Demonstration of Coordinated voltage control at SOREA site

Version 3.0

Deliverable 6.2

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1 Introduction

Moving towards a decarbonized scenario, the power grid is expecting a high penetration of distributed and renewable energy resources, which have a strong impact on the system architecture (i.e. unidirectional to bidirectional) and impose new challenges in maintaining the good functionality of the grid [1]–[3]. The high ratio of Distributed Energy Resources (DER) integration in the decarbonized scenario leads to technical difficulty to preserve the security and reliability of network operations and to ensure the fulfillment of the established voltage quality standards [4], [5].

In a traditional grid, voltage tends to drop at the end of LV line caused mainly by active power consumption throughout the line. The massive penetration of renewable energy resources in LV grid tends to reverse the voltage curve [6], [7].

There are two ways for controlling voltage by inverters: local voltage control where each inverter has to react in an individual manner with some strategies like with a fixed reactive power Q or reactive power function of voltage Q(V). Depending solely on these local strategies may lead to unexpected voltage behaviors at global level. The coordinated voltage control (CVC) aims to maintain voltage at some pilot points in a desirable band after performing of an optimization, which may include several different criteria [8].

The CVC algorithm is a centralized approach, which relies on real-time measurements from the network and remotely controllable voltage regulating devices. In this strategy, the participation of each inverter should be calculated every step by external controller which has a global supervision of the grid [9].

CVC is an important technique to harmonize and to improve the penetration rate of distributed renewable energy resources (DRES) to the electrical grid, thus contribution to the decarbonisation process. As more and more DRES are connected to the radial ends of the grid, the power quality is degraded due to their intermittency. CVC allows the DSO/TSO to maintain the required power quality in terms of voltage, while maximizing the benefit of the newly added DRES.

In general, CVC can be considered as an optimization techniques on secondary control layer [10]. It can be configured to consider complex criteria (minimizing injection of reactive power or harmonics, preference of DRES than fuel-based distributed generators (DG), etc.) other than the voltage quality (voltage deviation).

Based on the system setup, CVC can act on:

- The position of On Load Tap Changer in the substation,
- Installation of shunt capacitance,
- Pilot inverters in order to absorb or provide reactive power,
- Curtail active power of inverters
- Increase section of feeders,
- Add storage systems for voltage support,

Specifically, for the storage units, it controls their active and reactive power, whereas for the DG units, it controls mainly their reactive power.

The algorithm is designed to operate in discrete iterations, with the aim to keep the network in an optimal state (this optimal state is described by the optimization problem's objective function), throughout its operating time. This means that it does not "activate" only when a certain threshold is passed (e.g. voltage limit violation), but rather constantly (in discrete iterations). The minimum time for these discrete iterations has to be at least equal or greater than the total time that is required for one cycle of its operation to take effect. This total time is a sum of the following:

- Time needed for the real-time measurements to be received by the controller.
- Time needed for the controller to formulate and solve the optimal power flow (OPF) problem.
- Time needed for the outputs of the OPF (which are the set-points for the controllable devices) to be sent and received by the corresponding devices.
- Time needed for the controllable devices to implement these set-points.

The above indicate that the minimum time for the discrete iterations can vary for different networks, different communication network, different devices, etc. This means that in a hierarchical control scheme, the CVC algorithm acts as a form of secondary control, as it is not designed to respond to sudden changes/transients in the system (e.g. a big load being disconnected and reconnected within a minute or so). Its purpose is to optimize the steady state operation of the network.

As it has been explained in deliverable D3.2 Preparation of demonstration sites, in this deliverable, we present the implementation of such a CVC algorithm on the demonstration site: the microgrid of SOREA.

At SOREA demo site, only reactive power support by inverter is available and is used to counteract the voltage violation problem. When testing the CVC algorithm, we chose a 30 seconds iteration time for testing purpose (in reality, CVC is executed once every 15-30 minutes but it could be done with a much shorter time).

2 Description of the demonstration test-case

2.1 SOREA microgrid description

The considered microgrid in this demonstration is the ZAC du Pré de Paques branch of the LV grid of the substation Pre de Paques of SOREA's office. The single line diagram of the LV grid is presented on Figure 1. The microgrid is connected to the main grid via the Pre de Pâques substation (Figure 2). This substation has 4 outputs. In our demonstration, we consider only the ZAC du pré de Paques output, feeding the SOREA office (Figure 3) and several other buildings (Figure 4).

This branch of the LV grid hosts two main PV supplies: one rooftop PV system and three other PV systems installed on the sheds. Due to these installations; the microgrid often suffers from overvoltage during sunny days.

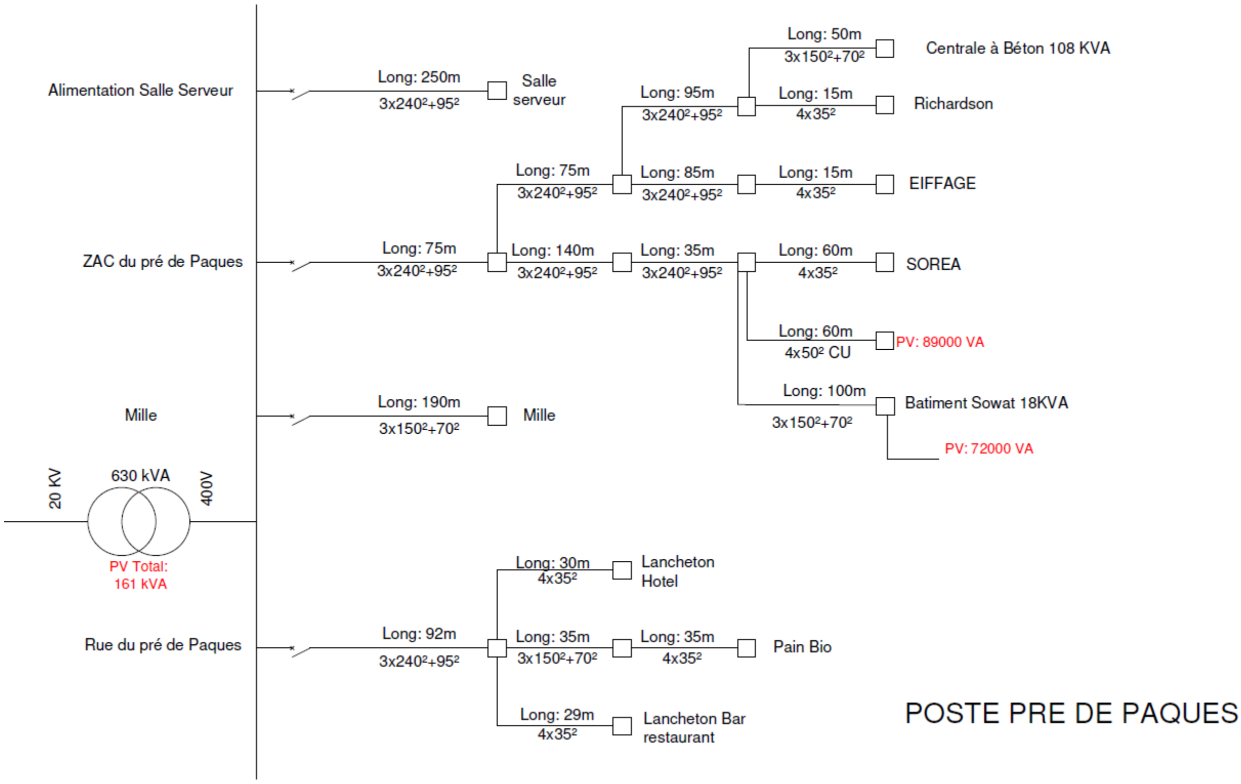

Figure 1: Single line diagram of Pre de Paques LV grid

Figure 2 : Pre de Pâques substation

Figure 3 : The SOREA office and one of the PV plant

Figure 4 : A load in the microgrid - the Effiage building

Only the PV systems over the sheds belong to SOREA. Rooftop PV system cannot be controlled. In our demonstration, we aim to control these controllable PV plants to act under the CVC. The considered microgrid is then represented and its buses are numerated as in Figure 5.

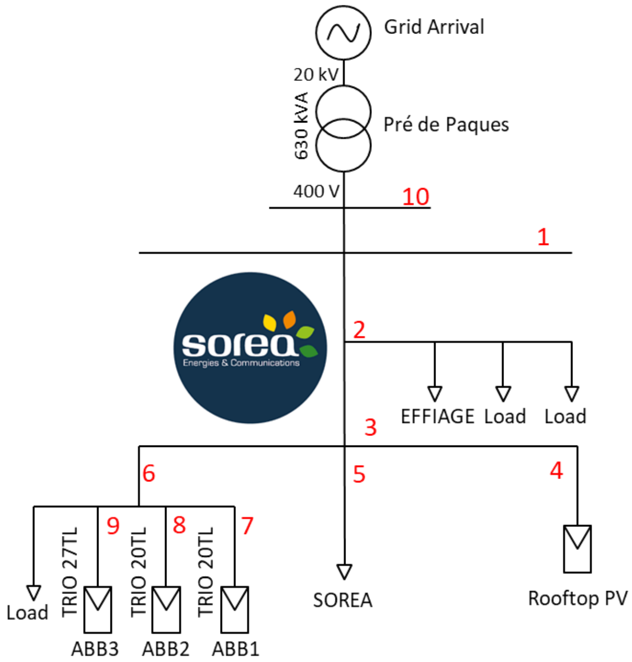

Figure 5 : Schematic representation of the microgrid in demonstration.

The buildings of Sowat, Richardson and Centrale à béton are not used during the period of the demonstration and therefore are not considered in the calculation. They remain in the model for possible reassessment in the future.

2.2 Description of the assets to be controlled

The three controllable PV systems in the microgrid are connected via the three inverters:

- Two ABB TRIO 20.0-TL at bus 7 and 8 (for simplicity, we call them ABB1 and ABB2).
- One ABB TRIO 27.6-TL at bus 9 (for simplicity, we call it ABB3).

Table 1 shows the technical description of these inverters

Table 1: Description of inverters

output	TRIO-20.0-TL-OUTD	TRIO-27.6-TL-OUTD
AC connection to the Grid	Three phase 3W or 4W+PE	
Rated output voltage (Vacr)	400 Vac	
Output Voltage Range (Vacmin...Vacmax)	320...480 Vac	
Rated Output Power (Pacr)	20000 W	27600 W
Maximum Output Power (Pacmax)	22000 W	30000 W
Rated Output Frequency (fr)	50 Hz	
Output Frequency Range (fmin...fmax)	47...53 Hz	
Maximum apparent Output Power (Sacmax)	22200VA	30000 VA
	The rated power Pacr is also guaranteed with cos(fi) = 0.9	
Rated Power Factor (Cosphiacr)	>0.995, adj. ±0.9 with Pacr=20.0 kW, ± 0.8 with max 22.2kVA	>0.995, adj. ±0.9 with Pacr =27.6 kW, ± 0.8 with max 30kVA

The inverters are controlled in reactive power (Q).

2.3 Coordinated voltage controller algorithm

The interested Coordinated Voltage Control aims to control the three inverters for optimizing the microgrid performance around three criteria:

- Minimizing voltage deviation around nominal value.
- Minimizing amount of reactive power that have to be injected.
- Minimizing power loss

The CVC optimization problem is then formulated as:

$$H = \begin{bmatrix} V_1 & V_2 & \dots & V_9 & Q_1 & Q_2 & Q_3 \end{bmatrix}^T$$

$$\min_H \left(c_L \sum_{i=1}^{10} \sum_{j=1}^{10} (-G_{ij}) * \left[V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij} \right] + c_V \sum_{k=1}^{10} (V_k - 1)^2 + c_Q \sum_{l=1}^{3} Q_l^2 \right)$$

$$V_{\min} \le V_i \le V_{\max}, i = 1, \dots, n$$

$$I_j \le I_{\max}, j = 1, \dots, m$$

Where c_L, c_V and c_Q are chosen weights for the different criteria in the function. The optimization is subjected to power flow constraints and equipment constraints (line current limit, BESS, PV and OLTC).

- Equality conditions are formulated from the power flow constraints

$$P_{Gen\_i} - P_{Load\_i} = V_i \sum_{j=1}^{n} V_j \left[G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right]$$

$$Q_{Gen\_i} - Q_{Load\_i} = V_i \sum_{j=1}^{n} V_j \left[G_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij} \right]$$

- Inequality conditions are formulated from the voltage constraints, equipment constraints and line current limit constraints.

$$0.9 \leq V_i \leq 1.1$$
$$0° \leq \theta_i \leq 360°$$
$$\left|Q_{PV}\right| \leq P_{PV} * \tan(\cos^{-1}(pf))$$
$$P_{PV}^2 + Q_{PV}^2 \leq S_{PV,nom}^2$$
$$\left|Y_{ij} * (\tilde{V}_i - \tilde{V}_j)\right| \leq \max I_{ij}$$

3 CVC performance assessment in simulation

Before implementation on the real SOREA microgrid, we made an assessment of the CVC functionality and performance in simulation with PowerFactory and Matlab. Figure 6 presents the single line digaram of SOREA's feeder modelled in PowerFactory.

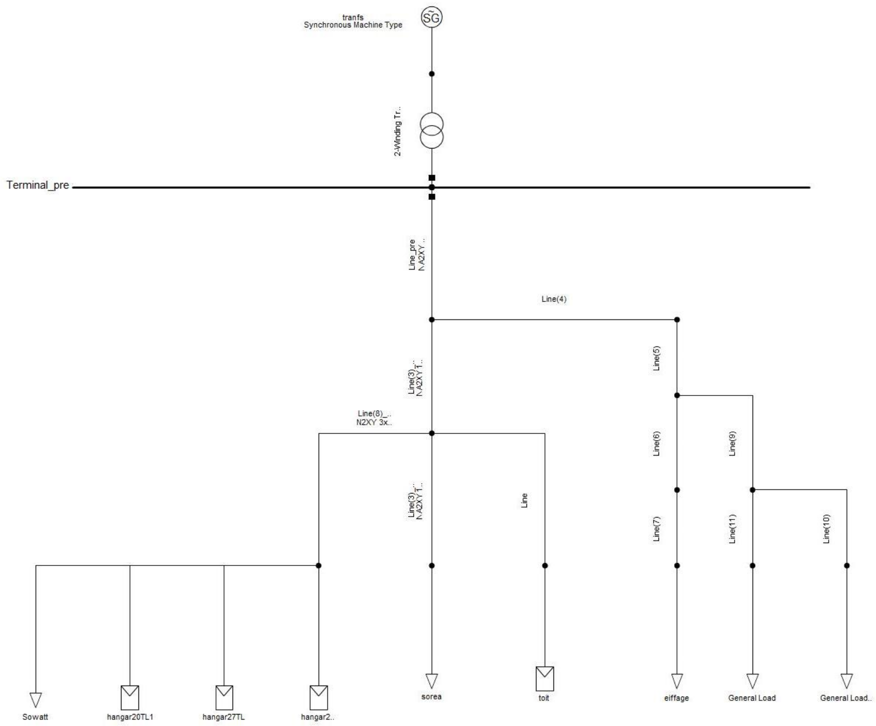

Figure 6 : Microgrid model in PowerFactory

In order to validate the optimization algorithm, a co-simulation platform based on FMI standard has been implemented for evaluating performance of the obtained solutions. Power Factory represents the grid simulator and Matlab contain the optimization algorithm. The flowchart (Figure 7) presents the strategy followed to perform the co-simulation platform.

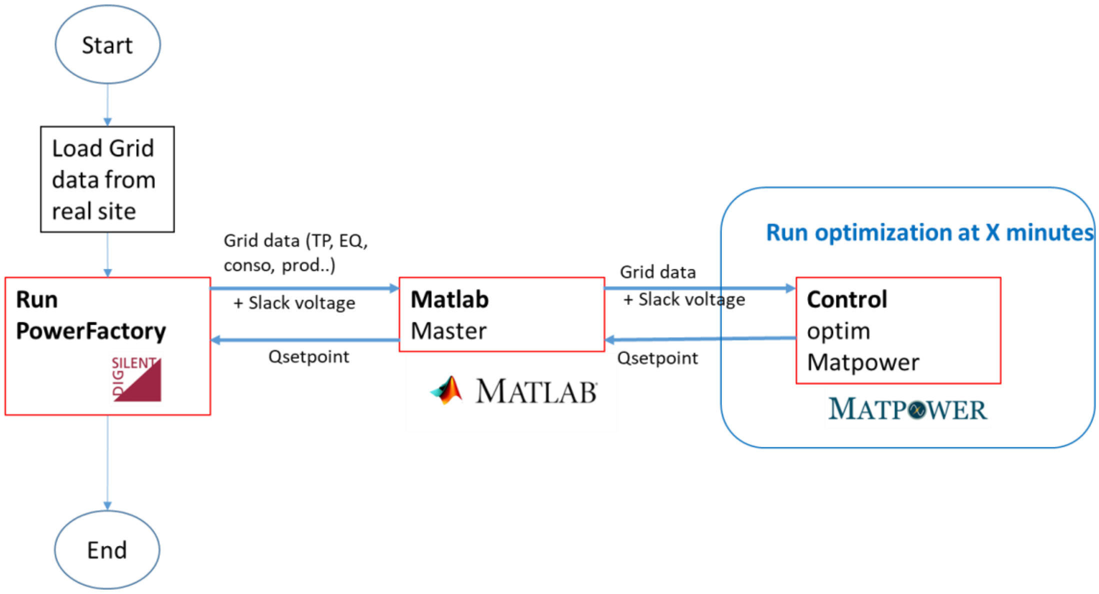

Figure 7 : Co-simulation for assessment of the CVC functionality.

From the simulation of one full day, both bus bars (SOREA point of coupling (POC) and feeder at Substation) present a slight increase of voltage as we can see in the Figure 8 between 10 O'clock and 15 O'clock.

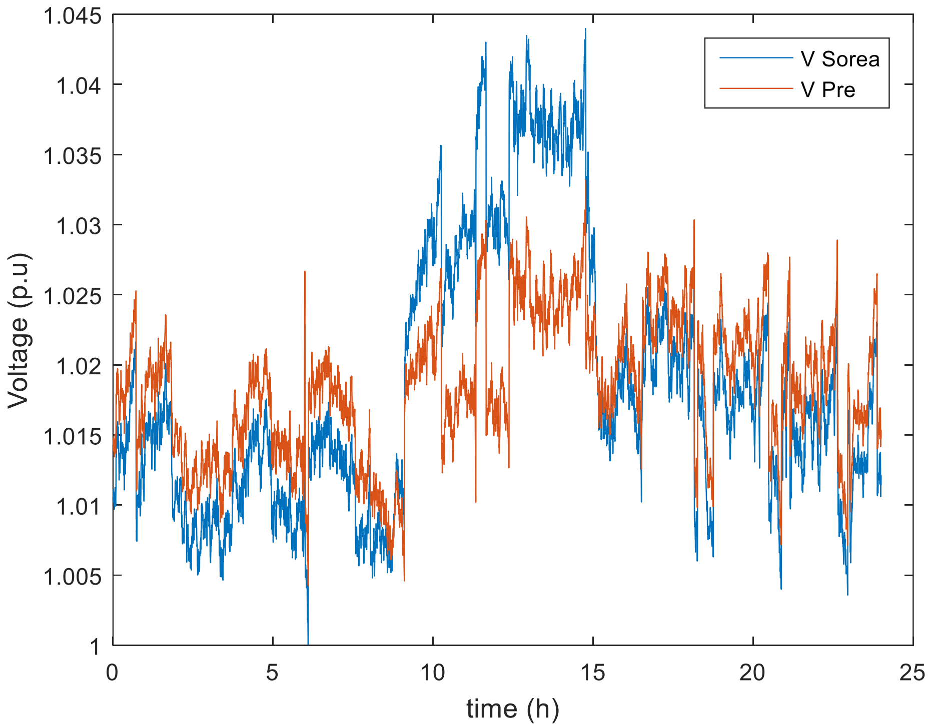

Figure 8 : Voltage at SOREA and substation Pre de Paques before optimization

The voltage raise is related to the power injection from the installed PV systems. Figure 9 shows active and reactive power injection into the grid (inverter ABB TRIO 27.6TL). Without optimization strategy, the reactive power of all inverters are not controlled and equal to zero.

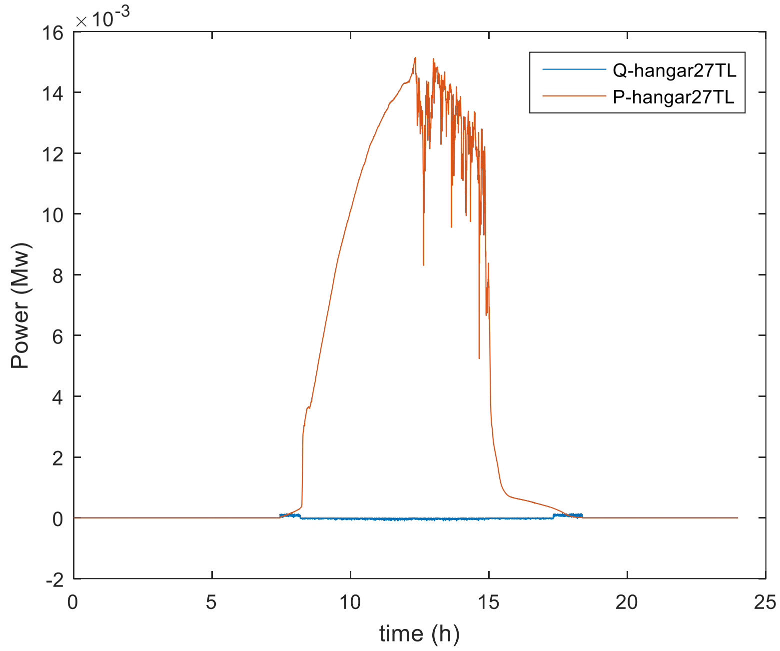

Figure 9 : Power injection from the ABB3 inverter (ABB TRIO 27.6TL).

As the optimization algorithm has less than three second CPU, therefore we decided to calculate the reactive power every one minute.

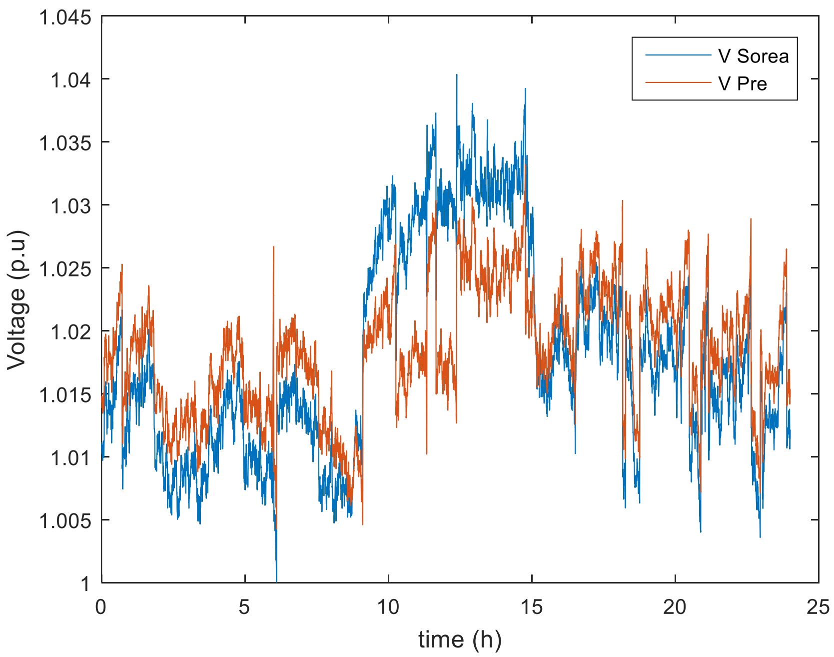

Figure 10: Voltage at substation and SOREA POC after optimization

Figure 10 shows voltage profile at substation of Pre de Paques and SOREA POC after optimization. Figure 11 shows the injected active power and the absorbed reactive power of inverter ABB TRIO 27TL as controlled by the CVC.

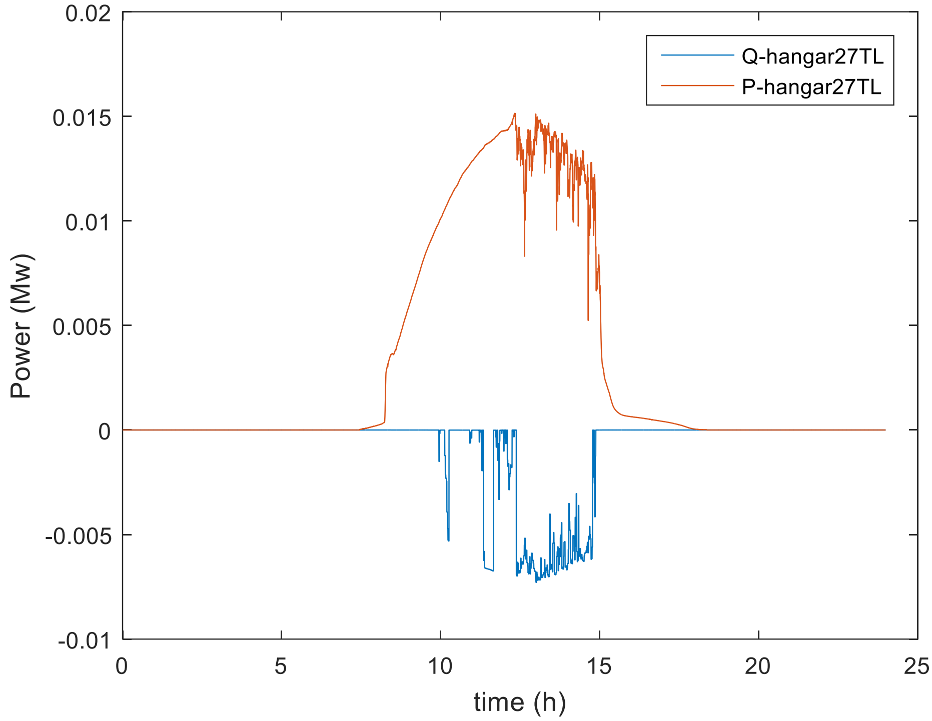

Figure 11: Active and reactive power of ABB trio 27TL

Figure 12 shows the impact of optimization algorithm before and after optimization to the voltage at the SOREA POC. There is a considerable reduction in voltage deviation.

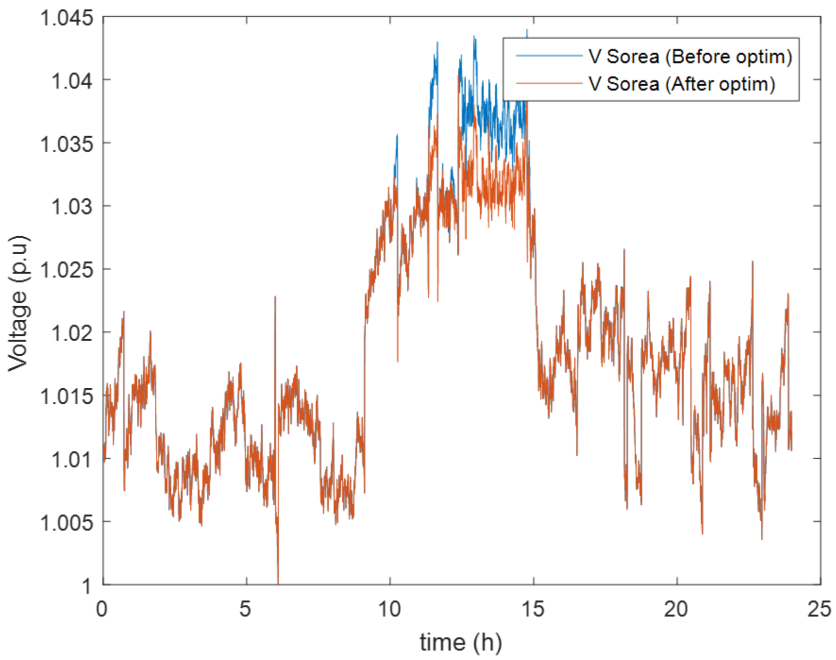

Figure 12 : Voltage AT SOREA before and after optimization

The performance of the CVC algorithm is then validated in simulation. We proceed in next section to the validation on the real microgrid.

4 Implementation of the CVC on SOREA microgrid

4.1 Measurement and communication infrastructure

In order to gather data and to implement the CVC algorithm, sensors, meters and communication instruments were installed at various points on the SOREA microgrid (Figure 13). They send P, Q and V measurements to an Open Platform Communication (OPC) Unified Architecture (UA) server, which in turn forwards the data to CEA Supervision, Control and Data Acquisition (SCADA) system over internet via a secured Virtual Private Network (VPN). Figure 14 shows the architecture of the communication and measurement has been implemented at SOREA site.

Figure 13 : Measurement and communication instruments are installed at SOREA's site.

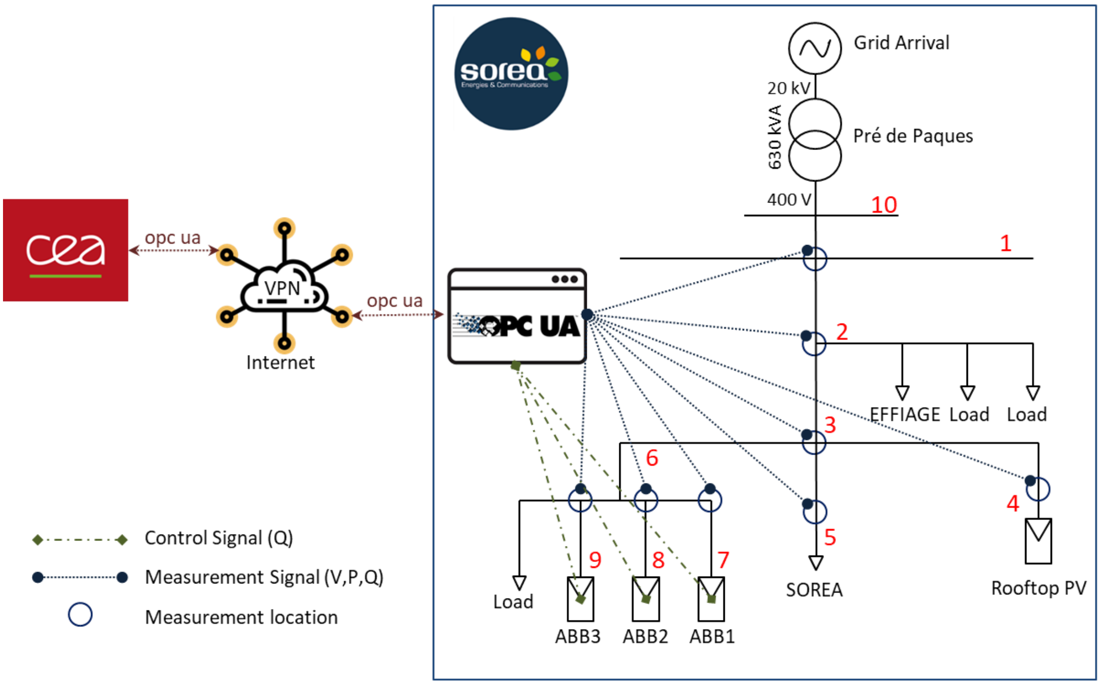

Figure 14 : Measurement and communication architecture at SOREA site.

In general, the sensors take measurement every 200 ms and send it back to CEA for optimization.

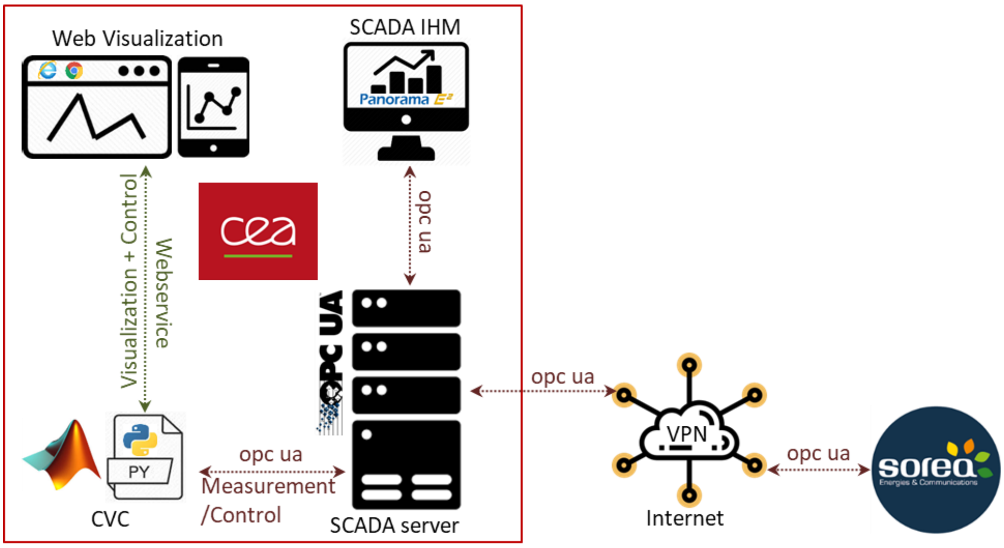

Figure 15: Data processing and optimization at CEA site

On the other side, at CEA, the measurements are received by the SCADA server, where it is also logged to a history server. The CEA SCADA system (Panorama E2) provides a user interface (Figure 16) where one can visualize the measurements from the SOREA microgrid and control the three ABB PV inverters.

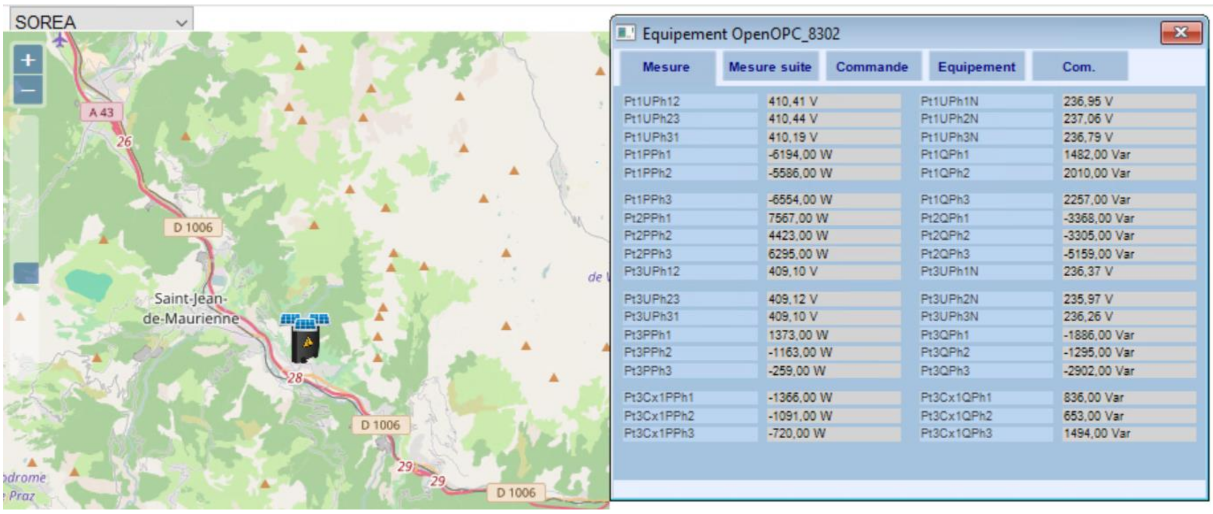

Figure 16 : Supervision interface of the SOREA demonstration site on the Panorama SCADA system.

To facilitate the deployment of the CVC and its integration with the SCADA server in real-time, the algorithm is ported to Python. In this way, every computer (PC) with Python and with access to the SCADA server can execute the algorithm and visualize the results, instead of limiting to PC equipped with OPCToolbox license.

4.2 CVC algorithm deployment

The CVC algorithm described in section 2.3 is then implemented on a PC with access to the SCADA server. For each initiation, it queries the grid data from the SCADA server, optimizes and sends back the set points. The algorithm requires the topology of the network that it controls (buses, connections between branches, branch impedance, branch current limits, etc) in order to create the admittance matrix Y (as well as its real and imaginary components G and B). It is necessary therefore to reconstruct the grid data from the measurement. To eliminate the measurement errors, moving average is executed over a frame of 10 seconds for each variable before being registered to the input. It is possible to modify the duration of this frame. The CVC then takes the measurements from the grid, executes a power flow analysis with the measurement vector for the specified topology (bus/branch matrix) and then formulate the optimization problem.

In general, the formulation of measurement vector and the constraints depends on the configuration and the topology of the considered grid. The optimization vector is formulated on the basis of controllable equipment in the network and finally, the objective function is formulated from the desired criteria. This analysis also allows us to determine the necessary procedure for transferring such a CVC algorithm from one platform to another platform.

Each time the CVC is executed, it follows the procedure described in Figure 17.

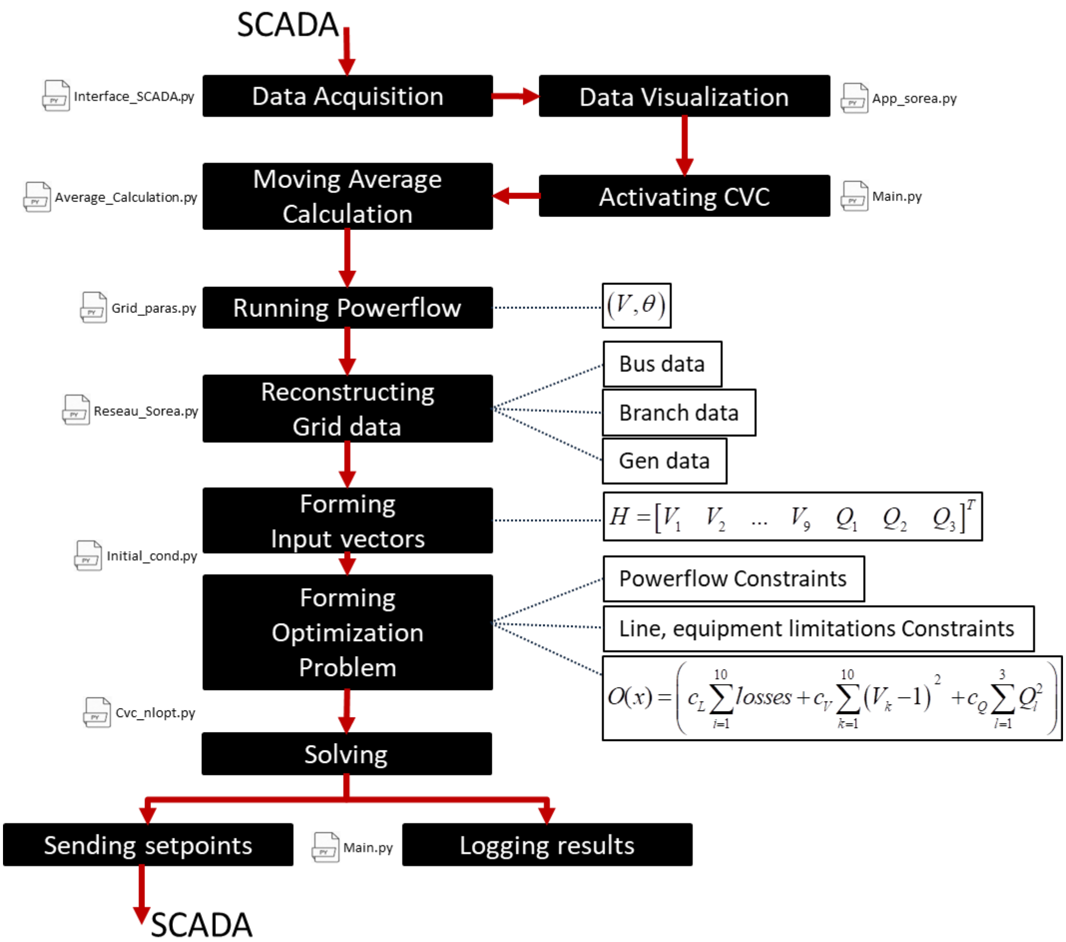

Figure 17 : Progress of an iteration of the CVC algorithm.

Particularly in this test-case of CVC on the SOREA microgrid, the implementation and optimization process is described in a few steps:

1. Measurements are stacked and the moving average is calculated to eliminate/reduce the influence of possible measurement errors.

2. The average measurements are organized and are registered as inputs to the CVC function.
3. Power flow analysis is executed on the inputs for the specified topology (bus/branch matrix) to determine the Magnitude V_i and angle θ_i of the voltages of all buses. This step can be done via existing libraries such as Matpower or Pypower.

   It is noteworthy that the rooftop PV plant at bus 4 is not controllable, but it still influences the power flow. It is therefore counted as a bidirectional load and its P, Q are registered to the bus matrix instead of gen matrix.
4. The optimization variable is formulated:

$$x = \begin{bmatrix} V_i & \dots & \theta_i & \dots & Q_1 & Q_2 & Q_3 \end{bmatrix}^T$$

   Input vector [x] contains the variables (outputs) of the optimal power flow problem. The first 2*n variables are uncontrollable, since they describe the magnitude and angle of the bus voltages. The rest are the controllable variables, which in order are, the Q set-points of the three ABB PV inverters. In essence, once the OPF problem has been solved, vector [x] describes the new values of the magnitude and angle of the bus voltages of the network, when the set-points have been implemented by the corresponding devices.
5. Equality conditions are formulated from the power flow constraints

$$P_{Gen\_i} - P_{Load\_i} = V_i \sum_{j=1}^{n} V_j \left[G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij} \right]$$

$$Q_{Gen\_i} - Q_{Load\_i} = V_i \sum_{j=1}^{n} V_j \left[G_{ij}\sin\theta_{ij} + B_{ij}\cos\theta_{ij} \right]$$

6. Inequality conditions are formulated from the equipment constraints (PV) and line current limit constraints.

$$0.9 \le V_i \le 1.1$$
$$0^\circ \le \theta_i \le 360^\circ$$
$$\left|Q_{PV}\right| \le P_{PV} * \tan(\cos^{-1}(pf))$$
$$P_{PV}^2 + Q_{PV}^2 \le S_{PV,nom}^2$$
$$\left|Y_{ij} * (\tilde{V}_i - \tilde{V}_j)\right| \le \max I_{ij}$$

7. Finally, the three considered criteria (voltage deviation, amount of injected reactive power and power loss) are regrouped into an objective function with respectively weight coefficients:

$$O(x) = c_L \sum_{i=1}^{10}\sum_{j=1}^{10} -G_{ij} * \left[V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij} \right] + c_V \sum_{k=1}^{10} \left(V_k - 1\right)^2 + c_Q \sum_{l=1}^{3} Q_l^2$$

   Where c_L, c_V and c_Q are chosen weights for the different criteria in the function (Figure 18).

8. The objective function is then solved using the nlopt package (Python) (Figure 19) or Optimization toolbox (Matlab) to determine the optimized set points.
9. The set points are sent to the primary control for execution.

```
def obj(self, x, grad):

    self.previous_args = self.current_args
    self.current_args = x

    if grad.size > 0:
        grad[:] = (self.z_p + self.z_p) * x
    sum_v = 0.
    for i in range(self.n):
        sum_v += (1 - x[i])**2

    q_pv_only = np.zeros(self.n_pv_only)
    sum_q_pv = 0.
    for k in range(self.n_pv_only):
        q_pv_only[k] = np.dot(x, np.dot(self.zq_k[self.idx_pv_only[k]], x)) + self.q_load[self.idx_pv_only[k]]
        sum_q_pv += q_pv_only[k]

    Q_bat = np.zeros(self.n_b)
    sum_q_bat = 0.
    for k in range(self.n_b):
        Q_bat[k] = -np.dot(x, np.dot(self.zq_k[self.idx_bat[k]], x)) - self.q_load[self.idx_bat[k]]
        sum_q_bat += Q_bat[k]
    return 5*np.dot(x, np.dot(self.z_p, x)) + sum_v + (sum_q_pv + sum_q_bat)/10000
```

Figure 18: The objective function is formulated in Python

```
                              error * np.ones(self.n_b))

opt.add_inequality_mconstraint(lambda result, x, grad: self.ineq_pwr_constraints_bat_p_min(result, x, grad),
                              error * np.ones(self.n_b))

opt.add_inequality_mconstraint(lambda result, x, grad: self.ineq_pwr_constraints_bat(result, x, grad),
                              error * np.ones(self.n_b))

opt.add_equality_constraint(lambda x, grad: self.eq_v_im_0(x, grad), error)

if TAP != -100:
    opt.add_equality_constraint(lambda x, grad: self.eq_v_re_0(x, grad, TAP), error)

opt.set_min_objective(self.obj)
# x = opt.optimize(self.x0)
try:
    x = opt.optimize(self.x0)
except nlopt.RoundoffLimited:
    x = self.previous_args
minf = opt.last_optimum_value()
status = opt.last_optimize_result()
return [x, minf, status]
```

Figure 19: The optimization problem is then solved using nlopt package in Python.

The choice of solvers plays an important role in the precision and accuracy of the results. Particularly, in our test-case, we chose to use the COBYLA solver. It constructs successive linear approximations of the objective function and constraints via a simplex of n+1 points (in n dimensions), and optimizes these approximations in a trust region at each step. An interesting perspective of this research is experimentation with different available solvers and assessment of their performance for different classes of CVC problems, featuring different criteria.

Besides the main functionality of coordination of voltage control, the developed CVC function also provides a simple user interface accessible via common web browsers to visualize the data in real time (Figure 22) and to activate the control (Figure 20).

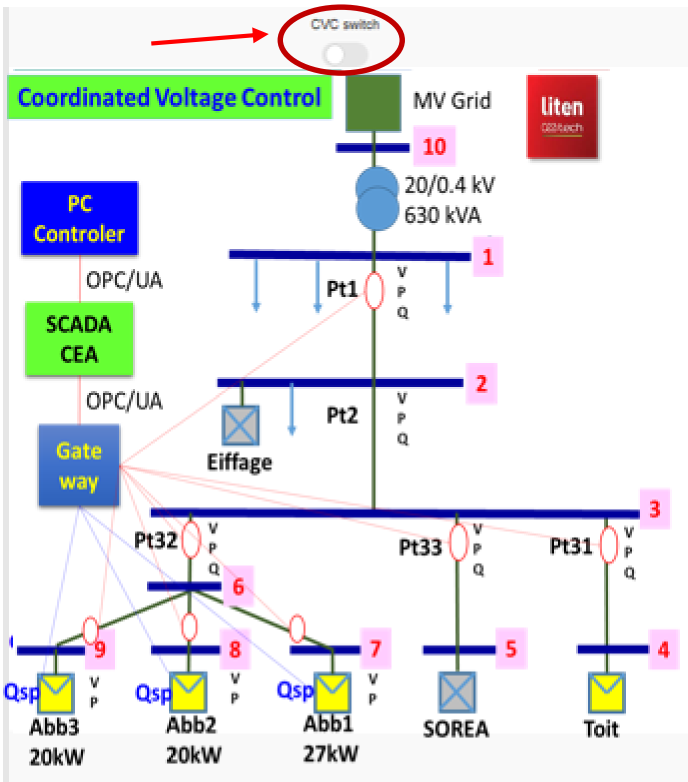

Figure 20 : Web Interface of the CVC algorithm

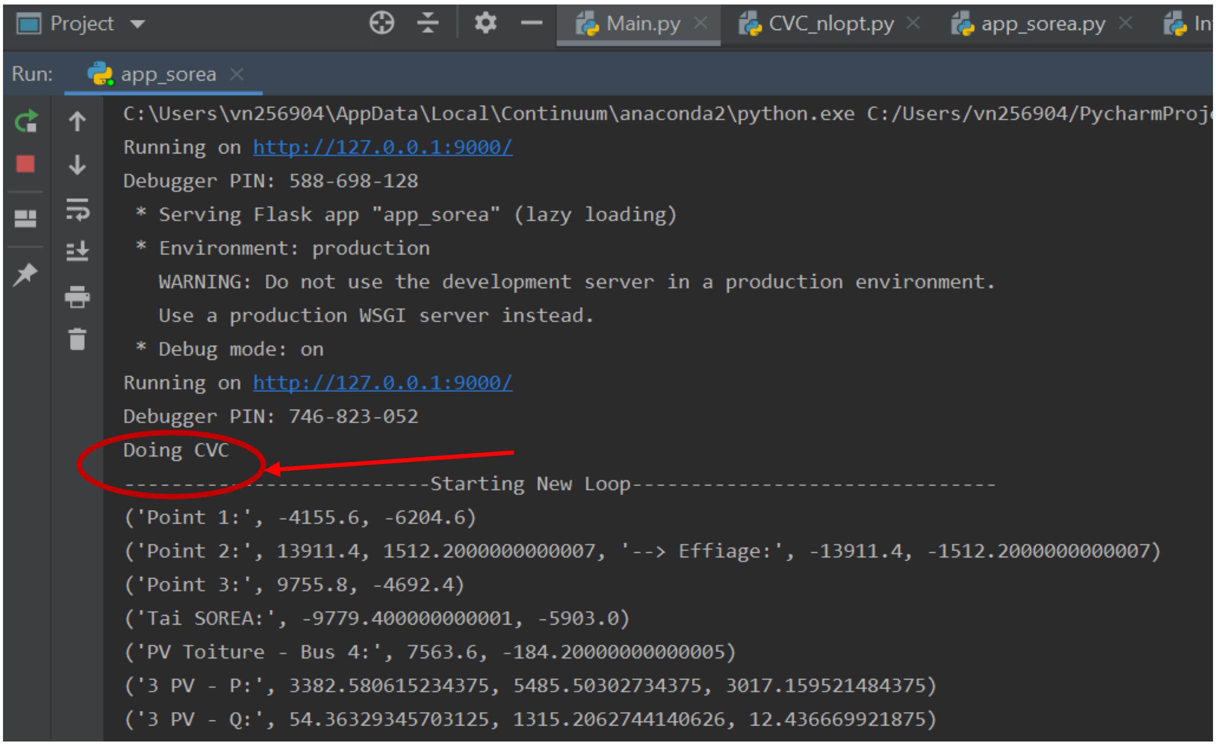

Figure 21 : The CVC is activated and is repeated once we turn on the switch.

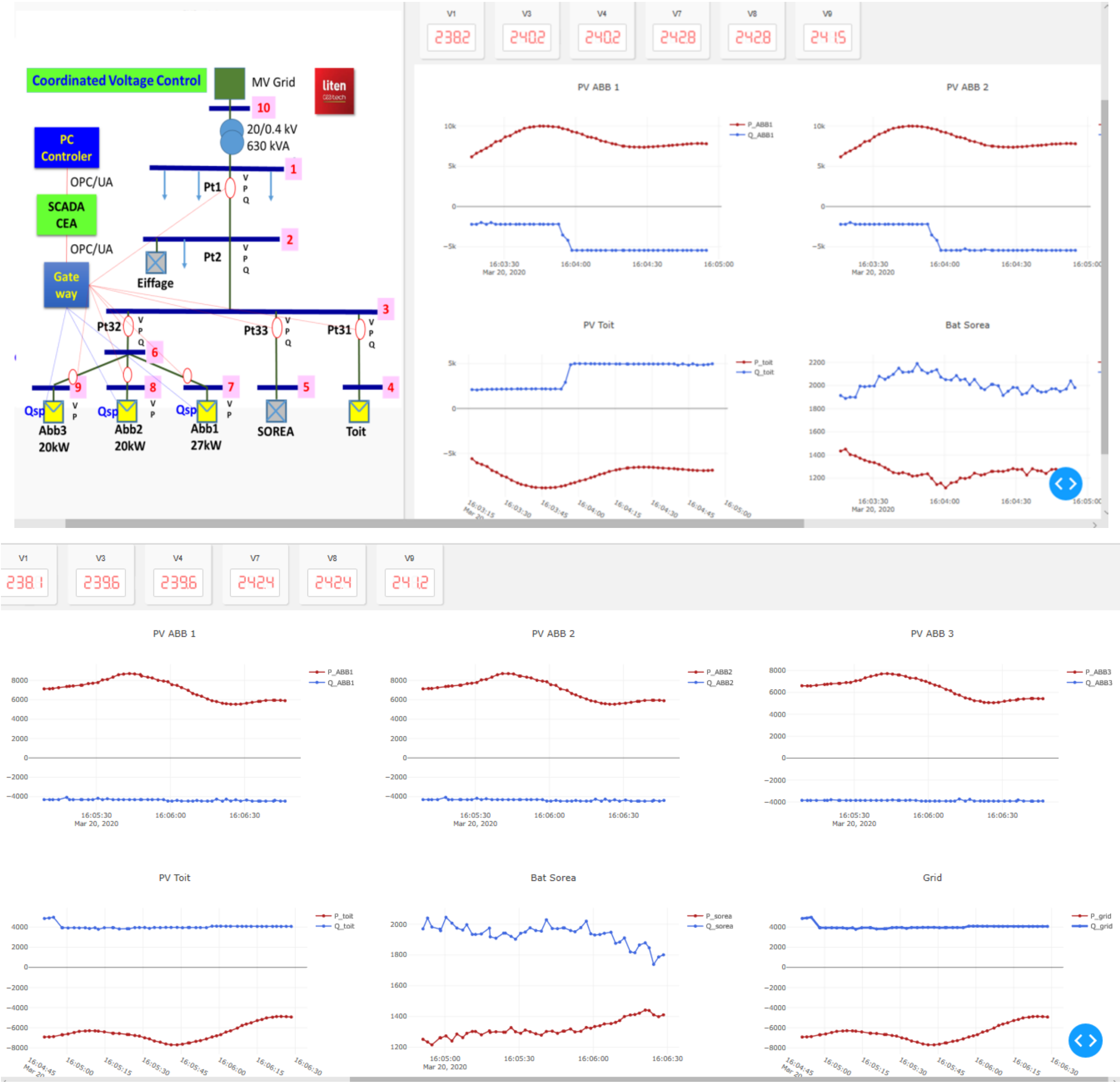

Figure 22 : Data visualization with the web user interface.

The CVC script is called once the CVC switch is turned ON.

The results are also logged into a .csv file with time stamp (Figure 23). The data format of the .csv file is as in Figure 24.

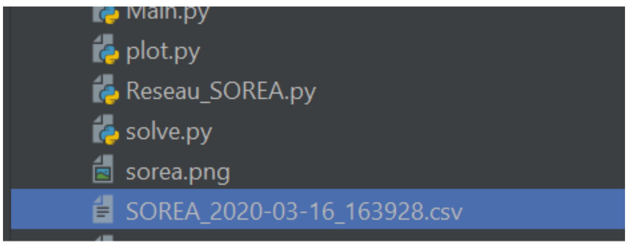

Figure 23 : Log file of the result

```
['Elapsed Time'] + ['V1'] + ['V2'] + ['V3'] + ['V4'] + ['V5'] + ['V6'] + ['V7'] + ['V8'] + ['V9'] + ['V10']
+ ['Ang1'] + ['Ang2'] + ['Ang3'] + ['Ang4'] + ['Ang5'] + ['Ang6'] + ['Ang7'] + ['Ang8'] + ['Ang9'] + [
    'Ang10']
+ ['P_Effiage'] + ['Q_Effiage'] + ['P_Sorea'] + ['Q_Sorea'] + ['P_Toit'] + ['Q_Toit']
+ ['P_PV1'] + ['P_PV2'] + ['P_PV3'] + ['Q_PV1'] + ['Q_PV2'] + ['Q_PV3']
+ ['SP_PV1'] + ['SP_PV2'] + ['SP_PV3'] + ['Total_Loss'])
```

Figure 24 : Format of the .csv logfile.

4.3 Experimental results

Once the CVC is activated, it starts with running powerflow and reconstructing the grid data for the formulation of the optimization problem.

The system summary of SOREA microgrid is given in Figure 25. The power flow analysis results in the bus and branch matrix as in Figure 26 and Figure 27.

From these data, the optimization problem is then formulated and solved using the nlopt package (Figure 28).

The outcome of the optimization problem is then adapted to the required format for PV inverter set points (Figure 29).

The results are then registered into a log file (Figure 30) that can be viewed and exploited in popular data processing software (e.g. Excel, Matlab, etc.).

```
Newton's method power flow converged in 3 iterations.

Converged in 0.05 seconds
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses                10  Total Gen Capacity       1.0           -0.0 to 0.0
Generators            4  On-line Capacity         1.0           -0.0 to 0.0
Committed Gens        4  Generation (actual)      0.0                0.0
Loads                 3  Load                     0.0                0.0
  Fixed               3    Fixed                  0.0                0.0
  Dispatchable        0    Dispatchable           0.0 of 0.0         0.0
Shunts                0  Shunt (inj)              0.0                0.0
Branches              9  Losses (I^2 * Z)         0.00               0.00
Transformers          0  Branch Charging (inj)     -                 0.0
Inter-ties            0  Total Inter-tie Flow     0.0                0.0
Areas                 1
```

Figure 25 : System summary of the SOREA microgrid

```
                          Minimum                      Maximum
                  -------------------------  -------------------------------
Voltage Magnitude   1.019 p.u. @ bus 4          1.024 p.u. @ bus 6
Voltage Angle      -0.00 deg   @ bus 0          0.14 deg   @ bus 4
P Losses (I^2*R)             -                  0.00 MW    @ line 2-4
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 0-9

================================================================================
|     Bus Data                                                                 |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    0  1.021  -0.004        -         -         -         -
    1  1.021   0.030        -         -       0.01      0.00
    2  1.021   0.061        -         -         -         -
    3  1.023   0.076        -         -      -0.01      0.00
    4  1.019   0.143        -         -       0.01      0.01
    5  1.023   0.061        -         -         -         -
    6  1.024   0.061      0.00     -0.00        -         -
    7  1.024   0.061      0.00     -0.00        -         -
    8  1.024   0.061      0.00     -0.00        -         -
    9  1.022   0.000*     0.01      0.01        -         -
                        --------  --------  --------  --------
               Total:     0.01      0.01      0.01      0.01
```

Figure 26 : Bus data of the microgrid

```
================================================================================
|     Branch Data                                                              |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   0      0      1     0.01      0.01     -0.01     -0.01     0.000      0.00
   1      1      2    -0.01      0.01      0.01     -0.01     0.000      0.00
   2      2      3    -0.01      0.00      0.01     -0.00     0.000      0.00
   3      2      4     0.01      0.01     -0.01     -0.01     0.000      0.00
   4      2      5    -0.01      0.00      0.01     -0.00     0.000      0.00
   5      5      6    -0.00      0.00      0.00     -0.00     0.000      0.00
   6      5      7    -0.00      0.00      0.00     -0.00     0.000      0.00
   7      5      8    -0.00      0.00      0.00     -0.00     0.000      0.00
   8      0      9    -0.01     -0.01      0.01      0.01     0.000      0.00
                                                             --------  --------
                                                   Total:     0.000      0.00
```

Figure 27 : Branch data of the microgrid

```
Data Acquisition Completed - Preparing Optimization Problem
('Total Loss:', 88.62737536830022)
Optimization Problem Formulated - Solving
Successfully Obtained a Solution
('Optimized Results:', array([ 1.06010658,  1.00842569,  1.04660712,  1.09165251,  0.9
        1.08166766,  1.03674907,  1.04880182,  1.05619156,  1.05517906,
       -0.00405006, -0.00867546,  0.00752076,  0.15240167,  0.03209752,
        0.03266639,  0.11965045,  0.02152933,  0.07011927,  0.04528645]))
('Min Objective Function:', 4.623347157383826)
----------Set Points for Q_PV---------
('P_pv, Q_pv', 6, ' : ', 3417.57548828125, -2980.348611163277)
('P_pv, Q_pv', 7, ' : ', 2595.308642578125, 342.1701463371057)
('P_pv, Q_pv', 8, ' : ', 2595.308642578125, -1289.5220565153636)
--------------------------------------------------------------------------------
Sending Set Points...
Writing Results to Log File
-------------------------Waiting 15 sec------------------------------
```

Figure 28 : Results of the optimization problem.

Figure 29 : The PV inverters act upon receiving set points and their influence to the grid

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Elapsed Time	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	Ang1	Ang2	Ang3	Ang4
2	12.45	1.0173	1.0168	1.0173	1.0191	1.0149	1.0195	1.0205	1.0203	1.0203	1.0178	-0.0092696	0.023576	0.049954	0.052514
3	39.69	1.0149	1.0141	1.0144	1.0156	1.012	1.0166	1.0177	1.0174	1.0174	1.0153	-0.014208	0.017912	0.044927	0.048785
4	74.21	1.0181	1.0174	1.0178	1.019	1.0154	1.0199	1.021	1.0208	1.0208	1.0186	-0.013667	0.017197	0.043728	0.047552
5	108.5	1.0169	1.0162	1.0166	1.0181	1.0142	1.0188	1.0198	1.0196	1.0196	1.0174	-0.013854	0.01878	0.042225	0.036515
6	139.4	1.0173	1.0165	1.0168	1.0182	1.0144	1.019	1.0201	1.0198	1.0198	1.0178	-0.014177	0.023276	0.047231	0.042166
7	167.4	1.018	1.0173	1.0178	1.0197	1.0154	1.02	1.021	1.0208	1.0208	1.0185	-0.010898	0.027362	0.049975	0.04402
8	196.6	1.0198	1.0191	1.0196	1.0216	1.0172	1.0217	1.0228	1.0226	1.0226	1.0203	-0.011622	0.026886	0.050445	0.044245
9	225.9	1.0206	1.02	1.0205	1.0224	1.018	1.0226	1.0236	1.0234	1.0234	1.0211	-0.01026	0.029229	0.051552	0.044734
10	255.4	1.0212	1.0205	1.021	1.0229	1.0186	1.0231	1.0242	1.0239	1.0239	1.0217	-0.010151	0.02934	0.052072	0.043973
11	283.8	1.0212	1.0208	1.0213	1.0232	1.0188	1.0234	1.0245	1.0242	1.0242	1.0216	-0.0040103	0.030055	0.060604	0.075797
12	312	1.0208	1.0204	1.0208	1.0225	1.0183	1.0229	1.024	1.0237	1.0237	1.0211	-0.001571	0.032723	0.063234	0.079986

P_Effiage	Q_Effiage	P_Sorea	Q_Sorea	P_Toit	Q_Toit	P_PV1	P_PV2	P_PV3	Q_PV1	Q_PV2	Q_PV3	SP_PV1	SP_PV2	SP_PV3	Total_Loss
13911	1512.2	9779.4	5903	7563.6	-184.2	3382.6	2742.8	2742.8	-41.626	2.2512e-06	290.87	-9.4981	6.015e-07	77.717	89.018
13230	1192.4	9753	5927.8	4831.4	-276.4	3384.7	2713.1	2713.1	1.314e-05	-2.4553e-05	1.9679e-05	2.9968e-06	-6.6125e-06	5.2999e-06	81.792
13592	1021.4	9400	5856	5182.4	-275.8	3381.3	2694.6	2694.6	-4023.8	4406	-1762.7	-918.4	1192.6	-477.11	79.519
14256	2140.8	9696	5817	5918.4	412	3378.4	2691.4	2691.4	-3456.8	145	4025.8	-789.52	39.282	1090.6	83.518
14250	3138.2	9761.8	5891.8	5352.6	365.6	3380.8	2691.7	2691.7	-5346.6	2365.2	1806.4	-1220.5	640.68	489.3	84.92
15258	3639.4	9657.8	5653.6	7674.8	431	3382.6	2666.7	2666.7	67.894	-1142	-166.85	15.492	-311.46	-45.505	90.318
15722	3491.4	9985.4	5910.8	8140	450.4	3392.9	2638	2638	-4.6319e-05	-6033.1	567.77	-1.0544e-05	-1658.3	156.07	94.819
14964	4011.4	10094	5678.6	8012	496	3397.4	2622.7	2622.7	4455.4	5723.3	-59.132	1013.2	1579.8	-16.322	93.033
14724	3920.6	9967.2	5873.4	7698.4	589.6	3406.4	2610.5	2610.5	6492.9	6075.3	4470.4	1473.5	1682.7	1238.2	91.467
11302	832.6	10165	6002.2	7775	-1105	3417.6	2595.3	2595.3	-2980.3	342.17	-1289.5	-674.66	95.171	-358.67	88.627
9153	891	10413	5877	6970.8	-1217.2	3453.6	2563.4	2563.4	-2352.5	4529.6	1065	-528.23	1271.2	298.88	84.91

Figure 30 : Extract from the log file of a test run on SOREA microgrid.

The grid data is also logged and visualized by the SCADA CEA system.

Figure 31 and Figure 32 shows measurements of injected active power and absorbed reactive power of the three ABB inverters from the SCADA of CEA, with different weight coefficients. The first one is more weighed on voltage deviation and is less weighed on power loss and amount of injected Q. The controller algorithm has been activated at 11:54 O'clock. The inverter then tried to contribute to regulate the voltage by absorbing reactive power. On the other case, the CVC algorithm is more weighed on the amount of Q injected and is less weighed on voltage deviation. As the CVC is activated at 15:30, the inverters reduced their injected Q, all in keeping the voltage in the limits.

The choice of weight coefficients depends therefore on the criterion that one would like to emphasize and would significantly influence the outcome of the algorithm. An interesting perspective in this case is actualizing a sensibility analysis of such criteria to the results.

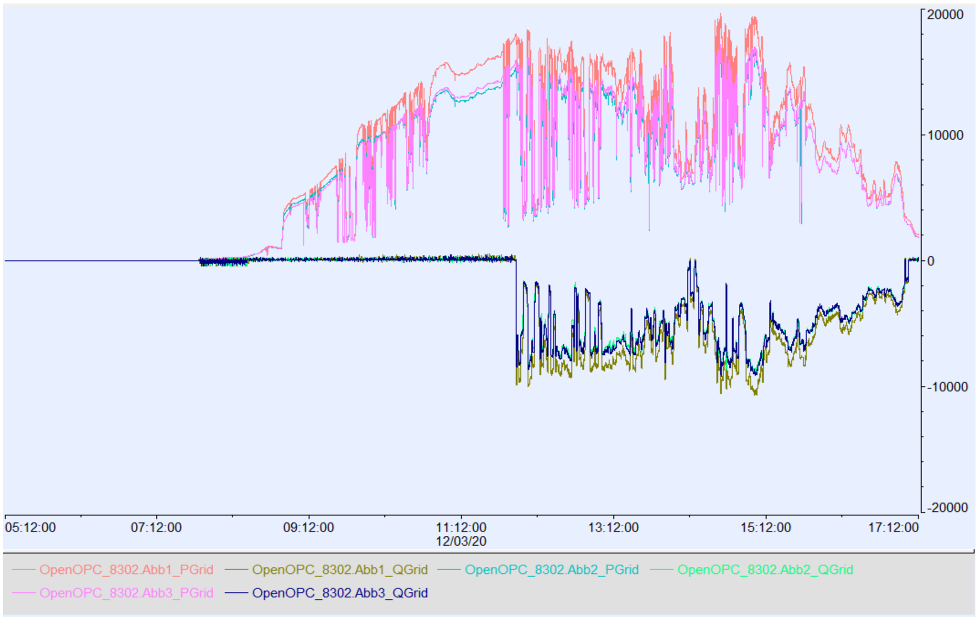

Figure 31 : Inverter's behaviors with a CVC weighed on minimizing voltage deviation.

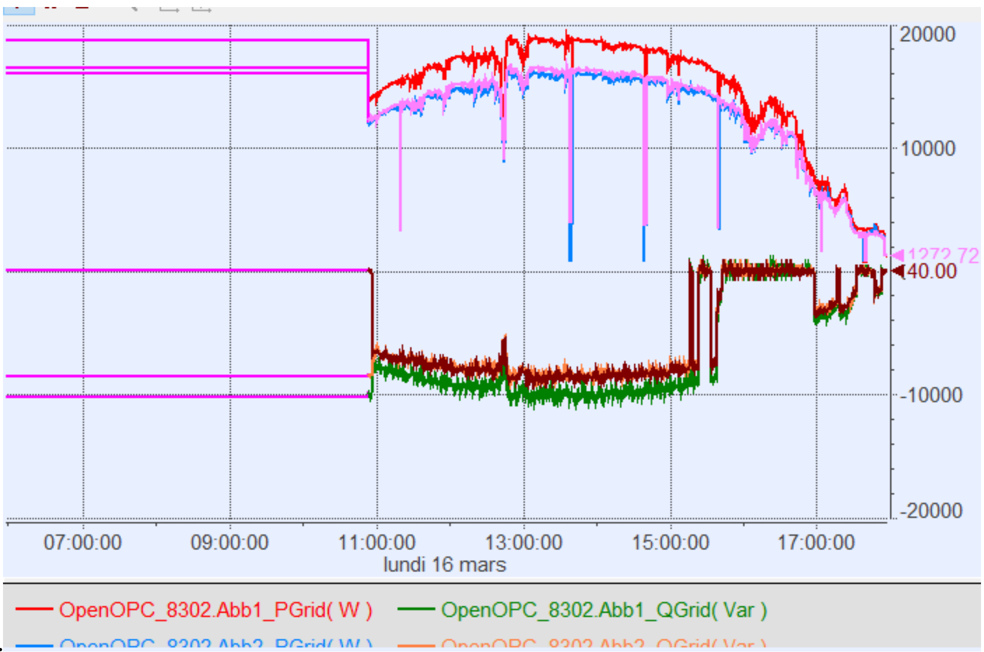

Figure 32 : Inverter's behaviors with a CVC weighed on minimizing injected Q.

5 Conclusions

The benefit and the performance of coordinated voltage control algorithm based on reactive power control of inverters has been investigated and explained in this deliverable. The algorithm is deployed on the microgrid of SOREA and its performance was assessed. It is acknowledged that the CVC is a multi-criteria optimization problem where the choice of solvers and weight coefficients influences strongly the outcome. Several interesting perspectives on assessment of solver performance and sensibility analysis were proposed.

Coordinated voltage control allows regulating voltage at pilot point following several optimized criteria and without investment and perturbation to the plant production, given that control voltage based on reactive power set point does not have any impact on the active power injection within cos phi between one and 0.9. This research highlights the possibility of PV inverters to contribute their services to grid operation.

6 References

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7 Appendix: Runtime log of one CVC loop on the SOREA microgrid.

```
-------------------------Starting New Loop------------------------------
('Point 1:', -2329.2000000000003, -6577.4)
('Point 2:', 11302.2, 832.5999999999995, '--> Effiage:', -11302.2, -832.5999999999995)
('Point 3:', 8973.0, -5744.8)
(' SOREA:', -10164.599999999999, -6002.200000000001)
('PV Toiture - Bus 4:', 7775.0, -1105.0)
('3 PV - P:', 3417.57548828125, 5190.61728515625, 3001.3314453125)
('3 PV - Q:', -593.00166015625, 2518.88916015625, -516.9748046875)
PYPOWER Version 5.1.4, 27-June-2018 -- AC Power Flow (Newton)



Newton's method power flow converged in 3 iterations.

Converged in 0.05 seconds
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              10     Total Gen Capacity       1.0          -0.0 to 0.0
Generators          4     On-line Capacity         1.0          -0.0 to 0.0
Committed Gens      4     Generation (actual)      0.0               0.0
Loads               3     Load                     0.0               0.0
  Fixed             3     Fixed                    0.0               0.0
  Dispatchable      0     Dispatchable         0.0 of 0.0            0.0
Shunts              0     Shunt (inj)              0.0               0.0
Branches            9     Losses (I^2 * Z)         0.00              0.00
Transformers        0     Branch Charging (inj)     -                0.0
Inter-ties          0     Total Inter-tie Flow     0.0               0.0
Areas               1
```

```
                  Minimum                  Maximum
            ------------------------  -------------------------------
Voltage Magnitude   1.019 p.u. @ bus 4         1.024 p.u. @ bus 6
Voltage Angle      -0.00 deg   @ bus 0         0.14 deg   @ bus 4
P Losses (I^2*R)            -                 0.00 MW    @ line 2-4
Q Losses (I^2*X)            -                 0.00 MVAr  @ line 0-9

================================================================================
|     Bus Data                                                                 |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    0  1.021   -0.004       -         -         -         -
    1  1.021    0.030       -         -        0.01      0.00
    2  1.021    0.061       -         -         -         -
    3  1.023    0.076       -         -       -0.01      0.00
    4  1.019    0.143       -         -        0.01      0.01
    5  1.023    0.061       -         -         -         -
    6  1.024    0.061      0.00     -0.00       -         -
    7  1.024    0.061      0.00     -0.00       -         -
    8  1.024    0.061      0.00     -0.00       -         -
    9  1.022    0.000*     0.01      0.01       -         -
                        --------  --------  --------  --------
               Total:      0.01      0.01      0.01      0.01

================================================================================
|     Branch Data                                                              |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
```

```
 #    Bus   Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
  0     0     1     0.01      0.01     -0.01     -0.01    0.000     0.00
  1     1     2    -0.01      0.01      0.01     -0.01    0.000     0.00
  2     2     3    -0.01      0.00      0.01     -0.00    0.000     0.00
  3     2     4     0.01      0.01     -0.01     -0.01    0.000     0.00
  4     2     5    -0.01      0.00      0.01     -0.00    0.000     0.00
  5     5     6    -0.00      0.00      0.00     -0.00    0.000     0.00
  6     5     7    -0.00      0.00      0.00     -0.00    0.000     0.00
  7     5     8    -0.00      0.00      0.00     -0.00    0.000     0.00
  8     0     9    -0.01     -0.01      0.01      0.01    0.000     0.00
                                                --------  --------
                                      Total:     0.000     0.00
Data Acquisition Completed - Preparing Optimization Problem
('Total Loss:', 88.62737536830022)
Optimization Problem Formulated - Solving
Successfully Obtained a Solution
('Optimized Results:', array([ 1.06010658,  1.00842569,  1.04660712,  1.09165251,  0.9       ,
        1.08166766,  1.03674907,  1.04880182,  1.05619156,  1.05517906,
       -0.00405006, -0.00867546,  0.00752076,  0.15240167,  0.03209752,
        0.03266639,  0.11965045,  0.02152933,  0.07011927,  0.04528645]))
('Min Objective Function:', 4.623347157383826)
----------Set Points for Q_PV---------
('P_pv, Q_pv', 6, ' : ', 3417.57548828125, -2980.348611163277)
('P_pv, Q_pv', 7, ' : ', 2595.308642578125, 342.1701463371057)
('P_pv, Q_pv', 8, ' : ', 2595.308642578125, -1289.5220565153636)
-----------------------------------------------------------------------------
Sending Set Points...
Writing Results to Log File
-------------------------Waiting 15 sec------------------------------
```