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Technical Report Lab Access User Project

## POwer sharing for Low-inertia Assets in Renewable-based Inverter Systems (POLARIS)

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# List of Abbreviations

| | |
|---|---|
| **AC** | Alternating Current |
| **BESS** | Battery Energy Storage System |
| **CTE** | Cumulative Tracking Error |
| **DC** | Direct Current |
| **DER** | Distributed Energy Resource |
| **DRTS** | Digital Real-Time Simulation |
| **EMS** | Energy Management System |
| **ERCOT** | Electric Reliability Council of Texas |
| **IBR** | Inverter-based Resources |
| **IDPS** | Inverter-dominated Power System |
| **LV** | Low-Voltage |
| **LVAC** | Low-Voltage AC |
| **LVDC** | Low-Voltage DC |
| **PCC** | Point of Common Coupling |
| **PE** | Power Electronically |
| **PHIL** | Power Hardware-in-the-Loop |
| **PLL** | Phase-Locked Loop |
| **PV** | PhotoVoltaic |
| **RTDS** | Real-Time Digital Simulator |
| **SG** | Synchronous Generation |
| **SPM** | Set Point Modulation |
| **TVI** | Threshold Virtual Impedance |
| **VPP** | Virtual Power Plant |
| **VSC** | Voltage Source Converter |

# Executive Summary

The scope of this technical report is to briefly present an overview of the POLARIS Lab Access project and highlight its research objectives, and research methodologies. In addition, this report outlines the main test procedures, the experimental setup leveraged for this Lab Access, along with the key research outcomes. A summary of this Lab Access is provided at the end of this report.

# 1 Lab-Access User Project Information

## 1.1 Overview

| USER PROJECT | |
|---|---|
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| **USER GROUP** | |
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| Organization, Country | Virginia Tech, United States (US) |
| **HOST Laboratory** | |
| Name | Dynamic Power System Laboratory (DPSL) |
| | University of Strathclyde |
| Country | United Kingdom (UK) |
| Start and End Dates | 03/12/2021 to 11/12/2021 (Part 1) |
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## 1.2 Research Motivation, Objectives, and Scope

In the modern power industry, due to the varied response characteristics of participating individual Distributed Energy Resource (DER), the cumulative response at the Point of Common Coupling (PCC) may exhibit poor dynamic behavior. This can be in the form of slow aggregated cumulative response, oscillations representative of lightly damped response, or unexpected overshoots. Coordinating the response characteristics of individual DER to improve the cumulative dynamic response during frequency events is desirable, particularly for systems with low inertia. Some studies have explored the composition of a Virtual Power Plant (VPP), i.e., the optimal sizing and siting of DERs through analytical (Aien et al., 2014), numerical (Khalesi et al., 2011), and heuristic (Abdelaziz et al., 2015) methods. The power allocation problem for varied applications (including VPPs) has been discussed, where the response speeds of DERs are taken into design consideration (Trovão et al., 2015; Song et al., 2019). This enables effective utilization of participating DERs characteristics to support set point regulation. However, the limitations of such approaches include: (i) the requirement of operational knowledge of the participating DERs, (ii) being an offline approach that does not take DERs response as feedback and therefore is only able to improve the speed of response but not eliminate any other undesired dynamic behaviors, and (iii) can be computationally expensive, which in turn limits the real-time application of the approach. These recognized research gaps motivate us to develop an approach to ensure dynamically robust set point regulation as a VPP.

The research objective of this Lab Access project is to create and execute experiments to evaluate, design, and improve new control and power-sharing architecture for a massively inverter-dominated power system. The electric power system, once dominated by traditional Synchronous Generation (SG), is experiencing a shift toward an increased share of Power Electronically (PE) interfaced distributed generation. This shift is mainly due to the increased integration of renewable energy resources, such as wind and PhotoVoltaic (PV) solar, which use PE-based inverters, also known as Inverter-based Resources (IBR). For example, in Ireland, the operators are expected to accommodate up to 75% instantaneous IBR generation. Such an operation scenario is likely to be more frequent in the future and merits attention. In previous work, (i) we have discussed reliability implications of angle droop without an associated explicit communication link for nominal frequency operation; and (ii) we have proposed a power-sharing algorithm that allows IBRs to deviate from their locally determined set points to participate in real power sharing once needed. These algorithms enable IBRs to participate in power-sharing based on an angle droop method that explicitly takes into account its ratings and preferred set points. The advantages of our proposed method, compared with the state of the art, include (i) unlike conventional droop, it results in an essentially constant-frequency operation without relying on secondary controllers, and (ii) it does not need communication for frequency restoration. In this project, the performance of the proposed architecture in different operating conditions will be evaluated via extensive experimental studies as enabled through the ERIGrid 2.0 Lab Access program. Our expected outcomes include,

- A report comparing the results obtained from our proposed angle droop-based method with those of other methods, including conventional droop.
- Guideline on best practices for implementation of the proposed power-sharing method.
- Scientific publications, including journal and conference papers, to disseminate our research outcomes and experimental results.

## 1.3 Structure of the Document

This document is organized as follows: Section 2 briefly outlines the state-of-the-art/state-of-technology that provides the basis of the POLARIS Lab Access user project. Section 3 briefly outlines the performed experimental setup along with the test plan, test procedures, and the methodologies exploited for experimental performance evaluation. Furthermore, Section 4 presents experimental results analysis and concludes this Lab Access project. Potential open issues and suggestions for improvements are discussed in Section 5.

# 2 State-of-the-Art/State-of-Technology

The electric power system is experiencing a shift toward an increased share of power electronically interfaced generation (Kroposki et al., 2017). This shift is mainly due to the increased integration of renewable energy resources, such as wind and PV solar (Eftekharnejad, Vittal, Heydt, Keel, & Loehr, 2013), which use PE-based inverters, also known as IBRs. For example, in Ireland, the operators are expected to accommodate up to 75% instantaneous inverter-based generation. In the United States, the Bonneville Power Administration service area has several times experienced 100% wind generation at night; the Electric Reliability Council of Texas (ERCOT) system had instances of 50% instantaneous penetration of wind. In Tasmania, the power system routinely experiences more than 70% instantaneous inverter-based generations (Kroposki et al., 2017).

This shift toward inverter-based resources brings about significant challenges in power system dynamics, stability, and control (Eftekharnejad et al., 2013). Most existing inverters are programmed to inject a certain value of power irrespective of the conditions of the grid. This mode of operation is termed grid following as the inverter synchronizes to the grid voltage ("follows the grid") via a Phase-Locked Loop (PLL) and normally operates as a controlled current source. However, the grid-following mode of operation is not adequate for an Inverter-dominated Power System (IDPS). This is because a PLL needs a relatively stiff voltage and frequency. While this requirement is normally met in a conventional SG-based power system, it may not be available in an IDPS. Therefore, some inverters may need to operate in a different mode, called grid forming, to control the voltage and frequency of their buses. In microgrid terminology, a similar objective is achieved using master and slave inverters (D. E. Olivares et al., 2014; Yazdanian & Mehrizi-Sani, 2014). In both cases, it is imperative to ensure power sharing among all inverters, i.e., coordinating dispatchable generation resources to meet the power demand under varying conditions.

In a conventional power system, power sharing is typically based on frequency droop, which stems from a synchronous generator's intrinsic relation between power (generation/load mismatch) and frequency (rotor speed) (Mousavi, Teymouri, Shabestari, & Mehrizi-Sani, 2019). This power-frequency droop can also be adopted for an IDPS via inverter controls. For example, (Arani & El-Saadany, 2013) discusses the control of inverters as a virtual SG, where the fundamental swing and electromechanical transient equations of an actual SG are implemented in the control logic. The advantage of this approach is that the IBR can use a similar controller as SG-based units. Frequency droop may also be employed for a 100% inverter-based system. For example, (Ramasubramanian, Vittal, & Undrill, 2016) demonstrates the applicability of frequency droop to operate an all-inverter North American interconnection. The European MIGRATE project (Guillaume, Thibault, Marie-Sophie, Florent, & Andreas, 2018) proposed an inverter control structure using the concept of Threshold Virtual Impedance (TVI). TVI improves the transient behavior of droop control but needs a secondary controller to restore the frequency to its nominal value. To obviate the need for a secondary controller, (Yazdanian & Mehrizi-Sani, 2016) proposes power-sharing of inverters based on their frequency transients; however, it assumes a stiff grid and does not handle power sharing for inverters connected after the transient.

In general, frequency droop (i) is a steady-state concept and does not explicitly deal with fast transients including those of inverters; and (ii) introduces a steady-state error in the frequency and needs a secondary controller to restore the frequency. In addition, in a 100% inverter-based system, the notion of frequency is relevant only for electrical quantities (rate of change of voltage angle) as there is no rotor to define mechanical frequency. Therefore, in such systems, the relevance and importance of frequency is not well-understood nor well-established. Based on this observation, the authors of (Ramasubramanian, Farantatos, Ziaeinejad, & Mehrizi-Sani, 2018) proposed a constant-frequency operation paradigm based on angle droop (Kolluri et al., 2017a) and discussed its reliability implications. In angle droop, power sharing is achieved by changing the angle of the terminal voltage of IBRs. References (Moussa, Shahin, Martin, Pierfederici, & Moubayed, 2018; Kolluri et al., 2017b) implemented angle droop for a parallel set of inverters connected to the same PCC in a microgrid via a series filter. However, it needs central coordination and a communication link to assign reference angles to the inverters. In (Kahrobaeian & Ibrahim Mohamed, 2015), angle droop is realized by an Energy Management System (EMS) that monitors the power flows and determines the reference set points for real and reactive power of the IBRs. If the communication link fails, the controller reverts to frequency droop. Reference (Majumder, Ledwich, Ghosh, Chakrabarti, & Zare, 2010) proposes angle droop for a power system; however, it does not consider different modes of operation of inverters and their current and real power limits during both transient and steady-state operations. Therefore, designing an angle droop controller for the power system merits more investigation to address these gaps.

The proposed Set Point Modulation (SPM) approach here utilizes our work in (Mousavi et al., 2019; Yazdanian & Mehrizi-Sani, 2016; Ramasubramanian et al., 2018; Ziaeinejad, Mousavi, Mehrizi-Sani, Ramasubramanian, & Farantatos, 2020) and experimentally evaluates our algorithm that allows the inverters to deviate from their locally determined set points to participate in real power-sharing once needed. The main contributions are as follows:

- A two-level coordinated SPM approach is proposed where the individual response characteristics of participating DERs are harnessed to provide an enhanced dynamic response at the PCC. The approach does not rely on prior knowledge of the participating DERs and is capable of robust set point regulation in real time, mitigating any undesired behavior in dynamic response. Furthermore, this approach is agnostic to the secondary-level control strategy and specifically how the reference set points are generated. Such effective control enables a greater potential for the participation of DERs in ancillary service provision, presenting a major benefit for DERs owners and aggregators.
- The proposed approach has been evaluated within representative Alternating Current (AC) and Direct Current (DC) networks independently, where the deployment of the proposed control is anticipated in the future to support frequency regulation in low-inertia power systems.
- The real-world applicability of the proposed approach is demonstrated by means of its validation using high-fidelity Power Hardware-in-the-Loop (PHIL) experimental setup at the Dynamic Power Systems Laboratory at the University of Strathclyde. This verifies the real-time operation of the proposed approach and its ability to deal with nonidealities that can be encountered when deployed in practice.

# 3 Executed Tests and Experiments

## 3.1 Test Plan, Standards, Procedures, and Methodology

This section outlines the applied test plan, used standards and procedures as well as the corresponding methodology of the Lab Access user project.

### 3.1.1 Test Standards, Procedures, and Plan

The superior performance and applicability of the proposed coordinated SPM control are demonstrated within a Low-Voltage AC (LVAC) network and a Low-Voltage DC (LVDC) microgrid. A DER in a microgrid can operate in grid-forming mode (Unruh, Nuschke, Strauß, & Welck, 2020) or in grid-following mode (PQ control mode (D. Olivares et al., 2014)). Grid-forming control modes are adopted to support islanded operation of the microgrid, while the majority of the DERs connected to the power grid operating in PQ control mode, controlling their real and reactive power outputs. The performance of the proposed coordinated SPM is therefore assessed for the following three scenarios within the context of Battery Energy Storage System (BESS) DER operating in PQ mode, and participating within a VPP for ancillary service provision.

- **Simultaneous Set Point Change:** This event represents a request of activation of reserves from a VPP distributed among the participating DERs. The assumption is that the request of activation is made at the same time, and therefore referred to as a simultaneous change in set point.
- **Staggered Set Point Change:** This event is complementary to the simultaneous change in set point where the activations are separated in time, i.e., the activation requests are sent at different points in time.
- **External Disturbance:** This represents a scenario where the performance of the control is assessed when the participating DERs are providing the requested reserves and the network is subject to a transient.

The performance of the proposed control is assessed in comparison to a reference controller without SPM. To further demonstrate the added value through the coordination, the performance is also benchmarked against the independent (level I only) implementation of SPM.

**Test Case A: LVAC Distribution Network**

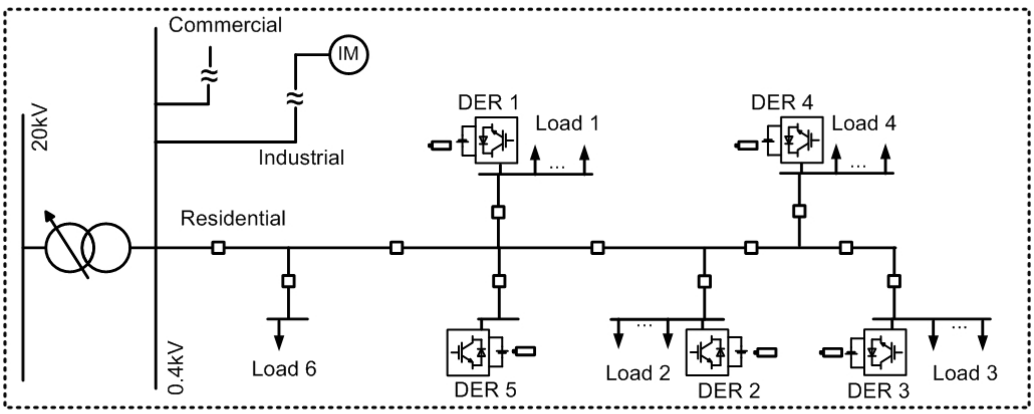


*Figure 1: LVAC distribution network.*

The CIGRE Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources is chosen as the test AC network, a simplified diagram of which is shown in Fig. 1 (Strunz et al., 2014). The network incorporates the important technical characteristics of public distribution networks with respect to its structure, symmetry, substation connection, protection, line types and earthing as detailed in (Papathanassiou, Hatziargyriou, & Strunz, 2010). The network comprises three feeders, residential, commercial, and industrial, tapped from an on-load tap changer with 5% regulation capacity at the primary side of 20 kV. The residential feeder is 0.4 kV overhead line serving a suburban residential area with six buses accommodating both single-phase and three-phase customers. The DERs at buses 1–4 are rated at 10kW each representing complementary storage installed to maximize energy utilization from PV. The DER at bus 5 represents an electric vehicle charging station, rated at its maximum power of 30 kW (fast charging). The following test scenarios will be tested and the associated experimental data will be collected during the lab access:

- **Simultaneous Set Point Change:** The performance for two changes in active power set point are evaluated, step up from 0 pu to 0.1 pu at $t = 0.5$ s and step down from 0.1 pu to 0 pu at $t = 2.5$ s.
- **Staggered Set Point Change:** The response of the system when staggered set point changes are issued to individual DER units has been analyzed with the three control approaches. The individual responses of the DER units to a step change in reference active power from 0 pu to 0.1 pu at $t = 4.5$ s for DER 1, at $t = 6.5$ s for DER 2 and DER 3 and a step change at $t = 8.5$ s for DER 4 and DER 5.
- **External Disturbance:** Irrespective of the network condition, strict power regulation is expected by the VPP due to the fact that in most cases the services of a VPP are requested for critical ancillary service provision. Therefore, when subject to an external disturbance, the participating DERs of the VPP are expected to continue the provision of the requested amount of power; however, due to the severity of the transient, the control of the DER might struggle to ensure regulation at the set point. The connection of the induction motor at the industrial feeder is the external disturbance under consideration. As no step change in the reference set point is issued, the maximum deviation from the set point $x_{\text{dev}}$ is calculated as the key indicator instead of the overshoot.

**Test Case B: LVDC Microgrid**

An LVDC network representative of the last mile distribution network interconnection as proposed in (Emhemed & Burt, 2014) and utilized in (Wang, Psaras, Emhemed, & Burt, 2021; Wang, Emhemed, & Burt, 2019) has been adapted for this study. The DC microgrid is interfaced with an AC grid through a two-level Voltage Source Converter (VSC). The VSC provides $\pm$0.375 kV DC pole-to-pole voltage at PCC. The DC microgrid supplies end users through dual active bridge converters with four buses. The DERs at buses 1-4 are rated at 20 kW, 25 kW, 15 kW, and 20 kW, respectively, each representing energy storage technology (e.g., PV or Electric Vehicle)

For the DC microgrid as presented in Fig. 2, the same scenarios are considered, simultaneous step up and simultaneous step down are applied at $t = 0.3$ s and $t = 0.32$ s, staggered set point change is applied at $t = 0.35$ s, and external disturbance is applied at $t = 0.43$ s.

**Test Case C: PHIL Aided Microgrid Experimental Validation**

To demonstrate the real-world applicability of the proposed approach and to appraise its technology readiness level, a rigorous validation through high fidelity PHIL experimental setup will

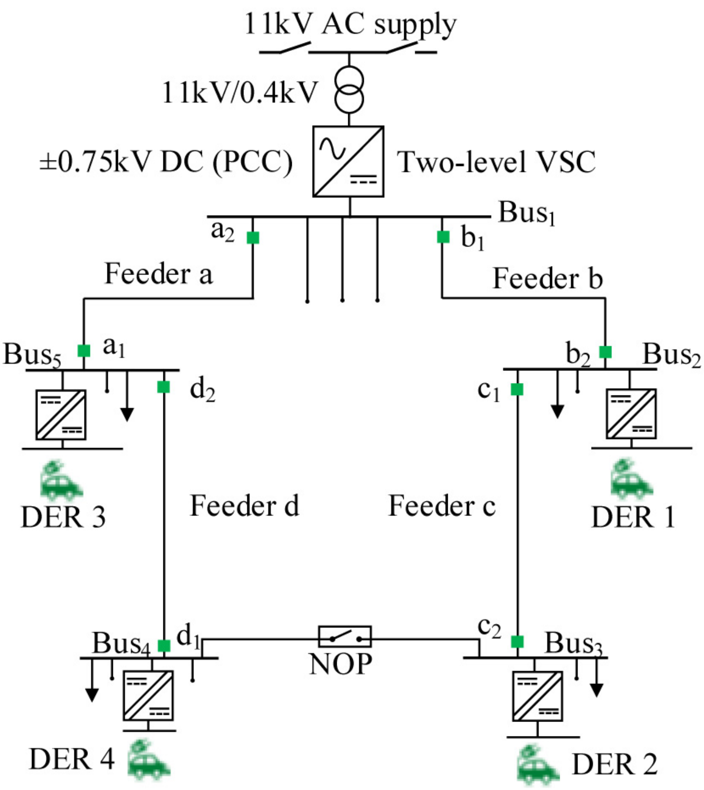


*Figure 2: LVDC microgrid under investigation.*

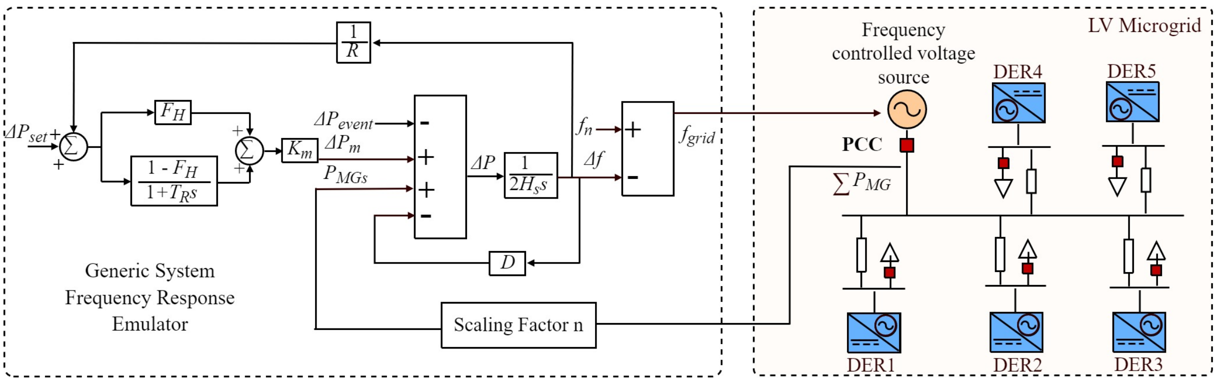


*Figure 3: Illustration of frequency regulation study incorporating generic frequency response emulator for PHIL test.*

be undertaken to repeat the test scenarios as listed in Test Case A and Test Case B. The system under test for the PHIL real-time testing is illustrated in Fig. 3.

**Test Case D: Experimental Validation of the Applicability in Grid Frequency Regulation**

The advantage of the proposed approach in the frequency regulation of a transmission network is demonstrated. A generic system frequency response model, tuned to reproduce Great Britain transmission network dynamics (Hong et al., 2019), is employed to emulate representative frequency response. The frequency from the emulator is used as an input for a frequency controlled voltage source connected to a Low-Voltage (LV) microgrid (adapted based on the

LVAC distribution network utilized in Test Case A) as shown in Fig. 3. The description and chosen values of the parameters of the generic system frequency response emulator are presented in Table 1, along with the adaptations to realize the LV microgrid from the LVAC distribution feeder.

*Table 1: Generic system frequency response emulator parameters*

| Variables | Description |
|---|---|
| $\Delta P_{set}$ | Synchronous generator change in power set point |
| $\Delta P_m$ | Change in mechanical power output |
| $\Delta f$ | Change in grid frequency |
| $f_{grid}$ | Grid frequency |

| Constants | Description | Value |
|---|---|---|
| $F_H$ | Fraction of power generated by the turbine | 0.1 |
| $T_R$ | Turbine reheat time constant | 4 s |
| $K_m$ | Mechanical power gain factor | 0.95 |
| $\Delta P_{event}$ | Change of power due to events | 100 MW |
| $H_s$ | Inertia constant | 2 s |
| $R$ | Droop constant | 0.05 |
| $D$ | Damping constant | 0.06 |
| $f_n$ | Nominal frequency | 50 Hz |

$^*H_s = H_0$ for the case study in Section V

A frequency event is emulated by introducing a power imbalance of 100 MW ($\Delta P_{event}$). The aggregators activate and request response from the DERs when the system frequency reaches the lower threshold of the operating frequency, i.e., 49.8 Hz. The sum of power response from the DERs ($\Sigma P_{MG}$) within the microgrid is scaled by a scaling factor $n$ and sent as an input to the generic system frequency response emulator. The active power response of the DERs and the consequent frequency profiles for the three cases, (i) no SPM, (ii) independent SPM, and (iii) coordinated SPM will be evaluated.

### 3.1.2 Performance Evaluation Methodology

To assist the performance evaluation of the proposed coordinated SPM and support the experimental validation of the Lab Access project, three key indicators have been defined:

- **Settling Time:** The time elapsed from when the signal of interest $x(t)$ digresses from within the defined error band $\epsilon$, subject to an external disturbance or a step change in the reference set point, to when $x(t)$ returns and remains within $\epsilon$ is referred to as the settling time $T_{\text{set}}$ and represented as:

$$T_{\text{set}} = \text{argmin}\{T_{\text{set}} \in \mathcal{R} \mid \forall\, t > T_{\text{set}} : x_{\text{band}}^{\text{upper}} < x(t) < x_{\text{band}}^{\text{lower}}\} \quad (1)$$

- **Overshoot:** Defining the maximum excursion of $x(t)$ subject to an external disturbance or after a step change in the reference set point as $x_{\text{max}}$, the overshoot is

$$x_{\text{os}} = \left| \frac{x_{\text{max}} - x_{sp}}{x_{sp}} \right| \quad (2)$$

- **Cumulative Tracking Error:** The sum of the tracking errors at every time step $T_s$ from the initiation of the external disturbance or step change in reference to the time when

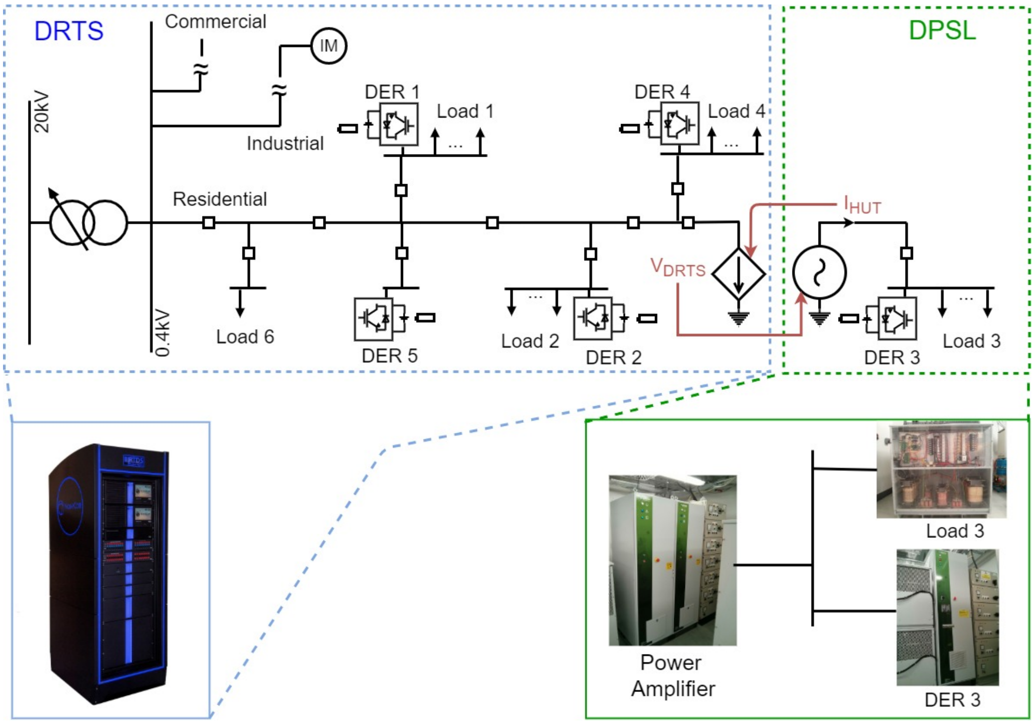


*Figure 4: PHIL implementation diagram.*

the measured output signal has settled (i.e., $T_{\text{set}}$) is referred to as Cumulative Tracking Error (CTE) calculated as:

$$S_e = \sum_{k=0}^{N} |x_{\text{sp}}[k] - x[k]| \tag{3}$$

where $N = T_{\text{set}}/T_s$. A smaller $S_e$ corresponds to better performance.

In this project, the performance of the proposed control is assessed in comparison to a reference controller without SPM. To further demonstrate the added value through the coordination, the performance is also benchmarked against the independent (level I only) implementation of SPM.

## 3.2 Test Set-up(s)

To demonstrate the real-world applicability of the proposed approach and to appraise its technology readiness level, a rigorous validation through high fidelity PHIL experimental setup has been undertaken at the Dynamic Power Systems Laboratory at the University of Strathclyde. The LVAC distribution network utilized for performance evaluation within Test Case A has been modified for PHIL experiment as shown in Fig. 4 in accordance with (Kotsampopoulos et al., 2018). The power system is split in two, DER 3 represented by 15 kVA four-quadrant converter emulating a BESS while the remainder of the network is simulated in real-time within the Digital Real-Time Simulation (DRTS) at a time step of 50 $\mu$s. The voltage measured at Bus 3 is reproduced within the laboratory using a 90 kVA four-quadrant power amplifier, also responsible for measurement of the response current and feed it back to the DRTS. The proposed control is incorporated within the real-time target used for hosting the control algorithm of the 15 kVA four-quadrant converter, operating with high fidelity measurements obtained at a sampling rate of 10 kHz. This presents a close to real-world implementation within a controlled environment, enabling validation that emboldens confidence in the proposed approach.

The performance of the hardware DER with conventional, independent and coordinated control approach subject to simultaneous step up, step down, staggered step change and external disturbance are emulated and implemented in this experimental setup.

## 3.3 Data Management and Processing

The experimental data is collected by using the data logging units in Real-Time Digital Simulator (RTDS) and Triphase converter and saved in the Onedrive folder to be shared between the Lab Access users and host laboratory staff. The key measurement data, such as frequency, voltage, and current of each DER are saved in .csv format and plotted using MATLAB.

# 4 Results and Conclusions

## 4.1 Discussion of Results-Test Case A: LVAC Distribution Network

As defined in the test plan section, the following test scenarios are performed and the key results are presented as follows:

**Simultaneous Set Point Change:**

The performance for two changes in active power set point is evaluated, step up from 0 pu to 0.1 pu at $t = 0.5$ s and step down from 0.1 pu to 0 pu at $t = 2.5$ s.

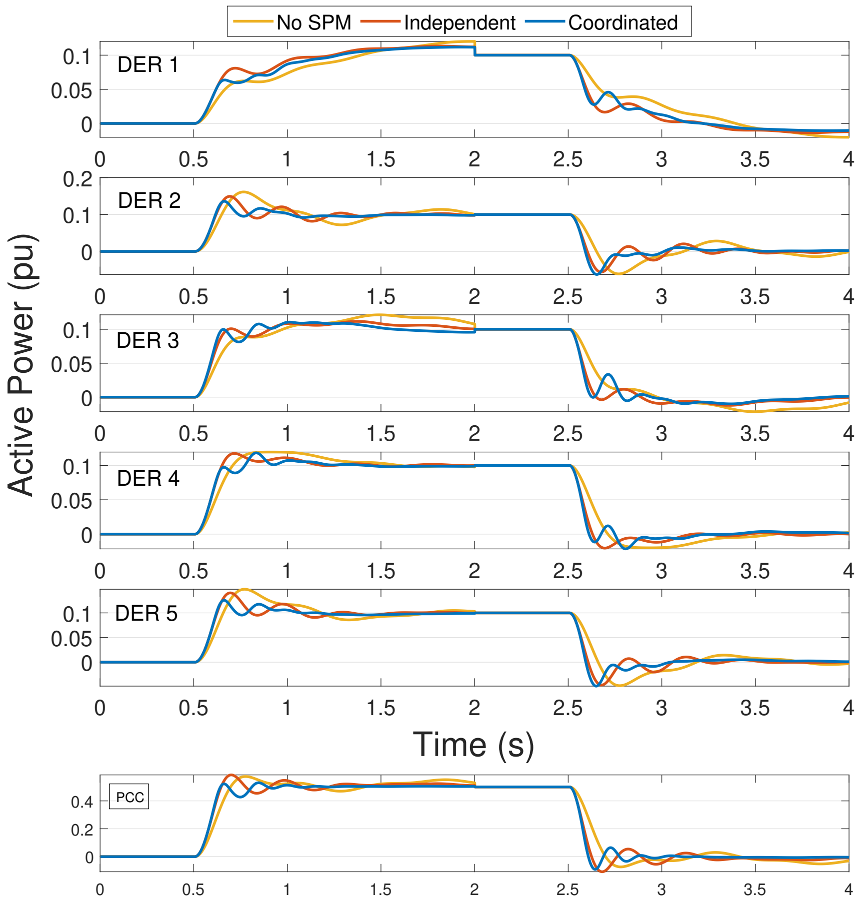


*Figure 5: Simultaneous set point change.*

The individual responses of the DERs are presented in Fig. 5 with the aggregated active power response at PCC presented in Fig. 6. As is evident, with no SPM each of the individual DERs present a relatively high overshoot with DER 2 exhibiting the highest overshoot of 61 %. Due to the varied responses of individual DER, the overshoot at the PCC is about 14.95 %. When independent SPM is incorporated, the individual DER response is improved in terms of both the overshoot and settling time, however, the overshoot at the PCC increases by about 2.3 %. With the incorporation of coordinated control, the response of individual DERs and the aggregated response at the PCC improves both in terms of overshoot and settling time. The CTE over time for a simultaneous step increase in reference active power set point is shown in Fig. 7 which further reinforces the improvement in dynamics introduced by the coordinated approach - a 100 % improvement compared to independent approach and 300 % compared to conventional approach with no SPM. Therefore, it can be said that an independent approach improves the local response of the individual DER while a coordinated approach ensures improved response at the PCC. From the perspective of a VPP, the individual response of a DER is of less value but an improved aggregated response with much tighter regulation in comparison to reference commands is critical.

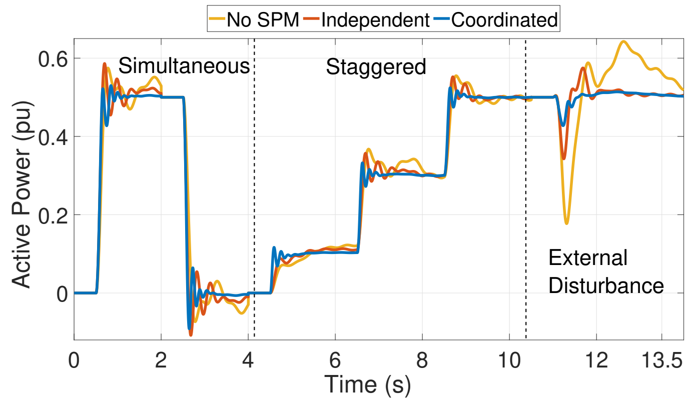


*Figure 6: Cumulative response at PCC.*

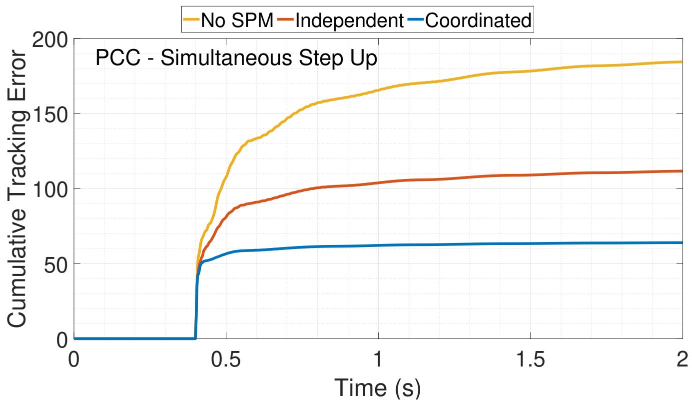


*Figure 7: CTE over time for simultaneous set point change - step up.*

**Staggered Set Point Change:**

The response of the system when staggered set point changes are issued to individual DER units has been analyzed with the three control approaches. The individual responses of the DER units to a step change in reference active power from 0 pu to 0.1 pu at $t = 4.5$ s for DER 1, at $t = 6.5$ s for DER 2 and DER 3 and a step change at $t = 8.5$ s for DER 4 and DER 5, are presented in Fig. 8 and the cumulative response at PCC in Fig. 6 (4 s−10 s). From Fig. 6 the distinctive improvement in tighter power regulation at the PCC is evident, however, it must be noted the DERs that do not receive a change in set point still contribute to power regulation. This reflects the coordination, where all the units work towards an improved dynamic performance at the PCC. The CTE for the three control approaches shown in Fig. 9 reveals a reduction of the error close to 50% when the coordinated algorithm is implemented in comparison with the independent approach for the staggered operation.

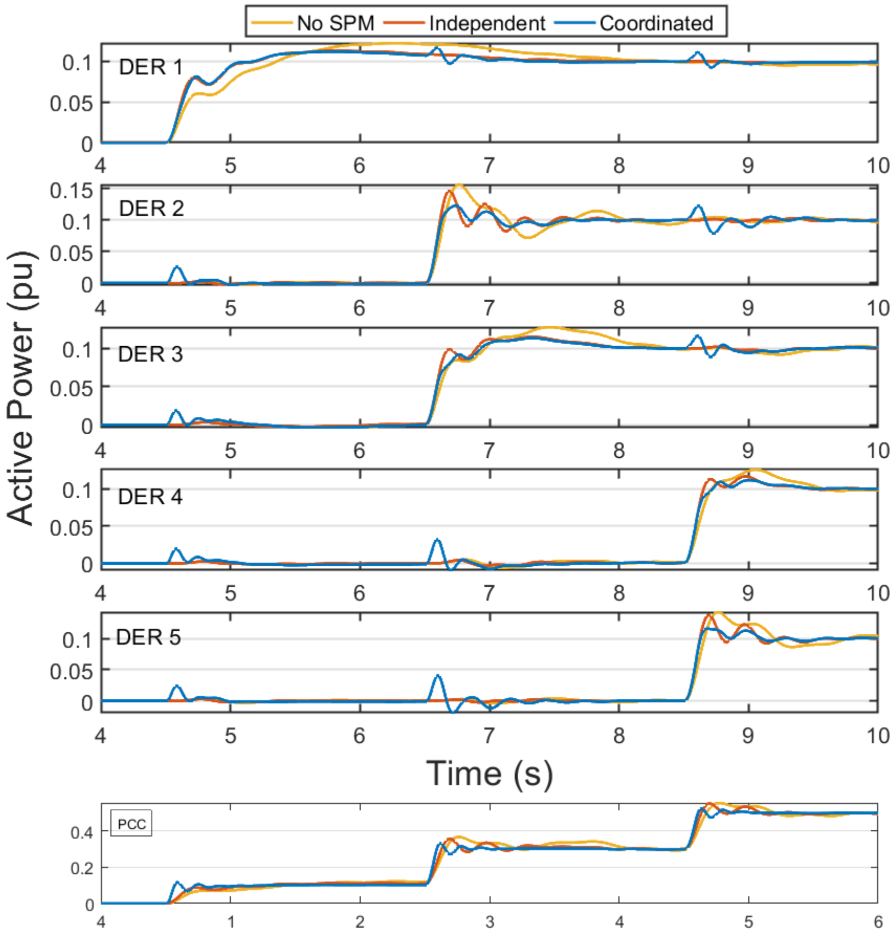


*Figure 8: Staggered set point change.*

**External Disturbance:**

Irrespective of the network condition, a strict power regulation is expected by the VPP due to the fact that in most cases the services of a VPP are requested for critical ancillary service provision. Therefore, when subject to an external disturbance, the participating DERs of the VPP are expected to continue the provision of the requested amount of power; however, due to the severity of the transient, the control of the DER might struggle to ensure regulation at the set point. The connection of the induction motor at the industrial feeder is the external disturbance under consideration. As no step change in the reference set point is issued, the maximum deviation from the set point $x_{dev}$ is calculated as the key indicator instead of the overshoot. The deviation in all the units can be seen from Fig. 10. This reveals that the approach without SPM suffers from instantaneous deviations from the set point of up to 87 %. These deviations can be controlled to 50 % with the use of the independent control approach and a further 5 %-15 % when the coordinated control is implemented. These can also be observed in a more general manner from Fig. 9, where the reduction in error is significant.

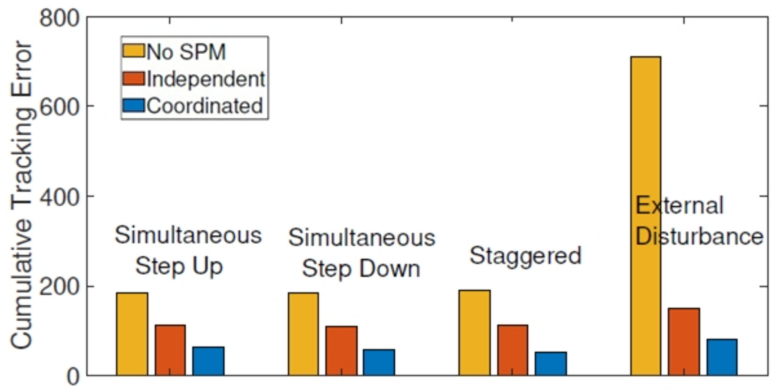


*Figure 9: CTE for scenarios under consideration.*

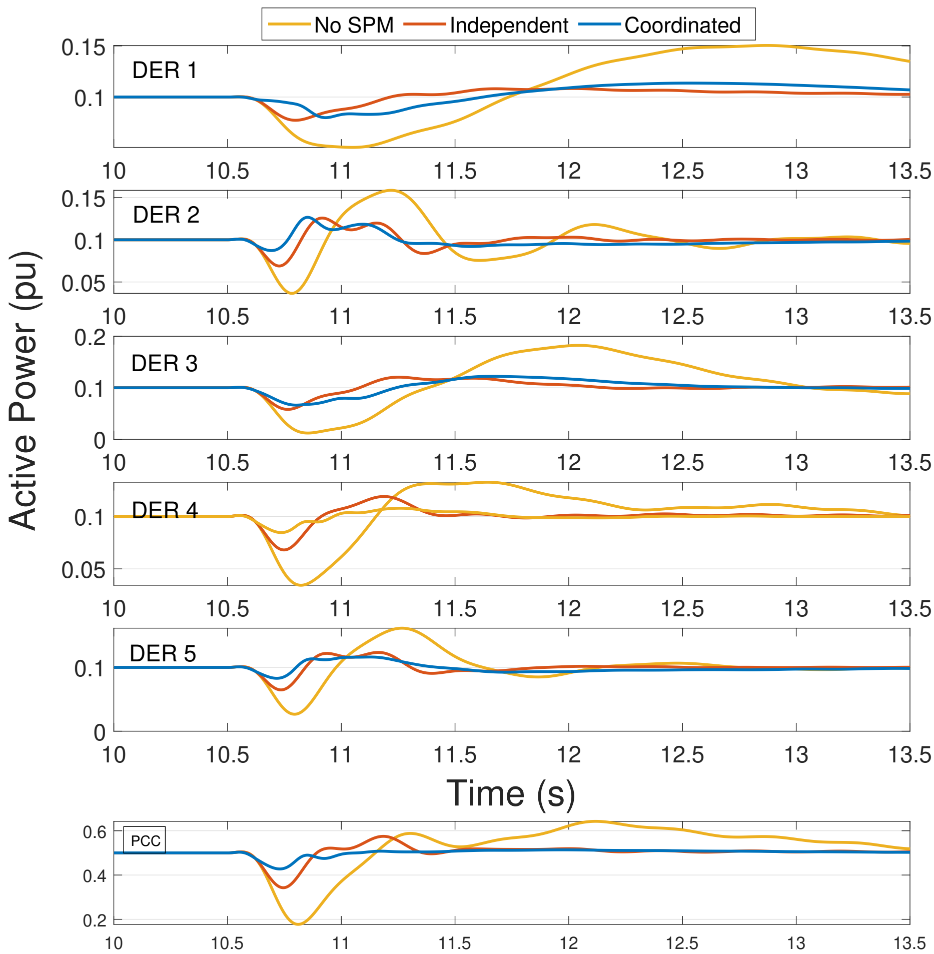


*Figure 10: External Disturbance.*

## 4.2 Discussion of Results-Test Case B: DC Microgrid

An LVDC network representative of last mile distribution network interconnection as proposed in (Emhemed & Burt, 2014) and utilized in (Wang et al., 2021, 2019) has been adapted for this study. The DC microgrid is interfaced to an AC grid through a two-level VSC. The VSC provides $\pm$0.375 kV DC pole to pole voltage at PCC. The DC microgrid supplies end users through dual active bridge converters with four buses. The DERs at buses 1-4 are rated at 20 kW, 25 kW, 15 kW, and 20 kW, respectively, each representing energy storage technology (e.g., PV or Electric Vehicle)

For the DC microgrid, the same scenarios are considered, simultaneous step up and simultaneous step down are applied at $t = 0.3$ s and $t = 0.32$ s, staggered set point change is applied at $t = 0.35$ s, and external disturbance is applied at $t = 0.43$ s. The individual responses of the DERs along with the aggregated active power response at the PCC are presented in Fig. 11.

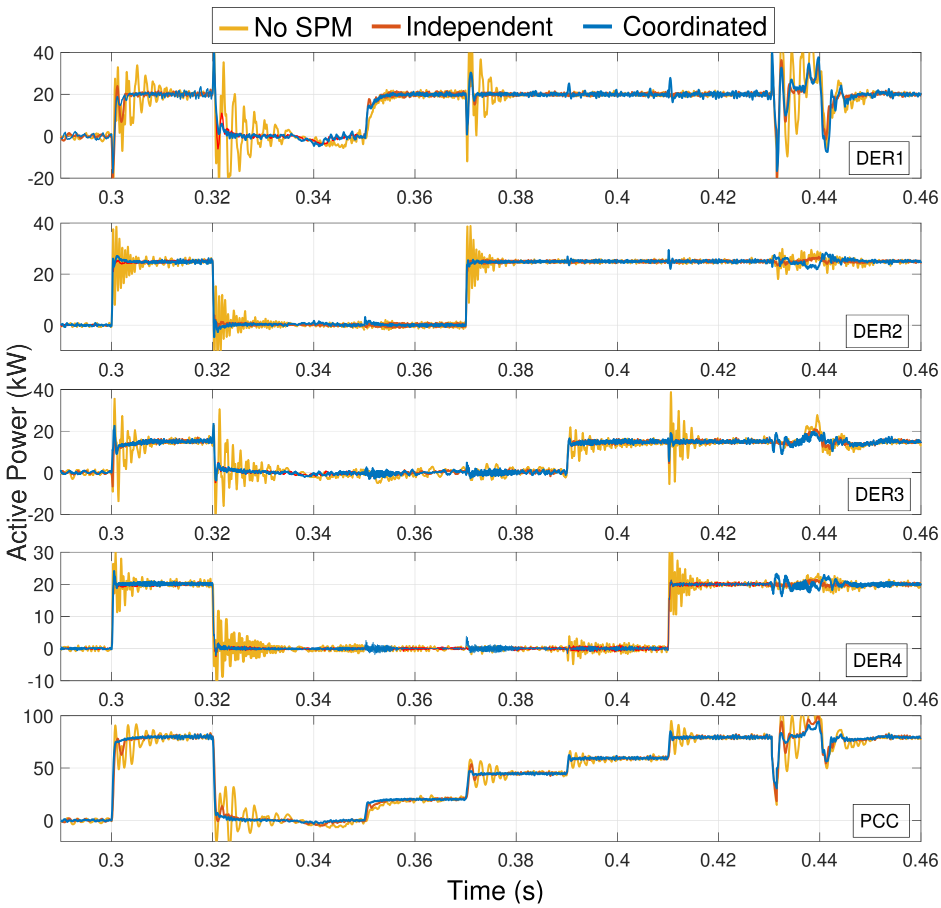


*Figure 11: Performance evaluation within a DC microgrid.*

In the simultaneous set point change scenario, with no SPM, each DER has a relatively high overshoot, especially DER 3 with the highest overshoot of 133.5%. With the implementation of independent SPM, the individual response of DERs is improved in terms of overshoot and settling time, resulting in a reduction of overshoot at PCC from 38.89% to 0%. When the coordinated control is incorporated, a similar reduction in overshoot at PCC is achieved in addition to smaller CTE as shown in Fig. 12, a 66.3% and 33.88% reduction compared to the cases without SPM and with independent SPM respectively.

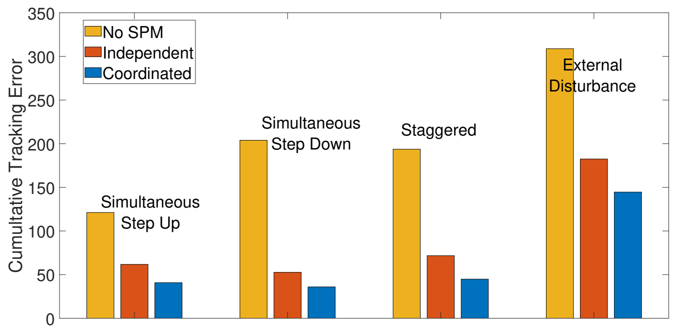


*Figure 12: CTE for scenarios under consideration - DC microgrid.*

For the staggered change in set point, each DER unit receives a step change request of 0 to their rated power - at $t = 0.35$ s for DER 1, $t = 0.37$ s for DER 2, $t = 0.39$ s for DER 3, and $t = 0.41$ s for DER 4 as shown in Fig. 11. Compared to the same scenario without SPM, implementation of independent SPM and coordinated SPM yields 3.4 %-50.4 % overshoot reduction, at the same time a 63 % and 76.9 % reductions in cumulative tracking error as shown in Fig. 12. The improvement of the dynamic response is also reflected in an external disturbance that is applied at $t = 0.43$ s.

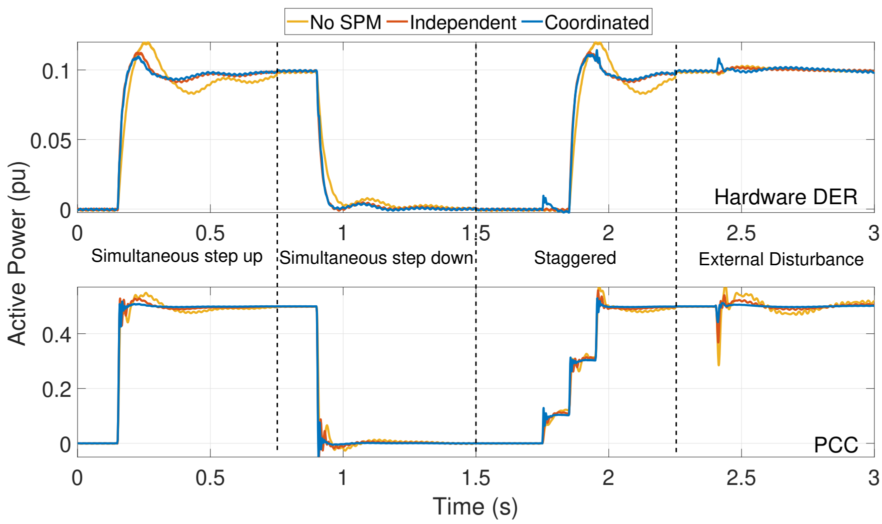


*Figure 13: PHIL evaluation results.*

## 4.3 Discussion of Results-Test Case C: PHIL Aided Microgrid Experimental Validation

The performance of the hardware DER with conventional, independent and coordinated control approach subject to simultaneous step up, step down, staggered step change and external disturbance are presented in Fig. 13 (top). The cumulative power response at the PCC is shown in Fig. 13 (bottom). The results are in conformance with the results discussed in Sections IV-A and IV-B, with level I only and coordinated approach demonstrating enhanced dynamic response in terms of overshoot and settling time. The CTE for cumulative power response at

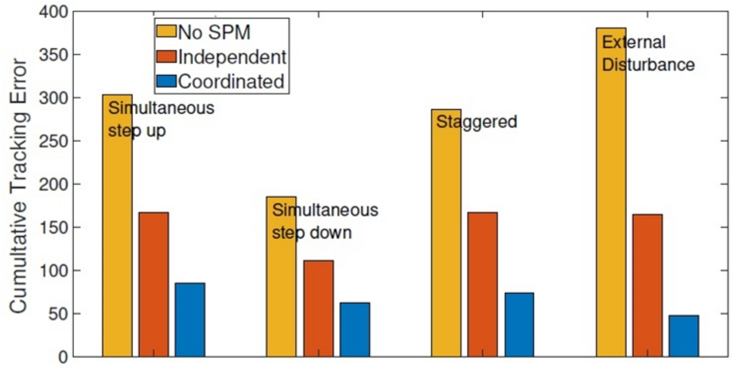


*Figure 14: CTE for scenarios under consideration - PHIL.*

the PCC is shown in Fig. 14 where the advantage of the proposed approach is clearly brought forward.

The PHIL evaluation therefore demonstrates the capability of the proposed approach to (i) be synthesized within a micro-controller for operation in real-time, and (ii) deal with non-ideal conditions such as measurement noise.

## 4.4 Discussion of Results-Test Case D: Experimental Validation of the Applicability in Grid Frequency Regulation

A frequency event is emulated by introducing a power imbalance of 100 MW ($\Delta P_{event}$). The aggregators activate and request response from the DERs when the system frequency reaches the lower threshold of the operating frequency, i.e., 49.8 Hz. The sum of power response from the DERs ($\Sigma P_{MG}$) within the microgrid is scaled by a scaling factor $n$ and sent as input to the generic system frequency response emulator. The active power response of the DERs and the consequent frequency profiles for the three cases, (i) no SPM, (ii) independent SPM, and (iii) coordinated SPM is presented in Figs. 15 and 16 respectively. In addition, the sensitivity of the approach to changing system inertia is evaluated by incorporating three different values of inertia. For the coordinated SPM approach, a communications delay of $Td = 0.5$ ms is incorporated.

As can be observed from Fig. 15, the improvement in active power response of the microgrid with the incorporation of independent and coordinated SPM is evident under all inertial values considered. Consequently, the independent and coordinated SPM approaches improve the dynamic frequency response of the transmission system as shown in Fig. 16. Particularly of interest is the case when $H = 0.5H_0$ (representative of future power system with reduced inertia), the no SPM and independent SPM approaches fail to regulate the frequency within the statutory limits defined as [49.5, 50.5] Hz. By coordinating the response of two fast-acting DERs within each of the microgrid (constituting to 40% proportion), the coordinated SPM approach is capable of regulating the frequency within the statutory limits. This demonstrates the valuable role the proposed approach can play in the future ancillary service provision market within a renewable-rich power grid.

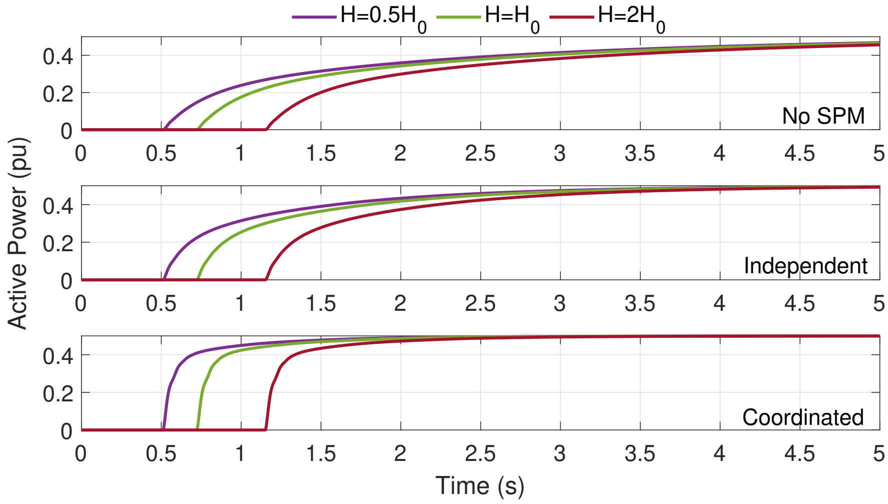


*Figure 15: Sum of active power responses of DER.*

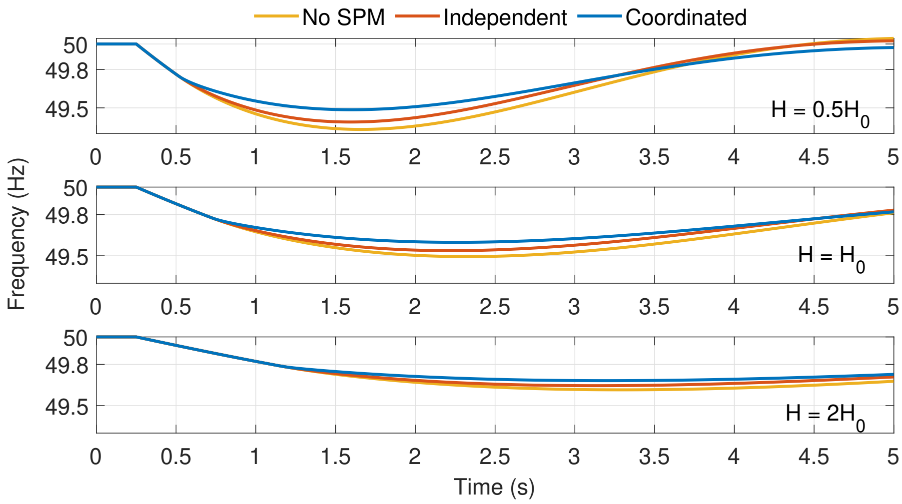


*Figure 16: Frequency response of the transmission network.*

## 4.5 Conclusions

In this Lab Access project, a two-level coordinated SPM approach to enhance the cumulative dynamic response of distributed DERs participating in ancillary service provision at a chosen PCC is proposed. The performance of the proposed approach is benchmarked against the conventional approach where no SPM is incorporated. It has been shown that both levels of control, independent and coordinated, perform significantly better than the conventional approach. Level I control improves the local response of the participating DER, however, does not help the cumulative response at the PCC. The coordinated approach in contrast improves the local dynamic response and the cumulative dynamic response at the PCC. The performance of the approach has been verified within a LVAC distribution network and a LVDC distribution network, demonstrating its flexibility for adoption within different networks. The real-world applicability of the approach has further been demonstrated through a high-fidelity PHIL experimental validation. In addition, the potential role of the proposed approach in the frequency regulation of a transmission network has been demonstrated. The proposed control will al-low virtual power plants to ensure tighter set point tracking at PCC's of interest such as the distribution-transmission interface and to participate in markets with more stringent time and regulation requirements as expected in future low-inertia systems.

This TA lab access went very well and all the planned tests have been carried out successfully. All the expected data was collected and processed. The main research outcomes have been published in a high-quality journal. Excellent collaboration and a great opportunity to undertake research activity under this Lab Access project.

# 5 Open Issues and Suggestions for Improvements

This TA lab access went very well with all the expected data collected. The main research outcomes have been published in a high-quality journal. Excellent collaboration. No open issues or suggestions for improvement so far.

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# Appendix A. Resultant Publication

## A.1. Journal Publication

Mazheruddin Syed, Ali Mehrizi-Sani, Maria Robowska, Efren Guillo-Sansano, Dong Wang, Graeme Burt, "Dynamically robust coordinated set point tracking of distributed DERs at point of common coupling", *International Journal of Electrical Power & Energy Systems*, Volume 143, 2022, 108481, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2022.108481.

**Abstract**

Low-inertia operation of small-scale power systems, such as a microgrid or a portion of a long feeder, requires careful coordination of the controller performance of the constituting devices. This challenge is exacerbated in microgrids serving the functionalities of a conventional synchronous-based generation unit while comprised of smaller DERs operating mainly interfaced through power electronics converters. This paper builds on the idea of set point modulation and proposes a two-level control strategy that aims to achieve superior performance at the point of common coupling (PCC) of microgrids by combining a local control level with a distributed and coordinated level. Several case studies on both AC and DC systems, the CIGRE low-voltage benchmark system as the AC system and a test DC microgrid, validate the performance of the proposed approach. The real-world applicability of the approach is established via a high-fidelity power hardware-in-the-loop (PHIL) experimental setup and an application case study on grid frequency regulation. The proposed approach enables a microgrid to participate in ancillary service provisions where speed and quality of regulation are critical.

**Keywords**

Ancillary services; Coordinated control; Distributed energy resources; Microgrids; Predictive control

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