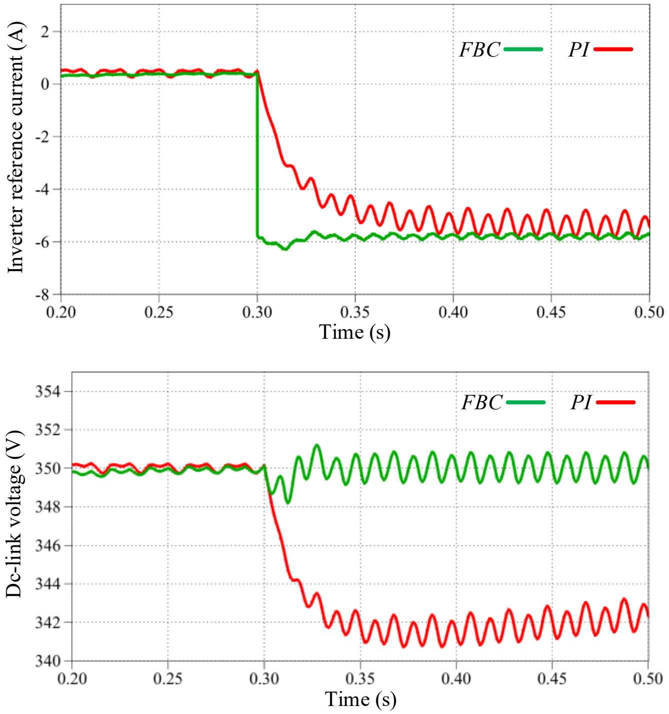


Dc-link voltage

PI settling time 150 ms

FBC settling time 50 ms (**3 times faster**)

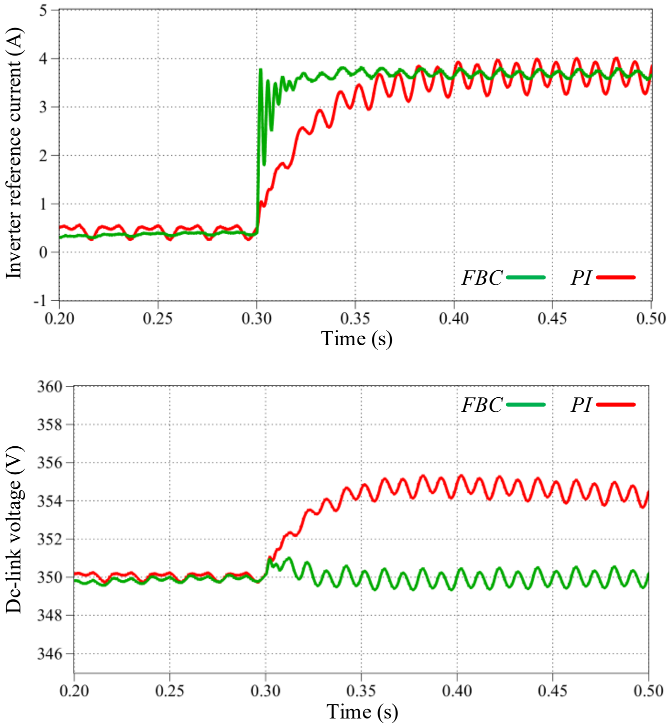
Simulation results with **FBC for the dc-link** voltage in (grid-following mode)



CASE A

Step change in dc load

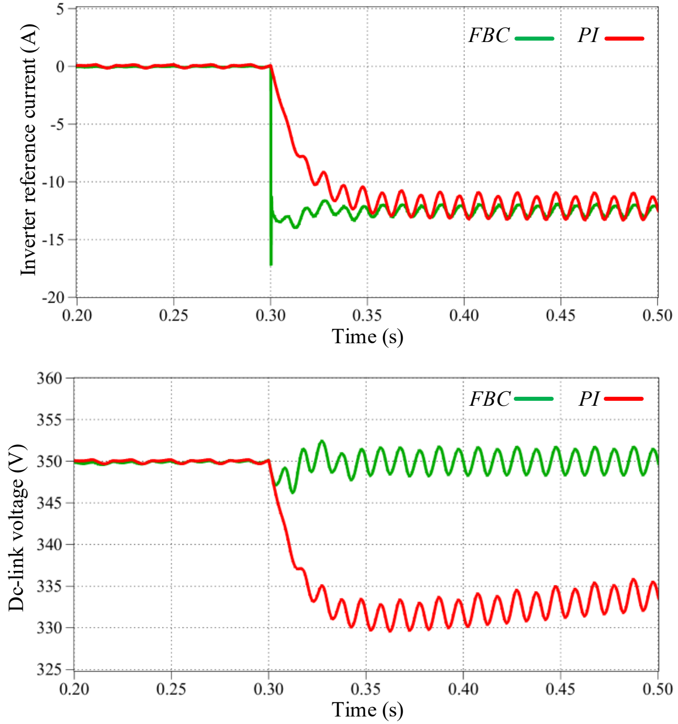
From 1000 W to 2000 W



CASE B

Step change in PV power

From 520 W to 1020 W



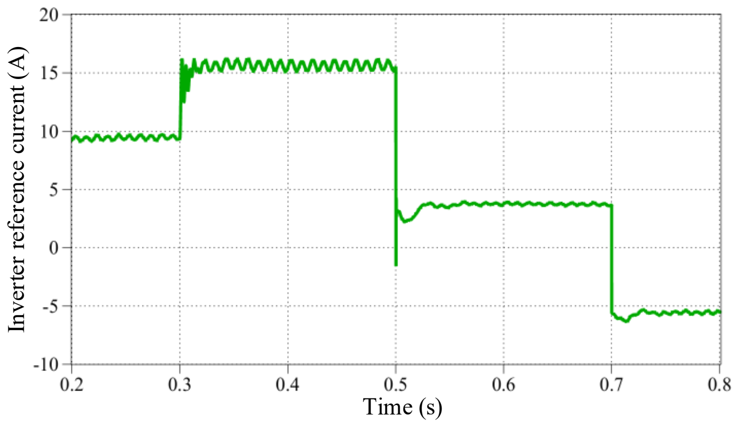
CASE

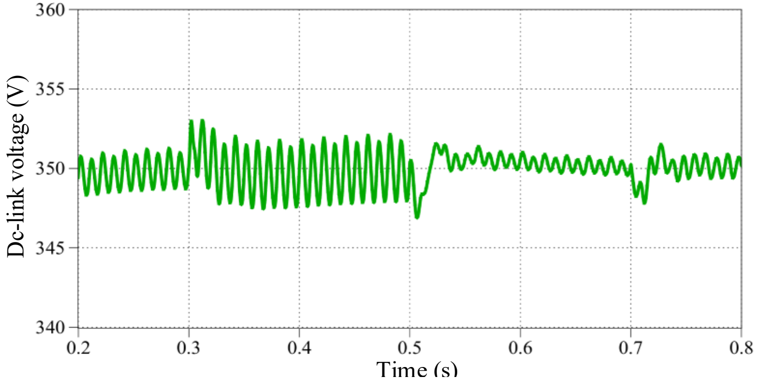
Step change in BSS power

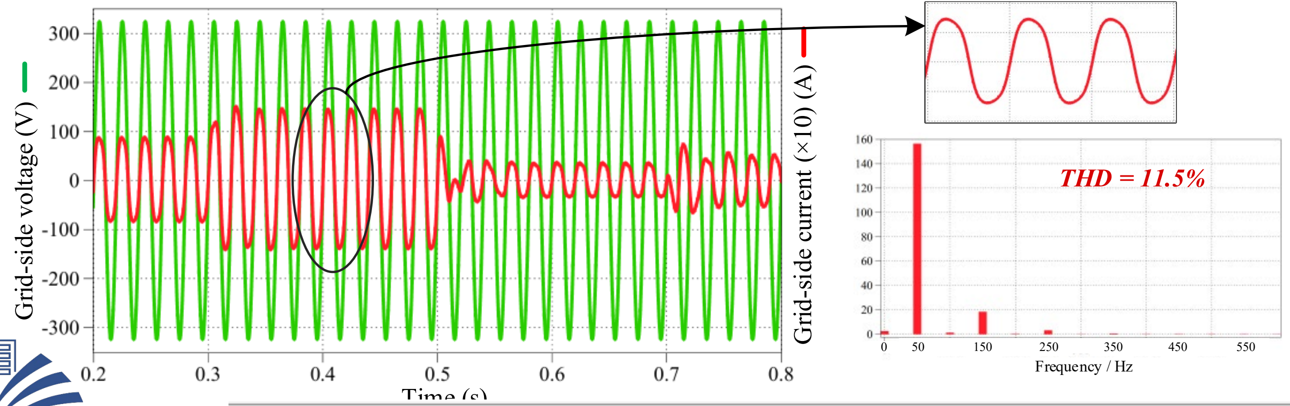
From 1000 W to -1000 W

In all cases, FBC response is much faster and the dc-link voltage is well maintained.

Simulation results with FBC for the dc-link and grid-current







- **Case D: Grid-side evaluation with FBC under Serial dynamic condition:**

- First, the battery discharges 1000 W, and PV outputs 570 W.

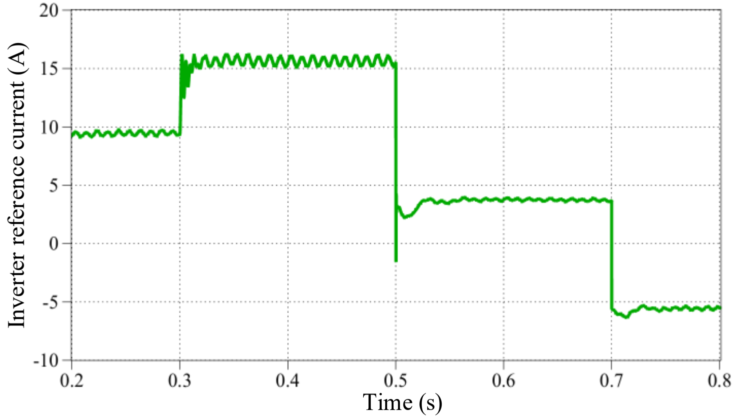
1. At t = 0.3 s, the PV power increases to 1600 W.

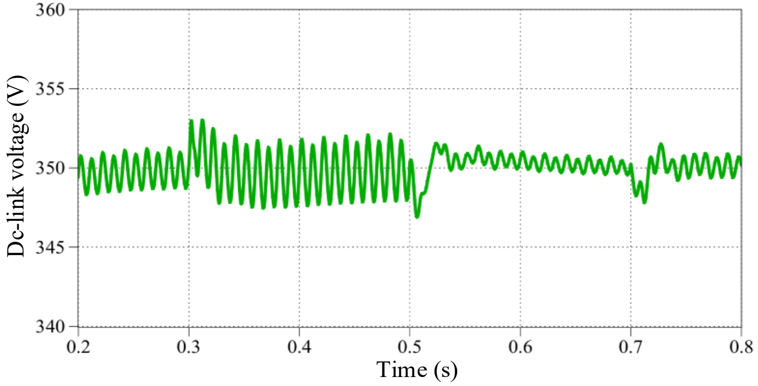
2. At t = 0.5 s, the battery mode changes to charging mode with 1000W.

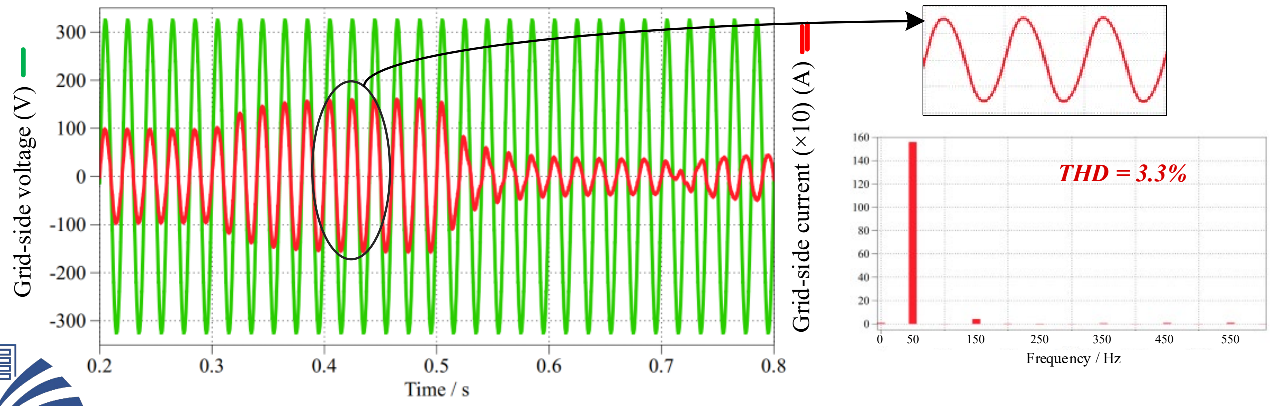
3. At t = 0.7 s, a dc load of 1500 W is added.

High THD for grid current

Simulation results with FBC for dc-link and **PR controller for grid current**





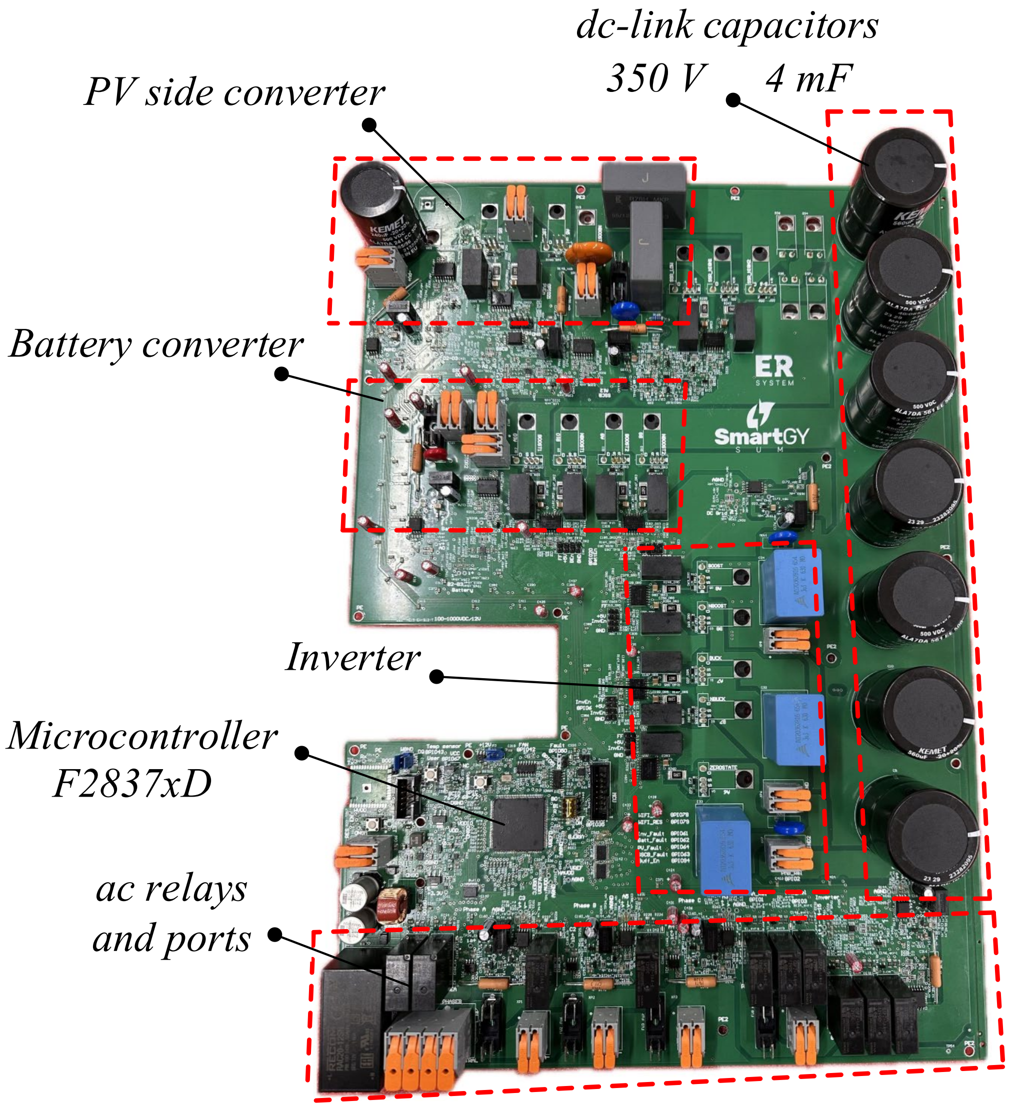


- **Case D: Grid-side evaluation with FBC under Serial dynamic condition:**
- First, the battery discharges 1000 W, and PV outputs 570 W.

1. At t = 0.3 s, the PV power increases to 1600 W.
2. At t = 0.5 s, the battery mode changes to charging mode with 1000W.
3. At t = 0.7 s, a dc load of 1500 W is added.

Low THD for grid current

Experimental verification

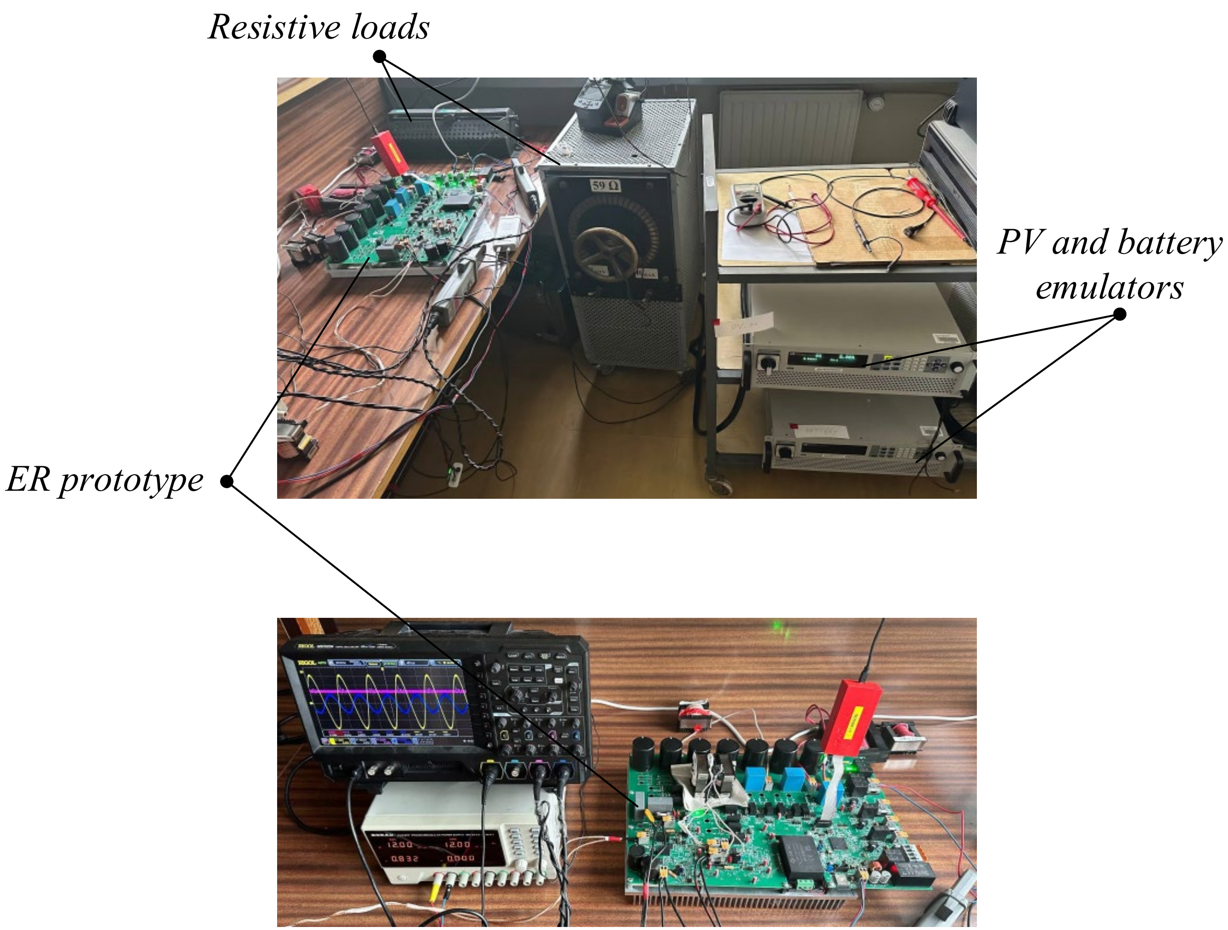


LABORATORY PROTOTYPE SPECIFICATIONS

Components Characteristics	
Switching frequency	62.5 kHz
Sampling time	32 µs
Dc-link capacitor	4760 µF
Inverter inductor	850 µH
LCL filters inductors	680 µH & 320 µH
LCL filter capacitor	3.3 µF
PV inductor	1.8 mH
Battery inductors	500 µH
Operating points	
Grid voltage	230 V
dc-link voltage	280-380 V (Nominal 350 V)
Battery voltage	250-360 V
PV voltage	200-450 V
Semiconductor elements	
Inverter MOSFETs	C3M0021120K
Battery converter MOSFETs	C3M0025065K
PV converter MOSFETs	C3M0025065K
SSCB MOSFETs	C3M0025065K

For experimental, **FBC is used in the dc-link**, while **for the grid current, the PR method is used**.

Experimental setup and results

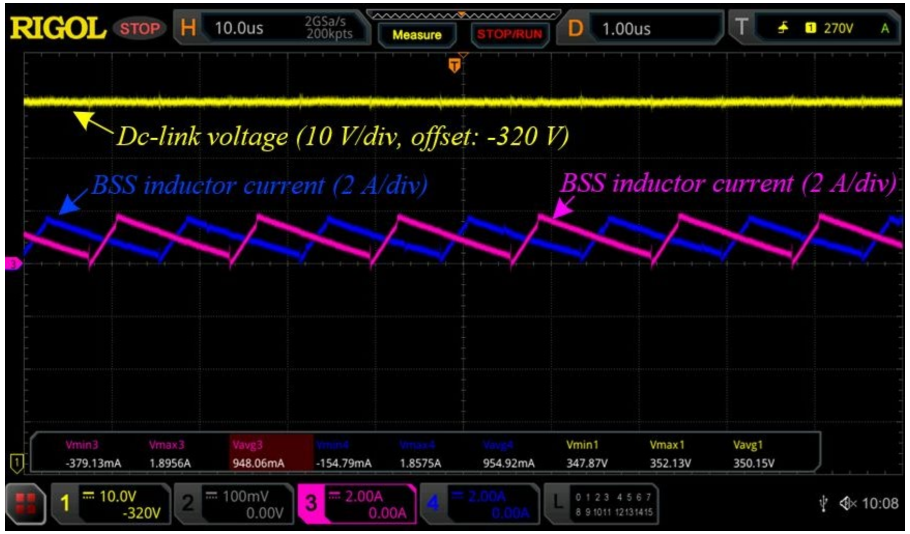


Resistive loads

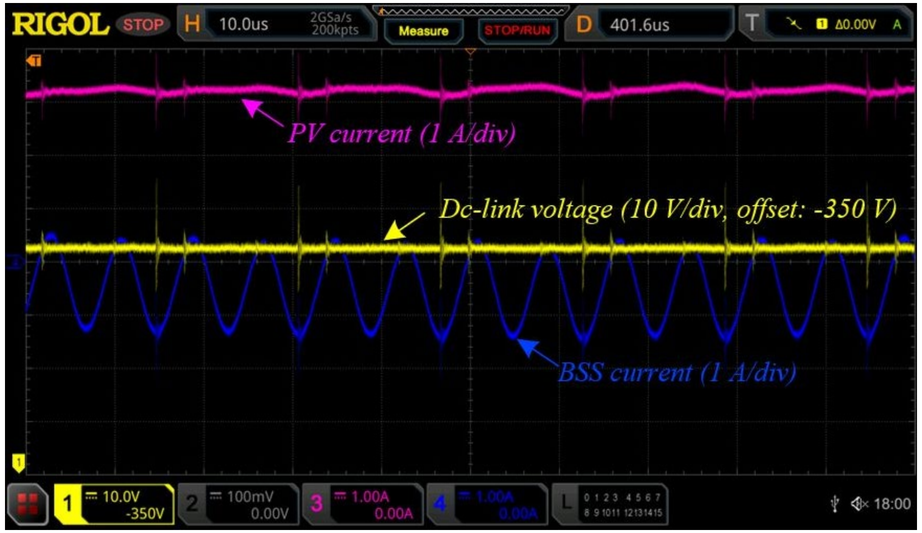
PV and battery emulators

ER prototype

DC mode

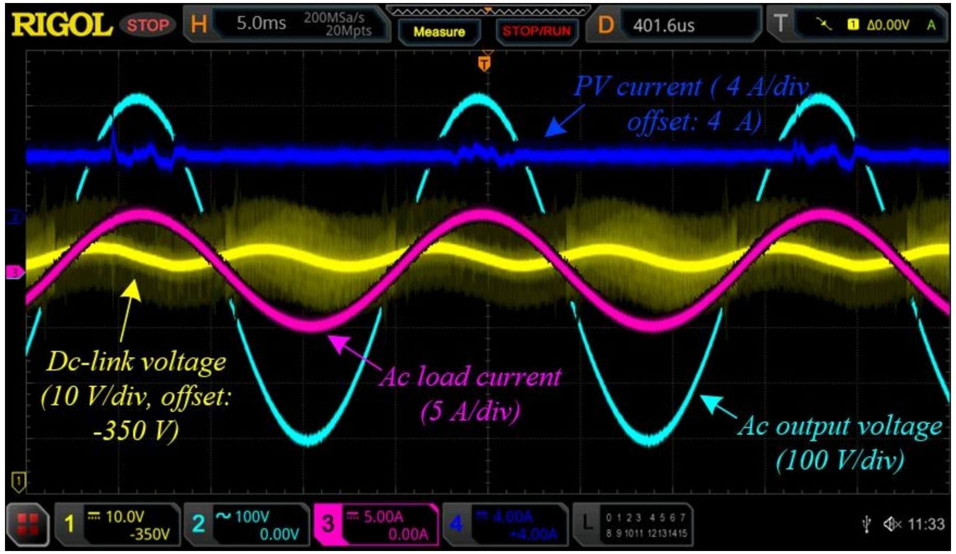


Inductor currents of the interleaved BSS converter and the dc-link voltage supplying a 194 Ω

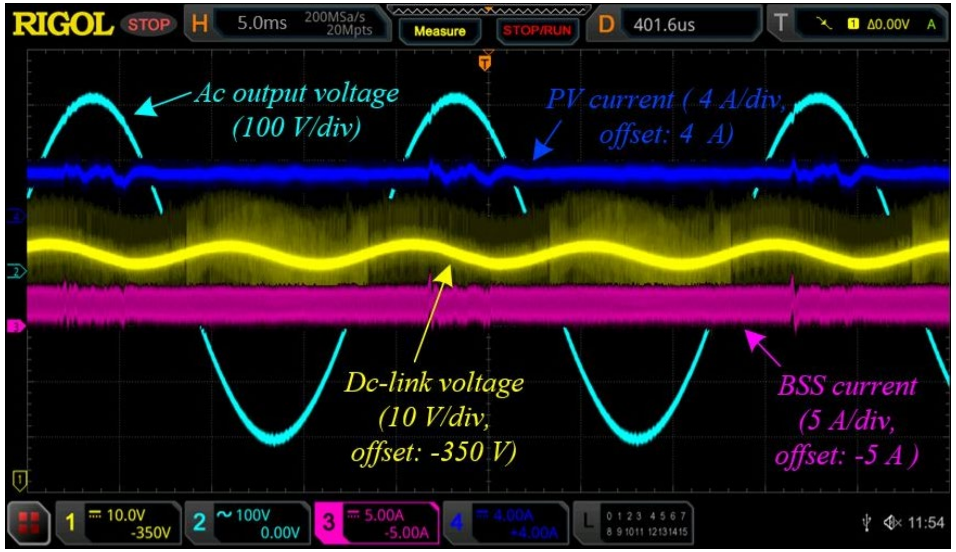


PV and BSS, while supplying a 194 Ω load and BSS is charging

Grid-forming mode

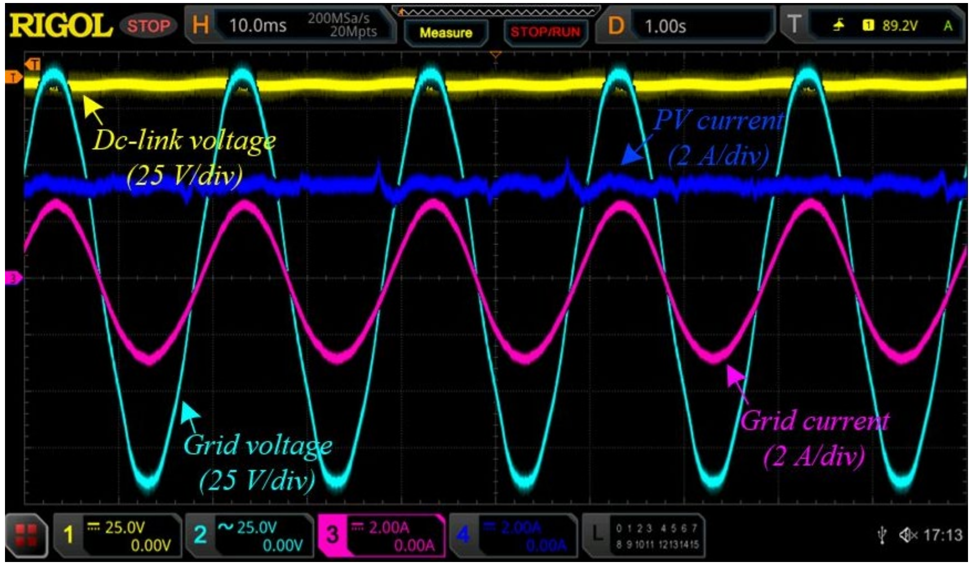


PV supplies both dc and ac load of 194 Ω (dc) and 59 Ω (ac)

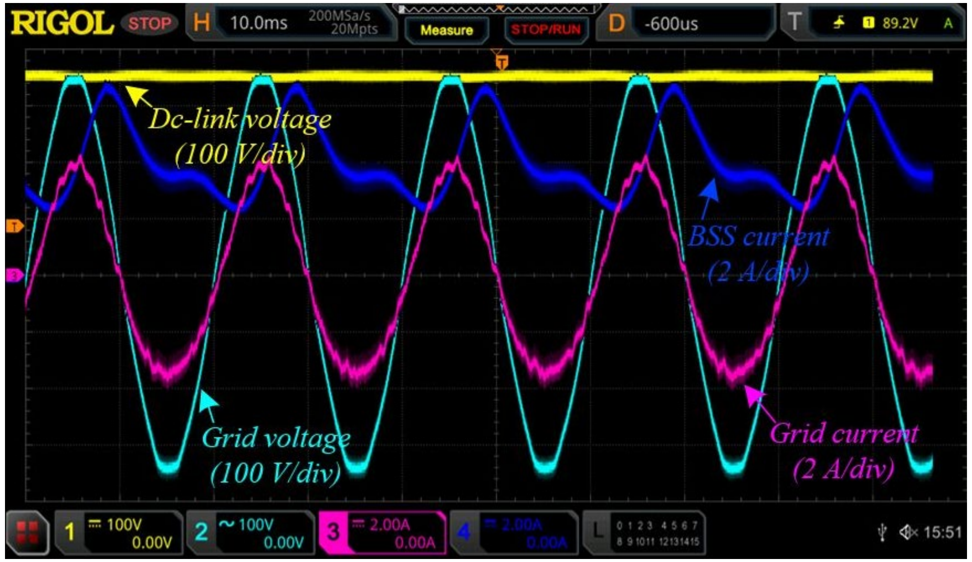


PV and BSS are supplying the same dc and ac loads.

Grid-following mode



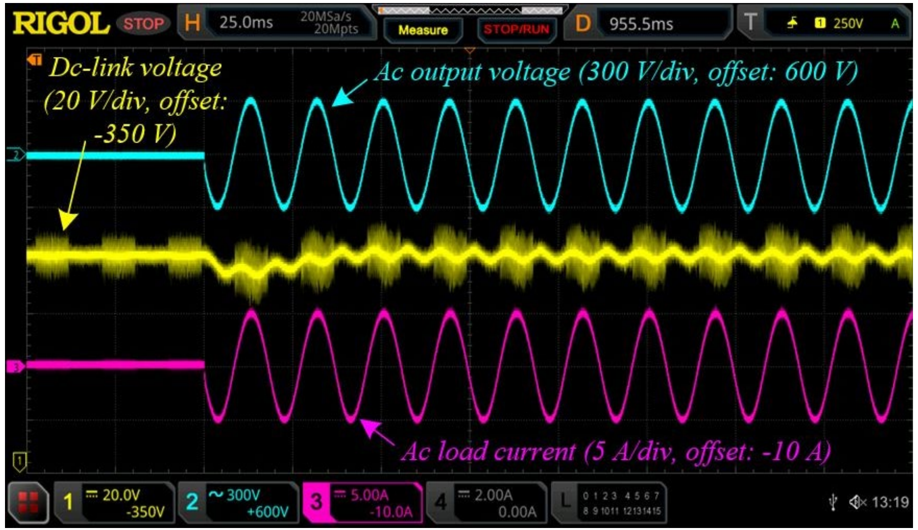
with the PV operating at 25% of the nominal voltage



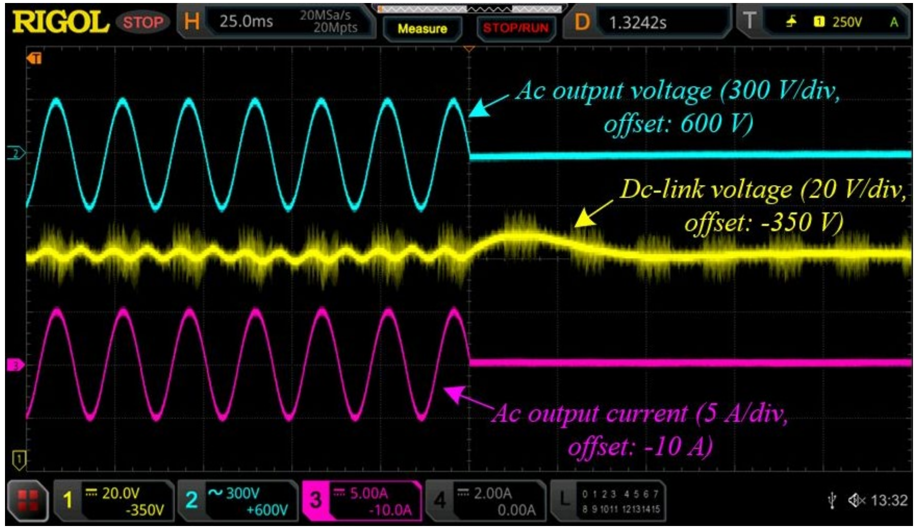
With BSS, injecting 400 W into the grid

Dynamic condition: Connecting and disconnecting a 59 Ω resistive load at the ac output.

FBC



Near 5 V undershoot and a settling time of around 40 ms



Near 10 V overshoot and a settling time of around 60 ms

PI controller

There is a near 35V undershoot

Settling time is almost 500 ms

Comparison and discussion

Simulation and experimental comparison

	Simulations		**Experiments**	
	Settling time	Undershoot	Settling time	Undershoot
PI method	150 ms	5 V	500 ms	35 V
FBC method	50 ms	3 V	40 ms	5 V

It is proven by simulation and experiment that the **FBC controller**, in comparison with PI:

- **has a faster response,**
- **smaller under/overshoot,**
- **but more difficult in the implementation.**

Conclusions of this work

- A **non-isolated ER** structure was proposed, **ensuring safety while reducing size, weight, and cost** by removing the isolation transformer.
- The **common-ground inverter** design effectively **eliminates leakage currents** by **sharing a single ground** between ac and dc sides.
- A **hybrid ac/dc structure is recommended for ZEB integration**, offering high efficiency and compatibility with current ac systems.
- **Comprehensive grounding and protection strategies were developed** for both ac and dc links to enhance reliability.
- The **single-cell three-phase configuration enables dynamic phase selection**, improving grid balancing and **reducing hardware cost**.
- **Using FBC, the dc-link undershoot was reduced** to <10 V with **a settling time of ~40 ms**, compared to 35 V and 500 ms for PI.
- Simulation and experimental results confirm the proposed system's **robustness and dynamic performance**.

Scientific novelty of the obtained results:

- **A new ER topology based on the SC-TP concept was developed** to reduce phase imbalance and lower cost by eliminating extra conversion cells.
- **It was shown that galvanic isolation alone cannot fully remove dc leakage currents**; equalizing the dc midpoint and ac neutral potentials is recommended.
- **A non-isolated common-ground ER was proposed** as a novel interlink between dc and ac residential grids with conventional grounding and protection schemes.
- **Flatness-Based Control (FBC) was applied to the ER** for the first time, offering faster and more reliable dynamic performance than classical control methods.

Comparative Evaluation of Isolated dc-dc Converters for Low Power Applications

Mohammadreza Azizi[1,2], Oleksandr Husev[1,2], Dmitri Vinnikov[2], Oleksandr Veligorskyi[1]
[1]Department of Radiotechnic and Embedded Systems, Chernihiv Polytechnic National University, Chernihiv, Ukraine
[2]Department of Electrical Power Engineering and Mechatronics, Tallinn, Estonia
Azizi.malayeru@gmail.com

***Abstract*— Isolated dc-dc**
important for utilizing renewable
used for direct connection to the
boosters for on/off-grid ac applic
and evaluates five popular types of
low-power applications. In this
performance of converters, the
these converters have been
components are then designed f
Using simulations in Simulink/MA
been evaluated and compared fro

Keywords— Isolated dc-dc co
Flyback, Forward, Push-pull, Full

I. INTRODU

Today, power electronic conv
home and industrial applia
development and improvement
subject of many studies. Due to
the need to use more green energ
converters as an intermediary bet
the grid is growing notably. Sinc
are dc, existing structures use a dc
an inverter. Although the use of si
ability to increase/decrease volt
researchers in recent years, they
use of dc-dc converters in dc or
topic of the day. Due to the dc na
and many dc loads, the use of
microgrids is conceivable in the r
Among the various dc-dc co

EMC) | 978-1-6654-9681-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/PEMC51159.2022.9962944

Back-to-Back Energy Router Based on Common-Ground Inverters

Mohammadreza Azi
[1]Department of Radiotechnic and E
[2]Department of E

***Abstract*—With the increase of**
resources (mainly photovoltaic), and the
in many buildings, the utilization of the d
system is being developed. For this purpo
multiple ac and dc ports are employed. By
enough standards to integrate the dc sy
and safety considerations are still a p
suggest the use of an isolated system, bu
increased volume and cost. This pape
router based on a back-to-back structure
inverters. Connecting the neutral wire o
negative port of the dc link eliminates
ensures safety. The proposed energy rou
ground inverters. Each inverter has five
ability to increase/decrease the voltage a
directions. The operation mode of the co
has been investigated and the simulation
confirm the accuracy of the overall s
compared to classical H-bridge inverter.

Keywords—— Energy router, n
ground inverters, back-to-back structure

I. INTRODUCTION

Due to the increasing integration of
resources in the domestic and distributio
the distribution system is changing fr
generation and consumption. New bu

g (CPE-POWERENG) | 979-8-3503-0004-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/CPE-POWERENG58103.2023.10227480

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energies

MDPI

Review

Grounding and Isola
Overview and Critic

Mohammadreza Azizi [1], Oleksandr H
and Carlos Roncero-Clemente [3]

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Abstract:
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Keyword

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Dc Leakage Current in Isolated Grid-Connected dc Nanogrid - Origins and Elimination Methods

Mohammadreza Azizi[1,2], Oleksa
[1]Department of Radiotechnic and E
[2]Department of Electric, Electro
[3]Department of Electrical Power E
[4]Faculty of Electrical and

***Abstract*—The LVdc system is a relative**
distribution sector, which seems to grow
future due to its promising advantages. In
protection and grounding are challenging is
galvanically isolated connection mode of dc
grid has high reliability, the leakage current
into the ac grid through the interwinding
insulation resistance between the prima
windings of the transformer. The way of
nanogrid can also be a determining factor in
and its dc components. This study deals with
in the galvanically isolated dc nanogrid. Th
dc leakage current and its relationship wi
grounding and finally provides solutions
components in the leakage current.

Keywords— Grid-connected dc na
grounding type, dc leakage current, capacitive

I. INTRODUCTION

The importance of using renewable en
from anyone. The share of renewables in
increased from 16% in 2004 to nearly
Among various sources, small-scale sola
increasing due to their simplicity in publi
lower running time. Based on statistics in 2
the total solar energy has been supplied t
solar power plant [2]. In addition, due

Energy R
A Sustainabl
for Future R
Buildi

by Mohammadreza Azizi, Oleksandr Huse
Joao Martins, and Oleksa

Energy supply has always been a criti
ments. In the last few years, the comb
crisis to power plants and the increas
the removal of the restrictions of Co
increase in the price of electricity. On t
from clean and Renewable Energy Sources (

Digital Object Identifier 10.1109/MPEL.2024.3525349
Date of publication: 25 February 2025

Fast and Robust Energy Router Control in Dynamic Conditions Using Flatness-Based Control Theory

Mohammadreza Azizi[1,2], Oleksandr Husev[1,3], Carlos Roncero-Clemente[2], Oleksandr Veligorskyi[1], Ryszard Strzelecki[3]
[1]Department of Radiotechnic and Embedded Systems, Chernihiv Polytechnic National University, Chernihiv, Ukraine
[2]Department of Electric, Electronic and Automation Engineering, University of Extremadura, Badajoz, Spain
[3]Faculty of Electrical and Control Engineering, Gdansk University of Technology, Gdansk, Poland
M.azizi@stu.cn.ua

***Abstract*—In this paper, flatness-based control theory is developed to enhance the dynamic performance of a multiport energy router. The energy router integrates multiple power sources and sinks, including photovoltaic systems, battery storage, the grid, and various loads. Consequently, any sudden change in a subsystem can induce dynamic conditions across the entire system. The presented method controls the grid-side inverter and regulates the dc link voltage. To implement this control approach, the system equations have been established, and it has been demonstrated that the system is differentially flat. Afterward, the controller design has been addressed. The simulation results confirm the proper performance of this method, and the comparisons made validate the high speed and accuracy of the system responses compared to conventional solutions.**

Keywords—Flatness-based control theory, multiport energy router, dynamic conditions, hybrid nanogrid.

I. INTRODUCTION

The penetration of power electronics in the electricity industry and emerging advancements in this field are now more comprehensible than ever. Power electronic converters have established a stable position in energy harvesting and power conversion. With the increasing adoption of photovoltaic (PV) systems in residential buildings and the emergence of PV-integrated energy communities, various power electronics solutions and Energy Management Systems (EMS) have been proposed [1], [2]. Among these, the Energy

ac loads, and the grid, any sudden change in these components can introduce disturbances into the system. Therefore, a control system capable of delivering a fast, robust, and precise response under dynamic conditions is essential.

Among the control methods suitable for dynamic conditions and nonlinear systems, Flatness-Based Control (FBC) theory has been introduced as a reliable solution [14]. This control method, initially introduced by Fliess, demonstrates excellent performance in managing nonlinear systems and provides robust capabilities for systems with multiple state variables and inputs. However, like other advanced control strategies, FBC imposes certain conditions that must be met. Similar to MPC, it first requires an accurate mathematical model of the system. Additionally, the system should be differentially flat, ensuring that the overall conditions of the flat system are met. In contrast, compared to methods such as MPC, FBC offers a lower computational burden. While MPC requires solving an optimization problem at each time step, FBC relies on analytical relationships, making it computationally more efficient. This control approach has been successfully applied across various domains, including mechanical and chemical systems, aerospace, and power systems, demonstrating its capability to manage nonlinear and dynamic systems while ensuring fast and stable responses. Over the past decade, several studies have explored the application of FBC in power electronics, yielding promising results in dynamic conditions [15]–[18].

ering (CPE-POWERENG) | 979-8-3315-1517-1/25/$31.00 ©2025 IEEE | DOI: 10.1109/CPE-POWERENG63314.2025.11027260

List of publications

- M. Azizi, O. Husev, C. Roncero-Clemente, O. Veligorskyi and R. Strzelecki, "Fast and Robust Energy Router Control in Dynamic Conditions Using Flatness-Based Control Theory," 2025 IEEE 19th International Conference on Compatibility, Power Electronics and Power Engineering (**CPE-POWERENG**), Antalya, Turkey, 2025, pp. 1-6, doi: https://doi.org/10.1109/CPE-POWERENG63314.2025.11027260. Conference Paper, indexed in Scopus.

- M. Azizi, O. Husev, R. Mbayed, E. Monmasson, J. Martins and O. Veligorskyi, "Energy Router: A Sustainable Solution for Future Residential Buildings," in **IEEE Power Electronics Magazine**, vol. 12, no. 1, pp. 75-86, March 2025, doi: https://doi.org/10.1109/MPEL.2024.3525349. Paper, indexed in Scopus Q2 Journal.

- M. Azizi, O. Husev, O. Veligorskyi, M. Turzvński and R. Strzelecki, "Dc Leakage Current in Isolated Grid-Connected dc Nanogrid - Origins and Elimination Methods," 2024 IEEE 18th International Conference on Compatibility, Power Electronics and Power Engineering **(CPE-POWERENG**), Gdynia, Poland, 2024, pp. 1-6, doi: https://doi.org/10.1109/CPE-POWERENG60842.2024.10604426. Conference Paper, indexed in Scopus.

- Azizi, M., Husev, O., Veligorskyi, O., Rahimpour, S., and Roncero-Clemente, C. (2023). Grounding and Isolation Requirements in DC Microgrids: Overview and Critical Analysis. **Energies**, 16(23), 7747. https://doi.org/10.3390/en16237747. Journal paper, indexed in Scopus Q2.

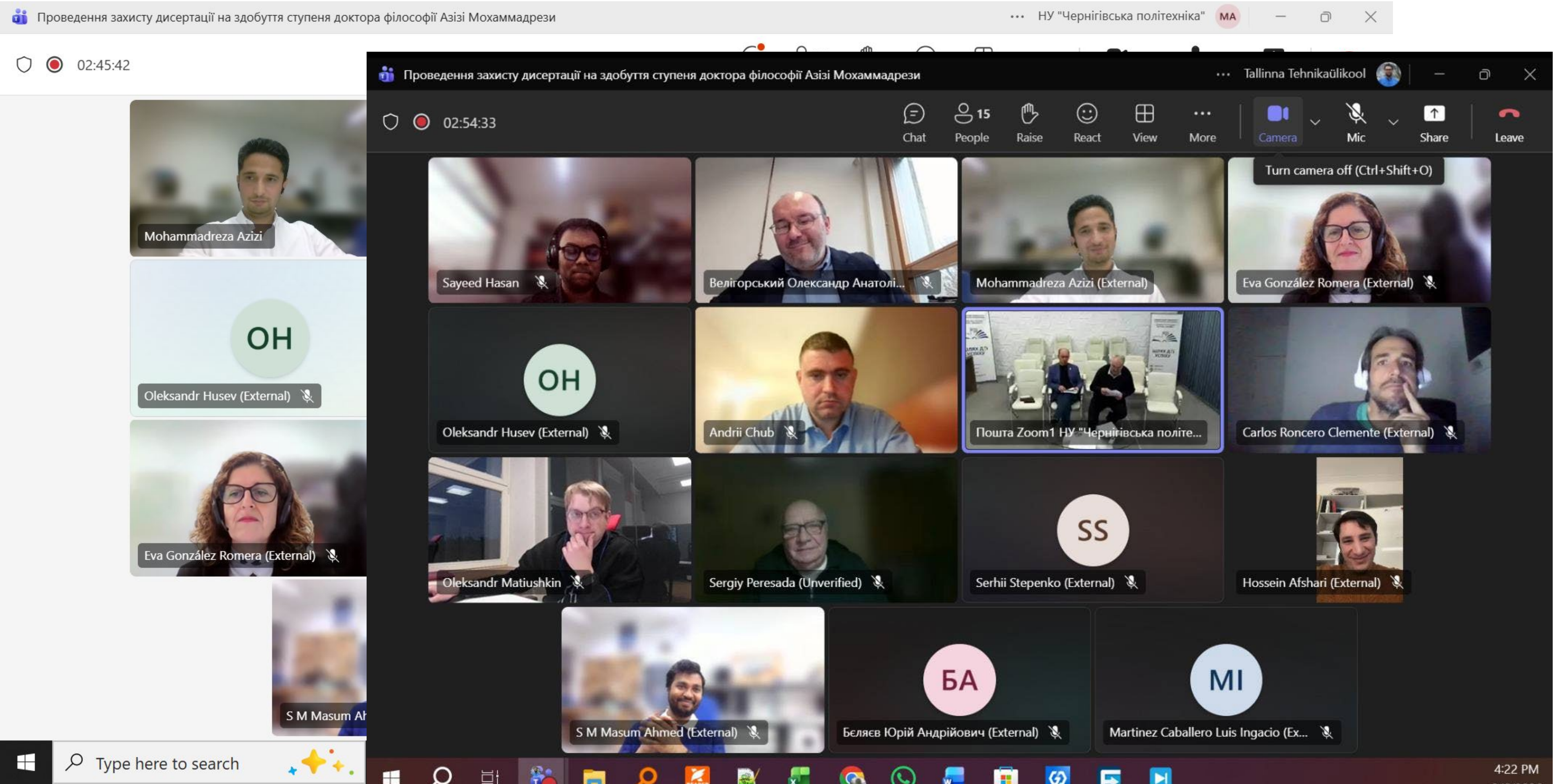
- M. Azizi, S. Rahimpour, O. Husev and O. Veligorskyi, "Back-to-Back Energy Router Based on Common-Ground Inverters," 2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering **(CPE-POWERENG**), Tallinn, Estonia, 2023, pp. 1-6, https://doi.org/10.1109/CPE-POWERENG58103.2023.10227480. Conference paper, indexed in Scopus.

- M. Azizi, O. Husev, D. Vinnikov and O. Veligorskyi, "Comparative Evaluation of Isolated dc-dc Converters for Low Power Applications," 2022 IEEE 20th International Power Electronics and Motion Control **Conference (PEMC)**, Brasov, Romania, 2022, pp. 7-12, doi: https://doi.org/10.1109/PEMC51159.2022.9962944. Conference paper, indexed in Scopus.

- M. Azizi, O. Husev, and D. Vinnikov, "Single-stage buck–boost inverters: A state-of-the-art survey," **Energies**, vol. 15, no. 5, p. 1622, Mar. 2022, doi: 10.3390/en15051622. Journal paper, indexed in Scopus Q2.

- " Non-Isolated Single-Cell Three-Phase Multiport Energy Router with Improved Dynamic Behavior " is in submission process for the IET Power Electronics Journal.

PhD defense on February 6th 2026



Проведення захисту дисертації на здобуття ступеня доктора філософії Азізі Мохаммадрези

НУ "Чернігівська політехніка"

Tallinna Tehnikaülikool

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- Dr. Andrii Chub
- Dr. Serhii Stepenko

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Thank you for your attention

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