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Power Hardware-In-the-Loop Validation of Post-Primary Voltage Control Scheme

Merkebu Z. Degefa*, Salvatore D'Arco, Andrei Morch and Atsede G. Endegnanew
Department of Energy Systems
SINTEF Energi AS
Trondheim, Norway
MerkebuZenebe.Degefa@sintef.no*

***Abstract*—The concept and experimental validation process of the Web-of-Cells (WoC) based Post-Primary Voltage Control (PPVC) developed in EU FP7 project ELECTRA IRP is presented in this paper. The main objective of PPVC is to provide an optimal and local voltage control replacing the conventional secondary and tertiary voltage control. The Power Hardware-In-the-Loop (PHIL) setup and the experimental results comparing the PPVC approach to traditional voltage control techniques are presented and discussed. The PPVC has demonstrated lower number of tap-changes and faster response to topology changes. To avoid simulation overrun in real-time environment, a slower simulation step is adopted for the electrical network model than the converter and grid emulator controller models in the Simulink model. The PHIL test conducted gives insight to the potential obstacles that may arise with increased number of cells and increased number of nodes in the network.**

Keywords—voltage control; converters; PHIL; real-time systems; OLTC

I. INTRODUCTION

The connection of future generation in power systems will substantially shift from central transmission to decentralized distribution systems increasing the risk of local voltage problems and congestions at LV and MV level. The resources required to regulate voltage levels are also moving from transmission level to distribution level together with the distributed generation units [1]. Hence, as central system operators at transmission level lose system overview, the coordination between operators at different voltage levels will be essential for effective dispatch of reserves.

The conventional voltage control lacks flexibility to respond to the fast and large fluctuation of operating conditions of the distribution feeder associated with the increasing penetration of distributed energy resources [2]. This may undermine the security and reliability of the network. Along with other important issues, such as frequency and balance control, the ELECTRA project attempts to address the problem with a new cell-based grid architecture, coined Web-of-Cells (WoC). Within the framework of the project several new control schemes based on the WoC concept have been developed and tested for frequency and voltage regulation [3].

Primary Voltage Control (PVC) is an automatic control of fast-acting devices such as automatic voltage controllers of generators. PVC aims to keep the voltage level at the node of the interconnection of the device close to the required set-point by managing the reactive or active power injections. On the other hand, PPVC brings voltage levels in the nodes of the entire network back to nominal values while optimizing the reactive power flows with the objective of reducing the losses in the network. PPVC utilizes any unit capable of offering reactive power such as generating units and storage systems. Moreover, depending on its optimal contributions to voltage control, active power may also be procured in case of PPVC.

PPVC typically operates in the time frames of current secondary voltage control and has proactive and restorative regimes. It intends to replace the present secondary (local) and tertiary voltage control (global). A safe upper and lower voltage level are defined as 0.95 and 1.06 respectively out-of-which a restorative voltage PPVC action shall be initiated.

This paper concentrates on presenting the development and the validation of the Post Primary Voltage Control (PPVC). The experimental validation has been implemented by SINTEF Energy Research in the Norwegian National Smart Grid Laboratory with PHIL experiments. Initial simulation results and a detailed presentation of the Optimal Power Flow algorithm has been presented on earlier publication by the authors [4]. This paper, however, presents the final PHIL implementation in laboratory and the techniques used.

This paper is organized in the following manner where section two introduces the Web-Of-Cells (WoC) concept and section three presents existing voltage control practices in the distribution network. Section four explains the Post-Primary Voltage Control (PPVC) method and is followed by discussion on the Power Hardware-In-the-Loop (PHIL) test setup in section five. After the presentation and discussion of the laboratory test results in section six, section seven concludes stating the main remarks.

II. THE WEB-OF-CELLS CONCEPT

The ELECTRA Web-of-Cells (WoC) concept divides the power system (grid) in smaller entities (geographical areas)-cells- with local observability and control by a cell operator that is responsible for the real-time control of the cell. Cells are connected with each other via tie-lines where neighboring cells can support each other in autonomous distributed collaborative way and can also decide on local activation optimization. Cells are not microgrids, the later can operate in grid-connected mode or islanded-mode, nevertheless cells are not required to be able to operate in islanded-mode. Hence, although microgrids can fulfill the definition cells, cells are not required to be as independent as microgrids.

Some of the characteristics of cells are:

- Cells can contain/span multiple voltage levels
- Dimensioning of cells takes into consideration computational complexity of detection and resolution, sufficiency of reserves providing resources and the spatial correlation of weather forecasting for RES.
- Cells do not need to be self-reliant for matching demand with supply. Rather, they may depend on structural energy imports of exports coming from large central RES power plants.

Voltage control in WoC concept is local and hence detection of voltage level and activation of resources will take place within each cell. In this study, a single cell is considered for the selected test network.

III. PRESENT VOLTAGE CONTROL TECHNIQUES

Currently, the voltage control in distribution systems is normally organized in terms of a three-step hierarchy: Primary, Secondary and Tertiary voltage control [5].

- ***Primary voltage control*** is executed by excitation generator voltage controllers and some fast regulators. The response time of primary control is almost instantaneous (a few seconds).
- ***Secondary voltage control*** coordinates the operation of voltage and reactive power regulators in a given distribution network zone in order to maintain the required voltage levels. The switching of compensating equipment such as capacitor banks and shunt reactors or the blocking of On-Load Tap-Changers (OLTC) is part of secondary voltage control action. The response time of the secondary control is a matter of minutes (200 to 300s).
- ***Tertiary voltage control*** involves voltage-level optimization using on-load calculations to modify settings of voltage and reactive power regulators. In tertiary regulation, the scheduling of V/Q can be carried out every 15 minute or every hour.

The inner workings of two of the voltage controllers relevant in secondary and tertiary voltage control, hence also to the newly proposed PPVC, are discussed briefly. Two devices capable of voltage regulation are on-load tap changers and PV converters.

A. *Onload Tap changers (OLTCs)*

A typical OLTC measures the busbar voltage at the power transformer LV side, and if no other additional features are enabled (i.e. line drop compensation) this voltage is used for voltage regulation. The voltage control algorithm then compares the measured voltage with the reference voltage and decides which action should be taken.

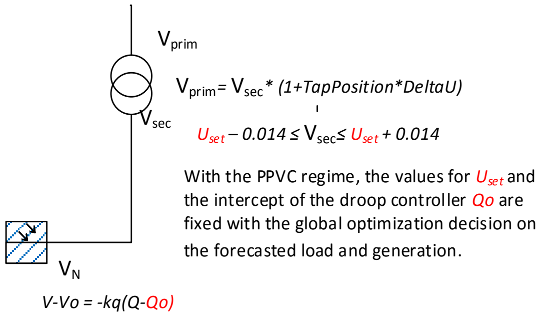

Fig. 1. Adjustable parameters for OLTCs and converters

In OLTCs, the number of the secondary side winding turns (N_2) and the primary side voltage (V_{prim}) are fixed. Hence, the secondary side voltage (V_{sec}) is regulated by changing the number of winding turns of the primary side (N_1). Increasing the primary side turn ratio decreases the secondary side voltage and if the primary turns of transformers are decreased, the voltage on secondary side is increased. Hence, the OLTC shall set tap positions aiming to keep the secondary side voltage within certain range (e.g. $1.026 \leq V_{sec} \leq 1.054$). A typical dead-band of the controller is about 75% of the OLTC step. In the CIGRE MV [6] test network the OLTC has a step size (*DeltaU*) of 0.01875 pu making the dead-band to be 0.75×0.01875 = 0.014. Fig. 1 presents the voltage control strategies followed in the validation process of the PPVC concept.

B. *Converter Droop controllers*

Theoretically, the voltage at the point of common coupling (PCC) of a grid-connected Voltage Source Converter (VSC) can be dynamically regulated by controlling the reactive power injected/absorbed by the VSC to/from the power grid [7]. Grid -supporting power converters can adjust active and reactive power reference according to their P/f and Q/V droop characteristics to participate in the regulation of frequency and voltage respectively [8]. A typical droop characteristics curve is plotted in Fig. 2. In general, there are two possible control variables from the droop controller characteristics curve to include in the optimal power flow formulation. The first is the slope of the droop controller and the second is the intercept (the point where the characteristics curve crosses the voltage axis in Fig. 2).

Changing the slope value will permit changing Q set-point for each node. The bigger the slope the higher the Q set-point for each node. However, when the slope changes sign from negative to positive infinity, during the vertical positioning of the straight line, the intended injection of Q changes to unintended absorption. In this situation, the search of the optimal slope in the optimization procedure may become unstable. This suggests avoiding the use of the droop slope parameter as an optimization variable in a first optimization study. However, looking at the y-intercept, the instability problem while searching optimal point does not appear since the shifting in the y-axis of the curve permits a smooth transition between absorbing and injecting reactive power Q.

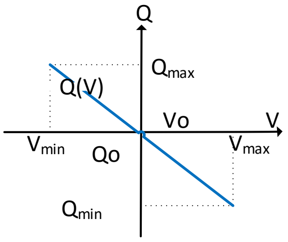

Fig. 2. Q/V droop characterstics of converter

The local operation of voltage controllers, such as OLTCs, following only the local point-of-power-coupling (PPC) voltage measurements will essentially lose the oversight of the entire distribution network especially with the presence of distributed generation. Hence, for faster mitigation of voltage level problems in other parts of the network where the local controllers are not 'seeing' and also to harness the distributed voltage regulating resources, the introduction and development of the PPVC concept is deemed essential.

IV. POST-PRIMARY VOLTAGE CONTROL

Essentially, PPVC enables preparation of reserves for near future requirements of voltage control. It foresees voltage violations coming by using forecasts of load and generation from historical data. PPVC also deploy all available resources after disturbances to take corrective measures of voltage level violations.

To summarize, the main advantages of the Web-of-Cells based PPVC over traditional secondary and tertiary voltage control can be summarized as:

1. PPVC can reduce the number of primary voltage control (PVC) activations by predicting future safe-band violations (proactive mode).
2. PPVC can restore the voltage levels in the nodes to the optimal values in case of unexpected events, while minimizing the total losses in the system (corrective mode).

A. *Proactive over/undervoltages mitigation*

The proactive mode is invoked every 15 minutes regularly to deliver the optimal set points for all controllable nodes in the network. The set points are calculated based on generation and load forecasts, wind speed and solar irradiation measurements. The 15-minutes cycle is selected as it represents a time window length tradeoff between the computational cost and accuracy of the forecasts. This optimal updating of set points continues unless unscheduled event occurs in the network [9].

B. *Restorative control voltage levels*

Inspecting the periodical (e.g. with sampling frequency about 1 Hz voltage measurements, recalculation of optimal set points will be triggered in an attempt to restore voltage levels.

With the PPVC scheme, OLTC setting and reactive power from inverters shall be decided from globally optimal loss minimization objective. (i.e. OLTC setting can be anywhere between the maximum and minimum limit and reactive power from inverter can be anywhere between the specific time's maximum and minimum potential)

The implementation of the PPVC concept is elaborated in Fig. 3. The electrical network is implemented using Matlab Simulink and the OPF is written using the General Algebraic Modeling System (GAMS). The objective in the OPF formulation is loss minimization and the OLTC and converter droop controller parameters are included in the constraint. As the tap setting is integer variable, the loss minimizing OPF is Mixed Integer Nonlinear Programing (MINLP) problem. As shown in Fig.3, the PPVC process starts as the Simulink based network start running. Every minute the voltage values are supplied to the PPVC function where constraint violations are checked. If voltage limits are violated, then the restorative mode calls the OPF to compute the optimal OLTC references and Q-intercepts. Otherwise, the PPVC function checks if 15-minutes proactive action window is reached and calls the OPF again. If neither proactive or restorative modes are invoked, then the simulations continues running by updating the minute level loads and generation values.

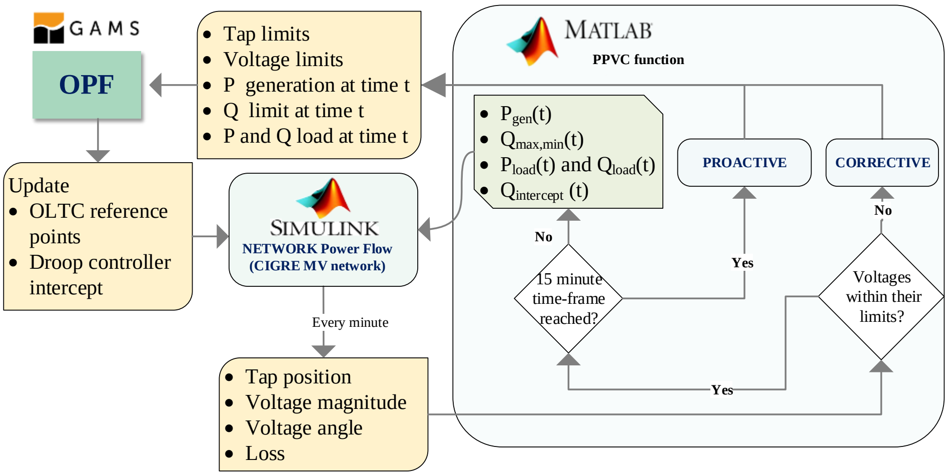

Fig. 3. Workflow for the proactive and the corrective (restorative) schemes of the PPVC

V. PHIL TESTING SETUP

Power Hardware in the Loop (PHIL) involves the interfacing of real-time systems (RTS) with a power hardware such as inverters where the RTS and the power device exchange power over the PHIL interface. The PHIL simulation techniques represents a massive simplification from hardware to software of both grid impedances and grid constellations resulting in flexibility and reduced cost [10].

A real-time simulator, by definition, needs to solve the model equations for one time step within the same time in a real-world clock [10]. The digital real-time simulation of the electric power system is the reproduction of output (voltage/currents) waveforms, with the desired accuracy, that are representative of the behaviour of the real power system being modeled [11].

This test is relevant in PPVC experimentation to study the response of converters as voltage regulators under sudden change of voltage levels and network configuration. The converters are essential resources of PPVC which naturally relies heavily on distributed flexible resources.

The National Smart Grid Laboratory is located in Trondheim at the campus of the Norwegian University of Science and Technology (NTNU) and it is jointly operated by SINTEF and NTNU. The laboratory is equipped to perform real-time simulations of electrical systems and their controls. For the PPVC experiment, we utilized the following equipment: OPAL-RT platform (OP5600 5 cores activated), 200 kW high-bandwidth (20 kHz) power converter operating as a grid emulator, three 60 kW converter units, and interface computer.

While the OPAL-RT was used as real-time simulator EGSTON-COMPISO power amplifier was utilized as grid emulator. The first physical converter represents the inverter of a PV system at bus 10, while the second converter in Fig. 4 is used to control the DC side of the converter in hardware-in-the-loop. To avoid overrun two different time steps are set for the electrical network system and the rest of simulation.

The CIGRE 15-bus benchmark network with eight PV connections and a wind turbine is utilized to study the PPVC scheme [6]. While the converters at bus-10 and 7 are connected to the converter hardware, the rest of the PV panels are updated with 'forecasted' (deterministic) minute level values. In Fig. 4, the conceptual experiment setup is presented where the PPVC function and the OPF algorithm are running on the interface computer. Keeping the 20 kV electrical system intact, proper scaling of the voltage reference to converters, P and Q references to the converters and the current injections to the electrical system has been performed.

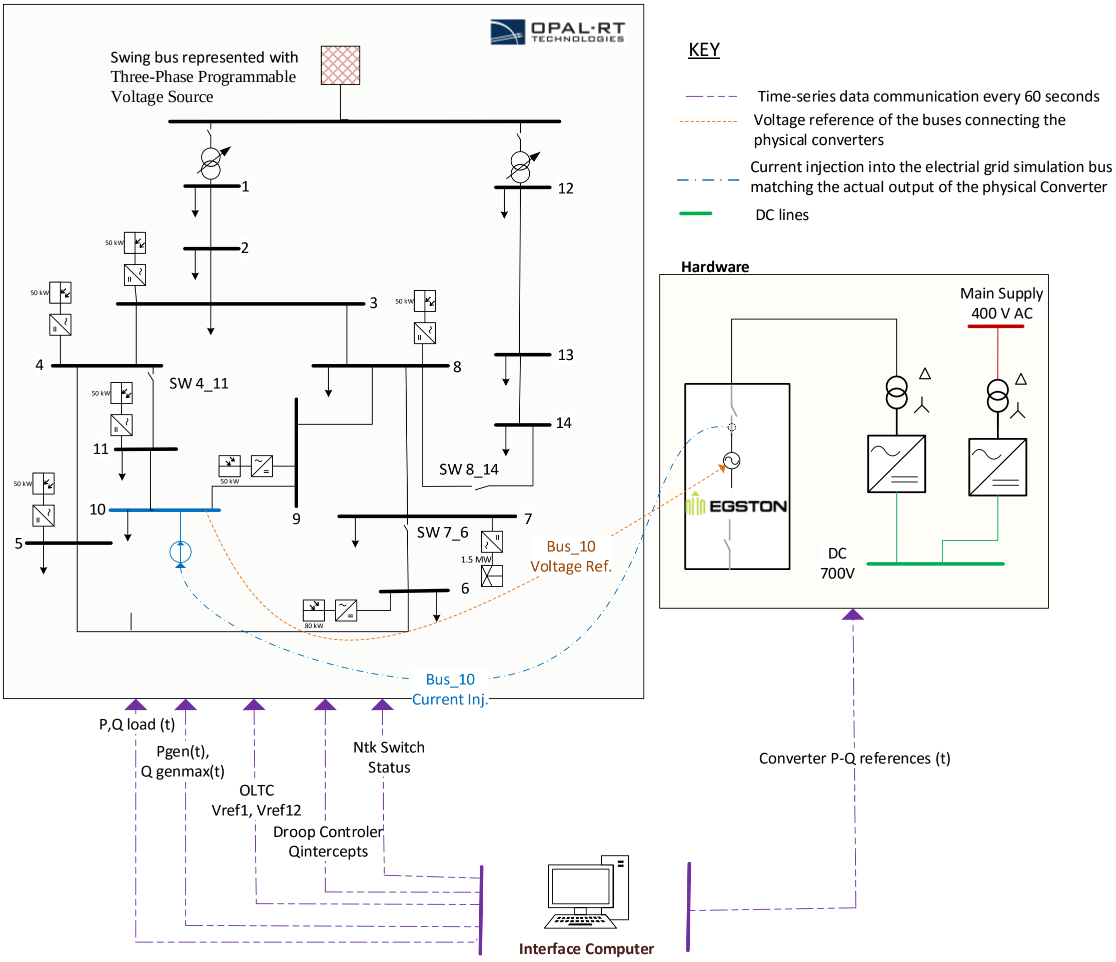

Fig. 4. The electrical connectivity of the grid emulator and the two converters in the laboratory

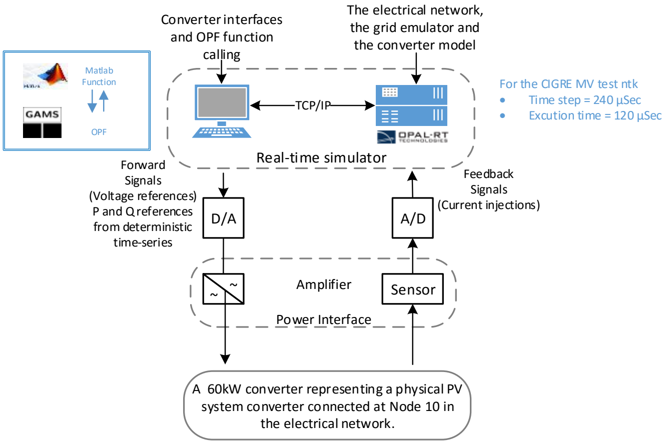

Fig. 5. The PHIL implementation setup

In the real-time simulation system, two slave subsystems ('ss-')consisting of the electrical network and the grid emulator models are prepared while the master block ('sm-') consists of the converter model. In the interface block ('sc-'), there is a MATLAB function block updating deterministic time-series values for load and generation. More importantly the function block is linked with GAMS based OPF and is called every 15-minutes in the proactive mode and anytime whenever voltage limit violation is detected in the network. In addition, the interface block performs most of the data acquisition while the simulation is running. Details of the actual experiment setup in the lab with electrical connections and communication links are presented in Fig. 5.

VI. LABORATORY TEST RESULTS

The validation of the WoC (single-cell) based PPVC method in the laboratory is carried out by studying four cases:

Case#1: Business-As-Usual case, with fixed OLTC reference and fixed intercept of droop controllers

In Case#1, the OLTCS have a fixed reference voltage (U_{set}) which is 1 pu and the converter droop controllers have zero intercept values (Qo) (see Fig. 1). As they normally operate in today's network the OLTCs and the converters adjust themselves automatically following the voltage level at the point of common coupling.

Case#2: Full PPVC, with optimized OLTC reference and optimized intercept of droop controllers

In Case#2, the OLTCs reference voltage (U_{set}) and the intercept values (Qo) of the converter droop controllers are optimally set every 15 minutes for proactive mode and at any time step for restorative mode.

Case#3: Case#1 with network reconfiguration

Case#4: Case#2 with network reconfiguration

In both Case#3 and Case#4 the normally closed switches in the network (see in Fig. 4, 'SW 8-14', 'SW 4_11' and 'SW 7_6') are opened after about 19 minutes. Figs 6 and 7 show voltage profiles for Case#1 and Case#2 for similar 30-minutes loading and generation conditions. While Figs 8 and 9 present the voltage profiles for Cases #3 and #4. Fig. 10 shows the total active and reactive power at the swing bus.

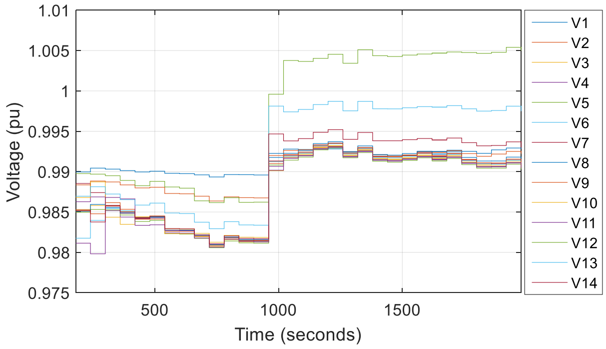

Fig. 6. BAU case voltage profiles from simulation (Case#1)

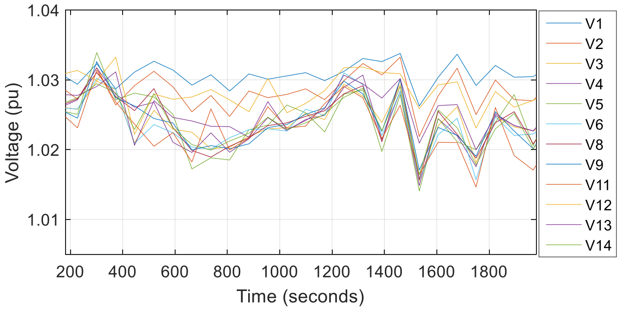

Fig. 7. The PPVC case voltage profiles from the PHIL test (Case#2)

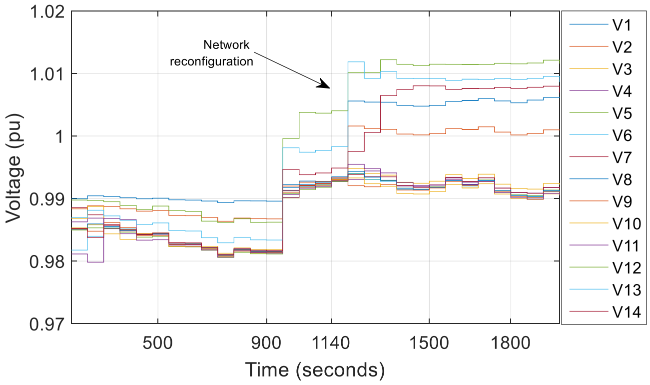

Fig. 8. BAU case voltage profiles from simulation (Case#3)

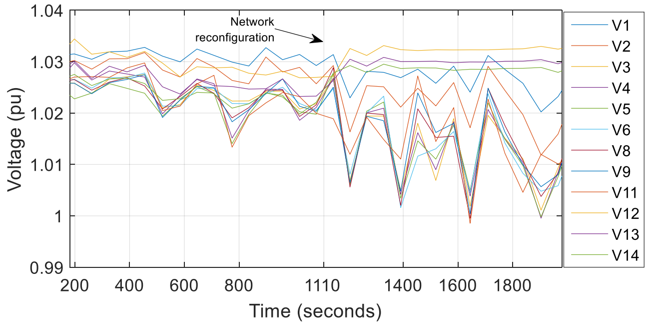

Fig. 9. The PPVC case voltage profiles from the PHIL test (Case#4)

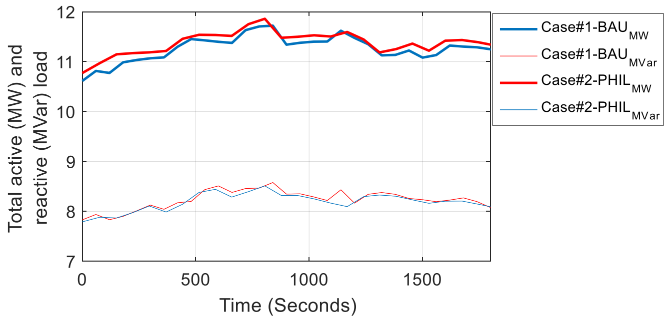

Fig. 10. Total active and reactive load demand at the slack bus (Case#1 and Case#2)

There has been one tap changes during the BAU case in normal situation (Case#1) and two tap changes for BAU case with network reconfiguration (Case#3). However, no tap changes have been experienced with both cases (Cases #2 and #4) of the PPVC implementation in PHIL test. Due to the continuous updating of the reference voltage of the OLTCs, lower intervention of tap changers is observed in case of PPVC than the BAU case.

As shown in Figs 6 and 7 the voltage profile is more stable in case of PPVC compared to the BAU case. This is essentially due to the pre-adjustment of the PPVC controllers based on the forecasted load and generations. The reference voltage for the OLTC has been updated every 15 minutes avoiding unnecessary involvement of OLTCs tap changes.

The PPVC controllers can adapt to network configuration changes better than the BAU cases. As shown in Figs 8 and 9, the OLTC reference voltages and the droop controller intercept points were positioned better for incoming loading scenarios and there was no need of OLTC tap change to mitigate the under-voltage problems. The response for network configuration change is fast in case of PPVC as well. The controllers can be re-adjusted if existing settings cannot respond to voltage limit violations in case of PPVC.

As it can be seen in Fig 10, the PPVC PHIL implementation in Case#2 demonstrated higher loss in active power and used the reactive power resources in the network more than the BAU Case#1.

VII. CONCLUSIONS

The newly introduced web-of-cells based PPVC approach in ELECTRA project has been tested in laboratory with PHIL test setup. Some of the benefits of the PPVC, such as fast response to changes in the network topology and lower intervention of tap changers, over the conventional voltage control practices are validated. The PHIL real-time test for single-cell configuration has already been met with overruns in case of universally same simulation time and hence different simulation time has been set for the electrical system and the rest of the system. Especially for larger networks the real-time test is highly susceptible to 'overrun'. Hence, efficient and fast OPF formulation and implementation is required in future as it is also needed for dividing big networks into multiple cell divisions.

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