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List of Abbreviations

CO	Project Coordinator
EC	European Commission
LA	Lab Access
UG	User Group
UP	User Project
PV	Photovoltaic
VVC	Volt-Var Control
VWC	Volt-Watt Control
IEEE	Institute of Electrical and Electronics Engineering
RTDS	Real Time Digital Simulator
PHIL	Power-Hardware-In-The-Loop
SCADA	Supervisory Control And Data Acquisition
IEC	International Electro-technical Commission
PC	Personal Computer
TCP/IP	Transmission Control Protocol/ Internet Protocol
DUT	Device Under Test
HL	Heating Load
kW	Kilo Watt
MW	Mega Watt
MVAR	Mega Var Ampere Reactive

Executive Summary

Integration of large scale of distributed photovoltaic (PV) generation resources in the distribution network can lead to technical challenges, particularly voltage rises caused by PVs power injection at the time of high solar radiation profile and low load demand. It is imperative important to apply control functions according to power rating of PV inverter, when their capacities are in wide range. In other words, these control functions need to performed based on available capacity from unequal size of PV inverters. Advanced controls like volt-var and volt-watt could allow the PV inverters gradually reduce their real power output as a function of measured bus voltage and provide reactive power support to maintain the network voltage within constraints. The study is performed to analyse voltage distribution profiles across the nodes, with implement of volt-var control (VVC) and volt-watt control (VWC) on PV inverter. The study is conducted in real-time environment, wherein, PV systems integrated in IEEE 13 bus distribution network is in real-time simulation (RTDS) with control functions performed via update of VVC and VWC. Furthermore, power hardware-in-loop (PV emulator, power amplifier with heating load) is integrated at one bus in the network. The complete operation of hardware components in real-time environment operates as smart-grid, having communication network.

1 Lab-Access User Project Information

1.1 Overview

The VTT Intelligent Energy lab is equipped with a local SCADA enabling monitoring and control, RTDS with current and voltage amplifier, communication emulator, and IEC 61850-based control and protection system. The facility in this lab meets all the range of infrastructure required to complete the research objectives. This includes PHIL (PV emulators), support for communication network, and real-time simulator (RTDS). In the past, the said lab was engaged with developing controllers for to maintain voltage stability using online estimation of voltage sensitivity.

The PERFECT (Performance analysis of PV integrated distribution network with combination of different control strategies and communication network) is primarily implementation of voltage profile analysis of PV integrated distribution network in Real-Time Digital Simulator provided by VTT Lab under ERIGRID 2.0 project in the time duration of one month with the help of Anju Yadav, Nand Kishor, Richa Negi, and Petra Raussi (VTT) et al. The project PERFECT was conducted with visit of Anju Yadav from 25.09.2022 to 22.10.2022.

The project was divided into three main phases. In the first phase, the IEEE 13-bus system with three phase PVs was configured. In the second phase, the PVs integrated in the system was controlled as VWC and VVC at base load and increased load conditions. In third phase, the study on PHIL was performed (using Cinergia) and control performance was analysed with the help of VTT member, Mikael Opas. The real-time simulation under various cases was planned, executed, observed and compiled with the help of other group members.

1.2 Research Motivation, Objectives, and Scope

Motivation:
The Author's research motivation is to apprise voltage rise caused by PVs power injection at the time of high solar radiation profile and low load demand. Advanced controls like volt-var and volt-watt could allow the PV inverters gradually reduce their real power output as a function of measured bus voltage and provide reactive power support to maintain the network voltage within constraints. Therefore, the project's objective was to assess dynamic interactions between control actions of PV inverters, achieved via control algorithm designed with update of VVC and VWC characteristics.

Objectives: The objectives of this project were to investigate the interaction between;
(A) PV inverters modeled in RTDS controlled via VVC/VWC and (B) existing PV inverters modeled in RTDS operated along with PV installation in the hardware (grid emulators at one of the buses in the network).
The complete test bed had features as:
<u>(A) System-I</u>: Distribution network with PV inverters implemented in RTDS. Some PV inverters (in RTDS) controlled via control algorithm with update of VVC and VWC. Both control algorithms were implemented on same communication network.
<u>(B) System-II</u>: PV emulators (PHIL) integrated at one of the buses in the network (in RTDS), included with System-I.

Scope:

To perform experiment for system having PV installation with control schemes VVC/VWC as described above, and existing PV installation with integration of PV emulator in the network. It was assumed that PV is installed in all the three phases with and without load connected at a given bus. Thus, all phases of a bus have PV installation.

Following tasks (T) were identified based on the objectives of this work:

Task 1 (T1): Voltage regulation in the network for System-I, with control algorithm via VVC and VWC for both with and without load changes.

Task 2 (T2): Voltage regulation in the network for System-II, i.e., with inclusion of PHIL (PV emulators).

Task 3 (T3): Voltage regulation in the network for System-II with control algorithm via VVC and VWC, interchanged among the PV inverters.

The above tasks (case studies) were planned for typical solar radiation with and without changes in load (operating conditions of power network) and voltage profile improvement.

Structure of the Document

This document is organised as follows: Section 2 briefly outlines the state-of-the-art/state-of-technology that provides the basis of the realised Lab Access (LA) User Project (UP). Section 3 briefly outlines the performed experiments whereas Section 4 summarises the results and conclusions. Potential open issues and suggestions for improvements are discussed in Section 5.

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

The voltage regulation in distribution network has been addressed in different timescales; centralized, decentralized and distributed level control. The voltage regulation formulated as an optimization problem [1] requires full information of the network, and have greater computation and communication requirement. They are usually operated at longer (e.g., 15 min) dispatch intervals. On other hand, in decentralized control, the set points of smart inverters are established via communication among the neighbouring inverters in [2]. However, there exists a high level of uncertainty and plug-and-play ability of distributed generation resources, and so the system conditions can change rapidly. As a result, decentralized control alone cannot sufficiently address the voltage regulation issue [3]. In some situations, bus voltages may still violate the operation limits even with the pre-specified droop settings and dispatch set-points. In [4], an optimal control law for decentralized autonomous control was suggested for large voltage fluctuations caused by varying PV output by utilizing a multi-agent system. Similarly, in distributed control, Q/P [C] and Q/V characteristics (curves) [5] strategy is implemented using only local measurements. It is agreed that pre-defined rules for framing these characteristics have resulted in stable performance and fast-converging, but their equilibria unfortunately do not coincide with the desired optimized power flow conditions [6]. Distributed control scheme remains effective, due to the use of local information when compared to a centralised control scheme, which may fail on the occurrence of latency in communication. As such local control schemes cannot guarantee optimal performance. This makes real-time coordination among local controllers necessary.

The comparison among different types of PV inverter control strategies and dispatch approaches based on voltage sensitivity, a centralized controller and the local voltage measurement is presented in [7]. The control system resiliency can be increased, being dependent on the local voltage control, especially when the communication based distributed control fails. This evolves into a hierarchical or multi-level control scheme. A two-stage control scheme using local droop control and distributed control [3], optimized dispatch and distributed operation [8], local and centralized control [9]. Most of the design strategy discussed in available literatures fail to provide a generalized selection criteria for control parameter settings. The presence of multiple PV inverters, each trying to control their local voltage may lead to oscillation [10]. In other words, undesired potential interactions arise among the PV inverters and distribution network impedance.

3 Executed Tests and Experiments

3.1 Test Plan, Standards, Procedures, and Methodology

The study was performed on an unbalanced distribution network (IEEE 13 bus network) developed in RTDS, as shown in Fig. 1.

Test Plan	Activities
Pre-visit	Discussion with host lab about the arrangement of components
1st week	Set-up of test-bed for performing the experiment in the cyber-physical environment
2nd week	Interfacing of softwares, hardware (power devices/emulators/communication network) and testing
3rd week	T1: Voltage regulation in the network for System-I, with control algorithm via updated VVC and VWC- data driven, T2: Voltage regulation in the network for System-II
4th week	T3: . Voltage regulation in the network for System-I with control algorithm via VVC and VWC, interchanged among the PV inverters.

As can be seen in Fig. 2, the experimental setup consists of RTDS (with part of distribution network), PV emulator, PHIL. In addition, a compatible communication network is also required to establish control and protection functions in the system. It is planned to use both wired and wireless network (standard protocol) in the experimental study. There is a need for at least one personal computer (PC) having MATLAB software installed.

3.2 Test Set-up(s)

It is proposed to consider an unbalanced distribution network (IEEE 13 bus network) developed in RTDS with load presented on bus 634, 645 and 671 and PV output with solar radiation profile is collected on bus 634, 671 and 680 (N, M, and F) as shown in Fig.1. Further analysis is performed after placing 3-phase PVs on these bus (capacity of each PV placed is 0.4125 kW). Next, complete integrated hardware and simulator, including computer (with MATLAB) is connected via communicated network (wired). As shown in Fig. 2 distribution network placement and size of PV inverter (in RTDS) will be controllable via updated VVC and VWC. The implementation of control on PV inverters can be understood from Fig. 2. The change in voltage profile occurs corresponding to VVC and VWC curves as illustrated in Fig. 3.

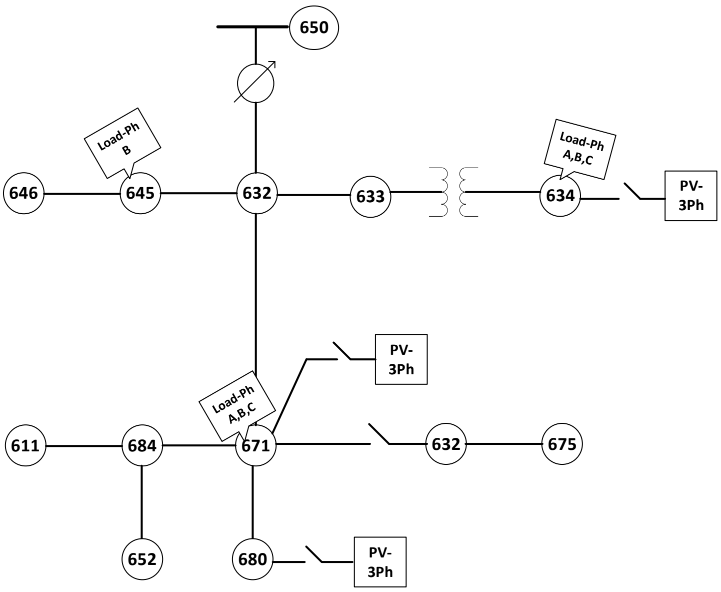


Fig. 1 IEEE-13 bus network

For System-I representation, with RTDS, it can be seen that VVC/VWC is applied on PV inverters of system-I. The experiment study on System-I, having above-described control options on PV inverters, will be next extended, to form System-II. As illustrated in Fig. 2 one PV emulator is now integrated into the network in RTDS.

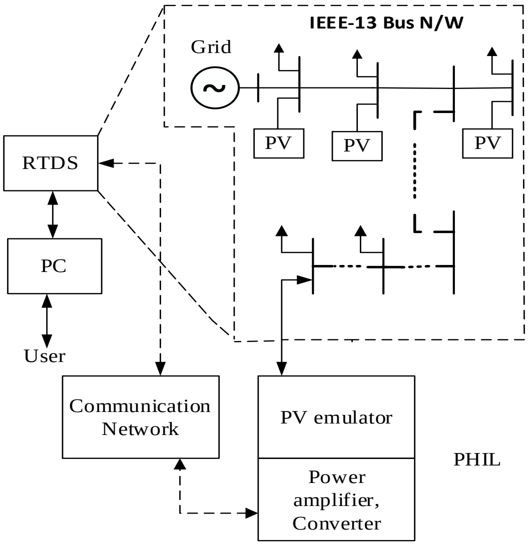
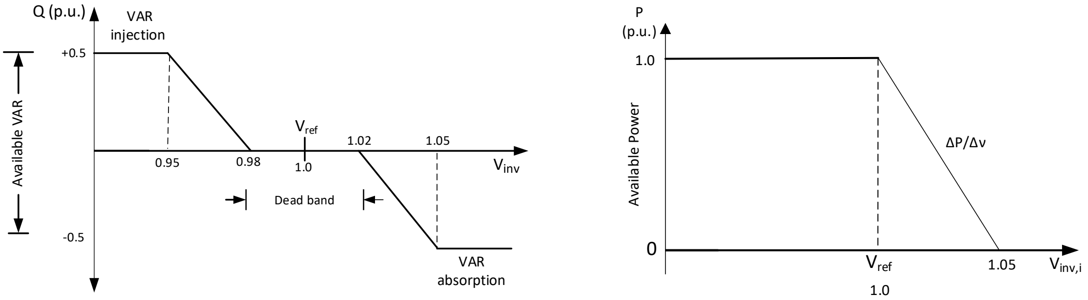


Fig. 2 Illustration of the testbed to conduct the experiment



(a) Volt-var characteristic (VVC)

(b) Volt-watt characteristic (VWC)

Fig. 3 PV inverter control characteristics

All the communications required for distributed control algorithm (applied on three PV inverters in RTDS) was implemented via a real communication network. The bus (having PV integrated) signal (in RTDS) was retrieved independently routed through communication card to control algorithm (in PC) and subsequently designed control signal was transmitted back to neighbouring PV inverter (in RTDS).

The real hardware of PV emulator was integrated at a feeder bus (System-II) and the complete setup used to perform PHIL is represented in Fig. 4.

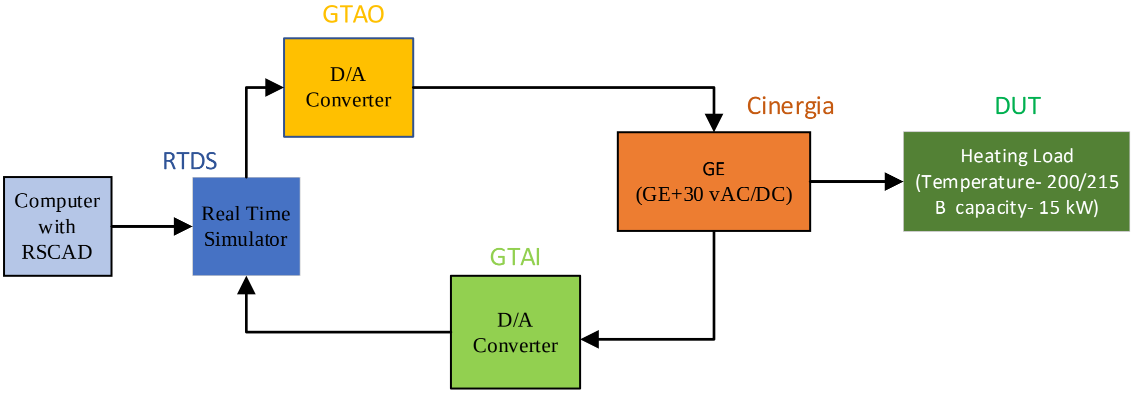


Fig. 4 Block diagram of components used to perform PHIL

3.3 Data Management and Processing

The results obtained from Real Time Digital Simulator are stored in a DAT file. The DAT file is a data file that contains information about the result, which has been stored and further analysed. The DAT file can be accessed using RSCAD, MATLAB, and using any text editor like Notepad. The user has extracted and analysed the DAT file using MATLAB. MATLAB provides freedom to plot the results among different available data (i.e., Voltage profile, Power profile, solar profile etc.).

4 Results and Conclusions

4.1 Discussion of Results

4.1.1 Discussion of Results without PHIL

The solar radiation profiles as shown in Fig. 5. Between the two profiles, difference is that, at 12:30 pm, SR_1 reaches as high as 1140 W/m^2, responsible for voltage violation (as discussed later) while SR_2 remains at 1000 W/m^2. In this section the analysis is divided into two cases, case A is performed for base load of IEEE-13 bus while case B is performed for changes (increment/decrement) in base load conditions.

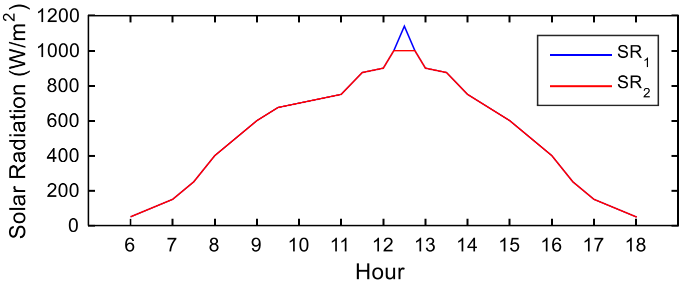
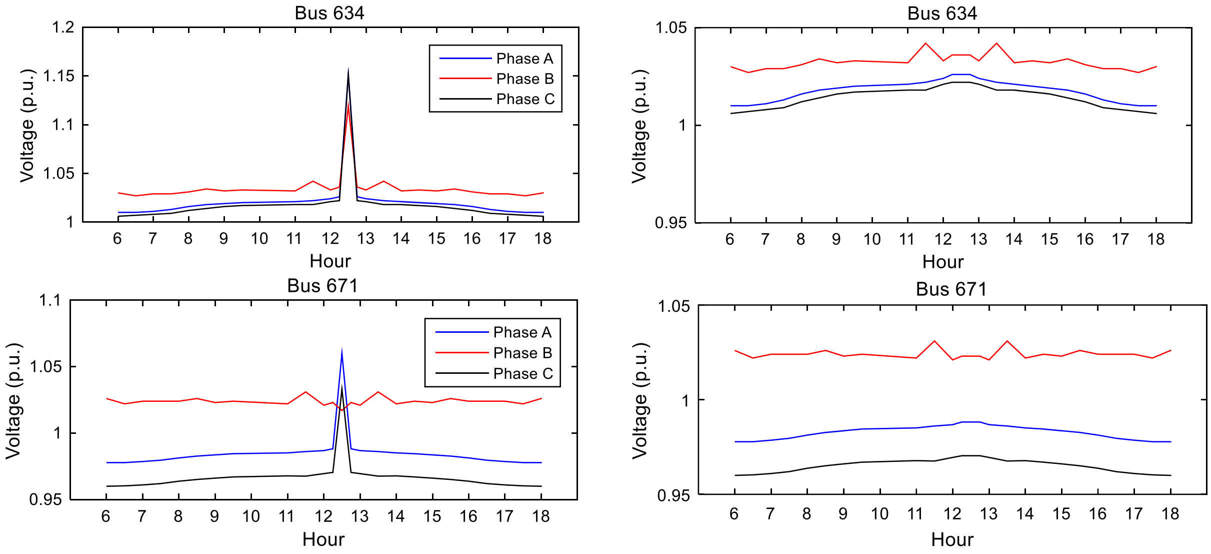
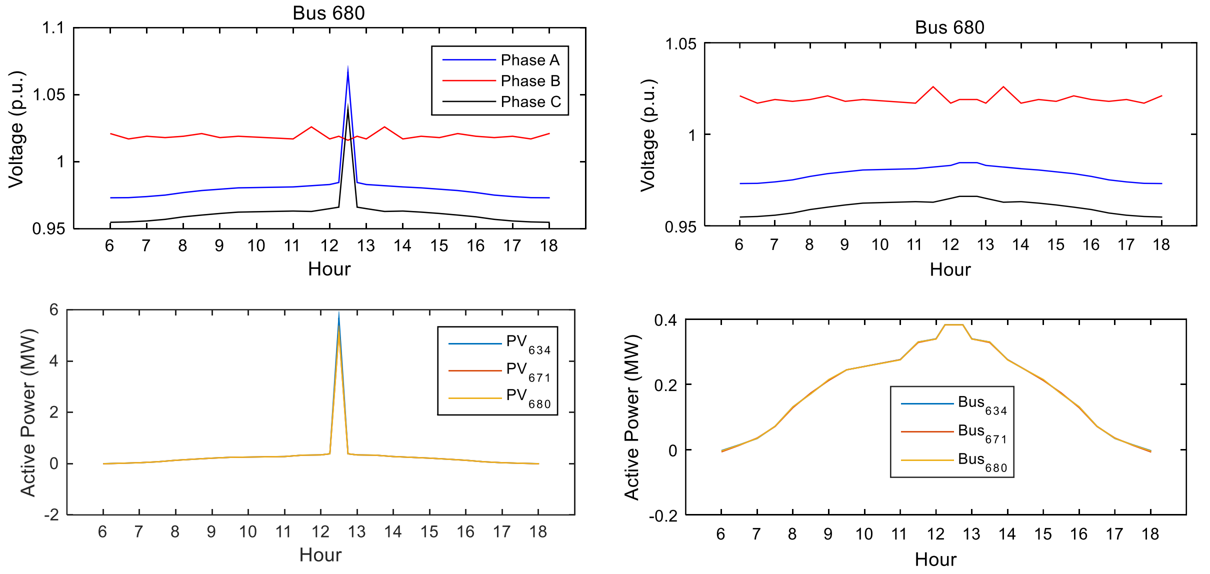


Fig. 5 Solar radiation

Case A: At base load of IEEE-13

The impact of these solar profiles on feeder bus voltages and PV powers injected into the network, at base load is presented in Fig. 6.



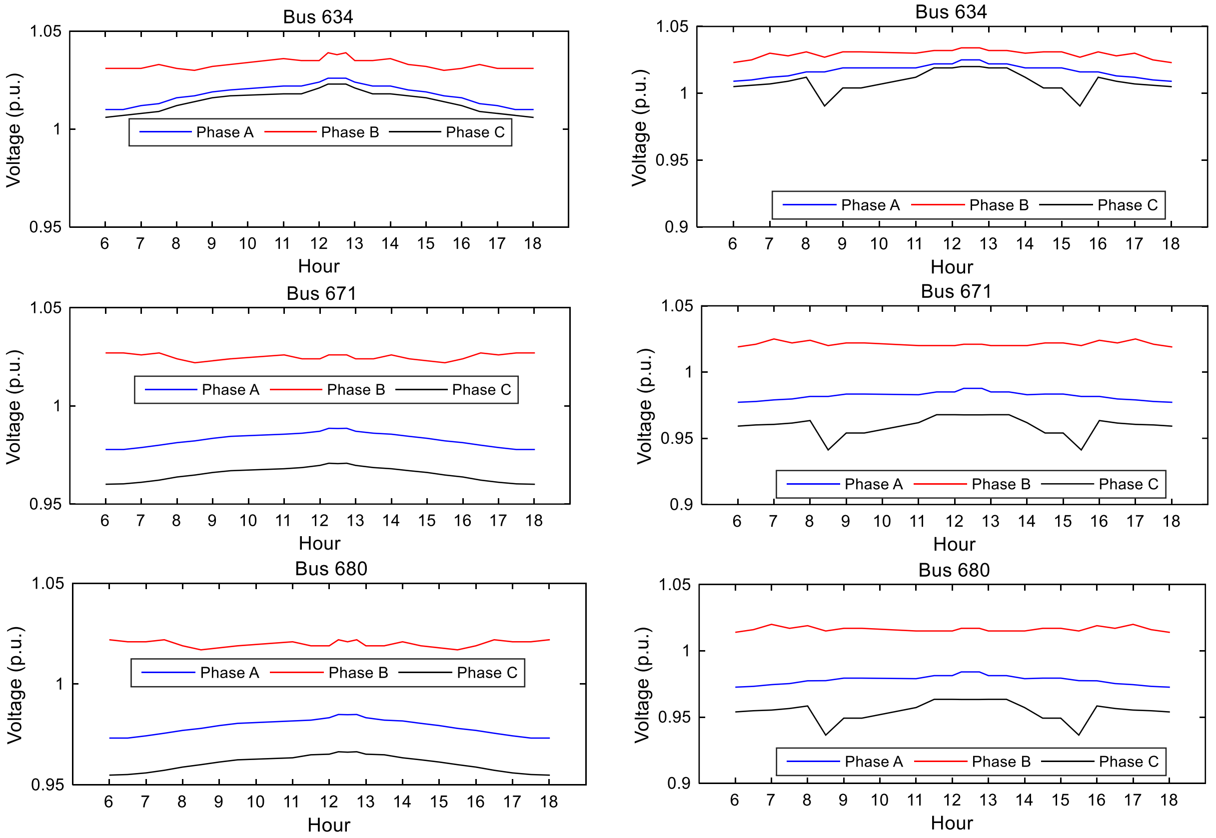


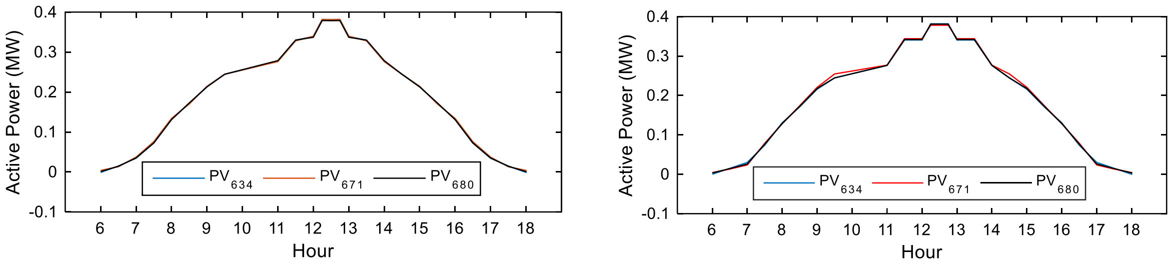
(a) For solar radiation-1 (SR_1)

(b) For solar radiation-2 (SR_2)

Fig. 6 Bus voltages and PVs power without control on PV inverters

The impact of local control (VVC/VWC) for SR_1 on feeder bus voltages and PV powers injected in to the network at base load is presented in Fig. 7.



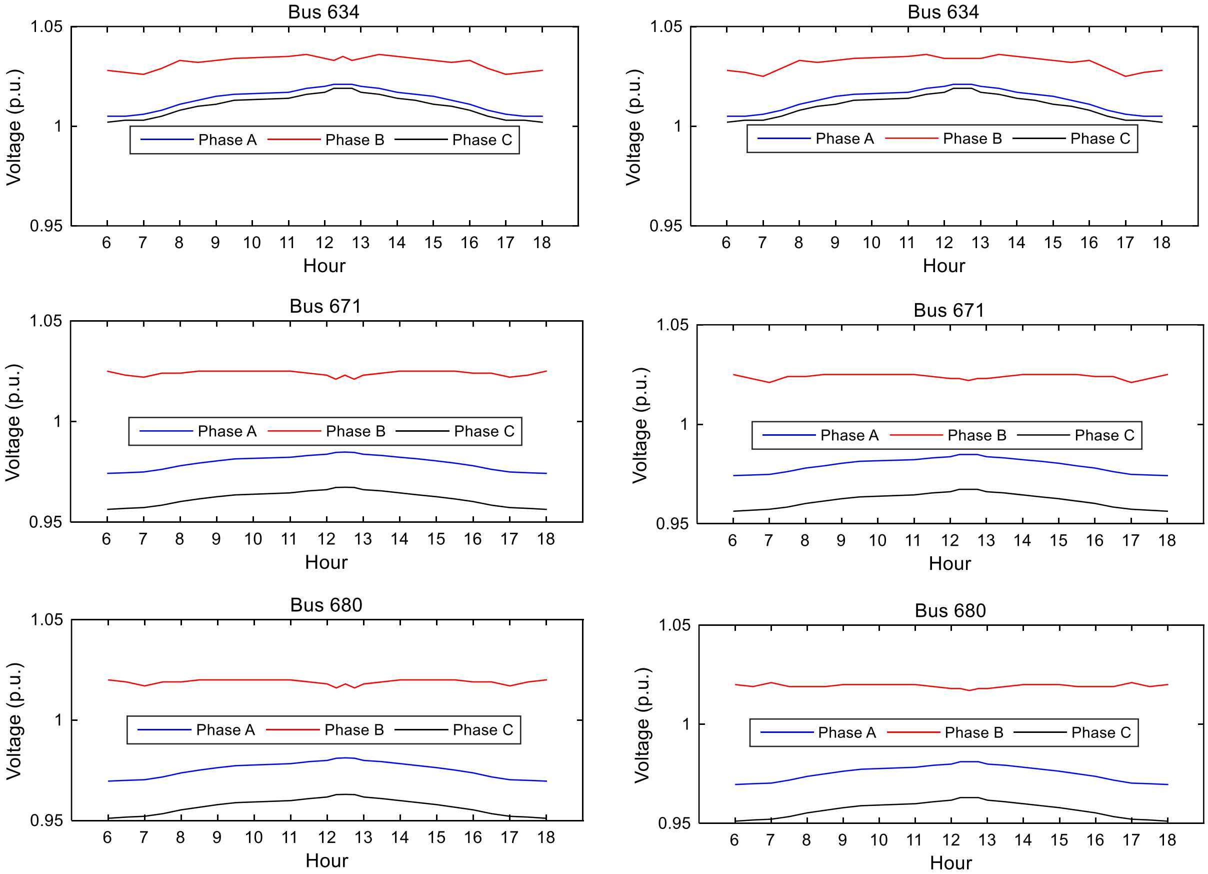


(a) VVC control (b) VWC control

Fig. 7 Bus voltages and PVs power with control on PV inverters for base load

Case B: For load changes

The impact of VVC and VWC for SR_1 on feeder bus voltages and PV powers injected into the system, at 10% increment with respect to base load is presented in Fig. 8.



(a) VVC control (b) VWC control

Fig. 8 Bus voltages with control on PV inverters for load change

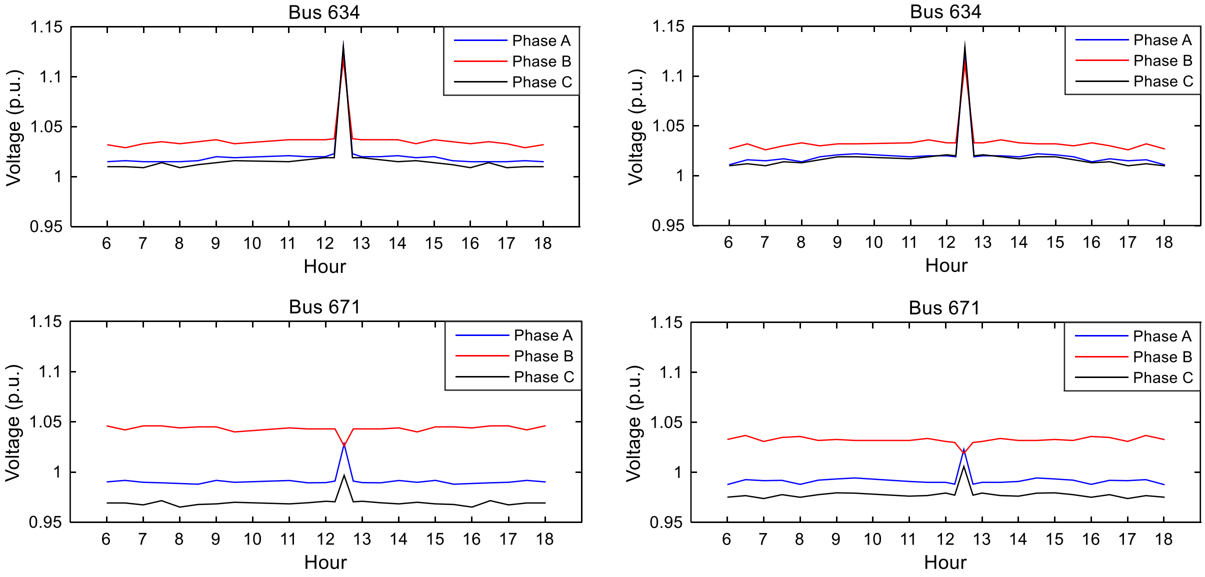
Further, six different load conditions are considered (i.e., base load, +5%, +10%, -5% and -10% at all bus load and +5% of bus-671 with -10% of bus-634) for better understanding of power supplied by the grid. Here, active power (kW), reactive power (kVAR) and apparent power (kVA) for 1140W/m^2 with VVC/VWC control is shown in Table 1. From the table, it is observed that after applying the control, the grid power supplied to the network has increased (decreased) with increase (decrease) in the load. Further, the grid power supplied via VWC remains lower as compared to power supplied with VVC.

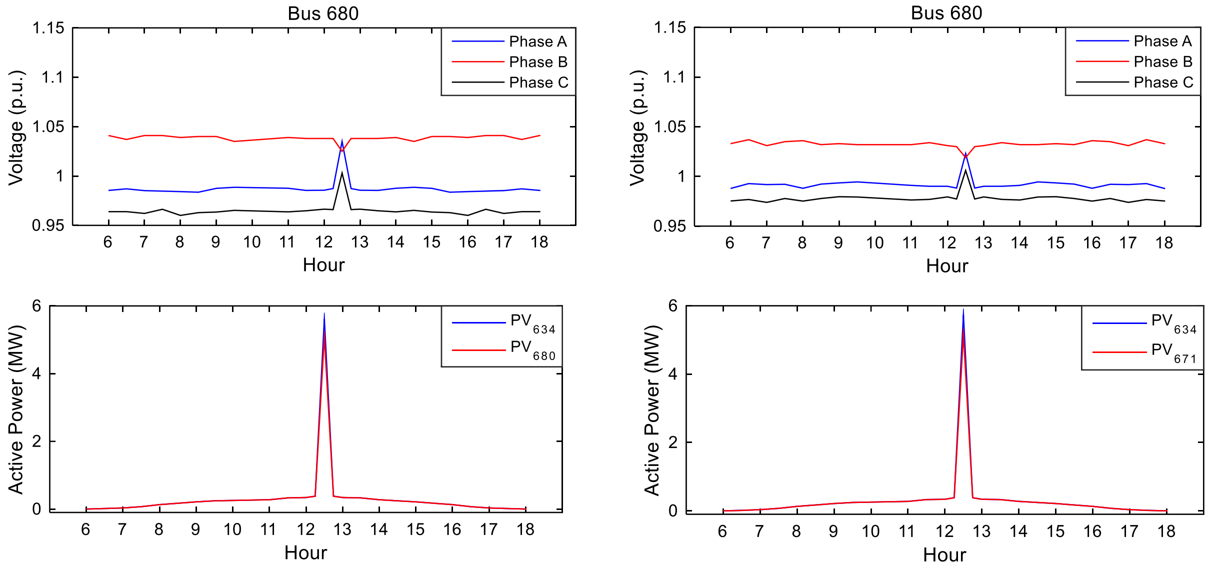
Table 1: Changes in power supplied by grid with changes in system load

Load condition/ Grid power	Without control			With VVC			With VWC		
	P	Q	S	P	Q	S	P	Q	S
Base load	-10860.0	6613.0	12710.0	2449.0	3043.0	3906.0	2447.0	3037.0	3900.0
+5% increment at all	-10870.0	6653.0	12750.0	2539.0	3109.0	4014.0	2531.0	3101.0	4002.0
+10% increment at all	-10910.0	6695.0	12800.0	2629.0	3177.0	4123.0	2629.0	3176.0	4123.0
-5% increment at all	-11170.0	6649.0	13000.0	2359.0	2975.0	3797.0	2361.0	2974.0	3797.0
-10% increment at all	-11020.0	6583.0	12840.0	2268.0	2909.0	3688.0	2256.0	2910.0	3682.0
+5% at bus-671 and -10% at bus-634	-10840.0	6616.0	12700.0	2468.0	3051.0	3924.0	2468.0	3050.0	3924.0

4.1.2 Discussion of Results with PHIL

With PHIL at one of the bus, its power supplied is 11.6 kW, which is very less as compared to power generated by the remaining two PVs i.e., 412.5 kW. Fig. 9 represents the impact of PHIL on voltage/power profile without local control applied in the PV inverters while Fig. 10 represents the impact of local control on voltage/power profile.

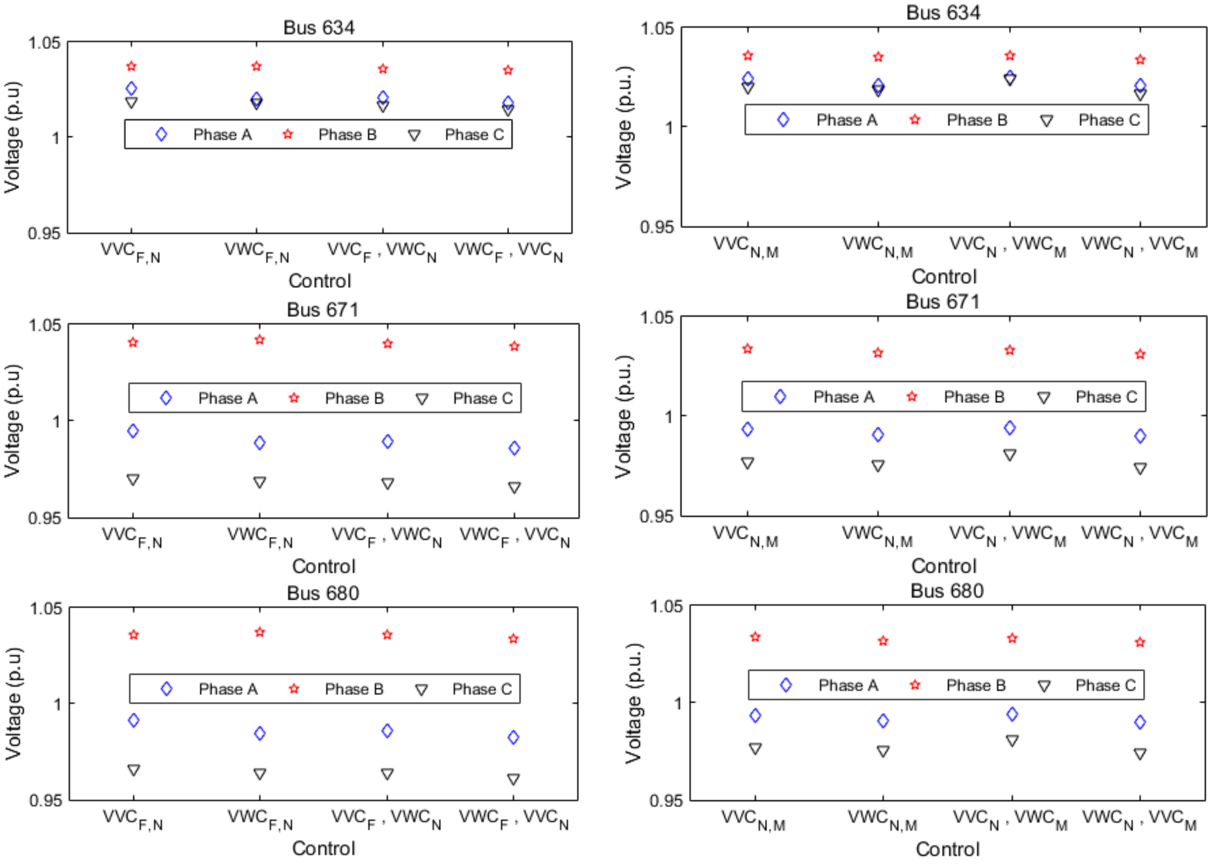




(a) PHIL on bus 671 (b) PHIL on bus 680

Fig. 9 Bus voltages and PVs power with PHIL and without control on PV inverters

Also, in study, either VVC, VWC or combination of VVC-VWC was applied on the PV inverters in RTDS. As shown in Fig. 10. x-axis presents the control methods, N, M, and F denotes Bus-634 (Near to grid), Bus-671 (Mid grid), and Bus-680 (Far from grid) respectively. Hence, four conditions of control actions are formed for two PVs placed in the network.



(a) PHIL on bus 671 (b) PHIL on bus 680

Fig. 10 Bus voltages and PVs power with control on PV inverters and PHIL

4.2 Conclusions

With the opportunity available via ERIGrid 2.0 Lab Access programme, the user group have explored and demonstrated the feasibility to implement VVC/VWC control on PV inverters and their combination in the network.

The facility in this lab met all the range of infrastructure required to complete the research objectives. This included PHIL (PV emulators), support for communication network, real-time simulator (RTDS), and CHIL. The study was conducted in real-time environment, wherein, PV systems integrated with another PV (PHIL-PV emulator) in IEEE-13 bus distribution network was real-time simulated (RTDS) with control functions, performed via update of VVC and VWC. The study is limited to the distribution network.

The implementation of PHIL in the system claims to provide active power support in real-time to the test system. But due to safety of hardware, we need to compromise with the power supplied by PHIL to protect the power hardware. Here PHIL supplied a very less percentage of power (i.e., 11.6 kW) that is not sufficient to create a noticeable change (violation) in system voltage. As such greater impact of integrating PHIL into the network could not be achieved.

The results obtained from the project will lead to a newer understanding of the voltage regulation in the distribution network, having PV inverters controlled using different forms of control algorithms. As a result, a system designer can get sufficient information about the controller performance in terms of robustness for PV inverters. In other words, results can be helpful to tune/adjust the characteristics/control parameters against the system uncertainties and dynamics due to radiation and load change.

5 Open Issues and Suggestions for Improvements

As a part of study during the visit, researchers could choose power (P<30kW) through PHIL as source of renewable energy for real-time analysis. This is due to the fact that, power injection from PHIL remained as a function of node voltage, at which the PHIL was connected in the network. In other words, power injection was controlled such that variation in node voltage was restricted within the limits of 0.95-1.05 pu. As such, power injection was limited to less than 30kW. Keeping the amount of power injection, between 10 kW to 15 kW, a noticeable change (violation) in system voltage was not observed at remaining nodes in the network.

In the test-bed, AC heating load (HL) that worked as DUT, with temperature 200/215 B and capacity of 11.6 kW was used with Cinergia model (for the grid emulator is GE+30 vAC/DC). The use of heating load applies nearly unity power factor and as such reactive demand does not arise in the network.

It can be planned to apply IEC 61850 communication protocol in the set-up towards the control actions on PV inverters. This is important, since renewable integration and its operation in smart grid environment can be expected from different protocols of communication network. The existing lab facilities can be extended to suit some of available communication networks. Additionally, if supplied power from PHIL (PV emulator) can be as high that can result in voltage violation in the network (RTDS), then combination of PHIL and CHIL can planned simultaneously to regulate the voltage in the network.

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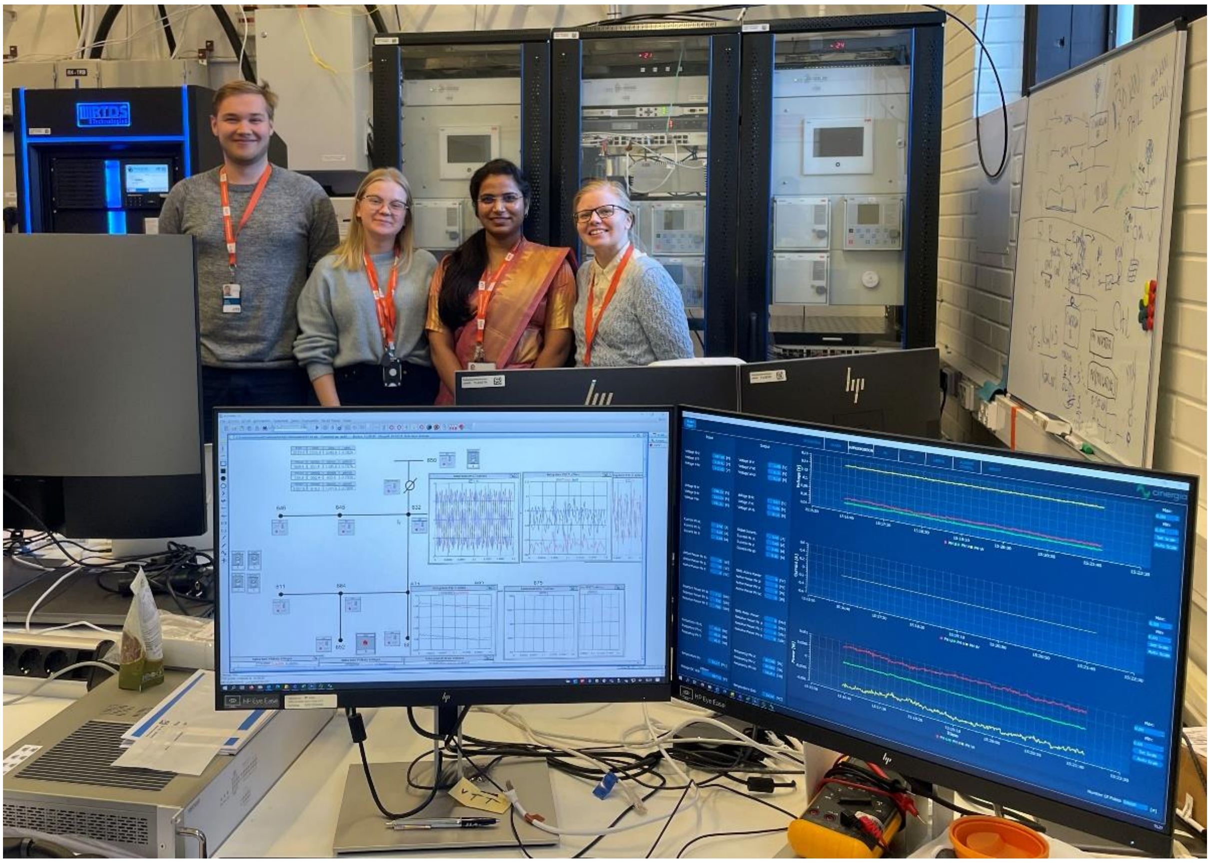

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