Dynamics of Inverter Droop Control and OLTC using Power Hardware In the Loop (PHIL)

(Ancillary Services Supply in Low Voltage Grid)

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ABSTRACT

Distributed Energy Resources (DER) sources installed closer to end users serve as local distributed generators, but they are regarded intermittent sources that pose a challenge to grid operators. Moreover, an increase in penetration of DER into the grid network has created problems related to power quality issues such as voltage sags and swells. 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. In resolving these power quality issues, the coupling DER-inverter becomes an effective tool in supplying ancillary services to the grid.

This paper explores the dynamic functionality of a modelled droop-controlled inverter against the conventional OLTC transformers in a Low Voltage grid. The experiment is 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. The test results show that inverter based DERs could enhance ancillary service provision at the distribution level by supporting the operation of the existing OLTC in realizing voltage control.

Keywords— Power Quality; Ancillary Services; DER; PHIL; Inverters; LV grid; Distributed Generation (DG).

1. INTRODUCTION TO LOW VOLTAGE DISTRIBUTION NETWORK

The inclusion of Distributed Generation (DG) units into distribution networks has aided grid capacity over time but also on the other hand affects the network in several manners. Such issues include the change of active and possibly reactive power flow which has an impact on the overall power flow in the network. The network becomes imbalanced, as some nodes in the network could be overloaded in comparison to other nodes and as a result, this can worsen the network voltage and bring about network losses. Furthermore, the issues mentioned above affect the operation of voltage control devices such as the On-Load Tap Changer (OLTC). Therefore, the research and reliability studies become important for DER sizing, optimum penetration, placement and operation in situations where the penetration of DER becomes significant [1-3].

The continuous grid voltage variation as a result of the high penetration of the DER sources could make the OLTC transformer taps work endlessly in bringing the voltage back to the ideal range and this could gradually reduce the lifespan of the OLTC over time [4].

The low voltage distribution network is described as the last part of the network from a substation to the customers where majority of the consumers are residential loads. Small scale DER units such as photovoltaics (PV), mini-scale wind turbines, etc., are now usually integrated into the low voltage distribution networks, which could be negligible to the grid operators until they are of a higher power rating in the region of hundreds of kilowatts which could affect power quality [5]. To maintain power quality in the distribution network, voltage and frequency support, which is the core of ancillary services, becomes significant and hence can be provided using the modern power devices such as the inverter with advanced control functions [5].

Ancillary services are distinct components of electric service required to support the reliable delivery of electricity and operation of transmission systems; it is fundamental for the power system operation to maintain the balance between generation and demand when variation occurs [6-7]. Generally, ancillary services are designed to support frequency stability (frequency control, power regulation, operating reserves); voltage control (tap changer control and reactive power control), power balancing (scheduling and dispatch of power) [6]. Various forms of ancillary service solutions were fully discussed in [7] with their strengths and weaknesses highlighted; the paper also presented a comprehensive solution for ancillary service provision for the smart grid.

Hardware in the Loop (HIL) is regarded as a process of integrating physical hardware and software during testing; it is acceptable as a viable option for power system testing and provides real-time interaction between the physical hardware and the simulated circuit [8]. The most essential part of a HIL simulation is the real-time simulator which computes the simulation model and offers I/O capabilities. This allows the user to alter parameters of either the Hardware under Test (HUT) or the software circuit design that runs via a digital simulator and observe results for the new condition in real time. PHIL integration allows users to see actual behavior of the HUT and supports scalability of the HUT [8-10].

PHIL is now globally accepted as a procedure and standard practice (IEEE P2004) for power systems testing. Using the IEEE P2004 standard practice, the authors of [5] presented the concept of PHIL testing for Power Conditioning System (PCS) to coordinate and improve grid frequency and voltage stabilization.

The application of the droop control concept is explored to resolve voltage instability and is employed in this research work to relieve the recurring tap changes of the OLTC by controlling grid voltage through ancillary service provision.

The rest of this paper covers the notion of OLTC, the reactive power Q(U) supplied by the inverter via droop control, active and reactive power generation concept. The latter part of this paper then presents the power hardware in the loop design; various test case combinations for voltage control, and finally concludes by outlining the benefit of this work and further future work.

2. Voltage Control In a Low Voltage (LV) Grid

In this section, the operation and response of the OLTC and the inverter droop control principle are examined as tools to improve grid stability.

A. *Voltage Droop Controlled inverter in a LV microgrid*

The droop control technique can be extended to inverters that link renewable energy sources to the grid and it is acknowledged as an effective method of inverter control in a multitude of operating scenarios and at different power levels [11-12]. The droop control strategy becomes useful in decentralized systems and is employed to resolve power quality issues with no need for communication kit to coordinate the integrated systems [16]. The inverter can therefore, be placed in the LV grid network as a shunt device to provide ancillary service (reactive power) to the grid, playing a crucial role stabilizing system voltage [17].

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 because of changes to the nominal voltage. Using recent standards, the droop curves can be implemented locally in the inverter [16]. The extent of the inverter's response is based on the configured parameters of the droop controller, i.e. the voltage dead-bands, Q_{min} and Q_{max} as shown in Fig. 1 below.

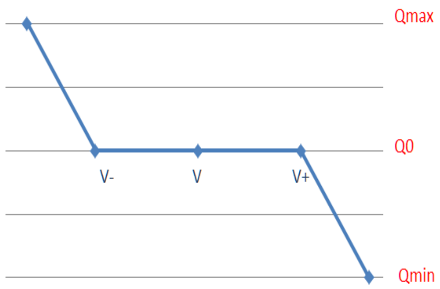


Fig. 1: The inverter's Voltage Droop Control

With the application of the droop, the inverter can positively contribute to feeder voltage control for high DER penetration concerns mention in section 1 above, and yields an improved voltage profile, reliability and reduction of transmission loss [11]. The response of the inverter controllers must be very fast in terms of responding to changes in network conditions and the advantages of using the droop control results in the overall system being more damped; it provides automatic harmonic current sharing via the inverters and phase errors barely affect active power sharing.

B. *OLTC Transformer in an LV microgrid*

The transformer is one of the oldest voltage control devices in power networks. It is used in a High Voltage (HV), Medium Voltage (MV) and LV grid applications. In order to maintain grid stability, it may be necessary to make use of power transformers with on-load tap changers to compensate the voltage drop/gain along the distribution feeders to keep the voltage within the nominal range. Various OLTC topologies have been discussed in [13] based on different configuration of the conventional two-winding transformer. OLTC utilises the conventional voltage control and responds to the change in the measured voltage and current of the secondary side of the transformer through appropraite tap switching.

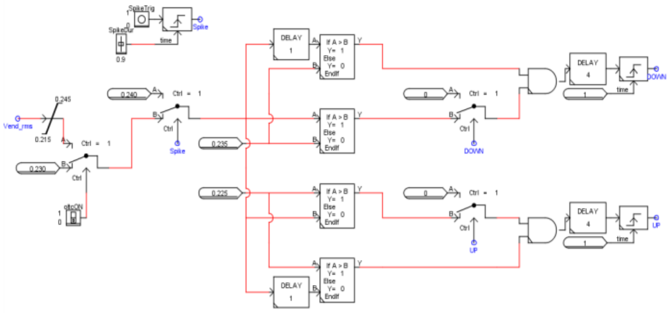


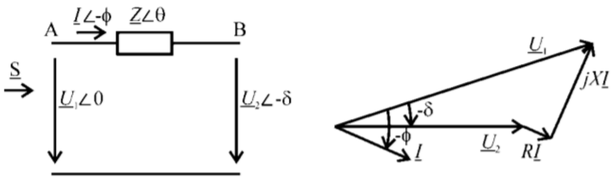
Fig. 2: The transformer's OLTC control

Although 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 deadband, 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, which is shown in Fig. 2, is utilized in this paper where a fixed step voltage change has been implemented in the OLTC controller. From the model in Fig. 2 above, 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%).

3. ACTIVE AND REACTIVE POWER CONCEPT IN LV GRIDS

When considering a Low Voltage grid, the power flowing into a line at point A towards point B as shown in Fig. 3a below is given as [14-15]:



(a) (b)

Fig. 3a: Power flow in line from Point A toward B *Fig. 3b: Phasor diagram representation [14-15]*

$$P + jQ = \underline{S} = \underline{U}_1 \underline{I}^* = \underline{U}_1 \left(\frac{\underline{U}_1 - \underline{U}_2}{\underline{Z}} \right)^* = U_1 \left(\frac{U_1 - U_2\ e^{j\delta}}{Z e^{-j\theta}} \right) \quad (1)$$

$$= \frac{U_1^{\ 2}}{Z} e^{j\theta} - \frac{U_1 U_2}{Z} e^{j(\theta+\delta)}$$

In the line, the Active and Reactive power flowing can be written as:

$$P = \frac{U_1^{\ 2}}{Z} \cos\theta - \frac{U_1 U_2}{Z} \cos(\theta + \delta) \quad (2)$$

$$Q = \frac{U_1^{\ 2}}{Z} \sin\theta - \frac{U_1 U_2}{Z} \sin(\theta + \delta) \quad (3)$$

From $Ze^{j\theta} = R + jX$, we can re-write equation (2) and (3) as:

$$P = \frac{U_1^{\ 2}}{R^2 + X^2} [R(U_1 - U_2 \cos\delta) + XU_2 \sin\delta] \quad (4)$$

$$Q = \frac{U_1^{\ 2}}{R^2 + X^2} [-RU_2 \sin\delta + X(U_1 - U_2 \cos\delta)] \quad (5)$$

Or,

$$U_2 \sin\delta = \frac{XP - RQ}{U_1} \quad (6)$$

$$U_1 - U_2 \cos\delta = \frac{RP + XQ}{U_1} \quad (7)$$

Various elements in a network are characterized by their ability to inject or absorb reactive power; assuming that an inductive load is represented by $R + jX$ and that $\underline{S} = \underline{U}_1 \underline{I}^*$ convention is used, then an inductive load absorbs positive VArs and a capacitive load produces VArs [14]. In (6) and (7), the angle δ can be controlled by regulating P, while the inverter voltage $\underline{U_1}$ is controlled via Q [15].

4. POWER HARDWARE IN THE LOOP (PHIL) TEST

For this paper, a Power Hardware in the Loop (PHIL) design was implemented in testing the dynamics of the ancillary service devices in the LV voltage micro grid set up. In the PHIL set up, a 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 was controlled using dedicated software via an ethernet connection and this gives the opportunity to load in either preset or an actual day’s solar insulation values and can be further varied during the simulation to observe the changes on the LV grid and the response of the connected ancillary service devices, i.e., the PV inverter and the OLTC.

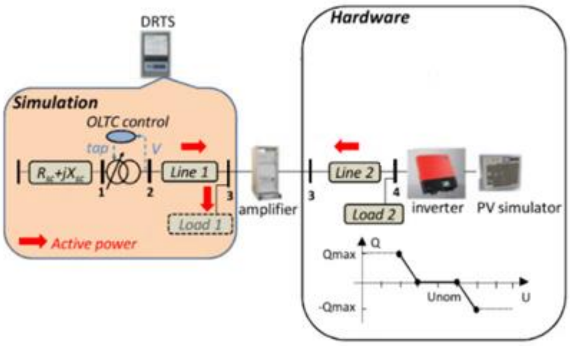


Fig. 3c: PHIL testbed with DG and OLTC Voltage Control [18]

Fig. 3c above is a block diagram of the PHIL test setup combining a physical inverter, PV simulator, line and loads to a simulated low voltage AC grid. The AC side of the LV grid was modelled and simulated using the Real Time Digital Simulator (RTDS) as shown in Fig. 3c above. A linear amplifier (4-Quadrant, 5kVA) was introduced in the PHIL setup to link the physical hardware to the RTDS.

Next, the 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 Q_{min} and $Q_{max.}$

A protection control circuit is included in RTDS to protect the laboratory equipment (inverter, amplifier, RTDS) from possible instability of the PHIL setup, since it is a closed-loop system. The AC circuit made up of an 11kv AC power source, active transformer with OLTC tap controls, PHIL instability protection control circuit, distribution lines and loads were designed via the RSCAD software (a Power Simulation software) and simulated in the RTDS.

In this experiment, three test cases were carried out to realize ancillary service contribution via the droop inverter and/or OLTC transformer. 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.

A. *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. 5 (Simulation) and Fig. 6 (PHIL hardware test) below. Due to the voltage drop, there was 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 20s.

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

The physical inveter in this experiment functions as a watt-priority inverter and, therefore, the remaining part of the inverter capacity can serve the purpose of reactive power compensation via the droop parameters.

The droop characteristics for the hardware inverter were set via the software gui of the SMA inverter with certain voltage values; the range (0.99 – 1.01 p.u) being the norminal value V_{norm}. Once the voltage rises/falls above/below V_{norm} due changes in load, the inverter supplies/absorbs reactive power up to Q_{min} or Q_{max} . For test case 2, the OLTC tap controller was deactivated so that only the inverter responds to the grid voltage changes. Initailly (before the loads were switched on at time t=7s to realise the grid voltage drop), the PV inverter generated a steady active power which was fed into the grid.

From the result recorded in Fig. 7 (Simulation) and Fig.8 (PHIL hardware test) below for test case 2, it can be seen that as a voltage drop was experienced, the inveter quickly kicks in to stabilise and compensate the grid with reactive power (*Qpv*) within 4s. In comparison, this is significantly faster response than that achieved by the OLTC in test case 1.

C. Test case 3 – OLTC and Droop Q(U) inverter.

In test case 3, the conventional OLTC voltage control and the PV interver droop were to resolve the voltage problems across the feeder. During the initial stage of the simulation and PHIL hardware experiment, the hardware inverter supplied steady active power while the grid voltage is maintained at the nominal value. When the loads were turned on, a voltage drop was experienced across the line; the OLTC tap position changed initially with fixed step changes and stabilization of the voltage was further realized through the inverter's *Q(U)* droop controller by supplying reactive power as shown in Fig. 9 and Fig. 10 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 number of step changes of the OLTC taps could be further reduced (lesser operation of the OLTC taps in realising voltage control) if the set parameter and the triggering time of the inverter droop controller are further modified. However the aim was to initally allow the conventioanl OLTC voltage control to to provide support before the hardware inverter droop controller was activated.

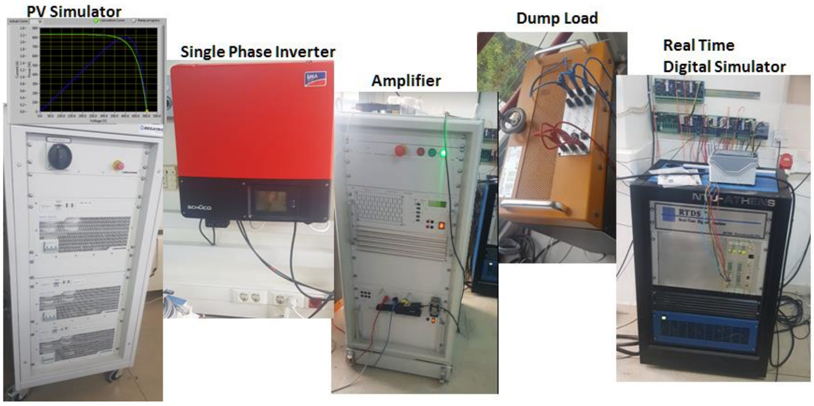
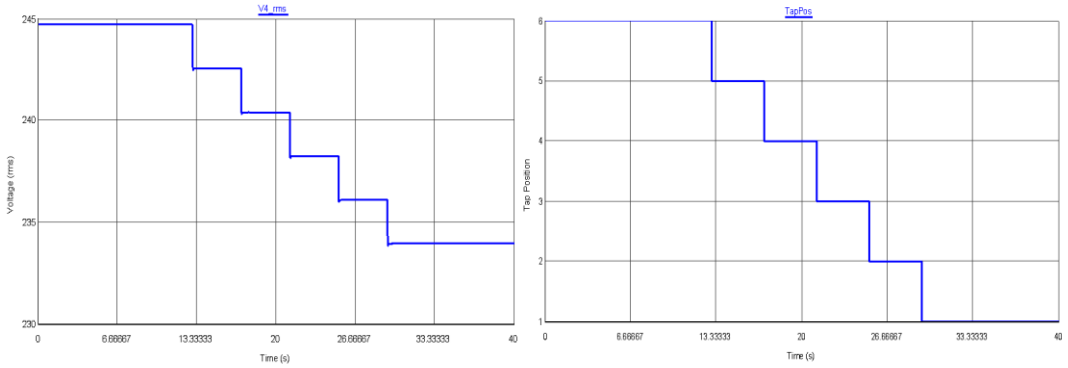
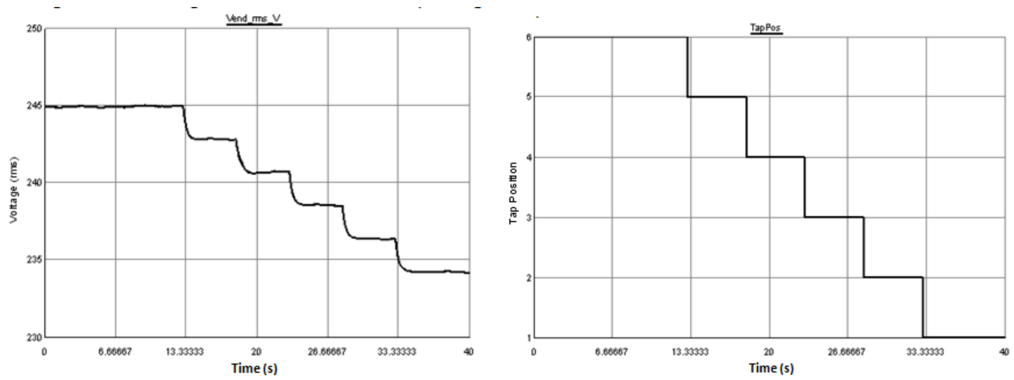


Fig. 4. PHIL Experimental Test Setup Facility



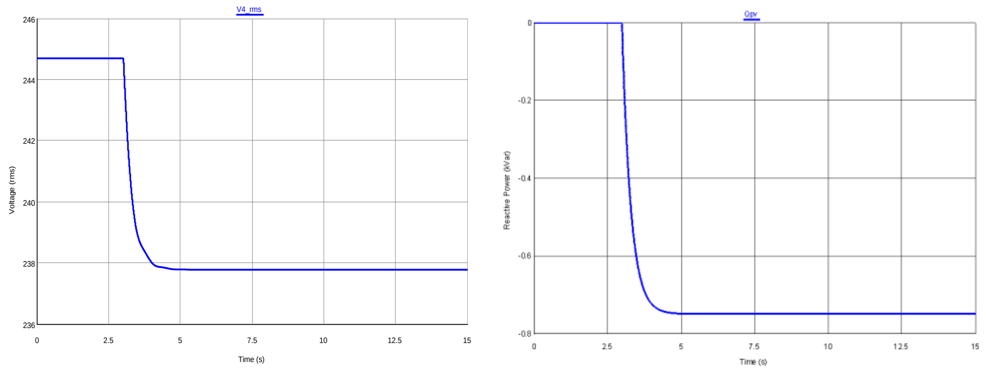
5a). Grid Voltage. 5b). OLTC tap position during voltage control.

Fig. 5. Simulation Case 1 – Voltage Control by OLTC only



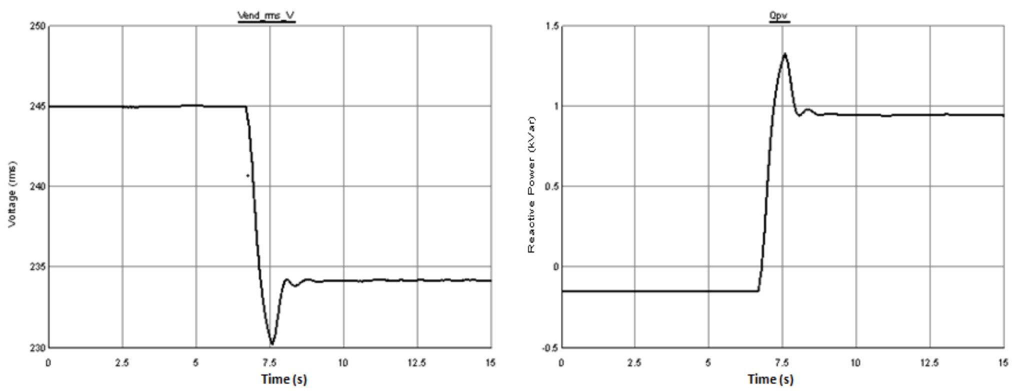
6a). Grid Voltage. 6b). OLTC tap position during voltage control.

Fig. 6 PHIL Test Case 1 – Voltage Control by OLTC only



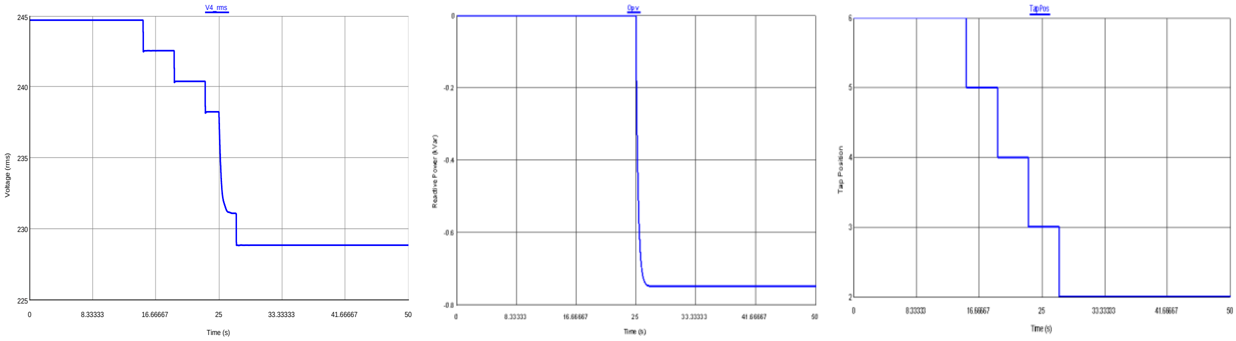
7a). Grid Voltage. 7b). Reactive power Qpv from the inverter.

Fig 7: Simulation Case 2 – Voltage Control by Q(U) droop inverter only



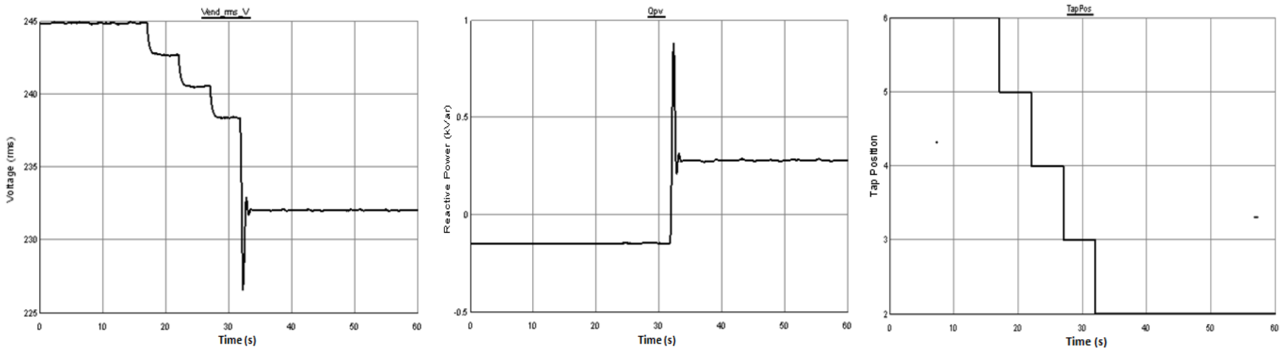
8a). Grid Voltage. 8b). Reactive power Qpv from the inverter.

Fig 8: PHIL Test Case 2 – Voltage Control by Q(U) droop inverter only



9a). Grid Voltage. 9b). Reactive power Qpv from the inverter. 9c). OLTC tap position during voltage control.

Fig 9: Simulation Case 3 – Voltage Control by OLTC and Q(U) droop inverter.



10a). Grid Voltage. 10b). Reactive power Qpv from the inverter. 10c). OLTC tap position during voltage control.

Fig 10: PHIL Test Case 3 – Voltage Control by OLTC and Q(U) droop inverter.

5. Conclusion

The above experiment was carried out to showcase the ancillary service supply opportunities from the inclusion of DGs in the LV grid, despite being regarded as intermittent sources by grid operators. Using the PHIL test set up, ancillary services where supplied to the grid using the conventional OLTC, which was further supported with the physical inverter's *Q(U)* Droop control which reduced the number of tap 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.

Acknowledgment

This research experiment has been performed using the ERIGrid Research Infrastructure and is part of a project that has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Grant Agreement No. 654113. The Support of the European Research Infrastructure ERIGrid and its partner Smart Grids Research Unit (Smart RUE) - Electric Energy Systems (EES) laboratory at ICCS-NTUA is very much appreciated. The authors acknowledge the support of Prof. Nikos Hatziargyriou.

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