After the RISEnergy Transnational Access, Users are required to submit a User Report. This should be done within 4 weeks after the Access is completed unless otherwise agreed. The User Report will be given to the User(s) by the WP2 leader. The report contains sections related to the work performed, the main results and observations that were achieved.

This document should be completed, signed, and sent by e-mail to risenergy@for.kit.edu.

Summary questionnaire for Users who have been granted Transnational Access (TA) under the RISEnergy project Horizon Europe TA scheme. More information on RISEnergy TA can be found in "General Rules" and in "Access Policy" which can be found on the RISEnergy webpage.

Please complete, sign, and send this form, together with the Cost claim by e-mail to risenergy@for.kit.edu with title: RISEnergy APPXXX - reports.

General information about the project

Project title (as used in Application)	Autonomous Smart Inverter Coordinated Control Modelling and Testing using Power Hardware-in-the-Loop System
Project number (APPXXX) and acronym (max 15 characters)	APP248
RISEnergy RI(s) accessed	TA25 - ICCS-EES-lab
Keywords (up to five, free text)	Smart inverter, microgrid, grid support functions, grid stability, hardware-in-the-loop
Arrival date (in town where RI is located)	25-Jan-2026
Departure date (from town where RI is located)	14-Feb-2026
Starting date of Access (first day at RI)	26-Jan-2026
Finishing date of Access (last day at RI)	13-Feb-2026
Number of days not using the RI (during the above period)	5
Reason for not using RI those days (describe)	Weekends and public holiday
Number of days using the RI	14
Number of Users granted Access (group size)	1
Comments	

User

User group leader or sole applicant (user group member 1)

First name	
Last name	
Affiliation / Employer	
Country of Employer	
E-mail	
User travelling to RI?	
Comments	

User group member 2

First name	
Last name	
Affiliation / Employer	
Country of Employer	
E-mail	
User travelling to RI?	
Comments	

Access Summary Report - work performed and initial results

Brief description of the objectives of your project (up to 200 words)

This work focuses on the development, implementation and experimental validation of advanced control strategies for smart inverters capable of providing grid-support functions in compliance with IEEE 1547-2018. A detailed real-time electromagnetic transient (EMT) model of a smart inverter, including converter and LCL filter dynamics, was developed to enable flexible and communication enabled switching among multiple grid-support modes. The implemented functionalities include Volt-VAR, Volt-Watt, Constant Reactive Power (CRP), Constant Power Factor (CPF) and Low/High Voltage Ride-Through (LVRT/HVRT).

To study coordinated operation in a practical distribution environment, three smart inverters were connected at different buses of the CIGRE low-voltage (LV) distribution feeder. This multi-inverter configuration enabled investigation of interactions among various control modes, power-priority settings and Volt-VAR characteristic curves under dynamic operating conditions. The designed controllers and grid-support functions were first validated through Controller Hardware-in-the-Loop (CHIL) testing using the PLECS RT Box, followed by Power Hardware-in-the-Loop (PHIL) experiment with a physical configurable inverter from Taraz.

Activities performed (up to 600 words)

The work was executed in three phases: (i) modeling and controller development, (ii) CHIL validation using PLECS RT Box and (iii) PHIL experimentation with Taraz configurable inverter system. Three smart inverters were connected at three different buses of the

CIGRE LV distribution feeder to investigate the interactions among various control modes, power-priority settings and Volt-VAR characteristic curves.

(i) Smart Inverter Control Development and Logic Implementation:

A EMT smart inverter model of 2-level IGBT converter with LCL filter as show in Figure 1 was developed, supporting dynamic control mode switching and communication-enabled operation. The following grid-support functions were implemented.

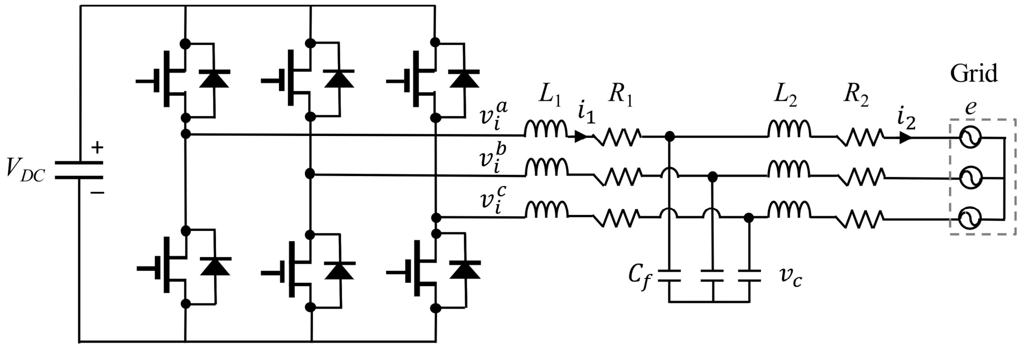

Figure 1 3-Ph inverter model with the filters

(ii) CHIL Validation

CHIL testing was executed using the PLECS RT Box with TIC2000 F28379D DSP module to close the loop between real-time EMT grid models and the embedded inverter controller. The CHIL testbed setup is shown in Figure 2.

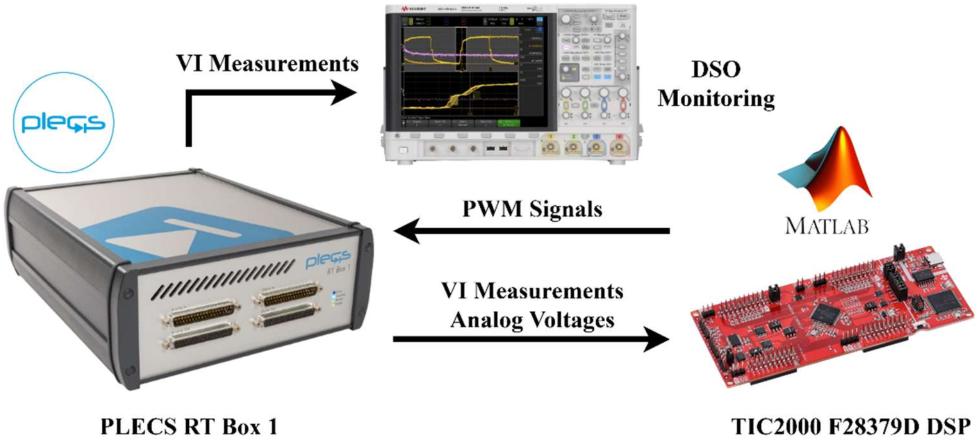

Figure 2 CHIL Testbed Setup Block Diagram

(iii) PHIL Testbed Setup and Validation

The experimental testbed was developed as shown in Figure 3 and 4. Regatron PV emulator, 3-Ph Autotransformer VARIAC, Taraz configurable inverter, PE RCP Box with TIC2000 F28379D DSP and dSPACE Microlabbox II (MLBXII) platforms with protection and measurement interfaces were used. The PHIL procedure followed a workflow to ensure safe synchronization and repeatable results.

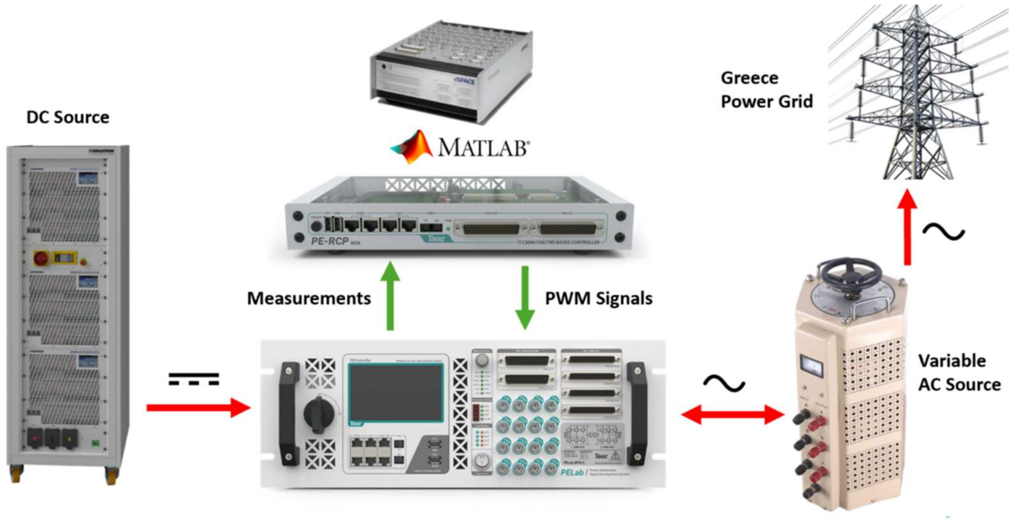

Figure 3 Experimental Testbed for PHIL Block Diagram

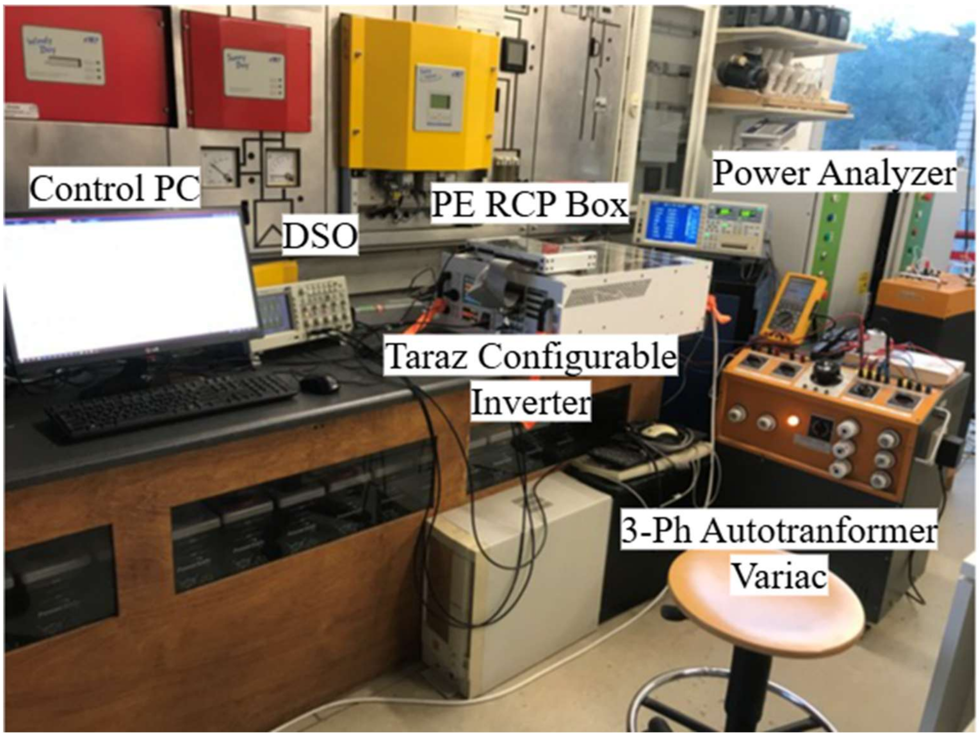

Figure 4 PHIL Experimental Testbed

The inverter control structure was implemented as shown here with the modes of Volt-VAR, Volt-Watt, Constant Power Factor (CPF) and Constant Reactive Power (CRP).

1. Volt-VAR (V-Q) Control:
   Volt-VAR was implemented as a piecewise linear droop.

$$Q(v) = \begin{cases} Q_1, & v \leq v_1 \\ Q_1 + (-Q_1)\frac{v-v_1}{v_2-v_1}, & v_1 < v < v_2 \\ 0, & v_2 \leq v \leq v_3 \\ (Q_4 - 0)\frac{v-v_3}{v_4-v_3}, & v_3 < v < v_4 \\ Q_4, & v \geq v_4 \end{cases}$$

2. Volt–Watt (V–W) Control:
   Volt–Watt was implemented to curtail active power above a voltage threshold.

$$P(v) = \begin{cases} P_{avail}, & v \le v_{start} \\ P_{avail} + (P_{min} - P_{avail}) \dfrac{v - v_{start}}{v_{stop} - v_{start}}, & v_{start} < v < v_{stop} \\ P_{min}, & v \ge v_{stop} \end{cases}$$

3. Constant Power Factor (CPF) Mode:
   CPF enforces a fixed power factor (pf) setpoint by computing reactive power reference from active power.

$$\varphi = cos^{-1}(pf), Q = Ptan(\varphi). sign(Q)$$

4. Constant Reactive Power (CRP) Mode:
   Constant Qmode regulates reactive power to a fixed reference within inverter capability.

$$Q = Q_{set}, s.t. \sqrt{P^2 + Q^2} \le S_{max}$$

The CIGRE LV distribution network as shown in Figure 5 is a benchmark radial feeder widely used for studying distributed energy resource integration, voltage regulation and control coordination in modern distribution systems. The network consists of multiple interconnected line sections (R-segments) supplying distributed load buses, forming a weak and resistive LV grid where voltage variations are highly sensitive to local power injections. In this configuration, smart inverters are connected at three different buses (Bus 15, 16 and 18) along the feeder, representing distributed photovoltaic or converter-based generation units. Due to the feeder's radial structure, electrical distance and line impedance significantly influence how control actions at one inverter propagate through the network and affect voltages at neighbouring buses. This makes the CIGRE LV feeder particularly suitable for analyzing inverter–grid and inverter–inverter interactions, evaluating grid-support functions such as Volt-VAR and Volt-Watt control and assessing coordinated voltage regulation strategies under dynamic operating conditions.

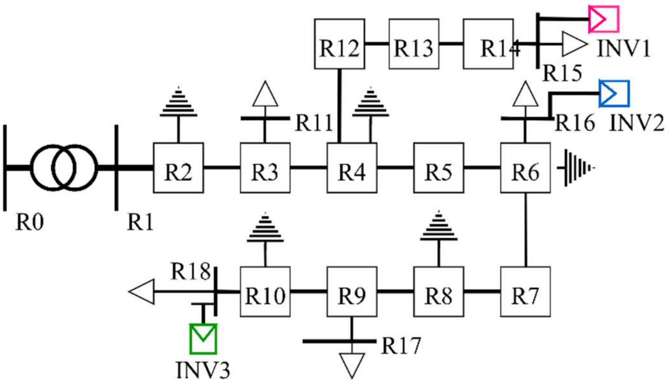

Figure 5 CIGRE LV Distribution Network

Scientific results (up to 800 words)

The CHIL, PHIL experimentation results and the inverter interactions results are presented in this section.

Experimental Results:

(i) CHIL Results

Figure 6 shows the inverter voltage and current waveforms when operating in CPF mode with the power factor reference set to 1.0. The results clearly indicate that the current waveforms are phase-aligned with the corresponding phase voltages. Since pf=1, the reactive power reference becomes zero, resulting in purely active power injection. The CHIL results confirm accurate decoupling of active and reactive current components in the dq frame controller.

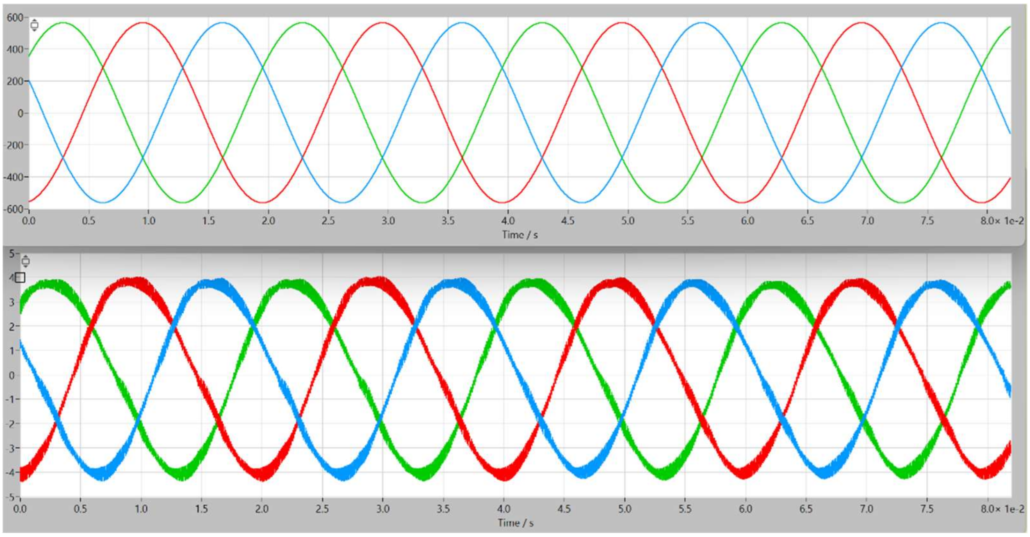

Figure 6 Inverter voltage and current at CPF and pf=1

Figure 7 shows operation in CRP mode with a reactive power reference of +0.6 pu (inductive). In this case, the current waveform is observed to lag the voltage waveform, confirming inductive behaviour. The phase displacement between voltage and current validates correct reactive power regulation. The inverter maintained the setpoint of 0.6 pu reactive power within the steady-state.

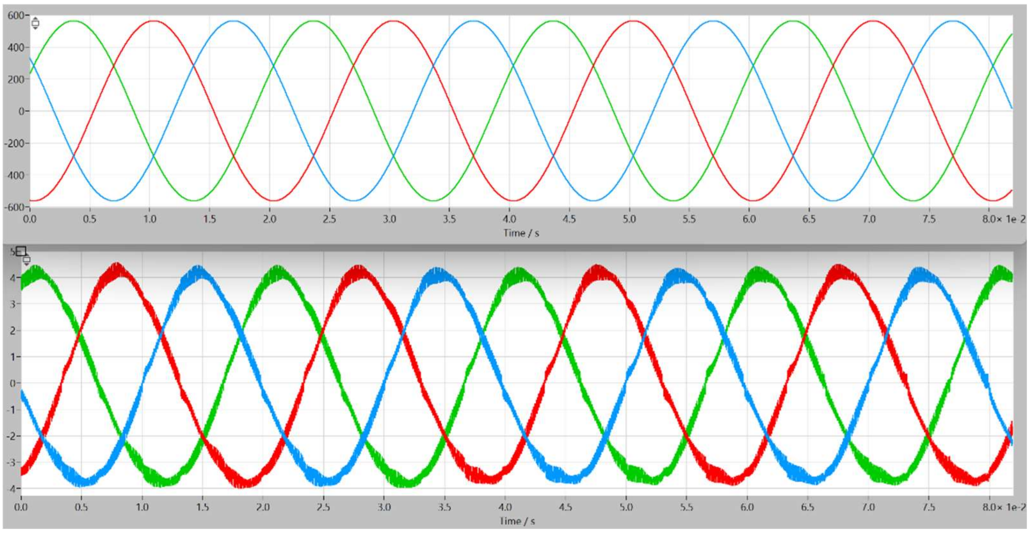

Figure 7 Inverter voltage and current at CRP of +0.6pu inductive

Figure 8 presents CRP operation at −0.6 pu (capacitive). Here, the current waveform clearly leads the voltage waveform, consistent with capacitive reactive power injection. The symmetry between inductive and capacitive operation confirms bidirectional reactive capability and correct sign handling in the control implementation. The inverter exhibited stable current tracking without oscillatory behaviour.

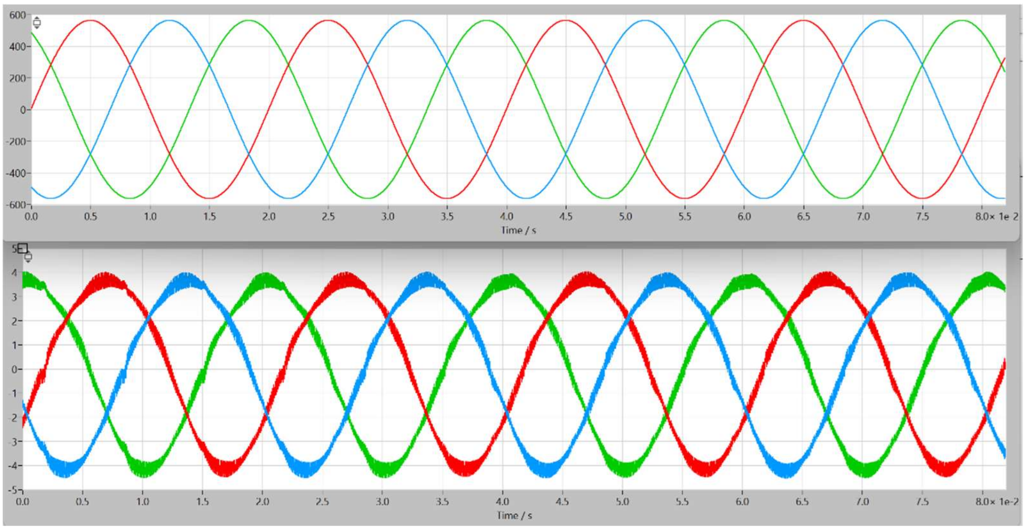

Figure 8 Inverter voltage and current at CRP of -0.6pu capacitive

Figure 9 shows the FFT spectrum of the inverter output current. The dominant spectral component appears at 50 Hz, corresponding to the fundamental grid frequency. Harmonic magnitudes at higher frequencies are significantly attenuated, confirming proper PWM implementation, effective LCL filter design, stable current controller tuning. The absence of significant low-order harmonics demonstrates robustness of the control architecture and validates that the inverter operates with high waveform quality under CHIL conditions.

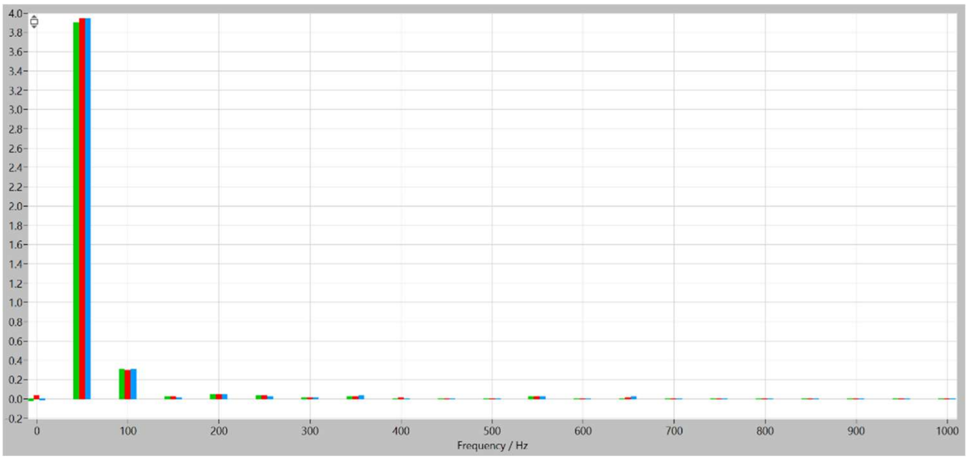

Figure 9 FFT spectrum of inverter current

(ii) PHIL Results

After successful CHIL validation, the controller was deployed in the PE RCP Box and dSPACE which is connect to the Taraz configurable inverter PHIL setup. The objective was to verify synchronization, voltage build-up and current injection under real power hardware conditions.

Figure 10 shows the PLL synchronization test for one of the phases captured on an oscilloscope prior to closing the grid contactor. Yellow waveform is inverter's PCC voltage and blue waveform is inverter generated voltage. The waveforms were recorded before physical grid connection. The inverter voltage is observed to be frequency and phase aligned with the inverter's PCC voltage, indicating successful PLL locking. The minimal phase error confirms stable operation of the PLL.

$$\theta_{PLL} = \theta_{inv}$$

This synchronization step is critical to ensure smooth grid connection without transient current spikes. This was verified for rest of the two phases as well.

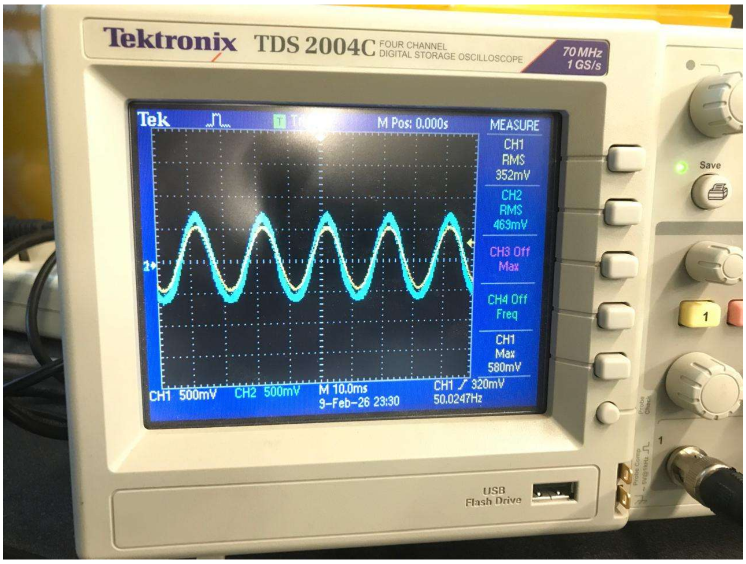

Figure 10 PLL Synchronization Check for phase A

Figure 11 shows the three-phase PCC voltage after closing the contactor. The waveforms exhibit balanced phase magnitudes, stable sinusoidal profiles, no observable distortion or instability. this confirms correct transition from synchronization mode to active grid-following operation.

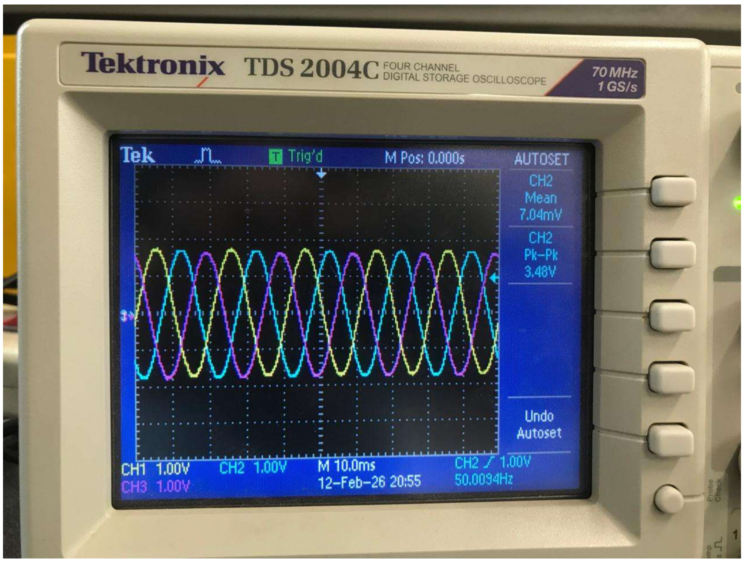

Figure 11 Inverter 3-Ph PCC voltage after grid connection

Figure 12 shows the three-phase currents produced by the inverter during grid-following operation. The currents are balanced across phases, sinusoidal in nature and stable in amplitude. The results demonstrate proper operation of the dq current controllers and accurate active/reactive power regulation in hardware conditions.

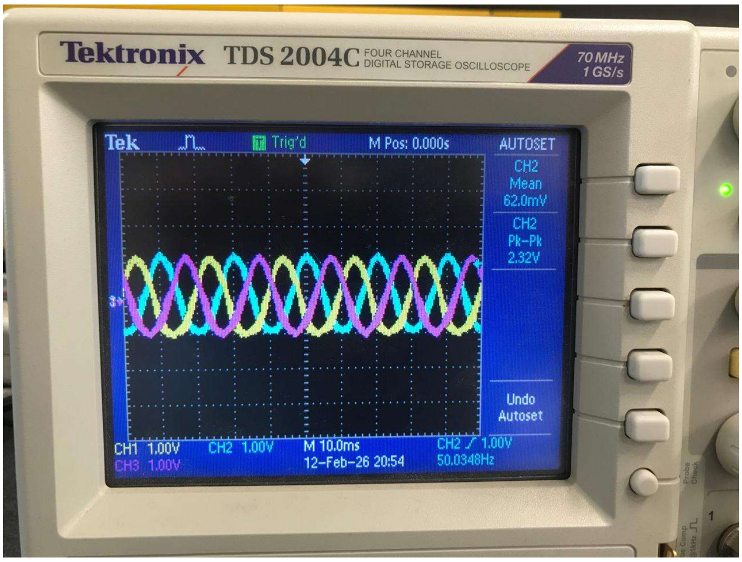

Figure 12 Inverter 3-Ph current after grid connection

The combined CHIL and PHIL results confirm the accurate implementation of inverter control functions, correct phase relationship between voltage and current for inductive and capacitive operation, high-quality sinusoidal current with dominant 50 Hz component and low harmonic distortion, reliable PLL synchronization prior to grid connection and stable three-phase voltage and current injection in real hardware conditions. The consistency between CHIL simulations and PHIL hardware experiments validates the fidelity of the developed control architecture and confirms readiness for advanced coordinated multi-inverter studies.

Interaction Studies in CIGRE LV Distribution Network:

(i) Control Mode Interaction

To investigate inverter interactions in the CIGRE LV distribution network, the operating mode of INV1 (50 kW at Bus 15) was varied while INV2 (40 kW at Bus 16) and INV3 (45 kW at Bus 18) were maintained in Constant Power Factor (PF = 1) mode. The results are shown in Figure 13. The voltage response at Bus 16 clearly shows that the control strategy of INV1 significantly influences the local voltage seen by INV2, despite INV2 operating in fixed CPF mode. When INV1 operates in Volt-VAR modes (Modes 2–4), the reactive power support provided by INV1 improves voltage regulation across the feeder, resulting in more stable voltage levels at Bus 16 during over-voltage events. In particular, active-power-priority (Mode 2) Volt-VAR operation provides moderate voltage support, whereas reactive-power-priority (Mode 3) and vector-scaling (Mode 4) strategies yield stronger voltage correction during over voltage. In contrast, Volt-Watt operation (Mode 5) primarily limits active power injection during high-voltage conditions, reducing over-voltage but offering limited improvement. The CPF operation of INV1 (Mode 1) shows the least dynamic voltage support. These results demonstrate that smart inverter control modes at one location can affect voltage profiles and operational conditions of neighbouring inverters.

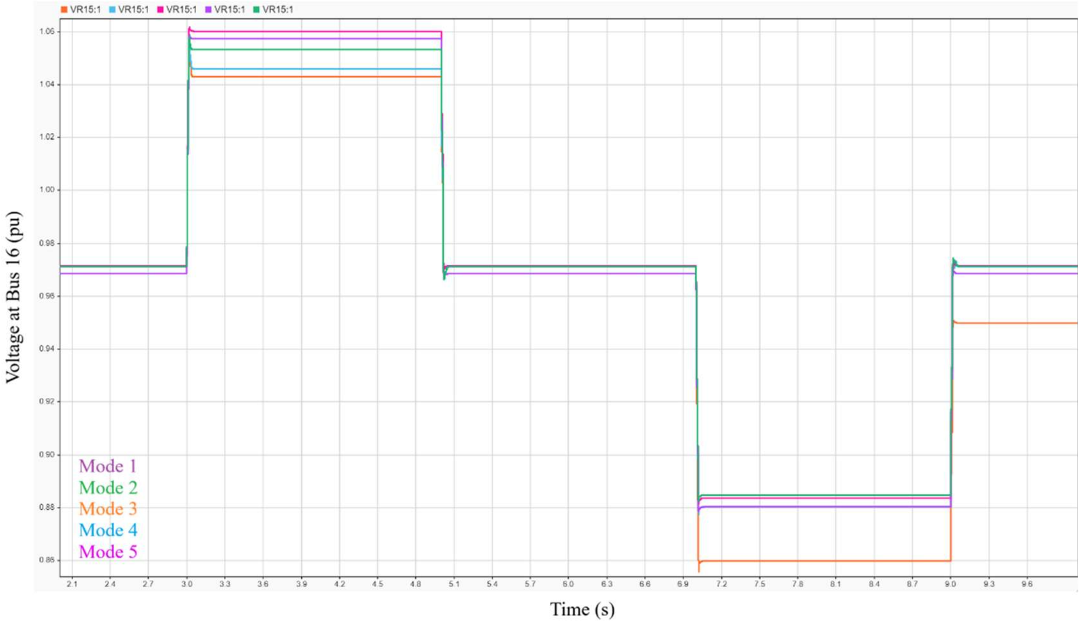

Figure 13 Control Mode Interaction

(ii) Volt-VAR Curve Interaction

In this case, the INV1 and INV2 is sized 2.5x and INV3 is sized 5x. INV2 is fixed in Volt-VAR mode with reactive power priority using custom curve 6, while INV1 and INV3 operate with the same control priority but different Volt-VAR characteristic curves as shown in Figure 14. The results are shown in Figure 15. The voltage measured at Bus 16 shows that the selected Volt-VAR curve has a clear influence on both the transient response and the final steady-state voltage. Immediately after the under voltage disturbance around 7.0 s, all cases exhibit a similar initial voltage drop, but the subsequent recovery differs noticeably depending on the curve shape. Modes 5 and 4 provide the best voltage support, settling at the improved steady-state values, which indicates that these curves trigger stronger or earlier reactive power injection in the undervoltage region. Modes 1, 2 and 3 show intermediate performance, while Modes 6 result in the lowest final voltages, suggesting comparatively weaker support under the same conditions. In addition, Mode 6 produces the most oscillatory response, with more pronounced dips and settling fluctuations, indicating that curve selection also affects damping and dynamic interaction among the inverters. Overall, the results confirm that even when all inverters use Volt-VAR with reactive power priority, the specific Volt-VAR curve strongly affects inverter coordination, voltage recovery and stability in the feeder.

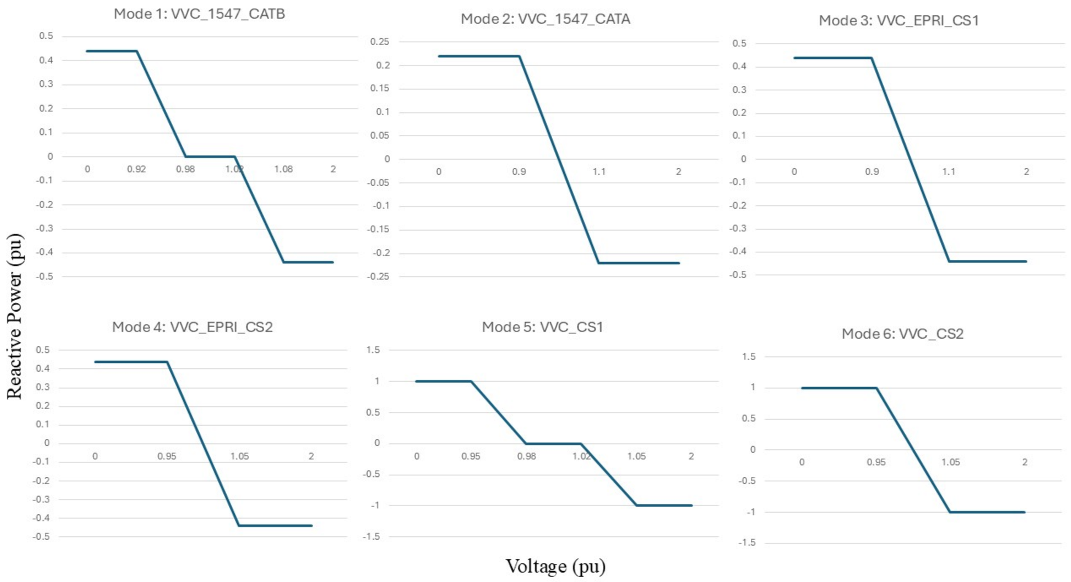

Figure 14 Volt-VAR Curves

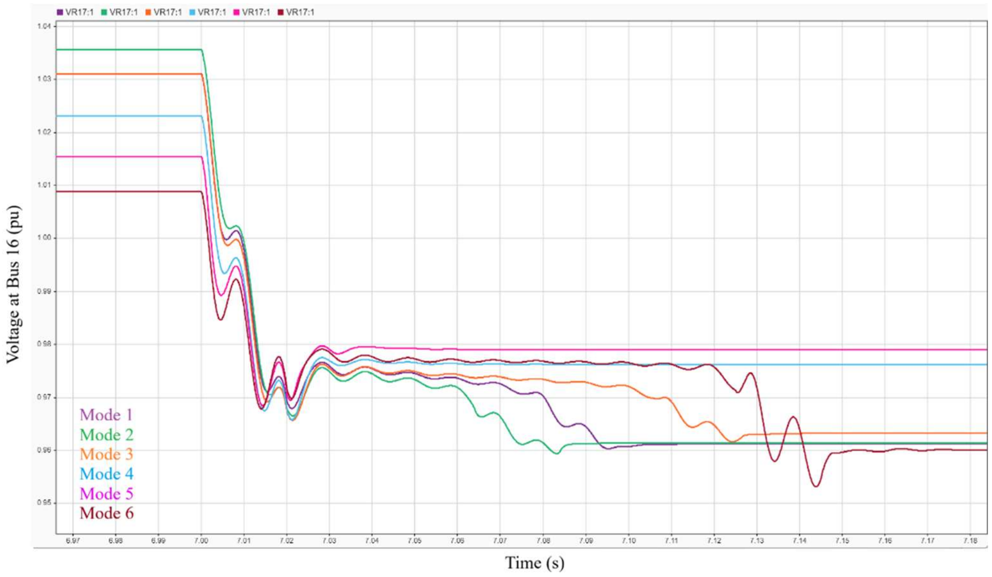

Figure 15 Volt-VAR Curve Interactions

Interpretation of the results (up to 400 words)

The experimental results obtained from both CHIL and PHIL studies validate the developed smart inverter control architecture and demonstrate its readiness for practical hardware deployment. The CHIL results first confirm the mathematical correctness, real-time feasibility and stable implementation of the various grid-support control modes. The exact phase alignment between voltage and current waveforms at CPF mode with unity power factor verifies the correct decoupling of active and reactive components in the dq reference frame. This confirms that the reactive power reference computation and inner current control loops operate as intended.

In CRP mode, the observed lagging and leading current behaviour corresponding to inductive (+0.6 pu) and capacitive (−0.6 pu) settings validates the sign convention, reference generation logic and reactive current regulation performance. The smooth and symmetrical transition between inductive and capacitive operation further indicates robust coordination and stable controller dynamics.

The FFT analysis further supports these conclusions by demonstrating the dominance of the 50 Hz fundamental component and effective suppression of harmonic content. This indicates that the PWM strategy, LCL filter design and current control bandwidth are appropriately tuned and that the control architecture does not introduce undesirable low-frequency oscillatory modes.

The PHIL results provide additional confirmation under real power hardware conditions. The PLL synchronization test shows accurate phase tracking prior to grid connection, ensuring safe and stable synchronization. Following connection, the balanced three-phase PCC voltages and currents confirm stable closed-loop grid-following operation even in the presence of physical converter dynamics.

Beyond single-inverter validation, the studies also highlight the interaction effects arising from different control modes and Volt-VAR curve selections in a multi-inverter environment. When multiple smart inverters operate simultaneously on the feeder, variations in control priorities and Volt-VAR characteristic curves significantly influence local voltage profiles, transient recovery and steady-state regulation. The observations show that stronger or earlier reactive power support from certain Volt-VAR curves leads to improved voltage stabilization, while other curve selections may introduce slower recovery or increased oscillatory behaviour due to coordinated reactive power responses among inverters. These findings emphasize the importance of coordinated controller tuning for reliable multi-inverter operation.

Main achievements during the TA related work (up to 250 words)

The successful configuration, commissioning and experimental validation of smart inverter control functionalities using both CHIL and PHIL platforms. The Taraz configurable inverter was operated in grid-following mode under reduced (35 V L–N RMS) and nominal (120 V L–N RMS) voltage conditions, ensuring safe hardware integration.
Another key contribution was the investigation of multi-inverter interaction phenomena in a distribution feeder environment. By deploying multiple smart inverters with different control modes and Volt–VAR characteristic curves, the studies demonstrated how inverter configuration choices such as power priority, Volt–VAR slope selection and active power limitation strategies directly influence feeder voltage regulation, transient recovery behaviour and steady-state coordination.

Key outputs include:

- A high-fidelity real-time EMT smart inverter model with experimentally validated embedded control implementation.
- Validated PHIL benchmark for CPF and constant-Q modes.
- Study of control-mode and Volt–VAR interaction effects on multi-inverter setup on a CIGRE LV distribution network.
- Verified synchronization performance, harmonic behaviour and stable multi-inverter operation.

This work establishes a strong experimental foundation for future research on coordinated distributed energy resource control and large-scale smart inverter deployment in modern distribution networks.

Data Management

All project data, including EMT models, controller firmware, calibration files and real-time CHIL/PHIL waveform recordings are stored on our local computers with backup copies maintained for redundancy. The developed models are held by Gokul Krishnan S and have been shared with ICCS-NTUA laboratory members for collaborative use and future experimental studies. The person responsible for data management, storage integrity and controlled access is Gokul Krishnan S, ensuring compliance with institutional data policies and long-term research usability.

Difficulties during the TA related work (up to 250 words)

The main challenge encountered during the TA period was ensuring safe experimental operation while commissioning and validating the smart inverter control functions in a real-time hardware environment. To mitigate potential safety risks associated with grid-following operation and controller tuning, the experiments were initially conducted at reduced voltage levels. Operating the inverter at 35V L-N RMS voltage enabled careful verification of synchronization performance, protection sequences and closed-loop current control stability without exposing the hardware or laboratory personnel to elevated electrical hazards. This validation approach allowed systematic testing of key functionalities such as PLL locking, precharge behavior, current reference tracking and mode transitions under controlled conditions. Once stable performance was confirmed, the inverter was progressively operated closer to nominal voltage levels for extended testing till 120V L-N RMS.

Intended publications

The outcomes of this project will be extended towards a coordinated multi-inverter control framework, building upon the experimentally validated smart inverter toolbox developed during the TA period. The toolbox is planned to be made open source to support reproducible research and broader academic collaboration.

Future work will focus on multi-inverter interaction studies and centralized coordination strategies, with results targeted for publication in IEEE PES Transactions and leading IEEE PES international conferences.

Expected impact

The validated smart inverter toolbox and the CHIL–PHIL experimental methodology developed in this project are expected to significantly advance future research on multi-inverter interaction, coordinated control and inverter-dominated distribution grids. By systematically bridging high-fidelity modeling with real hardware validation, the work provides a reliable framework for studying how different control modes, power-priority strategies and Volt–VAR curve configurations influence feeder voltage regulation, stability and inverter–inverter coordination. The interaction studies conducted in this work offer valuable benchmark insights into the dynamic behaviour of multiple smart inverters operating on the same feeder, highlighting the importance of coordinated controller tuning for secure and efficient grid operation. Such validated datasets and methodologies can support the development of next-generation control strategies for high renewable penetration scenarios. The planned open-source release of the developed models, control structures and experimental procedures will foster stronger collaboration and improve research competitiveness within the power systems community. Furthermore, future extensions toward large-scale coordinated inverter control and interaction-aware grid-support strategies may contribute to European standardization efforts, enable more sustainable renewable integration and create pathways for commercialization of advanced grid-support-capable inverter technologies.

Conclusions / additional comments

This project successfully developed and experimentally validated a smart inverter control architecture using an integrated CHIL–PHIL workflow. The study demonstrated accurate real-time implementation of key grid-support functionalities, including CPF, CRP, Volt–VAR and Volt–Watt modes, with stable synchronization, low harmonic distortion and reliable hardware operation. The strong agreement observed between EMT simulation results and power hardware measurements confirm both the robustness of the developed control framework and the fidelity of the real-time modeling approach. In addition to single-inverter validation, the work also investigated multi-inverter interaction effects, showing how different control modes, reactive power priorities and Volt–VAR characteristic curves influence feeder voltage regulation and coordinated inverter behaviour. These findings highlight the practical importance of coordinated control strategies in inverter-rich distribution systems. Overall, the project establishes a solid experimental foundation and benchmark for future research on interaction-aware smart inverter deployment and coordinated operation in modern power networks.

Did you complete the European Commission User questionnaire https://ec.europa.eu/eusurvey/runner/RIsurveyUSERS?

✓ *Yes* ☐ *No*

Feedback – HSE, Ethics and Satisfaction

Please rate on a scale from 1 (excellent) to 5 (poor). Feel free to provide additional comments

Practical information on how to apply for Transnational Access and the overall application process	1 (excellent)	2	3 (neutral)	4	5 (poor)
	✓	☐	☐	☐	☐

Comment

Information provided, once your project was accepted, on how to proceed	1 (excellent)	2	3 (neutral)	4	5 (poor)
	✓	☐	☐	☐	☐

Comment

Support received at the site(s) regarding technical/scientific matters and logistics	Have you got sufficient support from the RI staff during the project? If not, please, specify the problems. ✓ *Yes* ☐ *No*
Please specify any problems	
RI extension / upgrades required	In your opinion, is the RI needed to be upgraded? If yes, please give an explanation. ✓ *Yes* ☐ *No*
Some equipment's need to be purchased like three-phase power grid amplifier, bi-directional DC source, three-phase AC load and a good oscilloscope.	
Problems with local regulations	Have you had any problems with regulations of the visited RI owner (HSE, lab working hours, etc.)? If yes, please, specify ☐ *Yes* ✓ *No*
Please specify	
Health and safety issues	Did you encounter any health or safety issue during your research? Please provide details. ☐ *Yes* ✓ *No*
Please provide details	
Environment & Ethics	Did your research involve the use of elements that may cause harm to the environment, to animals or plants? Please provide details. ☐ *Yes* ✓ *No*
Please provide details	
Environment & Ethics	Did your research deal with endangered fauna and/or flora and/or protected areas? Please provide details. ☐ *Yes* ✓ *No*
Please provide details	
Environment & Ethics	Did your research involve the use of elements that may cause harm to humans, including research staff? Please provide details. ☐ *Yes* ✓ *No*
Please provide details	
Environment & Ethics – Dual use	Does your research have the potential for military applications? Please provide details. ☐ *Yes* ✓ *No*
Please provide details	

Environment & Ethics – Misuse	Does your research have the potential for malevolent /criminal/terrorist abuse? Please provide details. ☐ *Yes* ✓ *No*

Please provide details

Environmental issues	Were any potentially dangerous substances (materials / gases etc.) released into the environment (atmosphere, water, or land)? Please provide details. ☐ *Yes* ✓ *No*

Please provide details

Ethics issues	Are there any other ethics issues that should be taken into consideration? Please specify ☐ *Yes* ✓ *No*

Please provide details

Overall impression of communication and interaction after finishing your TA and related work

1 (excellent)	2	3 (neutral)	4	5 (poor)
✓	☐	☐	☐	☐

Comment

Suggestions for facilities not included in RISEnergy which you would use for your research

Three-phase Power Grid Amplifier, Bi-directional DC Source, Three-phase AC Load and A Good Oscilloscope

Suggestions how RISEnergy can improve future TA programme, how to make the TA more impactful and how to enable the achievement of high TRL levels

[Your suggestions]

Feedback – Pro-active Innovation Support

Awareness	Did you know about the pro-active innovation support of RISEnergy? ☐ Yes ☒ No

[Please specify how you learned about the pro-active innovation support]

<table>
<tr><td>Personal experience</td><td>Have you taken advantage of or benefited from the pro-active innovation support?
☐ Yes ☒ No</td></tr>
<tr><td colspan="2">[Please provide details]</td></tr>
<tr><td>Information/service provided by the pro-active innovation support?</td><td><table>
<tr><td>1 (excellent)</td><td>2</td><td>3 (neutral)</td><td>4</td><td>5 (poor)</td></tr>
<tr><td>☐</td><td>☐</td><td>☐</td><td>☐</td><td>☐</td></tr>
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I declare that the above provided information and especially that information on the number of days visited the RI is correct.

☒ *I have read the [RISEnergy privacy policy] for participation in the RISEnergy TA and consent to participation and the associated data processing.*

Your full name:

Your signature: