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Post-Primary Voltage Control using Optimal Power Flow for Loss Minimization within Web-of-Cells concept

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Abstract— **This paper presents the decentralized Post-Primary Voltage Control (PPVC) scheme which is introduced within the Web-of-Cells (WoC) concept in the ELECTRA IRP project. The PPVC improves the traditionally known secondary and tertiary voltage control schemes to develop a robust method coping with the emerging intermittent generation and variable loading in the distribution system. PPVC aims to utilize all available resources within a defined network area for voltage control purposes by taking loss minimization as an objective. To achieve that, the re-definition of voltage set-points in all controllable nodes within the area is performed using an Optimal Power Flow (OPF) algorithm. The proposed PPVC algorithm coordinates tap changers and other reactive power resources such as PV inverters proactively altering their settings for a recurring time-window. The settings are optimally computed by using short-term forecasted load and generation values. The PPVC algorithm has been implemented with MATLAB and the General Algebraic Modeling System (GAMS) tool for optimization and evaluated on The European CIGRÉ MV network, modified with distributed energy resources (DERs). Simulation results showing the impact of PPVC compared to the business-as-usual (BaU) way of voltage control are presented. In addition, laboratory tests coupling the GAMS-based OPF with OPAL-RT have been conducted to present the efficiency of PPVC in real-time applications.**

Index Terms--**GAMS, Loss Minimization, MATLAB, OPAL-RT, Optimal Power Flow, Voltage Control, Web-of-Cells**

NOMENCLATURE

N_b	Number of buses
i, j	Bus indices
V_i	Voltage magnitude at bus i
δ_i	Voltage angle at bus i
P_i	Active power at bus i
Q_i	Reactive power at bus i
P_{ij}	Active power flow in line i-j
Q_{ij}	Reactive power flow in line i-j
Pg_i	Active power generation at bus i
Qg_i	Reactive power generation at bus i
Pd_i	Active power demand at bus i
Qd_i	Reactive power demand at bus i
Y_{ij}	Admittance of line i-j
G_{ij}	Conductance of line i-j
B_{ij}	Susceptance of line i-j

I. INTRODUCTION

With the view to European Union's ambitions and targets, as defined in 20-20-20 [1] and the 2050 EU Roadmap [2], future power grids will be characterized by increased penetration of Renewable Energy Sources (RES) and Distributed Generators (DGs). In this context and considering the presence of new technologies, such as electric vehicles, electromagnetic trains and information and communication technologies (ICTs), it is necessary to revise the current monitoring and control practices in power networks. To meet tomorrow's challenges, a functional architecture that suggests the division of the network into smaller areas, where advanced techniques for balancing and voltage control can be applied, is proposed in the ELECTRA IRP [3], FP7 project. This concept is called Web-of-Cells (WoC).

Within WoC, a cell can be defined as a group of interconnected loads, generation and storage units with adequate installed capacity and monitoring infrastructure, so that it has the ability to resolve balancing and voltage stability issues in real-time at a local level [4]. From its definition, the WoC concept differentiates from the concept of microgrids as the operation in islanded mode is not required and the cell can rely on structural import/export power flows before the real-time operation [5].

This paper concentrates on Post-Primary Voltage Control (PPVC), a proposed scheme for decentralized voltage control for the future power system with high penetration of RES. This work has been done as a part of laboratory tests of PPVC at the Norwegian National Smart Grid Laboratory, operated by SINTEF and NTNU and resides on the deployment of a PPVC Use Case, which was developed within the ELECTRA IRP [6] project.

II. PPVC SCHEME

In today's power systems voltage control is traditionally performed in three hierarchical levels: primary voltage control (PVC), secondary voltage control (SVC) and tertiary voltage control (TVC) [7], [8]. PVC is an automatic mechanism mainly responsible for minimizing local voltage deviations in units with automatic voltage regulators (AVRs). SVC is responsible for the supervision and coordination of the reactive power contribution of the voltage regulators in a time frame of around a minute. TRC is performed within 10 min to 30 min and aims at optimizing the voltage set-points from secondary voltage control, by re-calculating them to minimize power losses or minimize the costs for resources to perform the voltage control.

In the WoC concept, voltage control is performed within each cell by PVC and PPVC. PPVC reserves resources for near future requirements of voltage control, as it foresees possible voltage violations by using forecasts of load and generation from historical data. Then, it deploys all available resources after disturbances to take corrective measures of voltage level violations. In PPVC, the advantages linked to the WoC concept, such as the increased observability or the improvements in the data management systems [9], allow the restoration/maintenance of the voltages and the optimization of the voltage profiles in a single step. PPVC implements for each time window (15 min) an OPF that ensures power loss minimization within the cell and restores the voltage set-points within safe limits in case of an unexpected event [6]. The proactive mode of PPVC is launched periodically every 15 minutes for window-ahead planning actions based on forecasts for the state estimation of the network, thus decreasing the number of interventions in the network and avoiding meaningless actions. However, to ensure voltage stability in a cell, corrective actions are triggered in real-time when unexpected voltage instability issues arise. In this way, PPVC poses an evolution over the traditional secondary and tertiary voltage control schemes. In Fig. 1 [6], the timeframe for both the proactive and corrective modes of PPVC are shown.

PPVC is implemented by a set of functions, which cooperate in order to ensure that all the data needed for launching the PPVC will be available. These functions can be common to other WoC Use Cases (UCs) and out of the PPVC scope itself, as their responsibility is to collect data such as power flow limits of lines, power generation limits and other forecasted data. The two core functions of PPVC are the "PPVC Controlling System" and the "PPVC Set-point Providing System". The "PPVC Controlling System" checks the current node voltage values and sends a trigger signal to the "PPVC Set-point Providing System" periodically (for every time window), except in case of a voltage event. The "PPVC Set-point Providing System" is responsible for receiving/storing the available data and for executing the OPF algorithm. OPF provides set-points for both nodes with AVR (Automatic Voltage Regulation) and nodes with discrete voltage control ability, such as transformers with on-load tap changers (OLTC), capacitor banks and controllable loads, which in PPVC participate in the voltage regulation procedure.

III. PROBLEM FORMULATION

The core algorithm of the PPVC operation is the OPF. The main aim of PPVC is to proactively mitigate over/under voltages and restore voltage levels to the pre-incident values. Unlike most of the cases of OPF, where cost minimization is examined, an OPF with a loss minimization objective is followed in the problem formulation in this study to evaluate voltage settings. Towards this direction, relevant examples are already in literature and many different approaches have been examined. In [10] and [11] interior point method (IPM) algorithm is proposed for the formulation of OPF problem. IPM is based on the conversion of inequalities into equalities by introducing in the objective function a logarithmic barrier that is a function of the slack variables [12]. Reference [13] proposes a mathematical algorithm based on the gradient method for optimal loss minimization and presents the results of its implementation in a microgrid. In other approaches like in [12], [14] and [15] genetic algorithms and search methods,

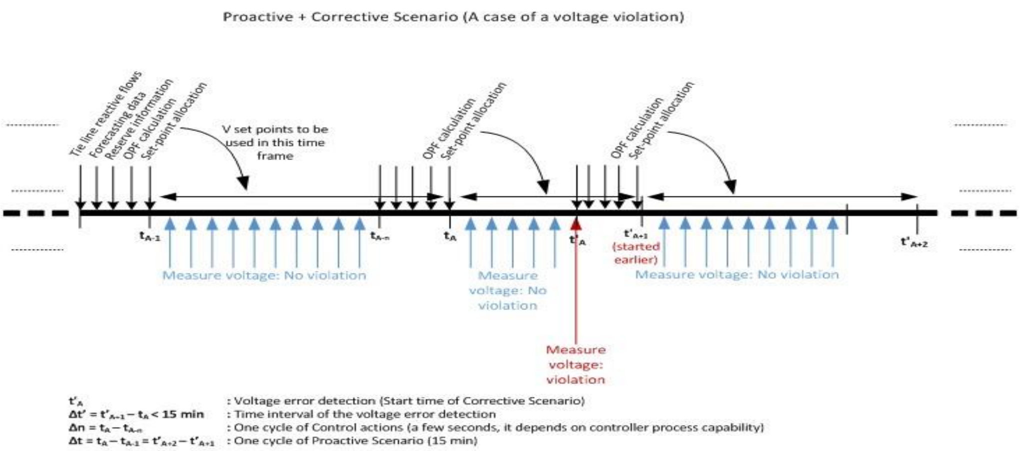

Fig. 1. Proactive and corrective mode of PPVC

like particle swarm optimization algorithms, are proposed to overcome the difficulties arising from non-convexity and to find a heuristic but high-quality solution [12].

In this paper, the formulation for loss minimization problem has been developed in General Algebraic Modeling System (GAMS), using the IPM algorithm. In order to take into account all resources available in the test case, apart from generators and nodes with AVR, a network with OLTC transformers and PV inverters is considered. The objective function and the relative constraints in this case are presented and the modifications to consider the tap changing function of the transformers are described.

A. *General Problem Formulation*

The optimal power flow problem is a nonlinear optimization problem, which can be described in general as follows.

Minimize f(x)
subject to g(x) = 0, equality constraints
h(x) ≤ 0, inequality constraints

1) Objective Function: As the PPVC aims at power loss minimization, the active power losses in the lines will be used to formulate the objective function as follows.

$$P_{losses} = \frac{1}{2}\sum_{i=1}^{Nb}\sum_{j=1, j\neq i}^{Nb} G_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] \quad (1)$$

where P_{losses} are the total power losses in the lines.

2) Equality Constraints: The power flow equations at each line *i* - *j* are presented.

$$P_{ij} = G_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] \quad (2)$$
$$Q_{ij} = B_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\sin(\delta_i - \delta_j)\right] \quad (3)$$

Hence, the objective function in (1) can be written as:

$$P_{losses} = \frac{1}{2}\sum_{i=1}^{Nb}\sum_{j=1, j\neq i}^{Nb} \left|P_{ij} + P_{ji}\right| \quad (4)$$

3) Inequality Constraints:

a) Thermal limits: The thermal limits of the lines were considered.

$$P_{ij}^2 + Q_{ij}^2 < \left(\sqrt{3}|V_N|\left|I_{max,ij}\right|\right)^2 \quad (5)$$

where: $|V_N|$ is nominal voltage and $\left|I_{max,ij}\right|$ is the maximum current for line *i-j*.

b) Voltage and generation unit upper and lower limits: For each node *i*:

$$V_{i,min} \leq V_i \leq V_{i,max} \ \forall i \in N_b \quad (6)$$

where: $V_{i,min} = 0.94$ is the lower voltage limit per unit (p.u.) and $V_{i,max} = 1.06$ is the upper voltage limit p.u. at bus *i*.
For each generation unit at node *i*:

$$Pg_{i,min} \leq Pg_i \leq Pg_{i,max} \quad (7)$$
$$Qg_{i,min} \leq Qg_i \leq Qg_{i,max} \quad (8)$$

where: $Pg_{i,min}$, $Pg_{i,max}$, $Qg_{i,min}$, $Qg_{i,max}$ are lower and upper limits at bus *i* for active and reactive power generation, respectively.

c) Capacitor banks: The reactive power injected in the network by the capacitor bank at bus *i*, $Q_{i,cap}$, should be considered as a constant reactive power injection in the *i* node, as follows.

$$Q_{i,cap} = \begin{cases} = 0, \text{when capacitor bank is not connected} \\ \neq 0, \text{when capacitor bank is connected} \end{cases} \quad (9)$$

d) PV Inverter constraints: The constraints for PV inverter's active and reactive power are shown.

$$\left|Q_{pv,i}\right| \leq \sqrt{S_{pv,nom,i}^2 - P_{pv,i}^2} \quad (10)$$

where: $P_{pv,i}$ and $Q_{pv,i}$ are active and reactive power output of the PV connected at node *i*. $S_{pv,nom,i}$ is the apparent power rating of the PV inverter. The exact value for the $Q_{pv,i}$ is further determined by the droop controller.

B. *Problem Formulation considering tap-changing function*

OLTC's role in today's networks is to regulate only the secondary side voltage of the HV/MV substation. Hence, it is positioned aiming to keep the voltage within certain range. However, in PPVC the tap changing function is exploited to mitigate voltage violations and contribute in loss minimization, and can be anywhere between the maximum and minimum limit.

To consider the tap changing function of the transformer, equations (2) and (3) were modified. A short description will be presented here but detailed analysis of the equations is available in [16].

1) Transformer equivalent circuit: In Fig. 2 [16] a simple circuit for the transformer with a complex tap ratio *t* in a line *i-j* is considered, with complex voltage and current values V_i, V_j and I_i, I_j respectively and admittance *y*, that is equal to Y_{ij} in the current notation.

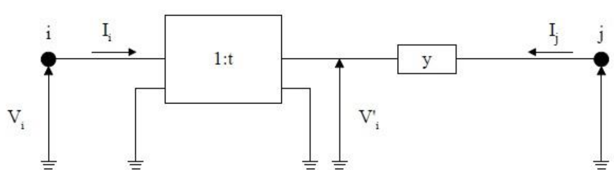

Fig. 2. Transformer equivalent circuit

In Fig. 3 [16] a comprehensive branch model is presented and the general equations in a matrix form are shown in (11). If no phase shift exists, $t^* = t$.

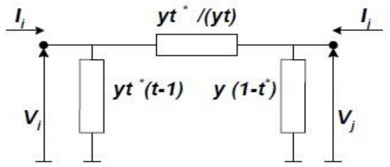

Fig. 3. Comprehensive branch model of the transformer

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} t^2 Y_{ij} & -t^* Y_{ij} \\ -t Y_{ij} & Y_{ij} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \quad (11)$$

Hence, the complex line flow from node i to node j can be reformulated as:

$$S_{ij} = V_i^2 t^2 Y_{ij} - V_i^* V_j t^* Y_{ij} \quad (12)$$

where the admittance Y_{ij} can be analyzed as:

$$Y_{ij} = G_{ij} + jB_{ij} \quad (13)$$

It should be noted that the total line charging susceptance $b_{n,susc}$ of the line i-j should be considered when computing the reactive power flow in line i-j and therefore the susceptance B_{ij} should be added as shunt capacitance only at node i or j, as it will be shown in the following equations.

2) Equality Constraints: Considering the above-mentioned modifications, the equations for active power flow from node i to node j in a line as derived from (11) are the following:

$$P_{ij} = t^2 V_i^2 G_{ij} - t V_i V_j (G_{ij} + jB_{ij}) \cos(\delta_i - \delta_j) \quad (14)$$

As $P_{ij} \neq P_{ji}$, the equations for P_{ji} are presented:

$$P_{ji} = V_j^2 G_{ij} - t V_i V_j (G_{ij} + jB_{ij}) \cos(\delta_j - \delta_i) \quad (15)$$

Respectively, the equations for reactive power flow from node i to node j in a line are shown:

$$Q_{ij} = -t^2 V_i^2 (B_{ij} + b_{n,susc}) - t V_i V_j (G_{ij} + jB_{ij}) \sin(\delta_i - \delta_j) \quad (16)$$

$$Q_{ji} = -V_j^2 (B_{ij} + b_{n,susc}) - t V_i V_j (G_{ij} + jB_{ij}) \sin(\delta_j - \delta_i) \quad (17)$$

IV. Network Description

The European CIGRE Medium -Voltage (MV) benchmark [17] modified with DERs has been chosen to be used within the ELECTRA IRP project as a grid representative of a cell, to test and validate the UCs in a preliminary approach. The scheme of this modified version is shown in Fig. 4. The HV/MV network is connected through 2 OLTC transformers with tapped secondary winding. The network consists of 8 photovoltaic units with 15% curtailment ability, 1 wind turbine, 2 batteries, 2 fuel cells and 2 combined-heat power devices (CHPs). The characteristics for the lines of the network can be found in [17].

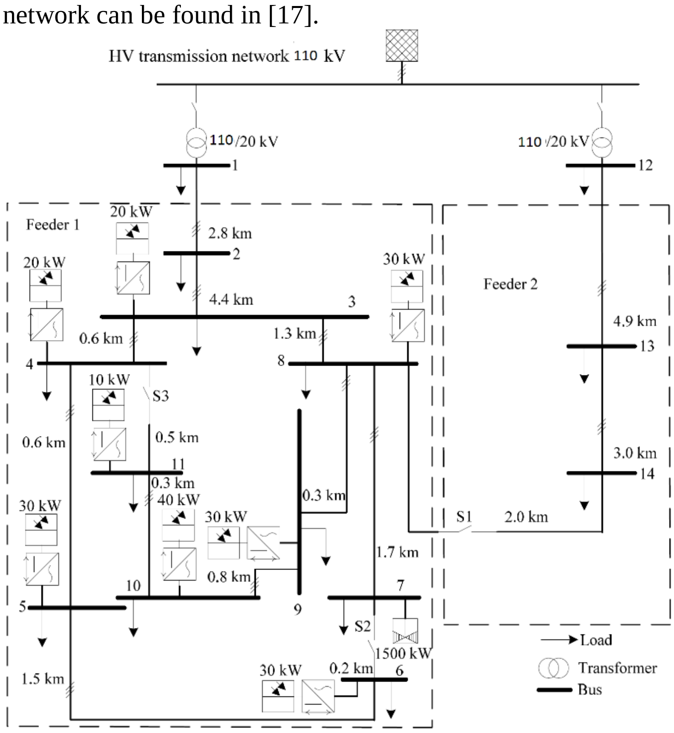

Fig. 4. The modified CIGRE MV network

The maximum generation of the generation groups and the maximum demand at each bus are shown in Table I. OLTC characteristics are displayed in Table II. For the calculations in p.u., S_{base}=25MVA, V_{base}=20kV and I_{max}=320A have been considered. In Fig. 5 total load demand for a representative day is presented.

TABLE I
GENERATION AND DEMAND

Bus	Generation (MW)		Demand (MW, MVAr)	
	DER type	Pmax	Pd	Qd
1	-	-	19.8390	4.6371
2	-	-	0.0000	0.0000
3	Photovoltaic	20	0.5017	0.2089
4	Photovoltaic	20	0.4317	0.1082
5	Photovoltaic Battery Residential fuel cell	30 600 33	0.7275	0.1823
6	Photovoltaic	30	0.5481	0.1374
7	Wind turbine	1500	0.0765	0.0474
8	Photovoltaic	30	0.5869	0.1471
9	Photovoltaic CHP diesel CHP fuel cell	30 310 212	0.5738	0.3556

10	Photovoltaic Battery Residential fuel cell	40 200 14	0.5433	0.1613
11	Photovoltaic	10	0.3298	0.0827
12	-	-	20.0100	4.6933
13	-	-	0.0340	0.0211
14	-	-	0.5401	0.2577

TABLE II
TRANSFORMER PARAMETERS IN CIGRE NETWORK

From node	To node	Connection	V_1 (kV)	V_2 (kV)	$Z_{transformer}$ (p.u.)
0	1	3-ph Dyn1	110	20	0.016+j1.92
0	12	3-ph Dyn1	110	20	0.016+j1.92

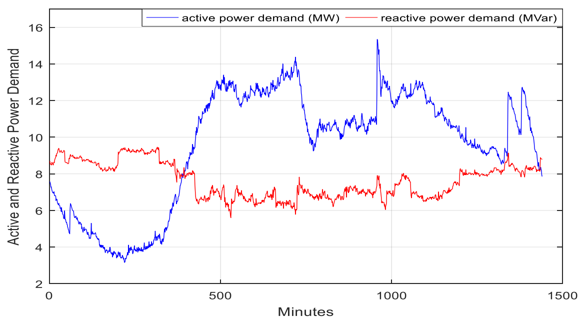

Fig. 5. Active and reactive power demand at Node 12

V. SIMULATION RESULTS

A. Software Testing

Data for generation and demand for each node per minute were used as input to the OPF algorithm, coupling GAMS with Matlab. In software testing, the added value of the proposed algorithm compared to today's techniques is highlighted. In business as usual (BaU) OLTC is only regulating the secondary side of the HV/MV substation according to a constant voltage value at the primary winding and inverter reactive power supply is driven by droop controller. Conversely, in PPVC OLTC setting and reactive power from inverters shall be decided from globally optimal loss minimization objective. By defining the position for taps and the amount of reactive power provided by inverters in an optimal way, PPVC achieves to restore voltages values within accepted boundaries and minimize power losses in one action.

In Fig. 6, voltage set-points between the BaU and PPVC for nodes 1 and 10 for a representative timeframe are compared. As it can be seen, voltage variations are limited in PPVC scenario. Especially in nodes with DERs, where PV inverter control is exploited, voltage variations are considerably mitigated. Voltage values in this case may be higher, but are still within safe limits.

In Fig. 7 a comparison for power losses between BaU and PPVC ensures that power loss reduction is greater in PPVC scenario, even 40% less than in BaU in some cases.

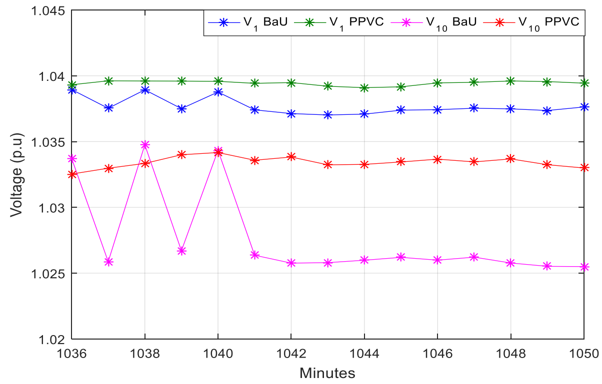

Fig. 6. Comparison for voltage set-points between BaU and PPVC

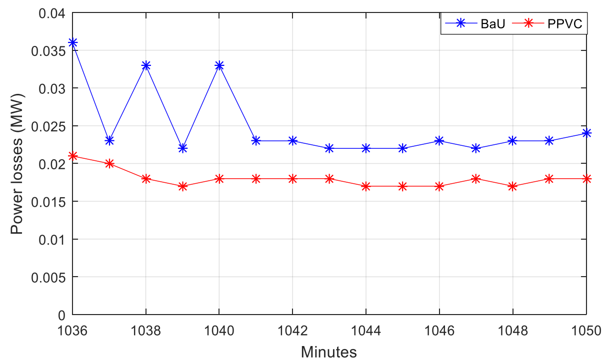

Fig. 7. Comparison for power losses between BaU and PPVC

The above results are consistent with the results of AC power flow executed in Matpower. However, a software comparison would be meaningless, as Matpower ignores by default any generator limits or branch flow limits [18].

B. Real-time Laboratory Testing

In order to evaluate the performance of the developed control algorithm in real applications, a laboratory validation coupling GAMS with the real-time simulator OPAL-RT through Matlab-Simulink was conducted, as shown in Fig. 8.

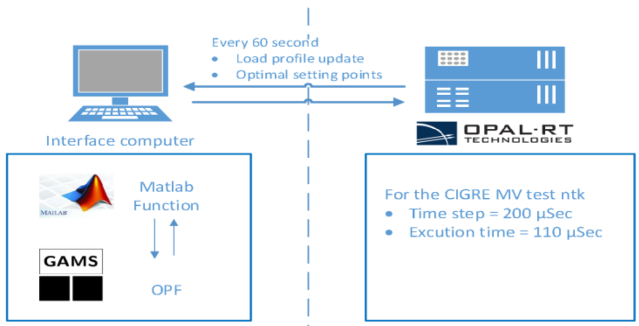

Fig. 8. Coupling scheme for lab testing

The network model in Fig. 4 was formulated in Simulink to be executable from OPAL-RT. In BaU, the OLTC is positioned so that the voltage at the secondary side can range within a certain range, in our case from 1.026 to 1.054 p.u.

The corresponding voltage step per tap is defined 0.01875 p.u. and the dead band used is 75% of this step, namely 0.014 p.u. However, if the voltage error does not exceed this dead band, OLTC is not triggered.

For the PPVC scenario, the Simulink model was modified in order to use as reference voltage value the voltage set-points resulting from the OPF algorithm and thus changing the voltage at the secondary winding according to the optimal values. Respectively, reactive power supplied from PV inverters is also defined by the PPVC algorithm.

Measurements for loads, production and voltage at the secondary winding of the transformer are available with one minute resolution. Control commands are sent from a Matlab function every 15 minutes periodically or when a violation is detected. Results for the voltage set-points for nodes 1 and 10 in Fig. 9 compare the BaU case with the real-time implementation of PPVC in OPAL-RT.

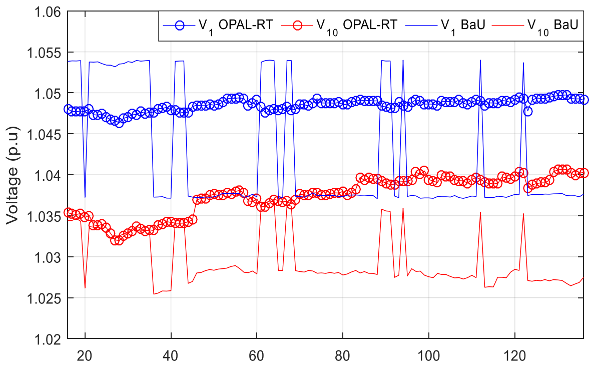

Fig. 9. Comparison for voltage set-points between BaU and OPAL-RT

In the real-time simulation, the proactive adjustment of tap set points and reactive power from inverters can also limit the unnecessary intervention of the OLTCs due to fixed voltage setting of OLTCs and local reference voltage measurement as it is in BaU, thus resulting in smaller voltage variations.

VI. Conclusions

In this paper, the PPVC scheme or decentralized voltage control is presented. PPVC suggests the implementation of an OPF algorithm based on loss minimization instead of the traditional secondary and tertiary voltage control. The algorithm defines the optimal position of tap settings of OLTCs and the amount of reactive power provided by PV inverters, Software and real-time laboratory testing for the validation of the PPVC algorithm were conducted to compare its performance with today's control schemes and ensure its efficiency in real-time applications. PPVC promises encouraging results for the control of future networks within WoC. The simulation results support viability of the suggested concept for decentralized voltage regulation within the WoC concept, which supports operation of network with a high share of RES. In future work, the PPVC algorithm will be implemented in a full hardware in the loop test, as the simulated components will be replaced by laboratory equipment available at the Norwegian National Smart Grid Laboratory operated by SINTEF/NTNU.

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