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.

Technical Report TA User Project

Distributed Energy Resources as tools for Power Management

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Table of Contents

Abbreviations

AS	*Ancillary Service*
BESS	*Battery* Energy Storage System
DER	Distributed Energy Resource
DSM	Distributed Generation
ESS	Energy Storage System
GFB	*Grid Forming Battery*
LV	*Low Voltage*
OLTC	*On-Load Tap Changer*
P	*Active Power*
PCC	Point of Common Coupling
PHIL	Power Hardware in the Loop
PV	Photovoltaic
Q	*Reactive Power*
RES	Renewable Energy Source
RTDS	*Real-Time Digital Simulator*

Executive Summary

This research proposes to address the voltage and frequency problems encountered in a Low Voltage microgrid via the application of the droop control concept in inverters. Although, DERs are characterized as intermittent sources which could cause issues in the grid, the approach to use DERs as reactive power management tool has presented a way for power quality issues to be addressed.

The main contribution of this research is to investigate and present the inverters with an ideal control parameter to participate in ancillary service provision and also to minimize the tap switching of the OLTC in the residential microgrid. In detail, the research investigates this solution in inverters working in grid-tied mode and also in an Islanded grid. Various DERs are introduced to create an ideal residential microgrid which also have prioritized and un-prioritized loads

The experiments are simulated and also done using Power hardware in the loop setup where hardware PV inverters and hardware battery energy storage system was run in parallel with simulated circuits in the Real-Time Digital Simulator (RTDS). The experimental results justify the essence of using inverters as reactive power management tools in the LV grid.

1 General Information of the User Project

User Project Title: Distributed Energy Resources as tools for power management
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User Group Member: Solomon Oyegoke

2 Research Motivation

Electrical power generation and its distribution is a very significant subject area. However, rapid increases in demand, diminishing supply of fossil fuel and an acute awareness of the negative impact of burning fossil fuels on the environment have raised concern on the sustainability of the traditional power system. As a result researchers continue to explore the use of Renewable Energy Sources (RES) as alternative sources of electrical power. It is expected that these Distributed Energy Resources (DER) will progressively play a key role in the electric power distribution system operation.

DERs are power sources installed closer to end users and can be aggregated to generate power necessary to meet regular demands. DERs such as storage and renewable technologies such as Photovoltaic generators and Wind turbines can help facilitate the transition of the existing grid toward a smarter grid. This gives the opportunity to explore the use of inverters coupled to the DERs as a tool to supply ancillary services. There are certain advantages associated with the use of DERs, but some DERs are intermittent sources that pose a challenge to system operators. Consequently, an increase in penetration of DERs into the grid network has created problems related to power quality issues such as voltage sags, voltage rise and harmonics.

The obligation of the grid operators to address power quality issues and energy demand has created an opportunity in the energy market due to the need for ancillary services. Ancillary services are necessary to sustain, secure and stabilize the operation of the electric power system; Voltage control and frequency control are the two ancillary services explored in this research.

Frequency instability defined as a mismatch between power produced from generators and power consumed by loads also arise from high penetration of installed DERs. The inclusion of a frequency response controller (such as Battery Energy Storage System) is therefore crucial to provide frequency stability. The implementation of voltage regulation services via the DER-Inverter also becomes a management tool for reactive power supply to the grid.

The aim of this research is to investigate the intelligent delivery of ancillary services to the grid by DERs acting as generators at residential levels (low voltage) to support the existing power system and to determine the extent to which these services can be integrated in the system. The inverters that are coupled to the DERs will not only generate active power but with the inclusion of droop control parameters, the inverter also supplies reactive power.

In this research, the exploration of Voltage control by utilising a PV inverter with modified control and algorithm to supply Ancillary services to a low voltage grid was reviewed. This control was designed to further supply reactive power and aid the operation of the existing On-Load Tap Changer (OLTC). Next, a decentralised approach was examined for multiple PV inverters in a modified low voltage benchmark model so as to analyse the ancillary service contribution of each inverter to the local loads and the LV grid at large toward the aim to improve power quality. Finally, an off-grid model of low voltage benchmark was explored with different DER mix to further understand the role of local generators in provision of ancillary services.

2.1 Objectives

From the specifics above, this research explores distributed decentralized control approach to inverters using a residential benchmark LV grid model. The following the main objectives are listed:

- Analysis of the PV inverter and the design of an ideal control parameter
- Examination of the OLTC as an existing ancillary service tool in power systems
- Residential grid modeling with renewable sources and storage systems
- Load analysis and Droop control to assist frequency and voltage control
- Different test scenarios explored using the power hardware in the loop testbed

2.2 Scope

The report explains the scenarios that are tested in the lab which includes the theoretical explanation and the results. In the entire sets of experiment, droop control technique is employed to realize optimum reactive power management via DER-inverters in a residential LV microgrid.

Droop is a popular control technique usually explored to supply voltage regulation servies where users can configure the inverter to generate ancillary services based on set limit applied to reactive power (*Qmin* and *Qmax)* and the voltage, ensuring the inverter can work at its maximum rating if required. The Droop is also explored as a means to reduce the recurring tap changes of the OLTC on the other end of the PCC.

The droop technique is verified in experiments having decentralized inverters in a LV grid and also in islanded microgrids with various DER-inverters and an energy storage system demonstrate the practicality.

3 State-of-the-Art/State-of-Technology

Global issues such as climate change, environmental pollution and power supply uncertainty are some of the main problems being tackled globally. The quest for possible solutions requires big investments and a major transformation to the energy sector in terms of its power-generating processes. Renewable energy sources generally continue to gain more grounds in residential applications, commercial markets and also for industrial applications. Distribution Generation (DG) systems can include a renewable energy resource e.g. solar panels, micro wind turbines; an inverter and a grid interconnection [1]. It is hard to predict their power output due to time-dependent and uncertain factors such as wind availability. As a result, integrating distributed energy resources into the traditional power grid will incur service reliability issues, which need to be carefully addressed [2].

However, the high penetration of renewable energy resources, storage systems and controllable loads, pose new challenges in the operation of distribution networks that must be carefully addressed [3, 4]. As a result the opportunity to supply ancillary services for grid support arises as it is crucial for grid operators to maintain voltage supplied within specified limits (for instance where voltage tolerance is set between -6% and +10% in the UK).[5].

PV inverters can potentially be used for reactive power compensation by modifying the controller to make them function as a distributed static compensator. Advanced inverters, combined with existing infrastructure and control systems could help towards localized management of voltage fluctuations and power flows. This requirement for localized reactive power provision and voltage control opens an opportunity for the DER generators to participate in the electricity market from reactive power generation (Ancillary Services) based on key components of residential photovoltaic and wind operated micro-grid system [4].

Ancillary services are facets of electric service required to support the reliable delivery of electricity and operation of power systems [6]. Voltage-Amp Reactive (VAR) compensation is a typical example of an ancillary service. Generally, ancillary services are designed to support frequency stability (frequency control, power regulation and operating reserves), voltage control (tap changer control and reactive power control), power balance (scheduling and dispatch of balancing energy). It also aids restoration of supply (black start capability and island operation), system management (power quality assurance, operation and asset management) [6].

Initially, ancillary services were mainly provided by large generators and huge capacitor banks; the integration of intermittent generation and the development of smart grid technologies have prompted a shift in the type of equipment that can be used to ideally provide ancillary services. Many of the ancillary services that are traditionally provided by spinning generators and voltage regulators can potentially be provided by the inverters that are installed with DERs to improve power quality in the grid [7]. Aside the fact that DERs are regarded as cleaner forms of generators, these energy sources can often be placed at close proximity to loads which in turn diminishes energy losses that could have been experienced on distribution lines.

This presents the concept of microgrid which is described as a power generating model that provides power to a local area with the ability to operate independently even when it is linked to a central or main grid and it may consist of loads, storage devices, control systems, micro sources and the Point of Common Coupling (PCC) [8, 9].
The microgrid should be able to support the integration of renewable energy sources or smaller

generators and to provide the opportunities to participate in the energy market. Furthermore, the microgrid should have some level of protection and Islanding capabilities to operate in stand-alone mode when an issue such as a fault is experienced in the grid network.

Load Management features in microgrid describes an effective system required for coordinating changes in loads during the day; this could be critical and non-critical loads that would temporarily allocate loads based on the available generators. Fig. 1 below presents a typical residential load curve with changes across the day and is used in our research to present various state of the LV microgrid and how the DERs can support locally.

The ancillary services discussed above can be coordinated and controlled via different methods; they can be designed with centralized control or distributed decentralised control and power aggregated from various DERs can become significant to grid operators [10, 11], Nevertheless, it is also important to understand that the integration of DERs into the existing power system has a number of drawbacks such as implementation complexity, transients caused from renewable sources and reliability issues [12, 13].

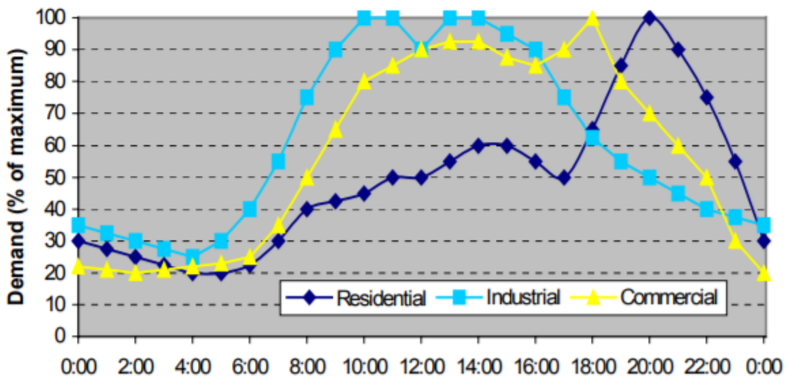


Fig. 1: Daily load curves - Residential loads [15]

4 Executed Tests and Experiments

In this project, the three experiment conducted were executed using Power Hardware in the loop (PHIL). The PHIL uses the real time digital simulator (RTDS). The section below provide general picture of the test beds, plan and parameters considered for the setup and procedure for executing the test.

4.1 Test Plan

1) EXP1 - Experiment 1 was a brief dynamic test conducted to present the PV inverter as a tool to for reactive power management that could support and relieve the existing OLTC. It was conducted using an inverter hardware, simulated loads, feeder lines and OLTC transformer to create an LV microgrid.

2) EXP2 - Experiment 2 was to examine the operation of a decentralized control inverters to provide Ancillary services to Low Voltage Grid using Power Hardware in the Loop where multiple inverters were utilised.

3) EXP3 – Test and Review ancillary provision from multiple inverters in an islanded microgrid using grid-forming battery as the main source, local loads served by wind energy, two PV inverters and a battery energy storage system to charge and discharge based on the requirement of the islanded grid.

Iv EXP1 and EXP2 were conducted considering a LV grid-connected testbed and in EXP3 an islanded microgrid is considered. EXP1 and EXP2 were conducted using the PHIL equipment in Fig 2 below however the simulated circuit in RTDS in EXP1 was completely different to that of EXP2.

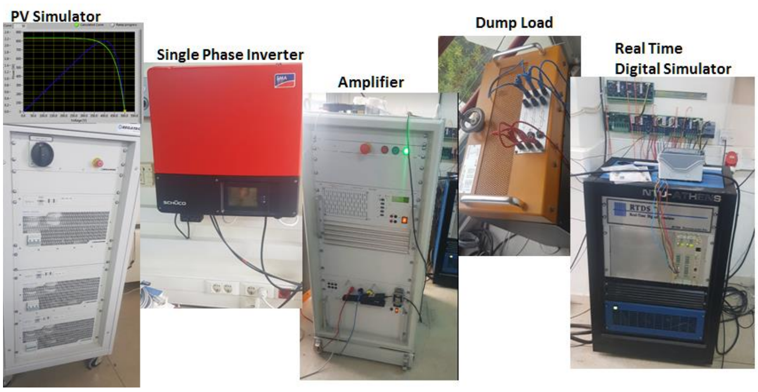


Fig. 2. PHIL Experimental Test Facility

4.2 Standards, Procedures, and Methodology

The procedures for the experiments are highlighted below:

1) Design a circuit, run the test as simulation
2) Check the simulation result to ensure result there qon't be any hazard for the hardware that will be connected
3) Connect the hardware devices to the RTDS and conduct experiment

4) Test and measure the voltage control support and response time of the OLTC
5) Test and measure the reactive power compensation established from the Droop controlled inverter and its response time
6) Test and measure the active power generated by all DG inverter when in grid-tied mode and islanded mode
7) Examine the contribution of the inverter to local loads
8) Vary the characteristics such as available PV power, Energy storage charge and discharge, wind and loads during experiment to create a various scenarios of the residential grid.
9) Obtain and Save the results in from RSCAB using MATLAB

5 EXP1 - Dynamics of Inverter Droop Control and OLTC using Power Hardware in the Loop (PHIL) Testbed

5.1 EXP1 - System and Test Description

The section investigates the dynamic functionality of a modelled droop-controlled inverter against the conventional OLTC transformers in a Low Voltage grid. The experiment was designed using the Power Hardware in the Loop (PHIL) test setup which combined a hardware DER-inverter, to a simulated low voltage AC distribution network.

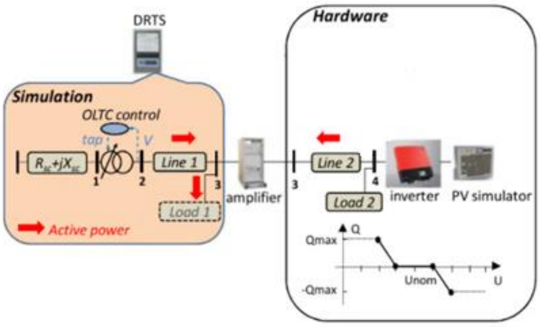


Fig. 3: PHIL testbed with DG and OLTC Voltage Control

Power vs. frequency *P(f)* droop, which is termed frequency control, causes the frequency to decrease as the real power load on the system increases and vice versa. On the other hand, the reactive power vs. voltage *Q(U)* droop control corrects voltage errors in the network by injecting or absorbing reactive power as a result of changes to the nominal voltage. The extent of the inverter's response is based on the configured parameters of the droop controller, i.e. the voltage dead-bands, *Qmin* and *Qmax* as shown in Fig. 4 below. The application of the Droop Control concept is explored to resolve voltage issues and it is employed in this experiment as a means to reduce the recurring tap changes of the OLTC toward grid voltage control through ancillary service supply.

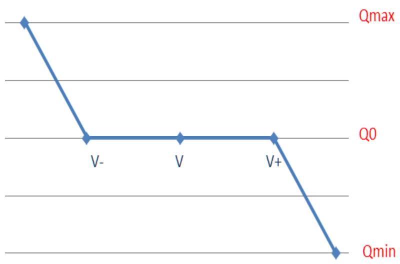


Fig. 4: The inverter's Voltage Droop Control

With the application of the droop, the inverter can positively contribute to feeder voltage control and results in an improved voltage profile. The design of the inverter controller's response must be very fast in terms of responding to changes in the LV network

On the other hand, the operation OLTC was also examined. Though the application of OLTC is an effective solution for overvoltage prevention; the effective control of the OLTC is essential to increase the transformer's lifespan and provide efficient voltage control in the grid during high PV generation periods. As a result, the mobile moving part (mechanical switches) of the OLTC transformer is subjected to wear and tear leading to huge maintenance costs. When the voltage falls outside the permitted dead-band, the automatic voltage control (AVC) relay of the OLTC then decreases or increases the secondary voltage by altering the OLTC tap position.

The OLTC control is shown in Fig. 5 below is utilized in this aspect of the experiment where a fixed step voltage change has been implemented in the OLTC controller. From the model in Fig. 5 below, a tap change occurs if the measured voltage is higher than 235 (~1.02pu) or lower than 225 (~0.98pu) for longer than 1 second. The starting tap position corresponds to voltage of 1p.u and the step size of each tap change was set to 0.01pu (1%).

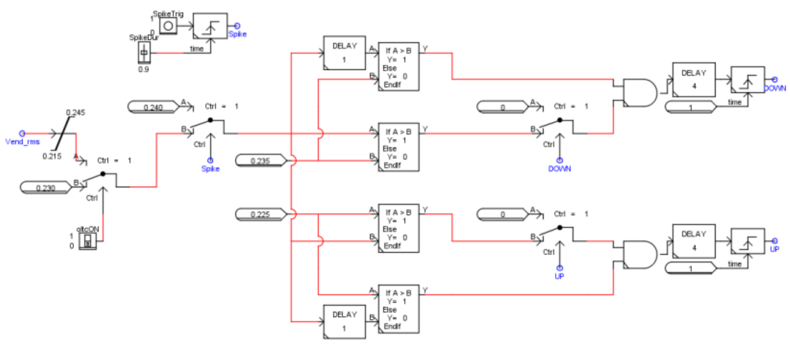


Fig. 5: The transformer's OLTC control

5.2 EXP1 - Test Setup

For EXP1, the Regatron PV Simulator was used to model the characteristics of the photovoltaic panels connected to the inverter (1 kilowatt PV in this design). The PV simulator is controlled using a dedicated software via Ethernet and this gives the opportunity to load in preset or an actual day's solar insulation values and can be further varied during simulation in order to see the changes on the LV grid and the response of the connected ancillary service devices i.e., the PV inverter and the OLTC.

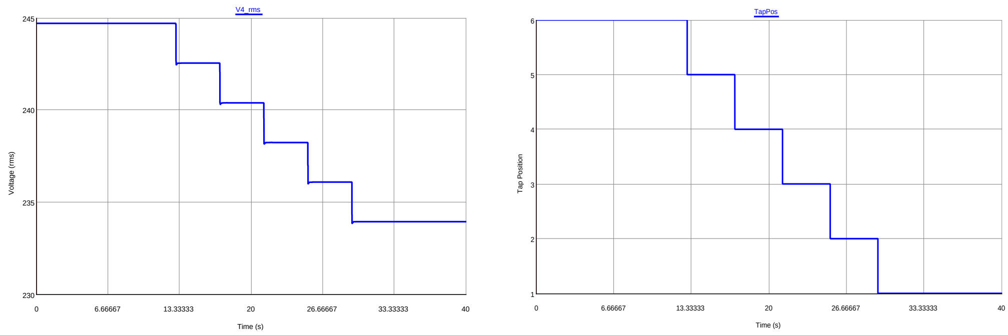
A linear amplifier (4-Quadrant, 5kVA) was introduced in the PHIL setup to link the physical hardware to the RTDS. A Sunny boy SMA inverter was coupled to the PV simulator on the DC side and to the amplifier on the AC side; the AC current of the inverter was also measured and sent back to the RTDS to close the loop of the PHIL setup. The inverter droop parameters were set through Ethernet to realize voltage stabilization via Qmin and Qmax.

5.3 EXP1 – Test Results and Discussion

In EXP1, three test cases were carried out to realize ancillary service contribution via the droop inverter and/or OLTC transformer simulated in the RTDS. The PHIL results were also validated against pure simulation test with no hardware. This is advisable so as to establish ideal parameters for the PHIL test and to avoid damaging the hardware equipment as a result of over current or voltages.

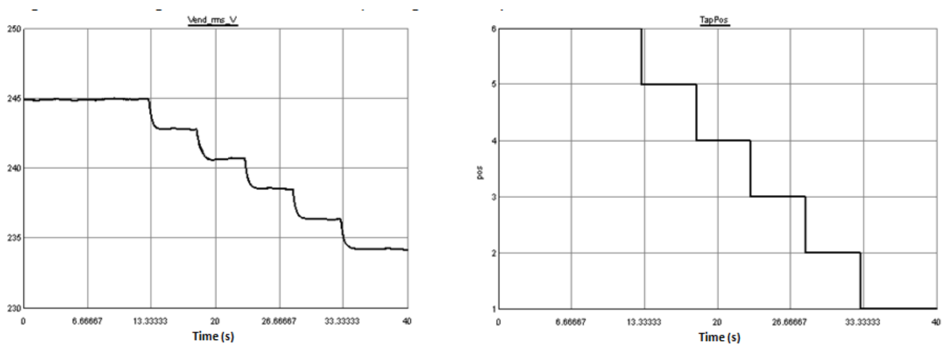
5.3.1 Test Case 1 – OLTC Only

The test commenced with no load and a fixed active power being supplied from PV inverter into the grid. The voltage at the end of the feeder line initially was unchanged and the OLTC tap position was kept constant untill loads were turned on at 13s time as shown in Fig. 6 (Simulation) and Fig. 7 (PHIL hardware test) below; resulting to the need for the OLTC to adjust the on tap position in order to stabilise the voltage. The OLTC tap moved 5 steps (position) until 33s and the correction was realised in about 20 secs simulation time.



(a) (b)

Fig. 6 Simulation Case 1 – OLTC only supporting the Grid Voltage and its tap positions

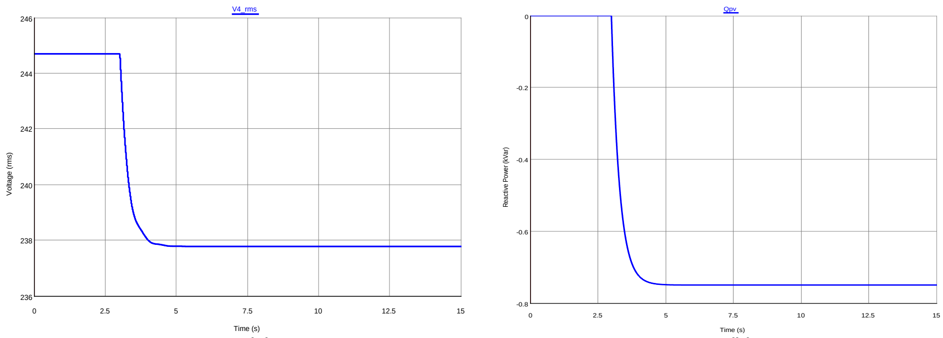


(a) (b)

Fig. 7 PHIL Test Case 1 – OLTC only supporting the Grid Voltage and its tap positions

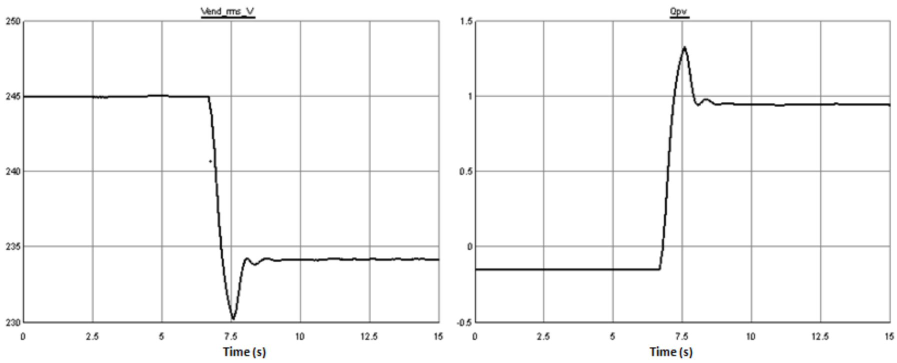
5.3.2 Test Case 2 – Droop *Q(U)* inverter only.

The physical inverter in this research functions as a watt-priority inverter and therefore the rest of the inverter rating can serve the purpose of power compensation via the droop parameters.
For the hardware inverter, the droop characteristics were set via the software gui of the SMA inverter with certain voltage values; (0.99 – 1.01 p.u) as deadband. Once the *voltage* is greater than 1.01p.u then the inverter supplies ancillary services up to Qmax or Qmin in the case of *voltage* going below 0.99 p.u. For test case 2, the OLTC tap controller was deactivated so that the inverter only responds to the grid voltage changes. Initially, the PV inverter generated a steady active power which was fed into the grid before the loads were switched on at time t=7s to realise the grid voltage drop.
From the result recorded in Fig. 8 (Simulation) and Fig.9 (PHIL hardware test) below for test case 2, it can be seen that the as a voltage drop was experienced, the inverter quickly kicks in to stabilise and compensate the grid with reactive power (Qpv) within 4s compared to the OLTC response in test case 1.



(a) (b)

Fig 8: Simulation Case 2 – Droop inverter only (Grid voltage and Reactive power *Qpv* from the inverter)



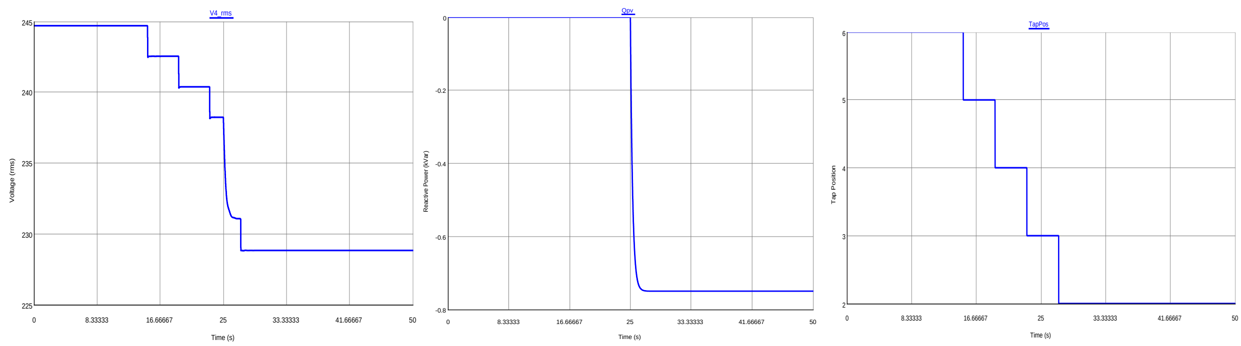
(a) (b)

Fig 9: PHIL Test Case 2 – Droop inverter only (Grid voltage and Reactive power *Qpv* from the inverter)

5.3.3 Test Case 3 – Combining OLTC and Droop *Q(U)* inverter control.

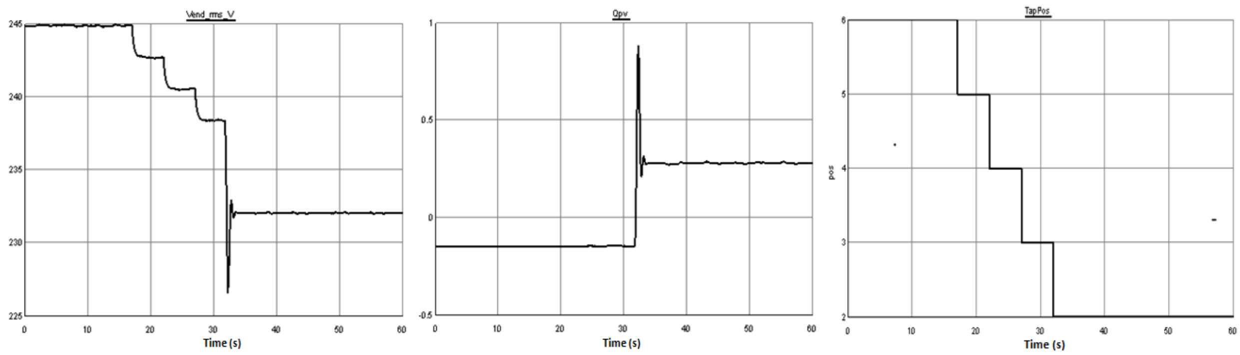
The conventional OLTC voltage control and the PV inverter droop were used as tools to resolve the voltage problems across the feeder in test case 3. During the initial stage of the PHIL experiment in test case 3, the hardware inverter supplied steady active power with the grid voltage being at the nominal range. Next, the loads were turned on and the nominal voltage experienced a drop across the line. To resolve the issue, the OLTC tap position changed initially with the fixed step changes, after which the inverter's Q(U) droop control assisted in further stabilization of the voltage by supplying reactive power as shown in Fig.10 and Fig.11 below. It can be seen that the OLTC had a lesser OLTC tap position (steps) because of the support from the hardware inverter's droop control in the PHIL experiment compared to the result in test case 1 above.

The result could show reduced number of step change of the OLTC taps if the set parameter and the triggering time of the inverter droop is further modified. However the aim was to initially allow the conventional OLTC voltage control to an extent before the hardware inverter droop were activated.



(a) (b) (c)

Fig 10: Simulation Case 3 – Grid voltage supported by OLTC and inverter's Droop control.



(a) (b) (c)

Fig 11: PHIL Test Case 3 – Grid voltage supported by OLTC and inverter's Droop control.

5.3.4 EXP1 - Summary

To summarize, EXP1 was carried out to showcase the ancillary service supply opportunities from the inclusion of DGs in the LV grid. Using the PHIL test set up, ancillary services were supplied to the grid using the conventional OLTC, which was further supported with the physical inverter's Q(U) Droop control and reduced the number of the OLTC's tap switching position. By extending the concept further from the results, a higher DG penetration could be considered to be of greater advantage to the grid if properly coordinated. An aggregation of multiple droop inverters could aid and reduce the operation of the OLTC taps when the DGs can compensate the grid a notable amount of reactive power where the DGs could be operated in a decentralized or centralized manner. This leads to the next experiment (EXP 2) where several DGs were presented and operated using the decentralized approach.

6 EXP2 - Decentralized Ancillary Services Support to LV Grid using Power Hardware in the Loop.

6.1 EXP2 - System and Test Description

In EXP2, investigation was carried out on the traditional power generators and how the inclusion of PV inverters with decentralized control approach support the LV grid through reactive power delivery which is based on droop characterises and active power based on the insolation levels.
The research test circuit was modelled with Power Hardware in the Loop (PHIL) as shown in Fig .2 where a single-phase PV inverter hardware operated in parallel with three other simulated PV inverters. With various forms of local loads at individual inverter nodes, an Ideal residential load curve was presented and used in the experiment to control the entire loads. The hardware PV inverter and simulated PV inverter had different apparent power but the same insolation curve was used to control the PV.

6.2 EXP2 – Test Setup

In this situation where there are no storage system employed in EXP2, there will be no control on the active power produced by the PV inverter as this is solely dependent on the solar insolation levels. On the other hand, the reactive power is controlled using a set of droop parameters though the reactive power can be limited by the inverter's apparent power and active power generated per time.

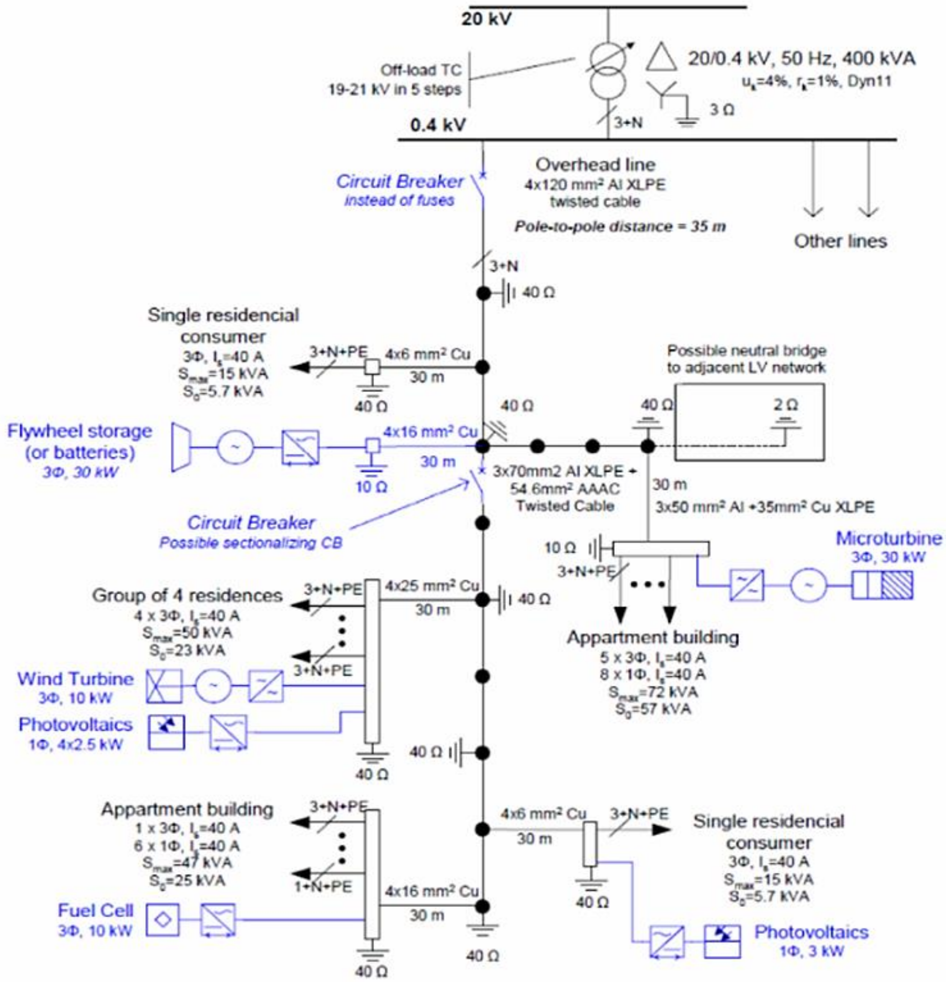


Fig. 12: CIGRE Low voltage Network Benchmark [14]

Based on local measurement, each decentralized PV inverter generates active power in the LV benchmark grid. The different capacity of the inverters also gave an opportunity to model different droop control parameters for each inverter in order to achieve maximum reactive power from each inverter. The OLTC control parameters used in Fig 4 was also applied in EXP2. The test circuit in EXP2 is a modified CIGRE low voltage benchmark shown in Fig 12 above where PV with inverters was used in place of other DER sources.

6.3 EXP2 - Test Results and Discussion

Four cycles of testing were conducted and highlighted below for EXP2.

6.3.1 Reference Testing

In this test, the LV residential grid model was run without the contribution of ancillary services from neither the OLTC nor the inverter droops. The attributes of the node voltage could be link to the corresponding nodal load requirement. It can be seen from Fig. 13 below that the secondary voltage remains at 230V

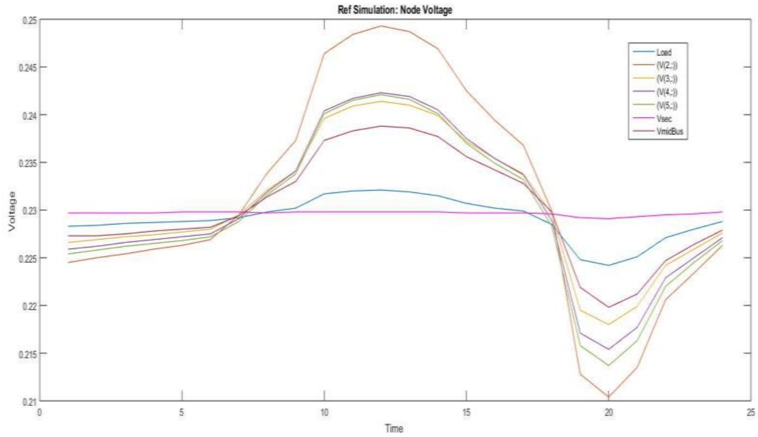


Fig. 13: EXP2 - Reference test – Node Voltage measurement without power compensation

6.3.2 Test Case 1 – OLTC only during testing

For this aspect of the test, the OLTC acts as the key supplier of ancillary services in the network as droop control in the PV-inverter hardware and the simulated inverters were deactivated.

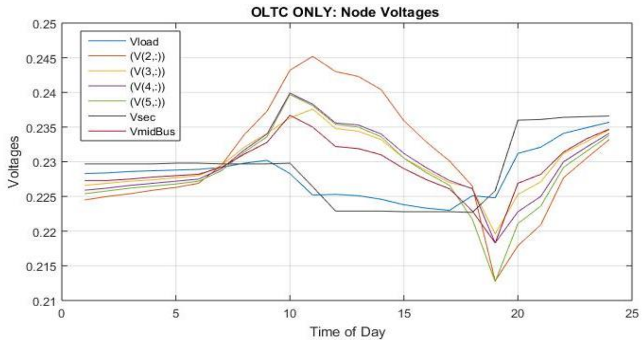


Fig. 14: EXP2 Test Case 1 - Node Voltage measurement with power compensation delivered by OLTC

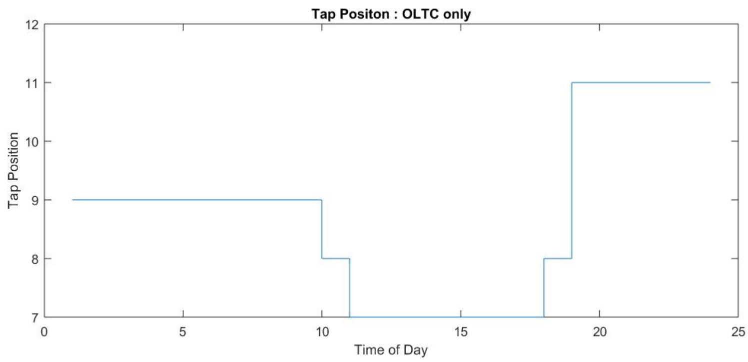


Fig. 15: EXP2 Test Case 1 – Tap switching position of OLTC during voltage control

6.3.3 Test Case 2 – Inverter Droop Control only.

In test case 2, the OLTC functionality was disengaged to measure the level of aggregated power provided by the entire inverters. In this case, active power generation was based on the available solar insolation and the supply or absorption of reactive power was based on the droop parameters.

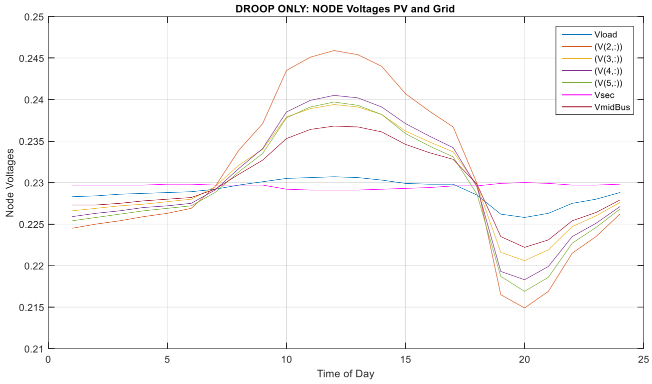


Fig. 16: EXP2 Test Case 2 - Node Voltage measurement with power compensation by the PV inverters

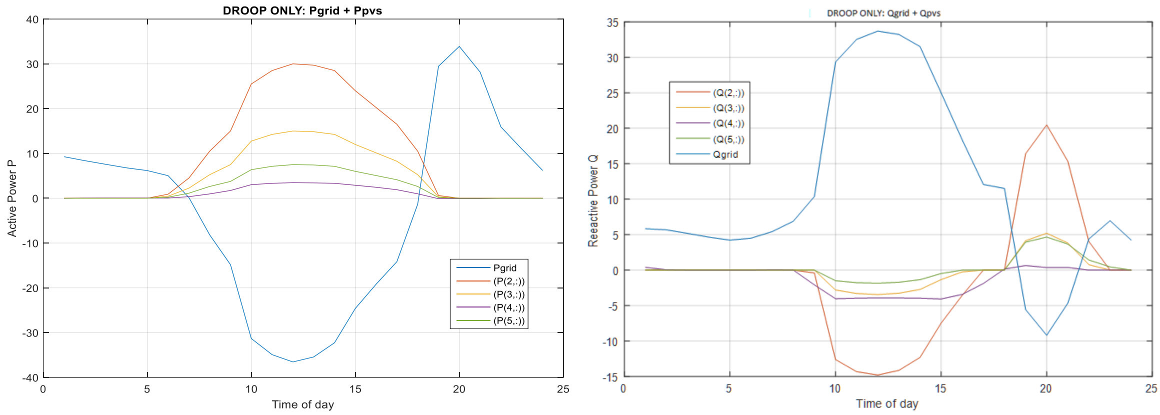


Fig. 17: EXP2 Test Case 2 – Active and Reactive power supplied by the inverters in the LV Grid

6.3.4 Test Case 3 – OLTC and Droop Control Inverters

For this test, both means of ancillary service supply to the residential grid were implemented paying attention to the response time, proficiency and contribution of both the inverter droop and the OLTC transformer.

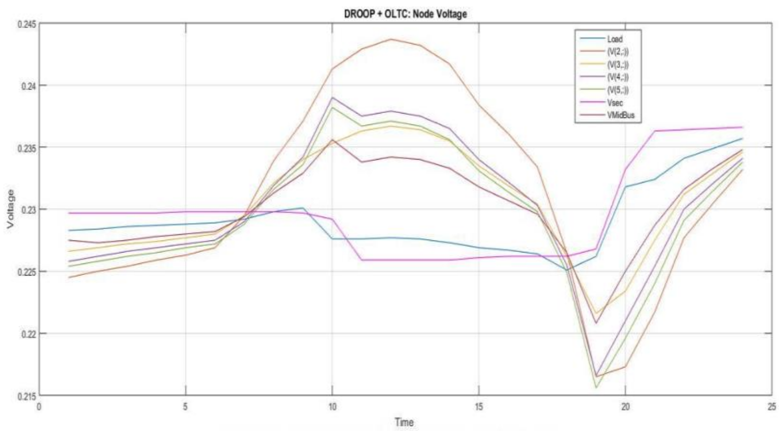


Fig 18: Test Case 3 -Measured Node voltages during OLTC and inverter’s Droop contribution to the LV grid

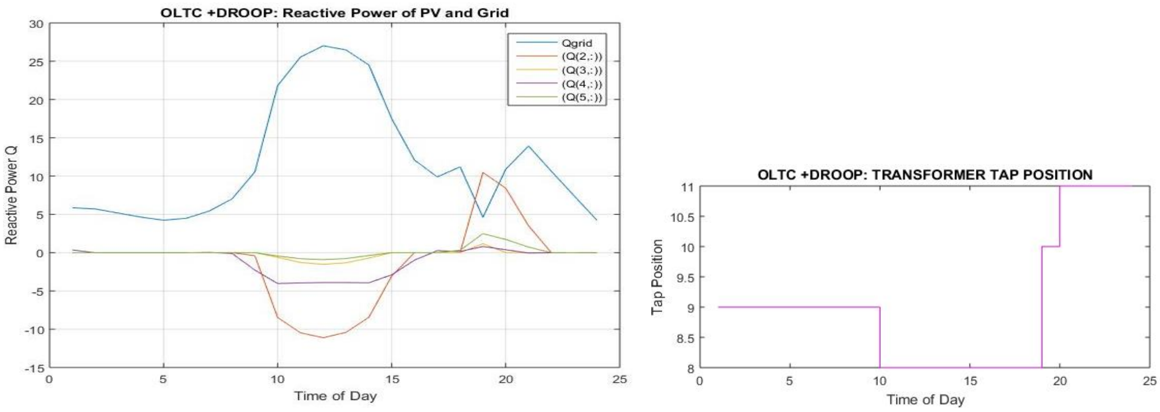


Fig 19: Test Case 3 - Reactive power via PV inverters and OLTC Tap Position during power compensation

6.3.5 EXP2 – Test Summary

From the result above, it can be seen that the PV inverters did not only generate active power but also reactive power and hence reduced the amount of the OLTC tap switching in Test Case 3 (Fig. 19) compared to Test Case 2 (Fig. 15) where only the OLTC was employed as the voltage control tool. At instances where the PV inverters support to the local residential loads was reached, it could be seen that power was supplied to the grid. Though the secondary node voltage (Vsec) only experienced a minor change in value during the experiment, the parameters such as length of the lines, inverter capacity and load size could be have been further reviewed but the notion of the PV inverters acting as reactive power management tool was realized.

7 EXP3 – Ancillary Service Delivery via DERs and Battery Energy Storage System in an Islanded LV Microgrid

7.1 EXP3 - System and Test Description

EXP3 focused on exploring ancillary service supply through multiple inverters in an islanded microgrid. The CIGRE LV benchmark was modified and a grid-forming battery inverter was introduced as the main source; fixed and variable local loads were used and were controlled using a residential load curve. Furthermore, Wind Turbine was included and simulated in RTDS with a daily wind curve; two PV inverters were simulated in RTDS (Current Sources) and a hardware battery energy storage system (BESS) was included to create a PHIL test facility operating in grid connected mode providing ancillary services.

The inclusion of the BESS was very significant to the test as Islanded grid require a means to store and dispatch excess power generated by other sources when needed. Five test scenarios were created by combining different instances of Loads, DERs and the generator supplied power over time as shown in table 1 below.

7.2 EXP3 – Test Setup

As a usual safety practice, simulation of these scenarios was first carried out before moving to the PHIL test; first the grid forming batteries initially served loads in the islanded grid and the profiles was examined. Next, the DERs generate power and the voltage profile was examined again; additional (Emergency) loads were then switched on causing a drop in frequency in the network and the BESS was employed to resolve the issue. The battery inverter then discharges the battery to help resolve the network frequency back to nominal value. In instances where the nominal voltage is affected due to higher inductive loads being switched on, the battery inverter supplies reactive power to help resolve the network voltage toward the nominal value. The battery is charged when the situation above happens in the other way round.

Test Case	Solar PV	Wind	Load	Test Scenario Comments
1.	L	H	M	Day with Less insolation, High gust of wind, Average load
2.	H	M	M	Sunny day with average load, Grid forming batteries gets charged
3.	H	H	L	Hardware Battery charges, min load capacity
4.	L	M	H	Battery discharges, max load capacity
5.	X	L	H	Night time, max load capacity
L = Low, M = Medium, H = High				

Table 1: Test scenarios examined based on various instances of Loads and the DERs

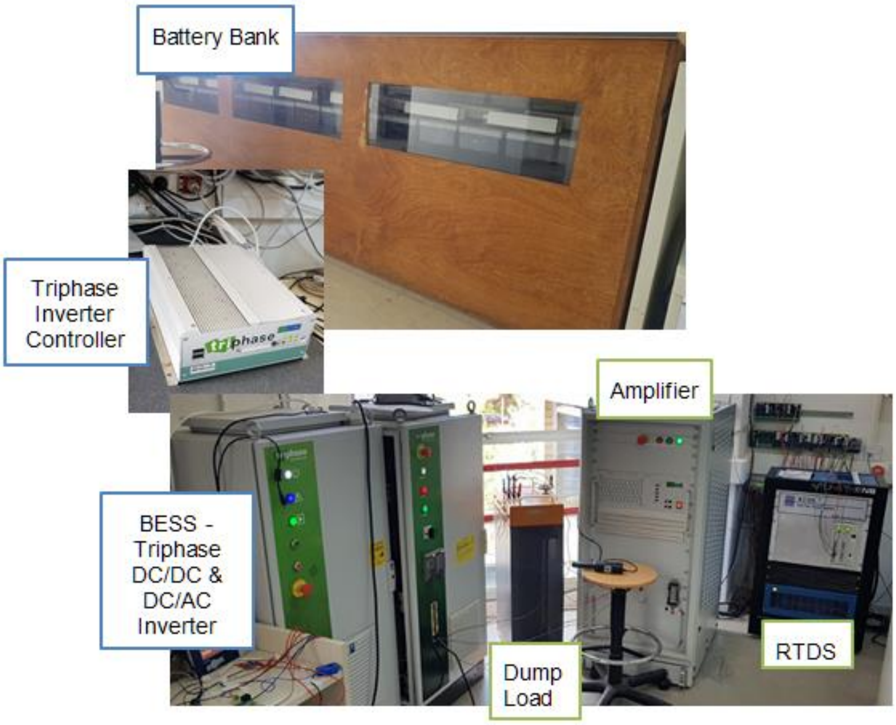


Fig. 20: PHIL setup for Islanded Grid Experiment

DG Plants	Capacity (KVA)	Droop control for Ancillary Service
Solar PV 1	10	P(f) and Q(U)
Solar PV 2	13	P(f) and Q(U)
Wind	3	Q(U) only
Battery Hardware (BESS_HW)	10	P(f) and Q(U)

Table 2: DG plants and their rating (EXP3)

7.3 EXP3 - Test Results and Discussion

As mentioned above, Table 1 shows the scenarios tested and the results are discussed below. The simulation result has been checked with the PHIL test result and they have similar attributes. For EXP3 only the PHIL test results are shown below. Due to time constraints and limitation of the RSCAD graphical display, each test is run for about 6 seconds; the first quarter of the result show the initial state of the PHIL testbed before application of droop control to the participating DGs.

7.3.1 Test Case 1 – Low Solar PV, High Wind and Medium Load

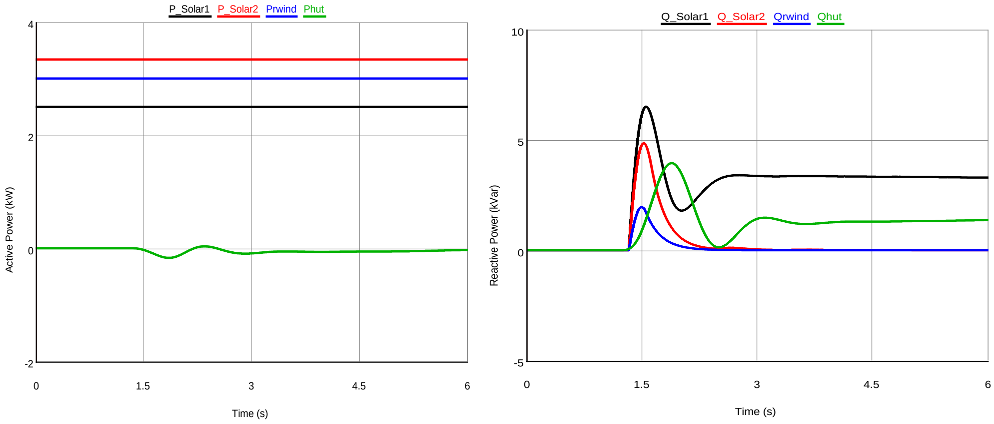


Fig. 21: EXP3 Test Case 1 – Active and Reactive power supplied by the simulated & hardware inverters

In test case 1, about 25% solar insolation, maximum wind power and half the load capacity was switched on. During this period, the Grid-Forming Batteries (GFB) was solely responsible for reactive power compensation as seen in Fig. 22 below.

The droop control was then activated in the test system and immediately there was a drop in the reactive power initially supplied by the GFB to the loads (from about 7.5 KVAr to 2.5KVAr); this was because the DERs such as the Solar PV1 and battery hardware (BESS_HW) was now available to supply reactive power as shown in Fig. 21 to the local loads and the node voltages were also improved (Fig. 22).

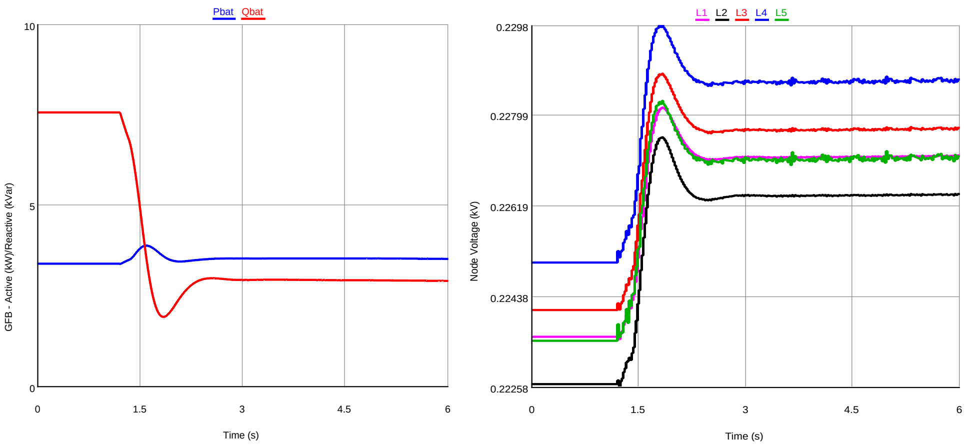


Fig. 22: EXP3 Test Case 1 – Active / Reactive power of GFB and Node voltages in the Islanded grid.

7.3.2 Test Case 2 – High Solar PV, Medium Wind, Medium Load

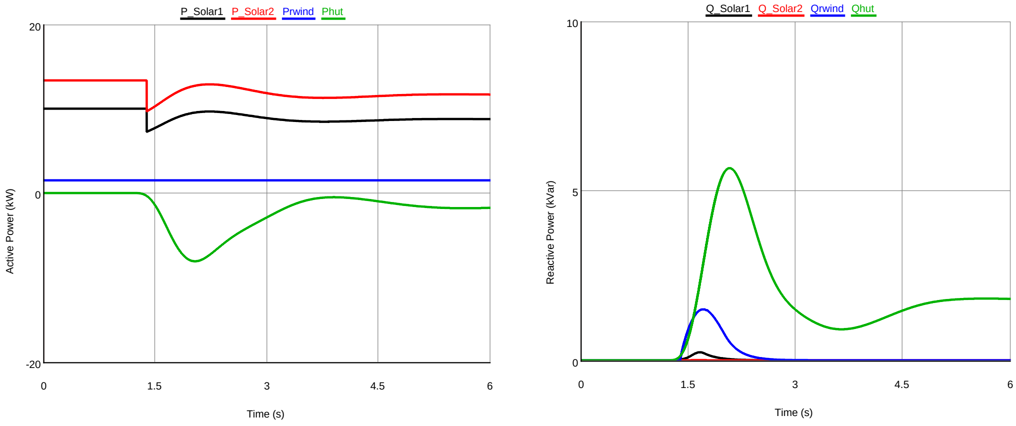


Fig. 23: EXP3 Test Case 2 – Active and Reactive power supplied by the hardware & simulated inverters

In test case 2, the PV inverters supplied maximum active power from full insolation level (Fig 23); on the other hand the wind inverter and local loads were half the rated capacity. At the point when the droops were activated, the PV inverters were already working at maximum KVA rating to supply active power to the local loads but the grid frequency was adjusted towards nominal as shown in Fig. 24 with the P(f) droop control.

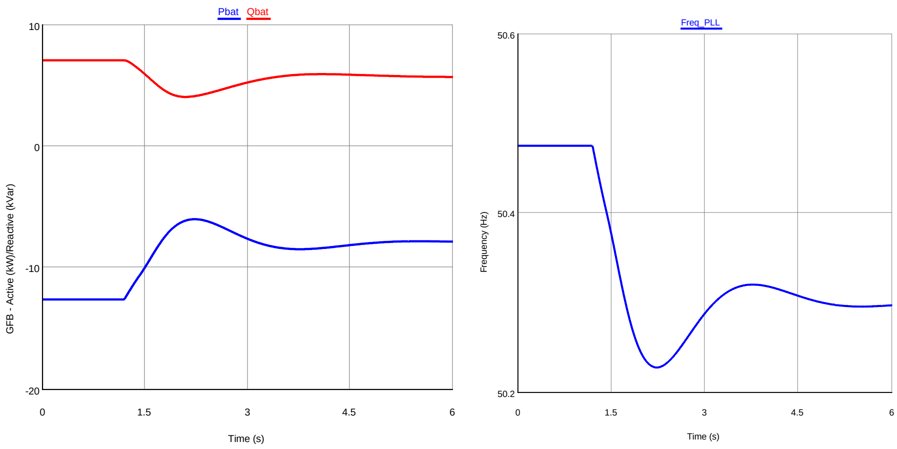


Fig. 24: EXP3 Test Case 2 – Active / Reactive power of GFB and the Frequency in the Islanded grid.

7.3.3 Test Case 3 – High Solar PV, High Wind, Low Load

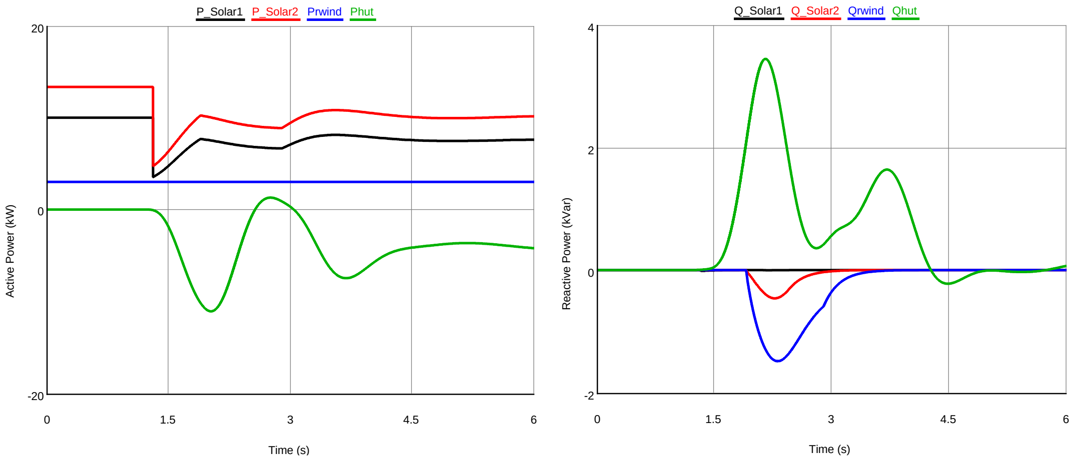


Fig. 25 EXP3 Test Case 3 – Active and Reactive power supplied by the hardware & simulated inverters

During the maximum operation of the wind and the PV inverters in supplying active power as shown in Fig 25, the residential load in use was 25% of the full rating. Due to the ratio of power generated by the DERs to the available loads being high, this gave an opportunity for active charging of the hardware battery as shown in Fig. 25 upon activating the droops. Furthermore, high frequency as a result of excess power generated by the DERs was adjusted (50.75 Hz to 50.4Hz) via the P(f) droop as shown in Fig. 26. Note that the wind and PV inverters were at unable to support with any Q in this instance due to max P, but the GFB continued to supply reactive power to the reactive loads as shown in Fig. 26. In the Islanded grid, the power stored by the Battery Hardware becomes useful when there are low or no solar or wind available.

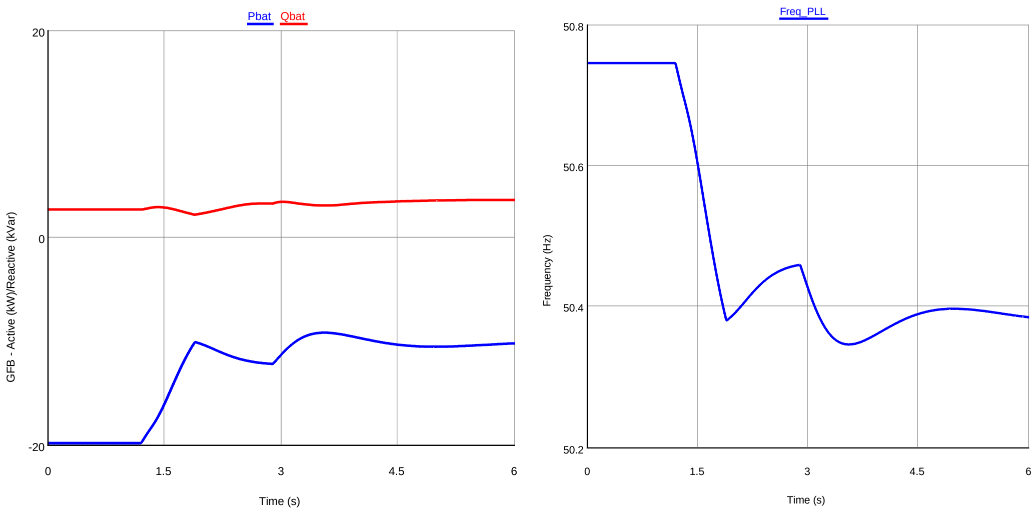


Fig. 26: EXP3 Test Case 3 – Active / Reactive power of GFB and the Frequency in the Islanded grid.

7.3.4 Test Case 4 – Low Solar PV, Medium Wind, High Load

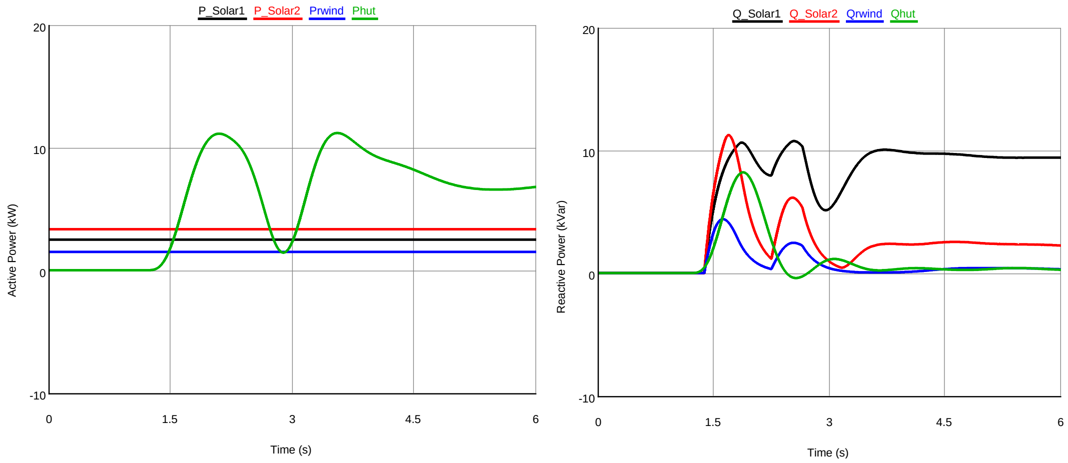


Fig. 27 EXP3 Test Case 4 – Active and Reactive power supplied by the hardware & simulated inverters

The results from test case 4 show an Islanded microgrid with a quarter of the PV power generated by Solar PV 1 and Solar PV 2 inverters; the wind inverter also contributed to the active power generated using 50 % of its rating and the residential loads were at maximum. This scenario correlates to the early evening toward the end of the day where the sunshine begins to go down and residents are back home utilizing more loads at once. In test case 4, it can be seen in Fig. 28 that initially the GFB fully supplied significant amount of active and reactive power to the loads in the islanded grid. This is because only a fraction of power required by the full load capacity was produced by the PV inverter and the wind.

Upon activating the droop controls, the PV inverters were then able to generate reactive power with remaining KVA capacity of 75% (Fig. 27) and the hardware battery also discharged to supply active power to the local loads (Fig. 27). The results after the droop activation in Fig 27 show a reduction in the value of the active and reactive power that was initially supplied by the GFB to the loads. Finally, it can be seen that due to the droop activation, the node voltages also improved toward nominal.

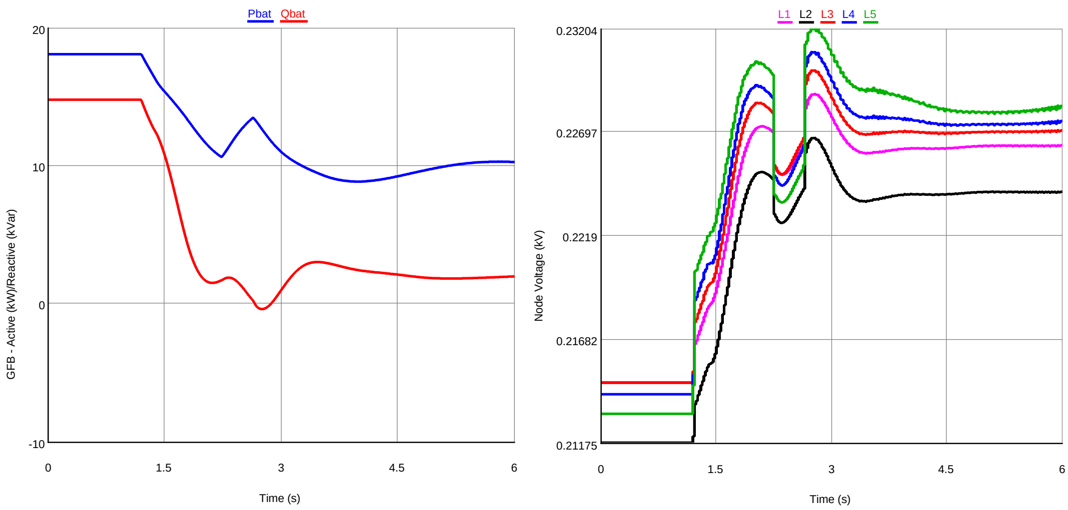


Fig. 28: EXP3 Test Case 4 – Active / Reactive power of GFB and Node voltages in the Islanded grid.

7.3.5 Test Case 5 – No Solar PV, Low Wind High Load

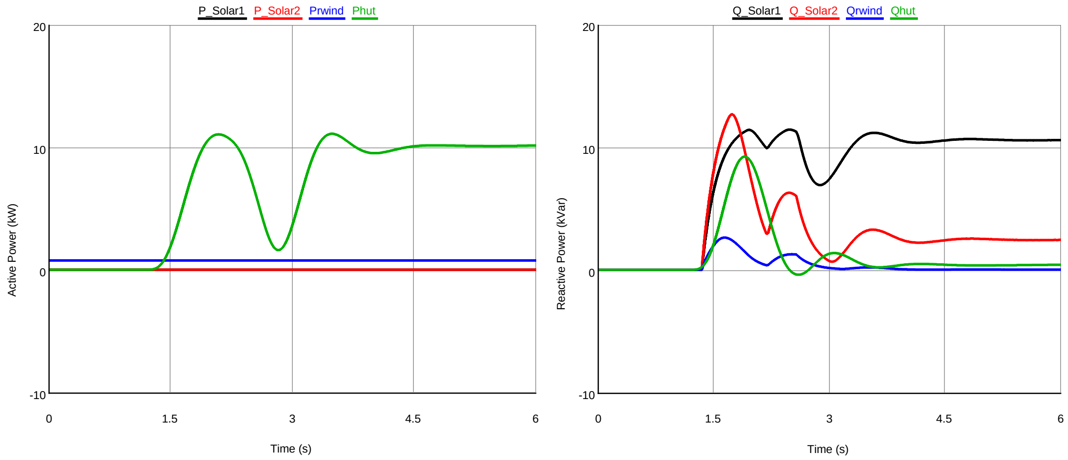


Fig. 29 EXP3 Test Case 5 – Active and Reactive power supplied by the hardware & simulated inverters

Test case 5 can be seen as the night time in a residential grid where the PV inverter is unable to generate active power. This means the inverter is unusable except its controller is modified to also generate research power proposed in this research. It can be seen in Fig. 30 that the GFB discharges power to the grid in other to meet the requirement of the max load capacity. It can also be seen that the voltages (Fig. 30) were affected due to little or no active power from the DER-inverters.

On the other hand, the islanded grid then experienced a significant change in the node voltages as the PV inverters can be seen generating maximum reactive power to the grid upon activation of droop parameters. Furthermore, the Hardware battery then discharges active power and relived the GFB active power dispatch; the reactive power from the GFB also significantly tend toward zero due to the PV inverters generating maximum reactive power.

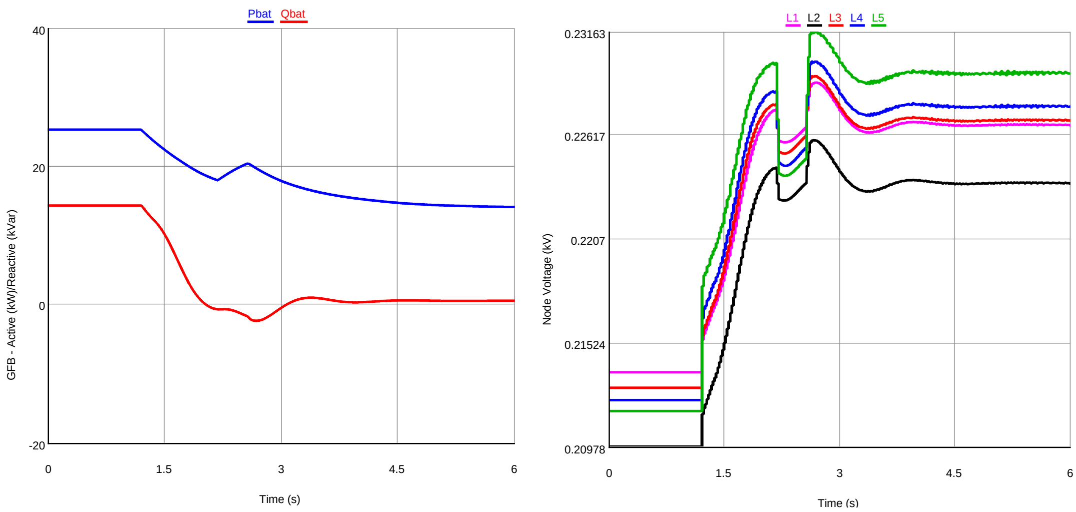


Fig. 30: EXP3 Test Case 5 – Active / Reactive power of GFB and Node voltages in the Islanded grid.

8 Conclusion

This project has addressed the voltage and frequency problems encountered in a Low Voltage microgrid via the application of the droop control concept in inverters using experimental validations to justify the use of droop control concept in inverters for both in grid-tied and Islanded microgrid. The grid-tied LV grid consists of multiple PV inverters and a hardware solar inverter operating in a decentralised manner. The islanded microgrid experiment utilised two simulated PV inverters, a wind inverter and a battery hardware inverter in a PHIL testbed. Simulations were performed first before running a PHIL experiment so as to strengthen the analysis of the microgrid control design, to know which parameters could be possibly adjusted so as to protect the PHIL during test.
Finally, the results from the experiment conducted have reinforced the idea of using inverters as reactive power management tools in the LV microgrid.
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10 Dissemination Planning

Based on the results derived, we are planning to prepare and submit three papers for publication, the first is an introductory paper to present the dynamics of the droop inverter and how it can be of support to the existing OLTC in provision of LV ancillary services. The next paper presents a more decentralized control methodology to Inverters coupled to different DER mixes not only to serve the local loads but also the aggregated power produced could also be fed into the main grid. The final paper examines the provision of ancillary services in an islanded LV grid where the battery energy storage system plays a vital role in conservation of power being produced by renewable sources in a decentralized control system. CIGRE LV grid benchmark is used in our research work. The publishers for these papers will be most likely IEEE / IET.

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13 Appendix

Solar Insolation and Residential Load Curve used in Experiment