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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

REEL Demo – Romande Energie ELectric network in local balance Demonstrator

Deliverable: 6c1 Report on soft-open point deployment

Demo site: Chapelle

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in collaboration with

Romande Energie, Morges

[Fribourg/Yverdon, 27.09.2020]

1 Description of deliverable and goal

1.1 Executive summary

A soft-open point (SOP) has been designed, assembled and is planned to be deployed to Romande Energie's Chapelle-sur-Moudon LV network. The 50 kVA SOP connects both LV networks fed by two distribution transformers. The project has included the design and testing of the SOP hardware, the integration into the existing network (including protection) and the design of suitable control modes. These control modes will reduce the adverse effects of distributed generation (voltage variation and component maximum loading), using either few dedicated measurement points or interfacing an existing GridEye system deployed for multiple applications.

The project also allowed to explore the implication of the deployment of an SOP in terms of protection and the coordination with various stakeholders within the DSO's organization.

1.2 Research question

The research question to be answered in this deliverable is: Can an SOP contribute to improve a real-world LV grid's performance in terms of voltage variations during different load/generation conditions and maximum transformer/cable loading?

1.3 Novelty of the proposed solutions compared to the state-of-art

The Soft-open point (SOP) has been described previously as a device that can help to increase a distribution grid's hosting capability for renewable power producers [1-4]. An initial prototype of 15 kVA has been successfully tested in a laboratory environment [5, 6]. In this deliverable, the device is brought to the distribution network, which implies two novel challenges:

- The SOP must be fit for continued autonomous operation and have a power of 50 kVA.
- The SOP must be integrated into the protection of the existing network, provide its own back-up communication and control system and be integrated into the DSO's daily operation.

1.4 Description

1.4.1 SOP principle applied to Chapelle-sur-Moudon (REEL) demonstrator

Figure 1 shows a geographic network map of the considered location: the village of Chapelle-sur-Moudon is fed by two LV networks with a 250 kVA MV/LV transformer each. At several locations, these two networks come close together. One location (in red on the map) has been selected by Romande Energie and HES-SO for the deployment of the 50 kVA LV SOP. The solar PV generation installed in these networks is unevenly distributed with 317kVA vs. 87kVA in each of them.

After the completion of simulations and a preliminary design of the SOP, a size of 50 kVA was determined. The SOP will comprise the actual converter hardware as well as control, protection and communication facilities. It will be housed in a cabinet, sketched in Figure 3.

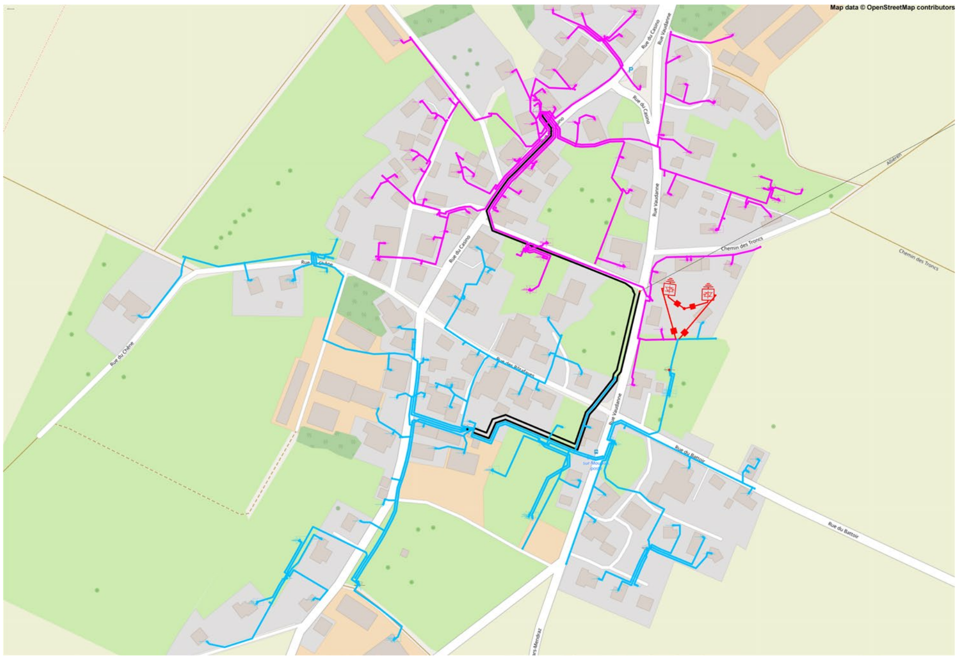


Figure 1: Geographic map of the two LV networks (blue/purple) in Chapelle-sur-Moudon and the interconnecting MV cable (black). Schematic view of the SOP position (red).

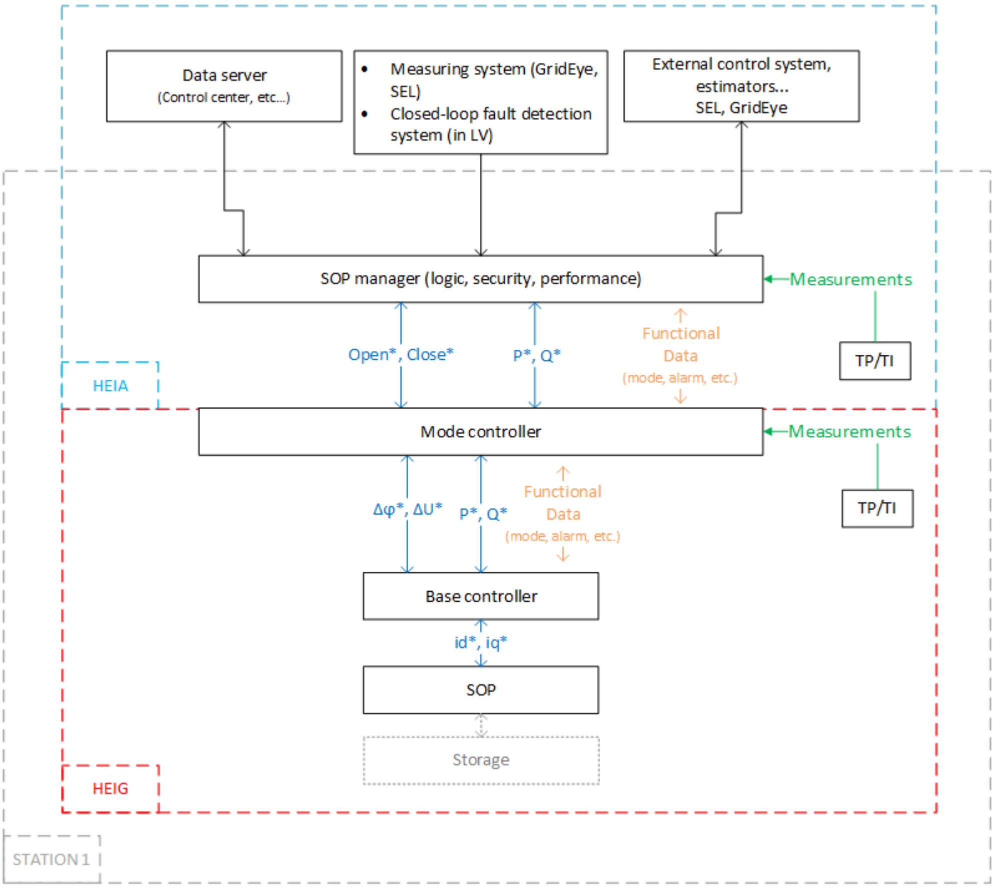


Figure 2: Control and communication architecture of the SOP

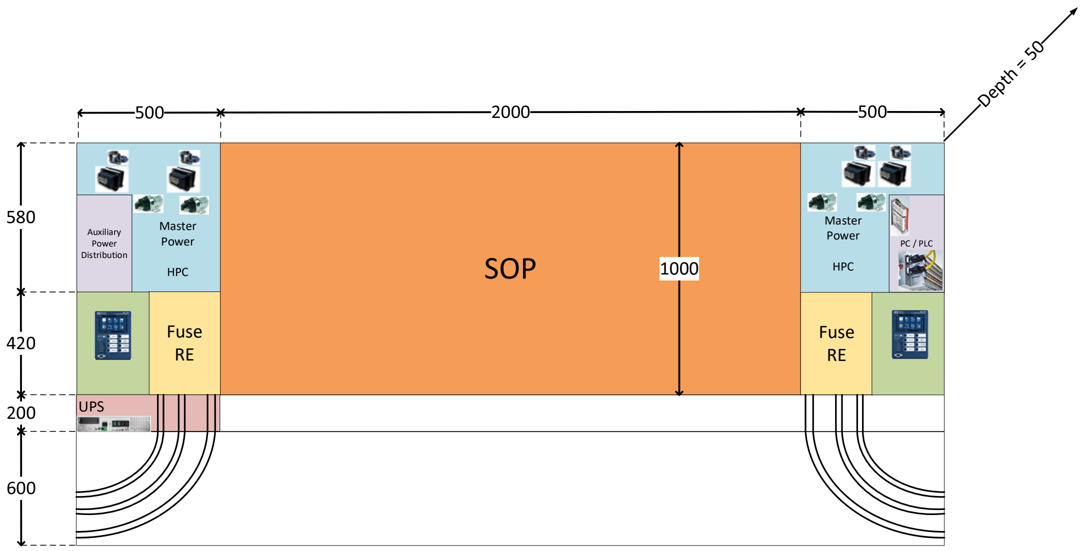


Figure 3: Schematic layout of the cabinet for the SOP prototype.

The control of the SOP is organized according to the architecture shown in Figure 2. The control is organized in several layers:

- The inner SOP controller generates current references in the d-q frame for the two back-to-back converters. Two modes have been investigated and published in [1]: switch mode and P/Q mode. The latter has been implemented in the SOP prototype.
- The SOP manager performs the grid control of the SOP by generating P and Q references (both ports of the SOP). The grid control modes are discussed further in section 1.4.2.1 below.
- Some grid control modes rely on external data which might be acquired using:
    - A dedicated set of external measurements with a dedicated communication link. Those measurements are located at the MV/LV transformer station.
    - The already deployed GridEye system which offers more measurement points within the LV distribution system (only one of the two LV networks though).
    - Optionally, with a link to a data server (e.g. a control center). This is not implemented in the prototype SOP.

1.4.2 SOP grid control and communication

1.4.2.1 SOP grid control

In order to improve the performance of the distribution systems connected to the SOP, three grid control modes have been implemented:

1. TRABA (Transformer Balancing): the objective is to balance the loading of the two distribution transformers (whilst not violating other loading constraints). This strategy is described in more details in appendix 4.1.
2. VSTB (Voltage profile shifting & transformer balancing):): the objective is to reduce a combination of the loading difference between the two distribution transformers and to reduce the voltage difference between the two connection points of the SOP. This strategy is described in more details in appendix 4.2.

3. VOLTSAME (Voltage SAME): the objective is to reduce the voltage drop between the transformers and the SOP connection points. This strategy is described in more details in appendix 4.3.

These three modes have been selected from a longer list in coordination with Romande Energie based on the criterion that they can still be operated if the connection to the GridEye system is lost.

In a first step, the three grid control modes have been compared to each other in simulations for 6 representative load situations. The comparison of the effectiveness is done using a scoring used in other SOP related activities within FURIES (see Appendix 4.4). The scoring takes into account the voltage variations during operation, the maximum loading of cables and transformers as well as the network losses (including the SOP). The lower the score is, the better the investigated variant is. Two benchmarks are used for the comparison:

- the current situation without an SOP
- the addition of an ideal line instead of the SOP

Figure 4 shows the result of the comparison: adding a line instead of an SOP would not bring the benefit envisaged (due to the circulation of reactive power, among other reasons). The addition of the SOP would improve the voltage and loading situation, whereas the VSTB strategy is the most promising in this case. For further comparison, the result of an OPF with an objective to minimize network losses (including the SOP) is shown with the label "PLOSS". This is only a theoretical comparison, since computing the setpoint of the SOP would in this case require the exact knowledge of all loads and infeeds into the network.

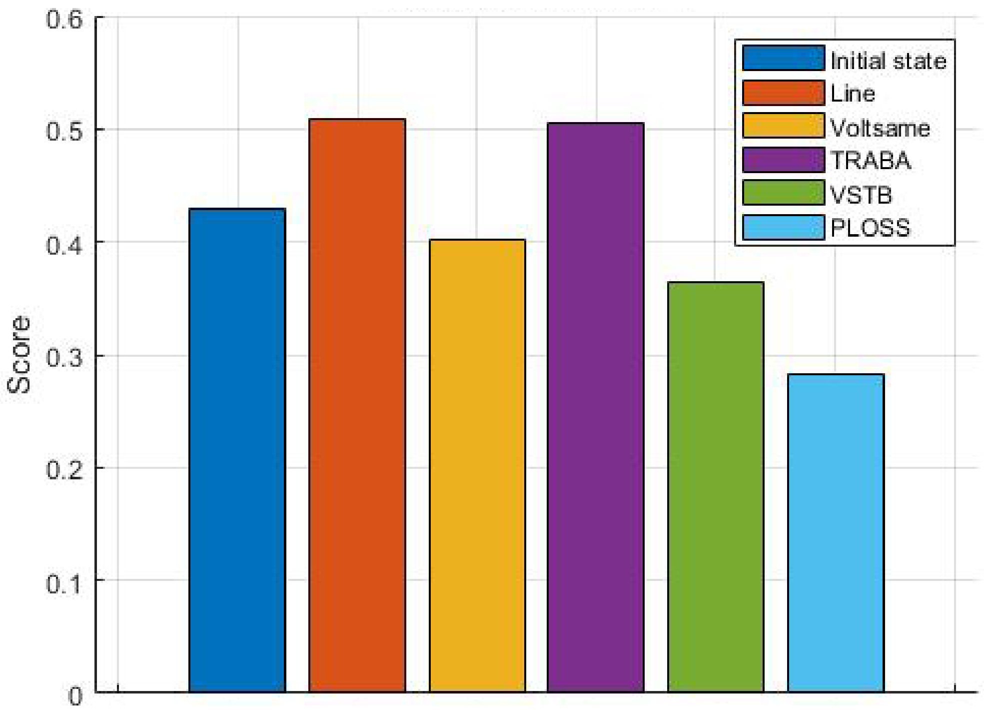


Figure 4: Performance comparison of different grid control modes for a 50 kVA SOP at the selected location within the Chapelle-sur-Moudon LV network.

1.4.2.2 SOP communication and protection

One of the requirements for the SOP protection and control system is to have a fail-safe way to detect a fault condition. No communication (wired internet) is pre-existing at either the SOP location or the transformer stations. Cellular networks cannot reach the guaranteed transmission times required and it is impossible to send UDP traffic to fixed IP Addresses in the public 4G network available at the site. Therefore, a system using a radio link for the transmission of IEC 61850 traffic between the measurement points at the transformer stations and the SOP was selected as shown in Figure 5. The measured currents and voltages at the transformer stations are sent to the SOP cabinet where protection relays implement the usual protection functions according to Table 1. The trip signals of the protection relays are operating the breakers located at the SOP terminals as illustrated in Figure 6. The SOP protection does not interfere with the LV system protection in place, which is relying on fuses. These fuses still interrupt faults on the LV feeders in the same way as before the addition of the SOP.

Figure 5: Acquisition and transmission of measurement values for the LV SOP.

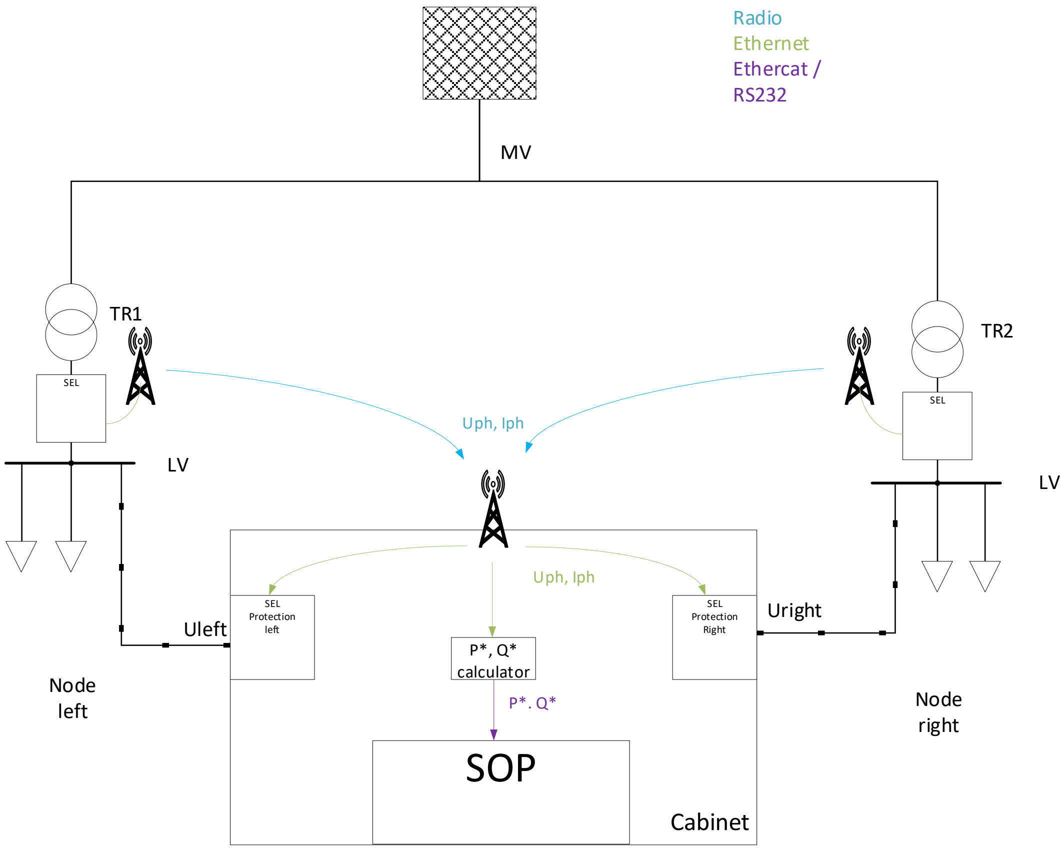


Figure 5: Acquisition and transmission of measurement values for the LV SOP.

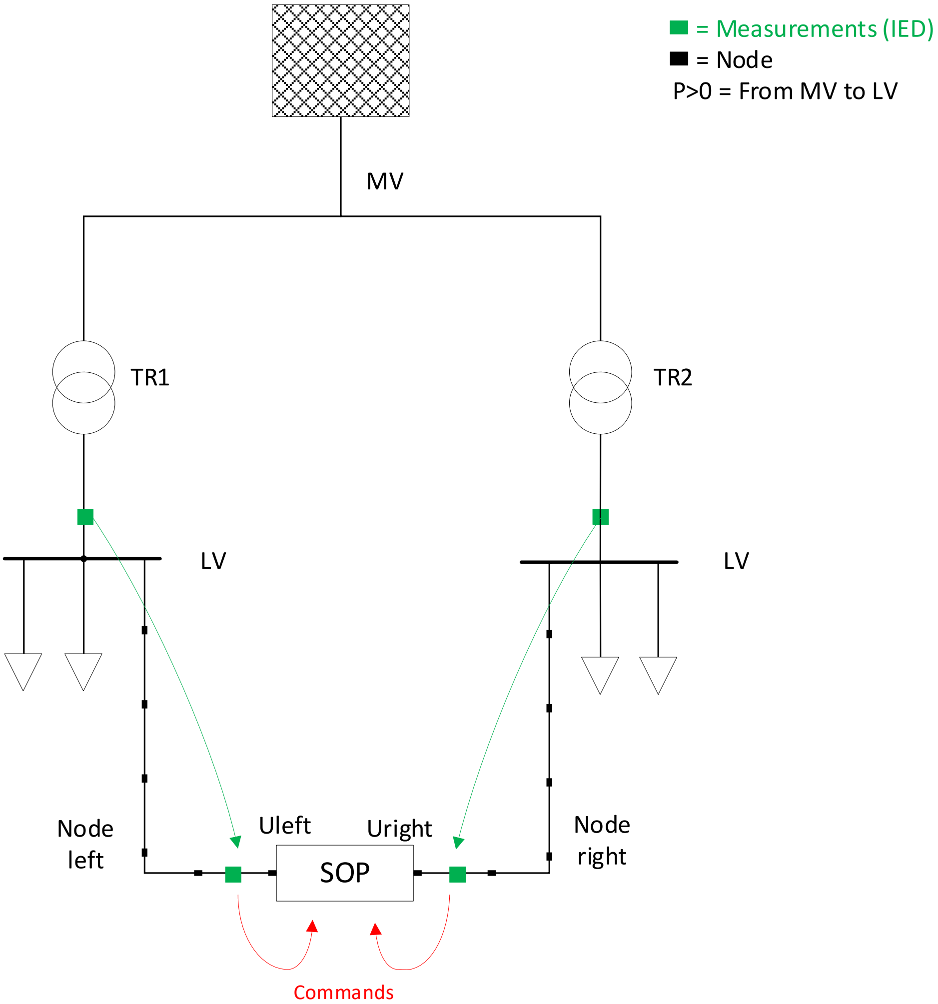


Figure 6: Location of the protection relays and communication links for the grid-side protection of the LV SOP.

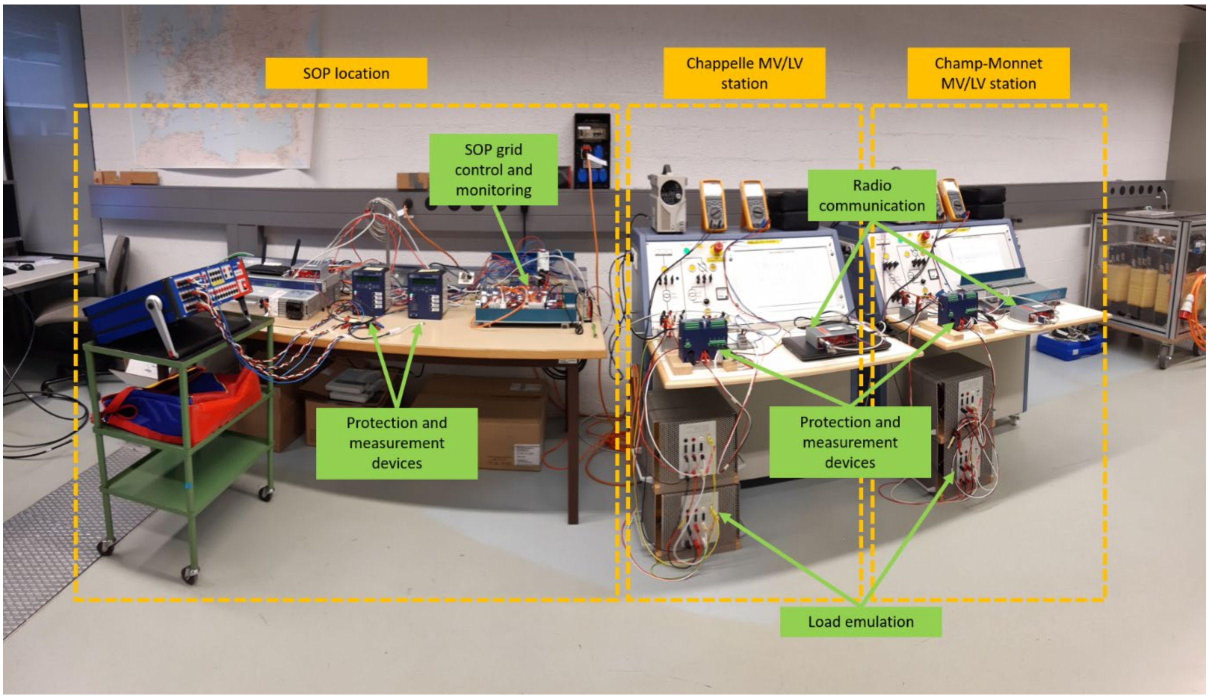


Figure 7: Laboratory mock-up of the SOP protection, control and communication equipment.

Table 1: Protection settings for the LV SOP.

Protection type	Function	Threshold	Source
Overcurrent	$I_{TR1, TR2} > I_{TripTR}$	I_{TripTR}=380A	1.05*I_{nomTR} [7]
Overcurrent	$I_{SOP\ Left,Right} > I_{Trip\ SOP\ Left,Right}$	$I_{Trip\ SOP\ Left,Right}$=75A	I_{nomSOP}
Under/over voltage	$U_{TR1,TR2}$ <> $U_{min,max\ A}$	U_{minA}=0.9 U_{maxA}=1.1	SN EN 50160
Under/over voltage	$U_{SOP\ Left,Right}$ <> $U_{min,max\ B}$	U_{minB}=0.8 U_{maxB}=1.1	[8]
Overvoltage	$U_{SOP\ Left,Right} > U_{maxmax\ B}$	$U_{maxmaxB}$=1.15	[8]
Under/over frequency	$f_{TR1,TR2}$ <> $f_{min,max\ A}$	f_{minA}=49.5Hz f_{maxA}=51.5Hz	[9, 10]
Under/over frequency	$f_{SOP\ Left,Right}$ <> $f_{min,max\ B}$	f_{minB}=47.5Hz f_{maxB}=51.5Hz	[8]
Auxiliary power supply	UPS trigger	UPS=ON	-

1.4.3 SOP prototype

As already mentioned, this prototype of 50 kVA is based on an initial prototype of 15 kVA SOP presented in [5, 6].

The new prototype is composed of 2 different units: a power unit and a control unit.

SOP power unit is composed of two 230/400 V 3-phase 2-level inverters in back to back with a central DC bus of capacitors (Cbus in figure 8) and two additional neutral active controllers (one for each side). Each inverter output is connected to an LCL filter, before entering in electrical network, to improve the THD of the system. The inductance for each neutral controller also improves the THD of the system.

SOP control unit measures the current and voltage at different locations in the power unit thanks to the measurement card designed by HES-SO Yverdon. Then a control card, also designed by HES-SO Yverdon, receives these measures, calculates and sends the control signal to the inverters and the neutral controllers. The control card also manages the temperature of the power modules thanks to temperature measurement cards designed by HES-SO Yverdon and fans on inverters' heat sink.

Other features are part of the SOP to ensure the control unit power supply, safety, starting and ending process, temperature management and communication.

The overall principle of the SOP is illustrated in Figure 8.

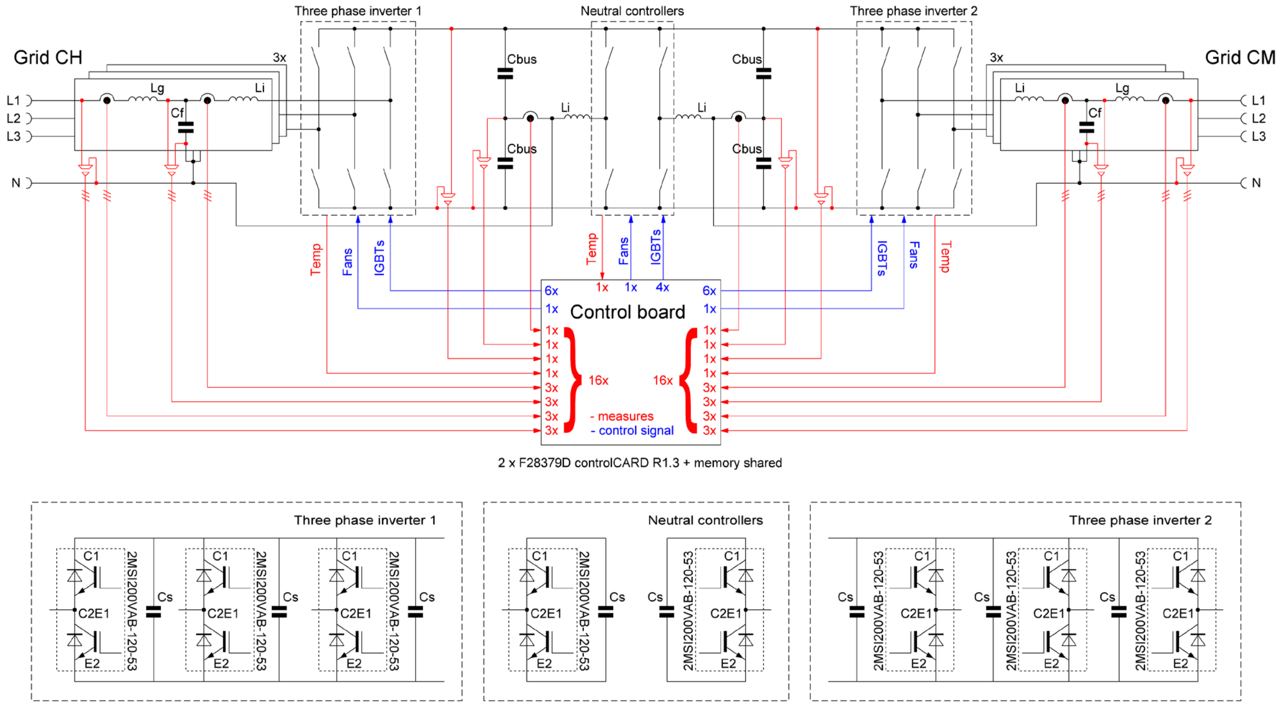


Figure 8: SOP principle schematic

1.4.3.1 Inverters design

1.4.3.1.1 Inverters sizing

One three phase inverter is realized thanks to 3 modules “2MSI200VAB-120-53” provided by Fuji Electric and composed of two IGBTs in series with freewheel diodes. Each module is connected in parallel with each other. The configuration is shown in Figure 8.

The SOP is designed to provide a nominal power of 50 kVA in the network. At this power, the current flowing through the module is 102.5 A peak. The DC bus voltage is 800 V. Taking a necessary safety margin, we decided to use these modules named “2MSI200VAB-120-53” with the characteristics summarized in table 2.

Module reference	Maximum voltage (V)	Maximum current (A)	Junction temperature (°C)
2MSI200VAB-120-53	1200	200	175

Table 2: “2MSI200VAB-120-53” power module characteristics

The two additional neutral active controllers are used to regulate the neutral conductor from both sides to the half of the DC bus voltage. The current in these controllers is approximatively the same as the one from the phase. This is why we decided to take the same power modules to regulate the neutral voltage of each side. Only one module is required for the regulation of the neutral.

The use of 1.5 µF polypropylene capacitor (Cs in figure 8) directly connected in parallel of each module is mandatory to reduce voltage spikes occurring during turn on and turn off of IGBTs.

1.4.3.1.2 Inverters thermal management

The results of the thermal study bring us to use a heat sink with fans. It has an equivalent thermal resistance of around 0.05 K/W for each inverter. The same heat sink is used for the two neutral controllers even if they dissipate approximately one third less of thermal energy to avoid the use of a different kind of heat sink.

A temperature monitoring of the power modules is performed by a temperature measurement card designed for this application. This card provides heat sink temperature between -20°C and 100°C. It allows to save energy by turning on fans only when it is necessary. Furthermore, control card is able to stop all the system if temperature becomes critical for power modules.

Figure 9 shows the temperature board.

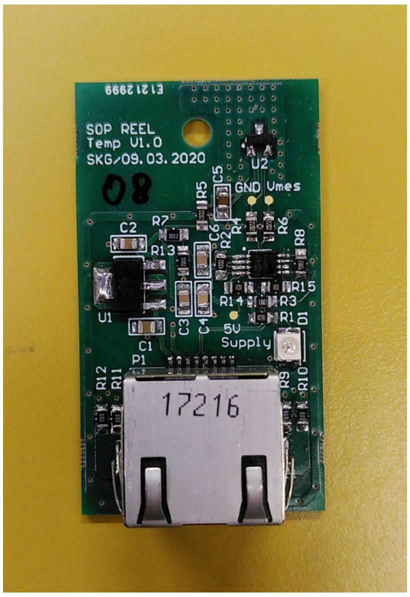


Figure 9: SOP temperature board

1.4.3.1.3 Power modules drivers

Each power module is directly controlled by a driver card designed for this application. This driver card turns on and off the IGBTs following control board instructions. It ensures the safety of the power module and provides the galvanic isolation to separate power unit from control unit.

Figure 10 illustrates one of the SOP 3-phase inverters with power modules, driver cards, DC-link polypropylene capacitors, temperature boards and heat sink.

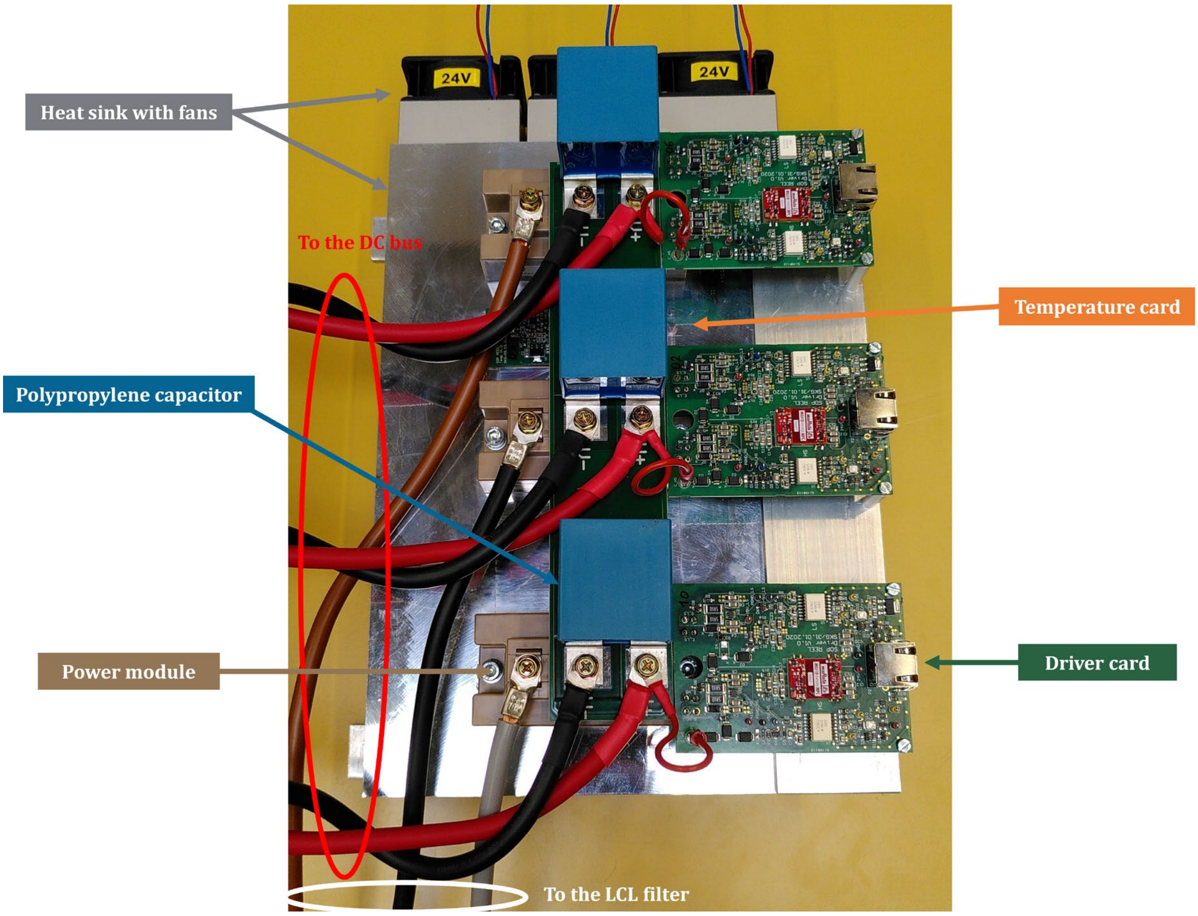


Figure 10: SOP 3-phase inverter

1.4.3.2 Filter design

The usefulness of LCL filters to connect a 3-phase 2-level inverter to the electrical network has been widely discussed and proved in the literature. The main issue of LCL filters is possible resonance phenomena. Accurate analysis of these phenomena have been realized. Simulations were made to validate them. Thanks to the chosen control strategy the results confirm that resonance does not exist in this application with the chosen filter values. The final values of the LCL filter are: Li = 330 µH, Cf = 47 µF and Lg = 150 µH.

1.4.3.3 DC bus design

The DC bus is constituted by parallel and series connections between electrolytic capacitors. Given that the system nominal voltage is U_DCbus = 800 V, the design consisted in choosing the right capacitors characteristics and connections to achieve the performance wanted. We chose to use "B43742A5478M000" from TDK. The capacitors have a rated voltage of 450 Vdc. This implies the connection in series of 2 groups of 3 parallel capacitors for each inverter. In the same time, it gives access to half of the DC bus voltage for neutral control.

Table 3 gives the characteristics of SOP electrolytic capacitors and global schematic of DC bus connection.

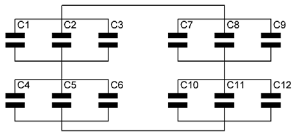
Capacitor reference	Rated voltage (V)	Capacitance (µF)	ESR 100 Hz 20 °C (mΩ)	DC bus connection schematic
B43742A5478M000	450	4700	20	

Table 3: SOP electrolytic capacitors characteristics

1.4.3.4 Control design

SOP follows a P/Q mode control strategy explained in 1.4.3.5.1.

This control is managed by a global control unit designed for this application. To improve the performance of the system and facilitate assembly process, we decided to "split" the global control unit into 4 different Printed Circuit Boards (PCBs):

- 1 x control card
- 16 x measurement cards (temperature and voltage/current)
- 8 x driver cards.

1.4.3.4.1 P/Q control mode principle

The additional features introduced in the 50kVA prototype with respect to the 15kVA can be found in [6]. It will be only shortly described here. As already presented (see section 1.4.1), SOP manager generates an active power P* and two reactive powers Q* references, one for each inverter. An SRF-PLL (Synchronous Rotating Frame – Phase Locked Loop) is used to synchronize each inverter with their own network. It allows the transformation calculation from abc to d-q rotating reference frame too. For power regulation in each inverter, the inner SOP controller generates current setpoints in the d-q rotating reference frame. These current references are compared with each inverter-side and grid-side measurements. Then PI regulators in d-q frame are used for calculation of PWM control signals. The last ones are the signals allowing the absorption or injection of active and reactive power from each inverter to their own network.

One inverter injects or absorbs reactive power from its network. It calculates the d-current in the rotating reference frame and shares it with the other inverter. This means they use the same active power reference value. Indeed, all active power is transmitted from a network to the other one through SOP.

The second inverter maintains the DC bus voltage to 800 V, injects or absorbs reactive power from its network and injects or absorbs the same active power value than the other one from its network.

In order to avoid DC-link unbalance problems due to AC grid unbalanced behaviour, a fourth leg with additional inductance connected to the medium point of the DC capacitors bank has been added to each inverter. Each additional neutral controller receives PWM signals calculated from one DSP. A special regulator is used to regulate each half of DC bus voltage. It includes a PI regulator on half of DC bus voltage and a modulated feedback of current entering in the DC bus middle point. These additional controllers improve the behaviour of the SOP during unbalanced grid conditions.

1.4.3.4.2 Control card

The control card is made of two Digital Signal Processors (DSP) F28379D. We made use of the control card R1.3 developed by Texas Instruments. Each DSP controls one inverter and one neutral controller, both connected to the same electrical network. Each DSP follows the same process. It receives measures from measurement cards. It communicates with the other DSP and with SOP manager to calculate the control signal to send to drivers and other features presented in 1.4.3.6. Communication between DSPs and between SOP manager and DSPs is realized thanks to an external shared memory.

Figure 11 illustrates the SOP control card.

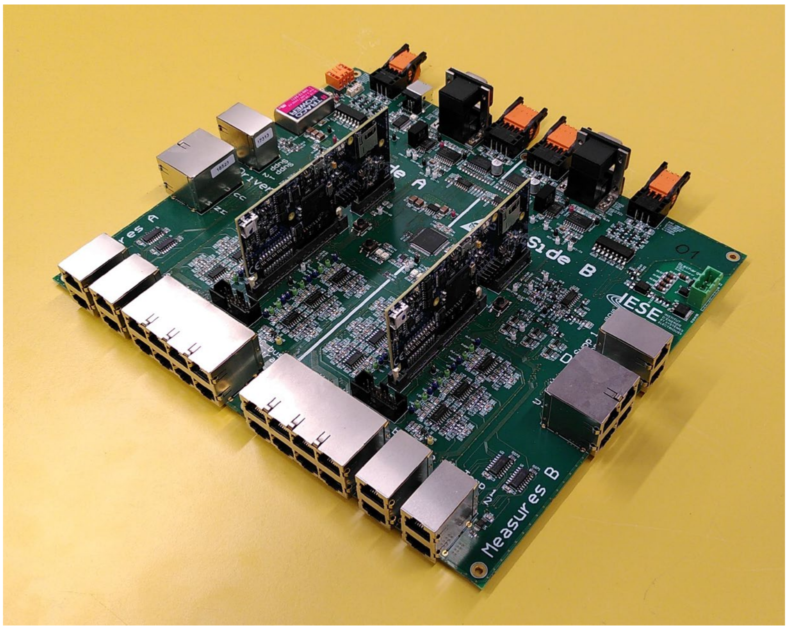


Figure 11: SOP control card

1.4.3.4.3 Measurement cards

Two different measurement cards are used for SOP:

- Measurement cards for voltage and current measurement;
- Measurement cards for temperature measurement;

Temperature cards are presented in 1.4.3.2.2.

For voltage and current measurement, each card provides one voltage and one current. The current is measured thanks to Hall effect sensors provided by LEM, while the voltage is measured with cables plugged in the P1 green connector (see Figure 12). The two signals are modulated and sent via RJ45 connection to the control card in a differential way. We used twisted pair shielded cables to reduce disturbances. Control card adjusts the signals received before entering the ADCs of the DSP.

Figure 12 illustrates SOP voltage/current measurement cards.

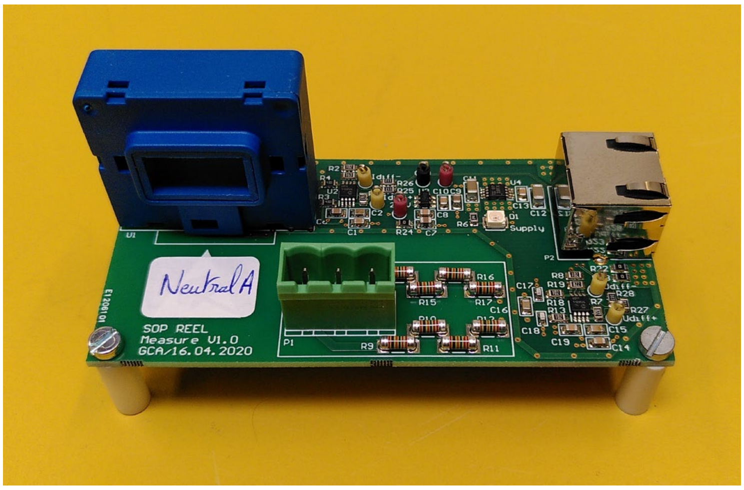


Figure 12: SOP voltage/current measurement card

1.4.3.5 Ancillary devices

SOP system needs additional features to function properly.

All the control unit requires a 24 Vdc power supply to work. This additional power supply is connected to one of the electrical networks.

To start SOP, a circuit for DC bus preload was added. It is composed of a 150 Ω resistor able to dissipate enough energy and one three-phase diode rectifier connected on each electrical network. It sets the loading time around 10 seconds. The discharge of the DC bus when SOP is stopped uses the same resistor to short-circuit the DC bus. It means a discharge time of approximatively 10 seconds too.

In addition, physical components like lights and emergency stop button are used to allow the user to physically stop the system if needed.

2 Achievement of deliverable:

2.1 Date

31.8.2020: SOP assembly in progress

1.12.2020 (planned): deployment to site

2.2 Demonstration of the deliverable

A 50 kW SOP has been designed, assembled and is being prepared for deployment in Chapelle-sur-Moudon. In addition, a control and protection scheme is in place within the two impacted LV networks. The system can operate in stand-alone mode or by interfacing the GridEye monitoring system.

3 Impact

Building and demonstrating the SOP technology has been a central activity of subtask 3.3 "Enabling component and converter technologies and applications". This activity has been planned from the beginning to be linked to the REEL demonstration project. As this project has undergone several re-orientations, delivering the SOP has been more challenging and required more effort than initially budgeted: network planning, protection and communication have been delivered additionally to the initial schedule.

Preparing the hardware design of the SOP has led to exploratory discussions with man-ufacturers: Nidec, OCEM and HES. At this point, none of these approaches has immedi-ately materialized into new projects, but this might happen at a later stage. The SOP la-boratory prototype is integrated into the ReInE laboratory at HES-SO Yverdon and will remain a permanent asset. The protection and communication part of the project has led to a new partnership between SEL and HES-SO Fribourg. Several tools and devices will remain in the power system laboratory of HES-SO Fribourg on a permanent basis.

References

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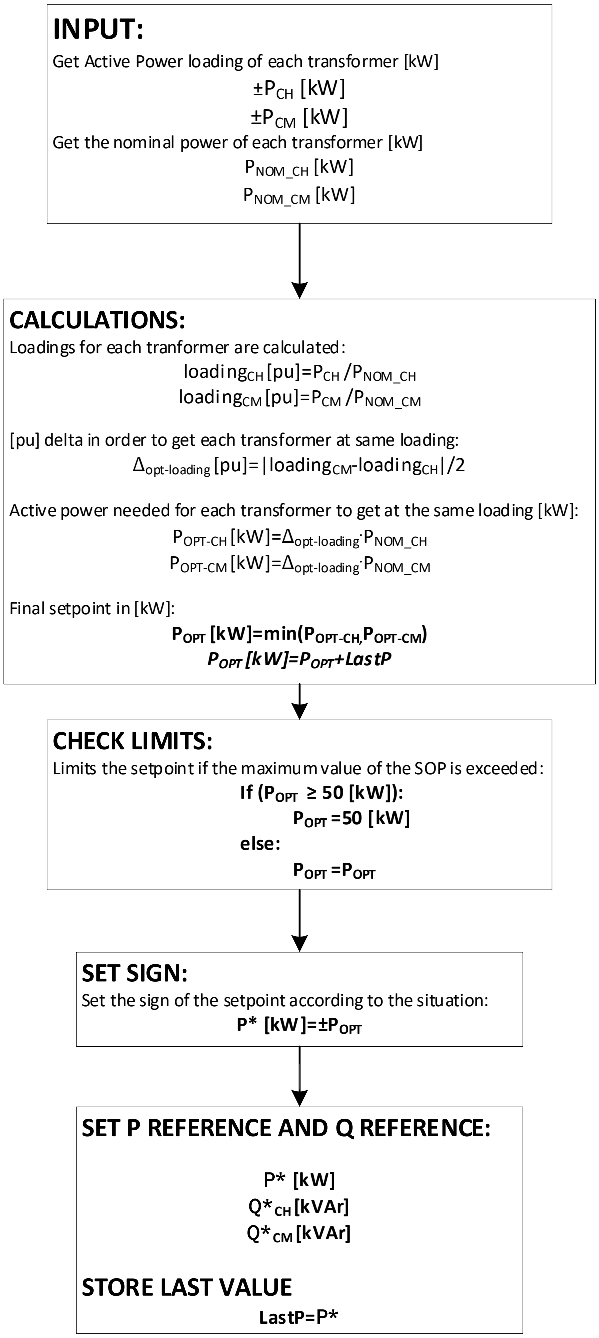
4 Appendix

4.1 Description of TRABA grid control mode



4.2 Description of VSTB grid control mode

INPUT:

Get voltages (each side of SOP and each transformer) [pu]

u_{LEFT}, u_{RIGHT}, u_{TR1}, u_{TR2}

Get Active Power loading of each transformer [kW]

$\pm P_{CH}$ [kW]

$\pm P_{CM}$ [kW]

Get the nominal power of each transformer [kW]

P_{NOM_CH} [kW]

P_{NOM_CM} [kW]

↓

CALCULATIONS:

Calculations for P settings

Loadings for each tranformer are calculated:

$loading_{CH}$ [pu]$=P_{CH}/P_{NOM\_CH}$

$loading_{CM}$ [pu]$=P_{CM}/P_{NOM\_CM}$

[pu] delta in order to get each transformer at same loading:

$\Delta_{opt\text{-}loading}$ [pu]$=|loading_{CM}-loading_{CH}|/2$

Active power needed for each transformer to get at the same loading [kW]:

$P_{OPT\text{-}CH}$ [kW]$=\Delta_{opt\text{-}loading}\cdot P_{NOM\_CH}$

$P_{OPT\text{-}CM}$ [kW]$=\Delta_{opt\text{-}loading}\cdot P_{NOM\_CM}$

Final setpoint in [kW]:

$\boldsymbol{P_{OPT}}$ **[kW]**$\boldsymbol{=min(P_{OPT\text{-}CH},P_{OPT\text{-}CM})}$

$\boldsymbol{P_{OPT}}$ **[kW]**$\boldsymbol{=P_{OPT}+LastP}$

Calculations for Q settings

Compute mean between U_{TR} and U_{SOP} for each side (CH and CM):

$m_{CM}=mean(U_{TR2},U_{sop\text{-}right})$

$m_{CH}=mean(U_{TR1},U_{sop\text{-}left})$

Compute delta between the mean values of each side (CH and CM) and 1pu:

$\Delta_{CM\text{-}Q}=1-m_{CM}$

$\Delta_{CH\text{-}Q}=1-m_{CH}$

Calculate setpoint for Reactive Power [kVAR]:

$\boldsymbol{Q^*_{OPT\text{-}CH}}$ **[kVAr]**$\boldsymbol{=\Delta_{CH\text{-}Q}\cdot kp_q}$

$\boldsymbol{Q^*_{OPT\text{-}CM}}$ **[kVAr]**$\boldsymbol{=\Delta_{CM\text{-}Q}\cdot kp_q}$

$\boldsymbol{Q^*_{OPT\text{-}CH} = LastQ_{\text{-}CH} + Q^*_{OPT\text{-}CH}}$

$\boldsymbol{Q^*_{OPT\text{-}CM} = LastQ_{\text{-}CM} + Q^*_{OPT\text{-}CM}}$

↓

CHECK LIMITS:

Compute equivalent power @CM's side:

If ($P_{OPT}>0$):

P_{OPT_CM} [kW]$=P_{OPT}/eff$

else:

P_{OPT_CM} [kW]$=P_{OPT}\cdot eff$

Get sign of Qch and Qcm (used later):

$sign(Q_{CH}) \rightarrow >0$: $q_{sign\text{-}CH}=1$

<0: $q_{sign\text{-}CH}=-1$

$sign(Q_{CM}) \rightarrow >0$: $q_{sign\text{-}CM}=1$

<0: $q_{sign\text{-}CM}=-1$

Compute apparent power for each side of SOP:

$S_{TOT\text{-}CH}=\sqrt{(P^*_{OPT})^2+(Q_{CH})^2}$

$S_{TOT\text{-}CM}=\sqrt{(P^*_{OPT\_CM})^2+(Q_{CM})^2}$

Check case:

1) $(S_{CH}\&S_{CM})>S_{MAX}$

2) $(S_{CH}>S_{MAX})\&(S_{CM}<=S_{MAX})$

3) $(S_{CH}<=S_{MAX})\&(S_{CM}>S_{MAX})$

4) $(S_{CH}\&S_{CM})<=S_{MAX}$

↓

SET SIGN:

Set the sign of the setpoint according to the situation:

$\boldsymbol{P^*}$ **[kW]**$\boldsymbol{=\pm P_{OPT}}$

Controls for <u>each</u> side (CM and CH) if SOP need to inject or consume Reactive Power:

If $(\Delta_{X\text{-}Q}>0)$:

Q^*_X [kVAr]$=-Q^*_{lim\text{-}x}$

else$(\Delta_{X\text{-}Q}<0)$:

Q^*_X [kVAr]$=+Q^*_{lim\text{-}x}$

↓

SET P REFERENCE AND Q REFERENCE:

P* [kW]

$\boldsymbol{Q^*_{CH}}$ **[kVAr]**

$\boldsymbol{Q^*_{CM}}$ **[kVAr]**

STORE LAST VALUE

LastP = P*

$\boldsymbol{LastQ_{\text{-}CH}=Q^*_{CH}}$

$\boldsymbol{LastQ_{\text{-}CM}=Q^*_{CM}}$

4.3 Description of VOLTSAME grid control mode

INPUT:

Get voltages at each side of SOP [pu]

u_{LEFT}

u_{RIGHT}

Get voltages at each transformer [pu]

u_{TR1}

u_{TR2}

CALCULATIONS:

Calculations for P settings

Calculate delta between U_{TR} and U_{SOP} for each side [pu] (CH and CM):

$$\Delta_{CM\text{-}P}=U_{TR2}\text{-}U_{sop\text{-}right}$$
$$\Delta_{CH\text{-}P}=U_{TR1}\text{-}U_{sop\text{-}left}$$

Calculate setpoint for Active Power [kW]:

$$\boldsymbol{P^*_{OPT} = (|\Delta_{CH\text{-}P}\text{-}\Delta_{CM\text{-}P}|/2)\cdot kp_P}$$
$$\boldsymbol{P^*_{OPT} = LastP + P^*_{OPT}}$$

Calculations for Q settings

Compute mean between U_{TR} and U_{SOP} for each side (CH and CM):

$$m_{CM}=\text{mean}(U_{TR2},U_{sop\text{-}right})$$
$$m_{CH}=\text{mean}(U_{TR1},U_{sop\text{-}left})$$

Compute delta between the mean values of each side (CH and CM) and 1pu:

$$\Delta_{CM\text{-}Q}=1\text{-}m_{CM}$$
$$\Delta_{CH\text{-}Q}=1\text{-}m_{CH}$$

Calculate setpoint for Reactive Power [kVAR]:

$$\boldsymbol{Q^*_{OPT\text{-}CH}\,[kW]=\Delta_{CH\text{-}Q}\cdot kp_q}$$
$$\boldsymbol{Q^*_{OPT\text{-}CM}\,[kW]=\Delta_{CM\text{-}Q}\cdot kp_q}$$
$$\boldsymbol{Q^*_{OPT\text{-}CH} = LastQ_{\text{-}CH} + Q^*_{OPT\text{-}CH}}$$
$$\boldsymbol{Q^*_{OPT\text{-}CM} = LastQ_{\text{-}CM} + Q^*_{OPT\text{-}CM}}$$

CHECK LIMITS:

Compute equivalent power @CM's side:

If ($P_{OPT} > 0$):

P_{OPT_CM} [kW]=P_{OPT} / eff

else:

P_{OPT_CM} [kW]=$P_{OPT}\cdot$ eff

Get sign of Qch and Qcm (used later):

sign(Q_{CH})→>0: $q_{sign\text{-}CH} = 1$

<0: $q_{sign\text{-}CH} = -1$

sign(Q_{CM})→>0: $q_{sign\text{-}CM} = 1$

<0: $q_{sign\text{-}CM} = -1$

Compute apparent power for each side of SOP:

$$S_{TOT\text{-}CH}=\sqrt{(P^*_{OPT})^2 + (Q_{CH})^2}$$
$$S_{TOT\text{-}CM}=\sqrt{(P^*_{OPT\_CM})^2 + (Q_{CM})^2}$$

Check case:

1) $(S_{CH}\&S_{CM})>S_{MAX}$

2) $(S_{CH}>S_{MAX})\&(S_{CM}<=S_{MAX})$

3) $(S_{CH}<=S_{MAX})\&(S_{CM}>S_{MAX})$

4) $(S_{CH}\&S_{CM})<=S_{MAX}$

SET SIGN:

Controls in which direction the Active Power flow should go

If ($\Delta_{CH\text{-}P} > \Delta_{CM\text{-}P}$):

P^* [kW]= $+P^*_{MIN}$

elif($\Delta_{CH\text{-}P} < \Delta_{CM\text{-}P}$):

P^* [kW]= $-P^*_{MIN}$

Controls for <u>each</u> side (CM and CH) if SOP need to inject or consume Reactive Power:

If ($\Delta_{X\text{-}Q}$>0):

Q^*_X [kVAr]= $-Q^*_{lim\text{-}x}$

else($\Delta_{X\text{-}Q}$<0):

Q^*_X [kVAr]= $+Q^*_{lim\text{-}x}$

SET P REFERENCE AND Q REFERENCE:

P^* [kW]

Q^*_{CH} [kVAr]

Q^*_{CM} [kVAr]

STORE LAST VALUE

LastP = P^*

LastQ$_{\text{-}CH}$ = Q^*_{CH}

LastQ$_{\text{-}CM}$ = Q^*_{CM}

4.4 Performance evaluation

This description of the performance metric is copied from REEL deliverable " Field test verification " which is still in preparation whilst the present deliverable is already released to FURIES for organizational reasons.

In order to give a unique score for each grid topology and for each management system when using the SOP, we combine the effect of four indexes:

1. Voltage index:

$$index_{\Delta u} = \frac{1}{n}\sum_{i=1}^{N}\left(\frac{\max_{k}\{u_{i,k}\} - \min_{k}\{u_{i,k}\}}{d_{\{max\}}}\right)^2$$

Where:

$\boldsymbol{N}$	Total number of load buses
$\max_{i}\{\boldsymbol{u}_{k,i}\}$ $\min_{i}\{\boldsymbol{u}_{k,i}\}$	Represent respectively the maximum and minimum voltage magnitudes for each “i” node among the “k” scenarios
$\boldsymbol{d}_{\{max\}}$	The maximum voltage magnitude deviation margin (according to DACHCZ guidelines, it corresponds to 6% at low voltage [11])

This index takes into account the maximum deviation of the voltage magnitude for each bus connected to a load among all scenarios.

2. Current index:

$$index_{\Delta i_{\{cable\}}} = \frac{1}{M}\sum_{j=1}^{M}\Delta i_{\{cable\},j} \;;\; \Delta i_{\{cable\},j} = \begin{cases} \dfrac{\max_{k}\{I_{(m,j),k}\}}{\dfrac{I_{n,j}}{2}}, & \dfrac{\max_{k}\{I_{(m,j),k}\}}{I_{n,j}} \geq 0.5 \\ 0 \quad , & \dfrac{I_{m,j}}{I_{n,j}} < 0.5 \end{cases}$$

Where:

$\boldsymbol{M}$	Total number of line connections
$\max_{k}\{\boldsymbol{I}_{(m,j),k}\}$	The maximum value of the measured current “m” for line “j” among the “k” scenarios
$\boldsymbol{I}_{n,j}$	The nominal current “n” for line “j”

For this index, we choose to penalize lines that are loaded more than 50% and to remove the contribution of those lower than that threshold. The current index gives an approach to translate the maximum loading of different lines in the network.

3. Maximum transformer loading:

$$index_{i_{TR\{max\}}} = \max_{i,k}\{i_{TR_{i,k}}\}$$

Where:

$\boldsymbol{i}_{TR_{i,k}}$	Loading in [p.u] of transformer “i” during scenario “k”

This index returns the value of a current in [p.u] for the transformer with the highest loading among all scenarios.

4. Losses index:

$$index_{losses} = \frac{1}{K}\sum_{k=1}^{K}\left(\gamma_k * \frac{P_{loss,tot,k}}{P_{load,tot,k}}\right)$$

Where:

$\boldsymbol{K}$	Total number of scenarios
$\boldsymbol{P_{loss,tot,k}}$	Total grid losses in [kW] for scenario “k”
$\boldsymbol{P_{load,tot,k}}$	Total load in [kW] for scenario “k”
$\boldsymbol{\gamma_k}$	Weighting factor for each scenario “k”, where $\sum_k \gamma_k = 1$

The losses index is in [p.u] and it computes the mean value of total losses among all scenarios. In this simulation studies, we assumed that total losses in each scenario include cables, transformers and converter losses (if SOP is connected) and the total load divides them in order to have losses in [p.u].

After collecting all indexes mentioned above, we can compute the score of each case study by using the following equation:

$$score = \sum_{j=1}^{J}(\alpha_j * idx_j)$$

Where:

$\boldsymbol{J}$	Total number of involved indexes
$\boldsymbol{idx_j}$	The normalized index
$\boldsymbol{\alpha_j}$	Weighting factor for each index “j”, where $\sum_j \alpha_j = 1$

The score value ranges between zero and one because indexes are normalised before the score computation. The best score is the lowest one because an index with a high value means that the electrical grid is approaching its limits by indicating for example a high deviation in voltage magnitudes or a high loading of cables and transformers or as well a lot of losses, depending on the computed index.

In order to compare the score between different study cases, we normalise each category of indexes by following these steps:

- We classify in a descending order the corresponding index among all case studies
- We compute the maximum deviation, i.e. the difference between the first and last index
- We compute the normalised index by using this equation:

$$idx = 1 - \left(\frac{index_{max} - index_{initial}}{\Delta max}\right)$$

Where:

$\boldsymbol{index_{max}}$	Index with the highest value (classified in the first position)
$\boldsymbol{index_{initial}}$	Initial value of the index
$\Delta\boldsymbol{max}$	The maximum deviation, i.e. the difference between the first and last index