Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

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: 6b Laboratory test of Soft Open Point Prototype

Demo site: Chapelle

Developed by

Mauro Carpita, Sébastien Wasterlain, Thomas Pidancier, HES-SO VD, Yverdon

Patrick Favre-Perrod, Chloé Dour, Mohamed Allani, Loïc Eggenschwiler, HES-SO FR, Fribourg

Dominique Roggo, Didier Blatter, HES-SO Valais-Wallis, Sion

in collaboration with

Romande Energie SA, Morges

[Fribourg/Yverdon, 27.06.2019]

Table of contents

1 Description of deliverable and goal

1.1 Executive summary

The soft-open point is a conceptual device introduced in the first deliverable of this activity "REEL Project – WP6, Preliminary study for soft-open point deployment into REEL Demonstrator" [1]. A reduced-scale prototype device has been designed and assembled in order to test different control modes under laboratory conditions. The prototype was briefly presented in the second deliverable "REEL Project – WP6, Design principle of Soft-Open Point".

The objective of this report is to show the design of the SOP prototype and its test within the GridLab laboratory in the HES-SO Valais in Sion. Some of these results were presented in [2].

1.2 Research question

The objective of the activity covered by the work in this report is to answer the following question:

- How does a reduced-scale SOP improve the voltage profile in a distribution system laboratory emulation?

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

A state-of-the-art in term of possible SOP structure was presented in [3]. Realizations with some common functionalities like different kind of FACTS ([4], [5], [6], [7]) and other work on SOP systems ([8], [9]) were acknowledged.

1.4 Comparison with other demonstrator activities

The SOP developed in this activity take an approach different and complementary to other approaches: the first prototype presented here is a reduced scale LV prototype rated for 15 kVA.

It was used to test different situations and scenarios as compared to a direct deployment into a real system where the topology cannot be changed and faults cannot be freely introduced into the system.

The building of a second prototype in LV will also be studied in this activity. Indeed, the MV prototype was abandoned due to the lack of space in the foreseen station and because the estimated price that was too high. The decision was made between all collaborators of this project to capitalize on the experience earned with the development of the first prototype and build a new one, to go up to 50 kVA and add the possibility to control the neutral point.

2 Introduction to the SOP

The soft-open point (SOP) is a power electronic device described in the previous deliverables [1] and [3]. Some elements will be repeated here for the sake of clarity. The SOP main purpose is to permit a meshed (or looped) operation of radially operated distribution networks, i.e. open loops. As shown in Figure 1, the chosen normally closed variant of the SOP represents a way to decouple load flows and fault currents:

- SOP is closed in normal conditions, thus establishing a meshed/loop network topology for load flows
- SOP opens (faster than mechanical breakers that remain in the distribution system) in fault conditions, thus establishing a radial network topology for fault currents.

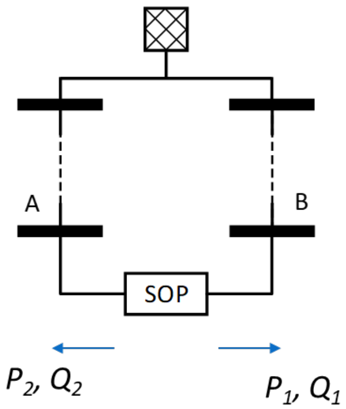


Figure 1. Illustration of the SOP inserted into a MV network

3 LV Soft-open point 15 kVA prototype

3.1 Design

The design principles of this prototype were presented in [3].

Here is a reminder of its features:

- 2-level VSCs (based on the PENELER converter presented in [10])
- 15 kVA
- 230/400 V
- LCL filters
- Possibility to add a battery storage via a custom made DC/DC converter
- CAN and SCI communication protocol available

The two back-to-back inverter are shown in the electrical cabinet in the Figure 2. The volume of the prototype was not optimized, in order to facilitate the accessibility of the various components.

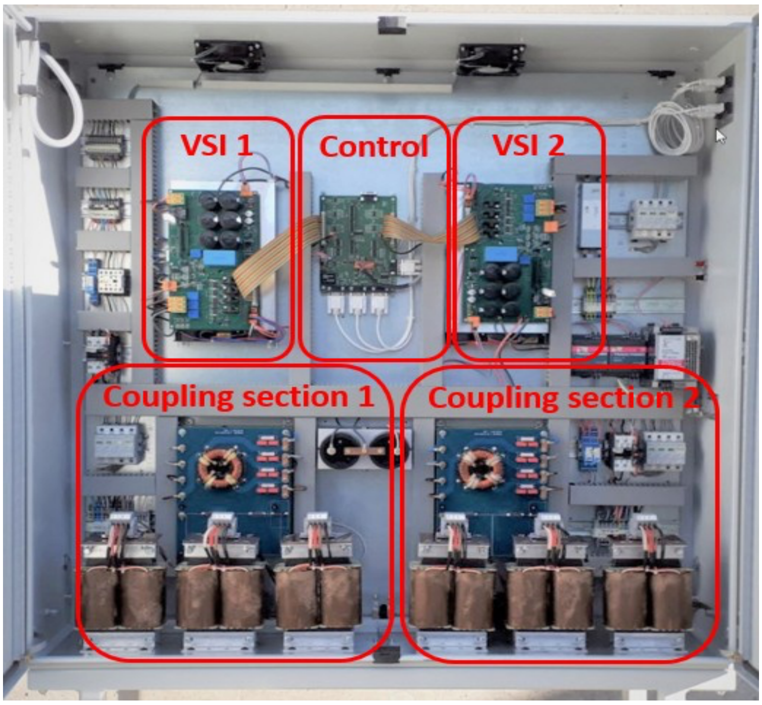


Figure 2. 15 kVA SOP prototype

In the Figure 3 we see the principle schematic and in the Figure 4 a summary of all the components used in the system and their physical and communication links between each other.

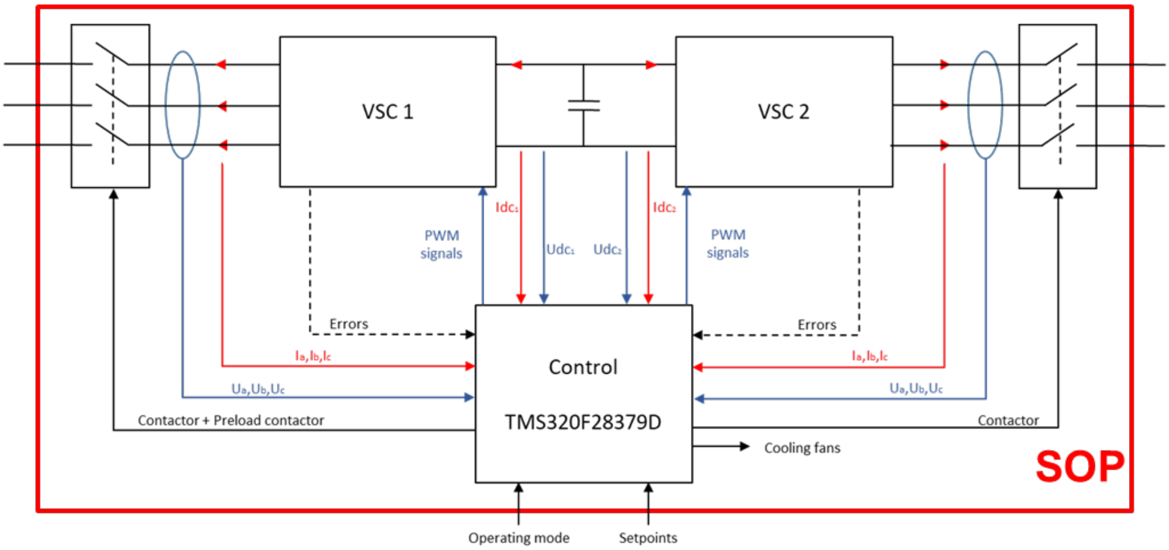


Figure 3. Control and measurements design

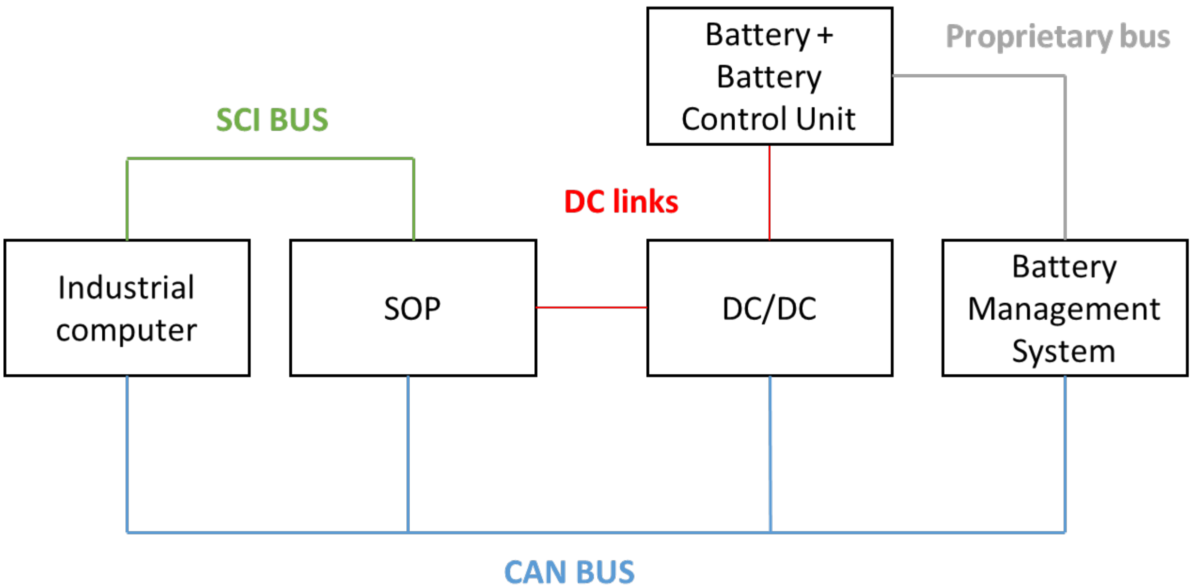


Figure 4. Links between the different components and communication architecture

It can be noted that the battery could be replaced by another DC source, such as PV production, a DC bus connecting different devices…

3.2 Control strategy

For these tests, the PQ control mode presented in [3] was implemented.

The VSC_1 controls the voltage on the DC bus at 700V with a PI controller (Figure 5) and the VSC_2 controls its active power (Figure 6). Both VSCs control their reactive power (Figure 7).

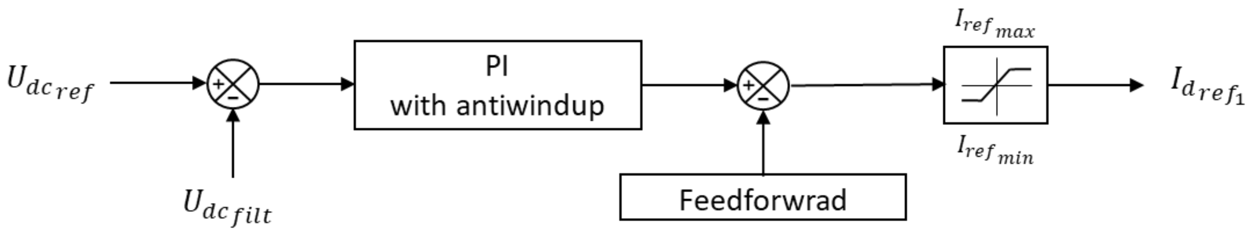


Figure 5. DC bus voltage control (for VSC1)

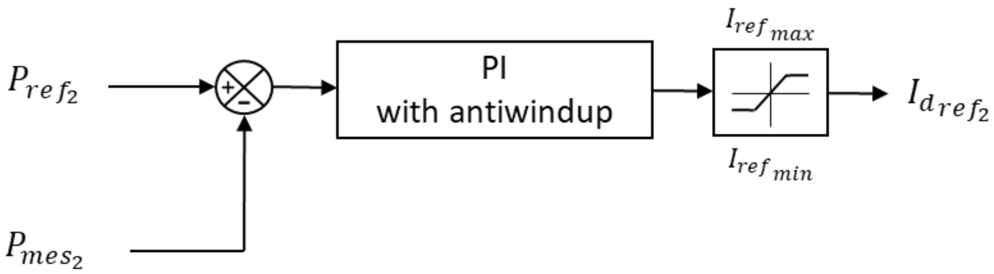


Figure 6. Active power control (for VSC2)

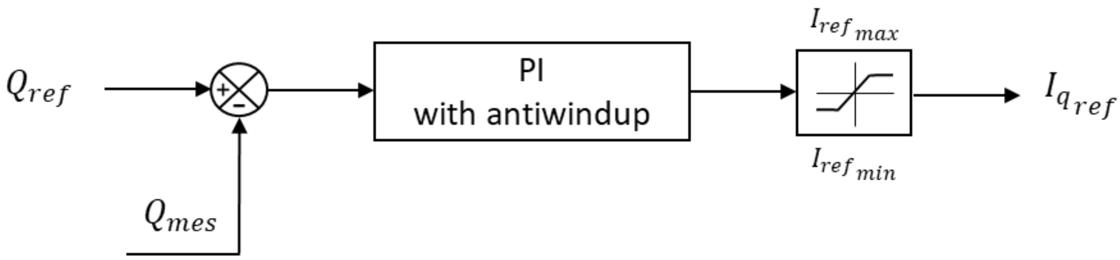


Figure 7. Reactive power control (identical for both VSCs)

Both VSCs have current control in the *dq* frame and we use a Space Vector Modulation (SVM) strategy that enables us to raise the output voltage of the converter by 15.5% but with the disadvantage of creating zero-sequence components if the converters share a common DC bus (which is obviously the case here). To avoid the problem of circulating zero-sequence currents we use an isolation delta/star transformer, placed between the VSC_2 of the SOP and its connection point.

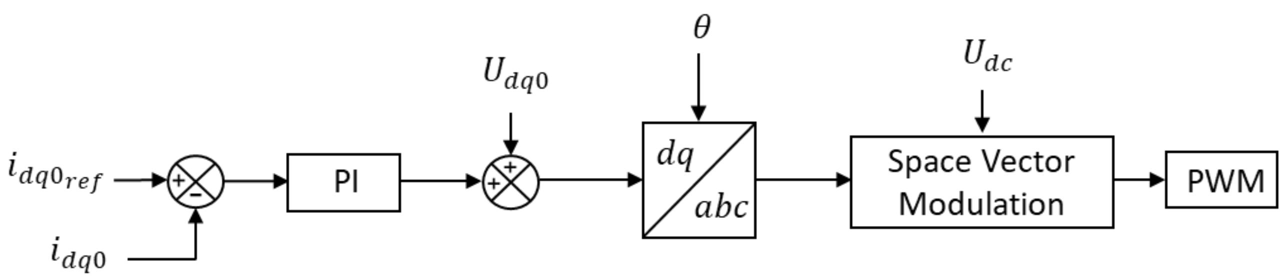


Figure 8. Current control in dq frame and SVM

4 Laboratory tests of the prototype

4.1 Introduction

4.1.1 Objectives

The goal of these tests were to demonstrate the capacity of the SOP to transfer active power between two feeders and to make inductive or capacitive reactive power independently, in order to respect the constraints of the network.

4.1.2 Test laboratory

The test were realized with the GridLab platform of the HES-SO Valais in Sion.

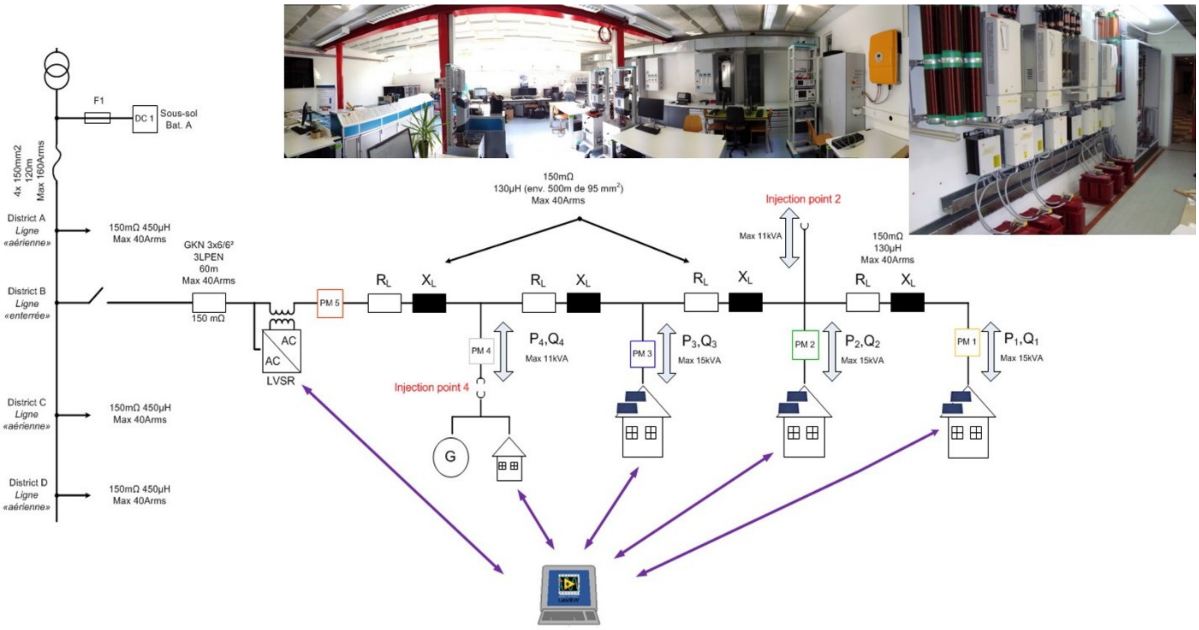


Figure 9. GridLab district, structure of a feeder 3x400V/40A

The GridLab "District" is made of 4 distribution LV feeders each rated 40A. Some emulated prosumers are connected to these feeders as we can see in the Figure 9. Each section between the prosumers are made of RL circuits reproducing the characteristics of the lines or cables (R_L and X_L on the figure).

The prosumers are made out of 3-phase bidirectional converters (ABB ACS 800-U) and their active and reactive power (max 15 kVA) can be programmed remotely with pre-established load profile.

In order to test other equipment two access points with 3x16 A protections are available on each feeder (PM2 and PM4 on the figure).

The network is connected to the school grid at its transformer input, thus the voltage level varies during the day, following the city-network voltage level.

	Resistance [m**Ω**]	**Impedance** [m**Ω**]
Line (each part of 500m)	150	141.4
Upstream cable	185	4.8

Table 1. Characteristics of the GridLab network

For these tests, only two feeders were used and connected to the SOP, as seen in the Figure 10. Different scenarios of consumption and injection were imposed to the prosumers.

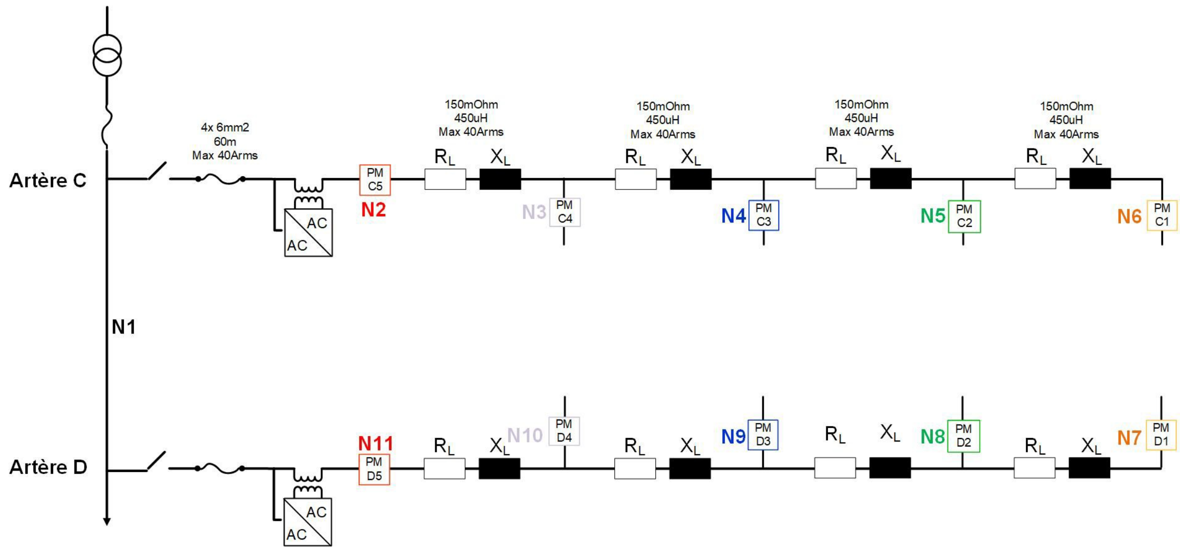


Figure 10. Scheme of the used network

4.2 Test scenarios

In the network shown Figure 10 the access points available are C2, C4, D2 and D4. We tested the 4 different combinations with various amount of production and injection. In the Figure 11 we can see the configuration C4D2 with the isolation transformer between the feeder D and the SOP.

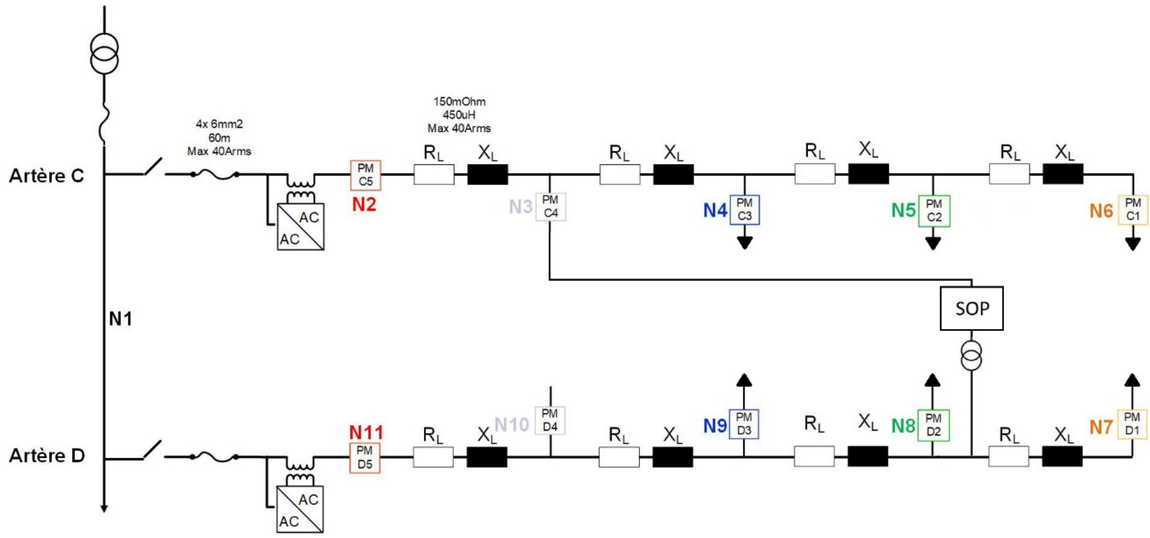


Figure 11. C4D2 configuration

Two families of case study were used, they are presented in Table 2 and Table 3.

Network situation 1: consumption on feeder C and production on feeder D			
	Case 1: the SOP transmit active power between the two feeders	Case 2: the SOP produce or absorb reactive power	Case 3: the SOP produce or absorb reactive power and transmit active power
Without SOP	I.0		
C2D2	I.1.1	I.2.1(a-b-c)	I.3.1
C4D4	I.1.2	I.2.2 (a-b-c)	I.3.2
C4D2	I.1.3	I.2.3 (a-b-c)	I.3.3
C2D4	I.1.4	I.2.4 (a-b-c)	I.3.4

Table 2. All studied cases with production and consumption

Network situation 2: consumption on both feeders			
	Case 1: the SOP produces reactive power (capacitive) on both sides	Case 2: the SOP transmit active power to balance the load	Case 3: the SOP produces reactive power and transmit active power
Without SOP	II.1.0	II.2.0	
C2D2	II.1.1	II.2.1	II.2.2

Table 3. All studied cases with only consumption

All these scenarios were first simulated with PowerFactory and the tests were realized with the SOP prototype in the GridLab.

4.3 Test configuration

As said in the paragraph 3.2 above, the VSC_1 controls the DC bus voltage at 700V. This means that we can only give an active power reference to the VSC_2, connected at the feeder D, and the active power consumed or injected at the feeder C results of this reference with the addition of the losses.

In order to be sure of the quality of the measures and to take into account the external perturbations on the voltage level, each test was realized during a period of 6 minutes, the first half without the SOP and the second with the SOP.

The setpoints for reactive power for the prosumers is at 0 but in reality there's a small reactive power measured for each load (a few hundreds of Var). Furthermore the converters have a power limitation when the voltage level at their point of common coupling is outside its nominal range (at around +-11% of the nominal voltage of 230V).

We have the following measurement devices associated with the measurements:

- A *Siemens SICAM P* at each point PM (see Figure 10) with a sampling time of 20s and without synchronization
    - RMS voltage
    - RMS current
    - Active power
    - Reactive power
- A *PEL103 Power-energy Logger* at both connection points of the SOP with a sampling time of 1s
    - 3 RMS voltages
    - 3 RMS currents
    - Active power
    - Reactive power
    - 3 voltage THD
    - 3 current THD

4.4 Results

All the results are available in excel files and only some of the most interesting cases are presented here.

For all the presented results in per-unit, the bases values are:

- I_{base} = 40 A

- V_{base} = 230 V

4.4.1 First scenario (I.1.1)

In this first scenario (parameters shown in Table 4), there is only consumption on the feeder C provoking a voltage drop and production on the feeder D which causes the voltage to go above the limit (but close enough so the converter at point D1 won't limit its power injection). We use the SOP to transmit active power between both sides to limit the voltage deviation.

Situation	SOP injection setpoints			Load on feeder C			Load on feeder D		
	P (on D side)	Q (on C side)	Q (on D side)	C3	C2	C1	D3	D2	D1
without SOP	0	0	0	5	5	10	-5	-5	-10
with SOP	-10	0	0	5	5	10	-5	-5	-10

Table 4. Setpoints for the first scenario (all power in kW and KVAR)

We can see in the Figure 12 that the SOP helps to maintain the voltage level within reasonable limits.

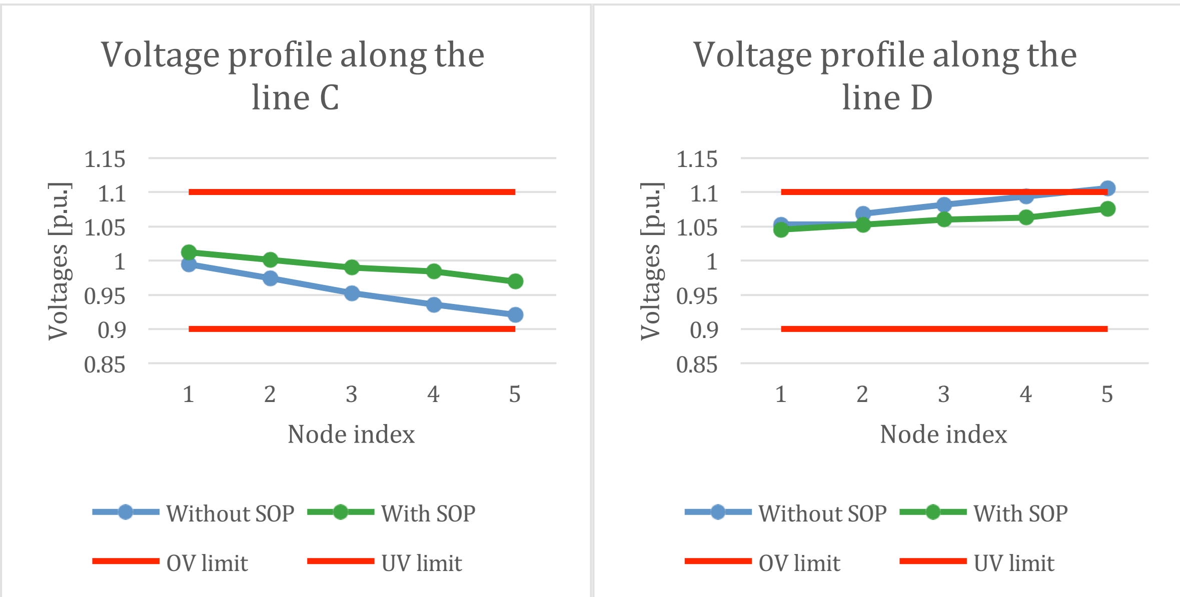


Figure 12. Voltages (in p.u.) on feeder C (left) and feeder D (right) for the first scenario

We can also notice in the Table 5 that the current on both feeders is reduced by the action of the SOP.

	Current at beginning of feeder C	Current at beginning of feeder D
Without SOP	0.81	0.60
With SOP	0.43	0.34

Table 5. Currents (in p.u.) at the beginning of the feeders for the first scenario

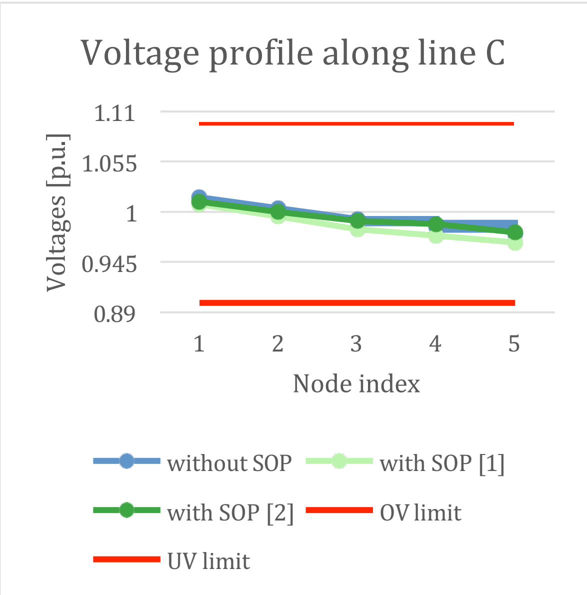
4.4.2 Second scenario (II.2.1 and II.2.2)

For the second scenario (parameters shown in Table 6) both feeders have only consumption but the feeder D is more loaded than the feeder C. We use the SOP to balance the loads on both lines (case with SOP [1]) and to raise the voltage level by injecting reactive power (case with SOP [2]).

Situation	SOP injection setpoints			Load on feeder C			Load on feeder D		
	P (on D side)	Q (on C side)	Q (on D side)	C3	C2	C1	D3	D2	D1
without SOP				5	2	5	5	5	10
with SOP [1]	4	0	0	5	2	5	5	5	10
with SOP [2]	4	9	9	5	2	5	5	5	10

Table 6. Setpoints for the second scenario (all power in kW and KVAR)

The Figure 13 shows that balancing the loads between both lines increase the voltage level on the feeder D while decreasing it on the C. Since the upstream cable is much more resistive than inductive (see Table 1) the effect of the reactive power is not as strong as it would be on a MV grid.



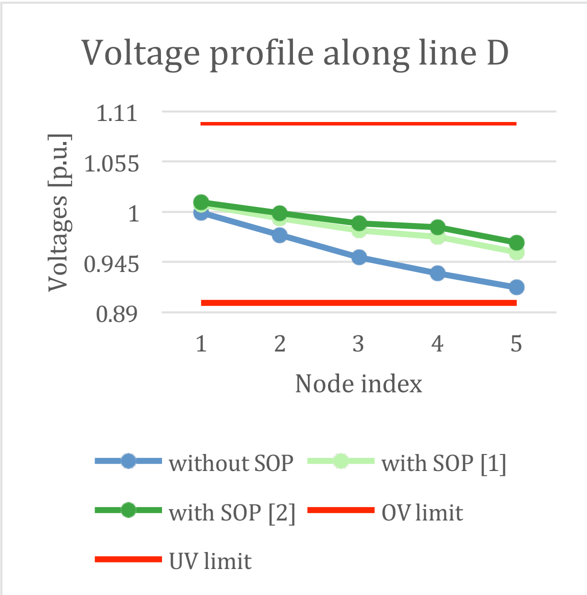


Figure 13. Voltages (in p.u.) on feeder C (left) and feeder D (right) for the second scenario

	Current at beginning of feeder C	Current at beginning of feeder D
Without SOP	0.46	0.79
With SOP [1]	0.69	0.67
With SOP [2]	0.73	0.70

Table 7. Currents (in p.u.) at the beginning of the feeders for the second scenario

4.4.3 Power source voltage limitation

The input voltage of the laboratory grid being uncontrolled some of the tests resulted in unpredicted overvoltages (roughly +11% of the nominal value) which resulted in a limitation of the power injected by the "prosumers".

In some cases the action of the SOP can't be seen only on the voltage level but also on the power injection level. In the Figure 14 we see that without the SOP the voltage at the last point of the feeder (D1) is above the +10% limit and the power injected is limited below 8 kW. The SOP helps to reduce the voltage and thus the converter at point D1 can inject up to 10 kW.

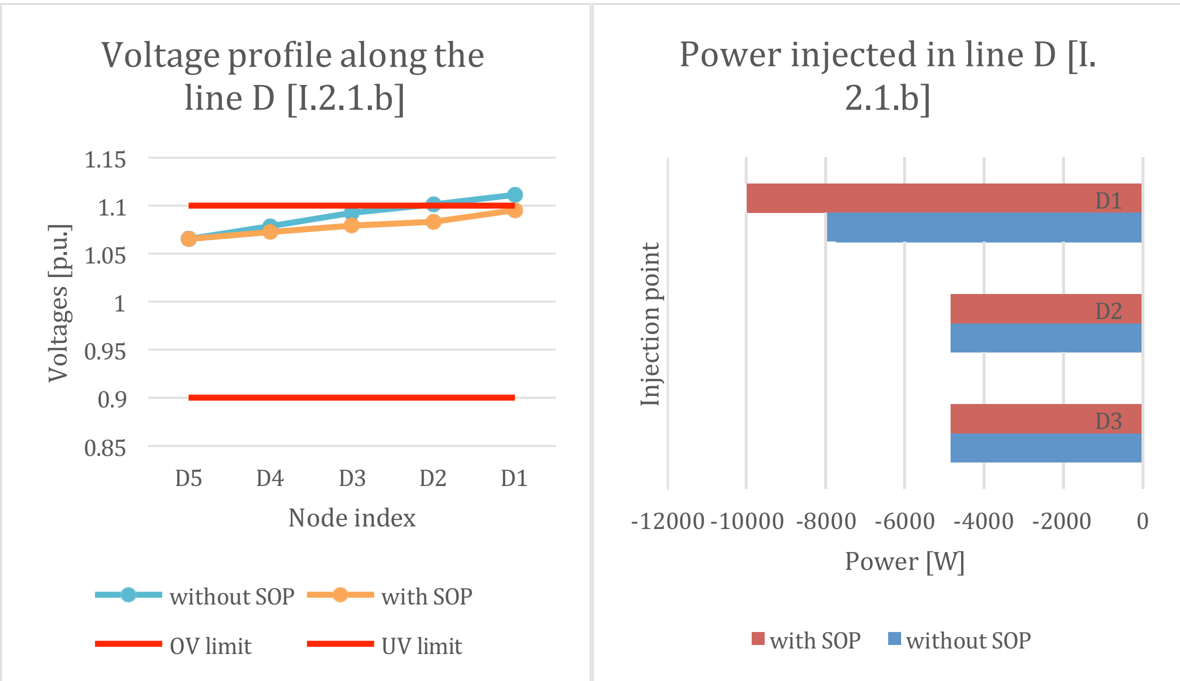


Figure 14. Voltage profil (left) and injected power (right) on feeder D for the test case I.2.1.b

5 LV Soft-open point 50 kVA prototype development

As described in the part 1.4, the MV SOP was abandoned and it was decided to make another LV SOP suitable for operation in Romande Energie's network.

The design is still under development at the HEIG-VD and the test site is under investigation by the HEIA-FR.

5.1 Design and features

The Figure 15 shows a working version of the design for this new SOP and the Table 8 presents the differences between the first prototype and the second iteration that will be installed in the grid.

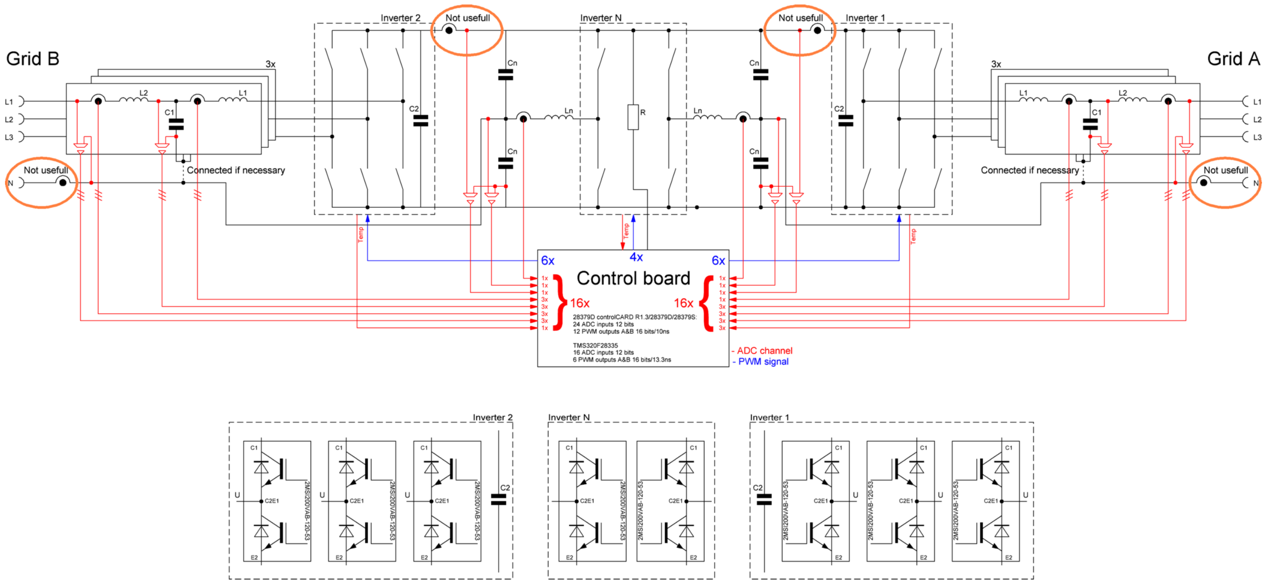


Figure 15. Envisaged design for the 50 kVA LV SOP

Issue	15 kVA	50kVA
Inverter topology	2-level inverter with 50Hz transformer for neutral provision	2-level inverter with neutral active controller
PLL	grid voltage Vq cancellation	SOGI type + Vq cancellation
Output filter	LCL	LCL
LC filter damping method	Passive	Active (virtual resistance)
Inverter-side current control	Yes (d,q current control)	Yes (a,b or a,b,c independents resonant current controllers)
AC voltage control	No	Yes (filter capacitor C measurement)
Grid-side current control	No	Yes (grid inductance L2 measurement)
P and Q power controller	Yes, based on the inverter side current (L1 measurement)	Yes, based on the grid side current
Grid forming capability	No	Yes, based on the capacitor C voltage

Table 8. Comparison between the 15 kVA and the 50 kVA prototypes

6 Achievement of deliverable:

6.1 Date

18.07.2019

6.2 Demonstration of the deliverable

15 kVA LV SOP prototype tested at GridLab, Sion in December 2018. Final analysis of data and reporting in March 2019.

7 Impact

The tests of the SOP in the laboratory environment showed an improvement in the voltage profile and in the load capacity of the overall network.

This work also resulted in a conference paper [2].

The feedback earned on the development and test of this prototype benefit the team for the design of the 50 kVA version.

8 References

[1] M. Carpita, S. Wasterlain, P. Favre-Perrod, L. Eggenschwiler and A. Grapperon, "REEL Project – 6a1, Preliminary study for soft-open point deployment into REEL Demonstrator," 2017.

[2] F. Attanasio, S. Wasterlain, T. Pidancier, M. Marchesoni, P. Favre-Perrod and M. Carpita, "Low Voltage Soft Open Point with Energy Storage: System Simulation and Prototype Preliminary Test Results,," *2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi, Italy,* pp. 254-261, 2018.

[3] M. Carpita, S. Wasterlain, M. Schiesser, T. Pidancier, P. Favre-Perrod, L. Eggenschwiler and A. Grapperon, "REEL Project – 6a2, Design principle of soft-open point," 2017.

[4] M. Eremia, C.-C. Liu and A.-A. Edris, Static Synchronous Series Compensator (SSSC), Advanced Solutions in Power Systems:HVDC, FACTS, and Artificial Intelligence: Wiley-IEEE Press, 2016.

[5] Y. Amirnaser and I. Reza, Static Compensator (STATCOM), Voltage-Sourced Converters in Power Systems:Modeling, Control, and Applications: Wiley-IEEE Press, 2010.

[6] J. Pourhossein, G. B. Gharehpetian and S. Fathi, "Unified Interphase Power Controller (UIPC) Modeling and Its Comparison With IPC and UPFC," *IEEE Transactions on Power Delivery,* vol. 27, no. 4, pp. 1956 - 1963, 2012.

[7] B. Tamimi, C. Cañizares and C. Battistelli, "Hybrid Power Flow Controller Steady-State Modeling, Control, and Practical Application," *IEEE Transactions on Power Systems ,* vol. 32, no. 2, pp. 1483 - 1492, 2016.

[8] J. M. Bloemink, "Distribution-level power electronics : soft open-points," Imperial College London, London, 2013.

[9] T. Green, "The Role for Power Electronics in Low-Voltage Distribution Networks," Imperial College of London, 2015.

[10] S. Wasterlein, H. Parisod, D. Roggo and M. Carpita, "EMC studies on grid integration of Distributed Energy Resources. A 10 kW, IEC-61850 compliant inverter design and preliminary test results," in *Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2016 International Symposium on*, Anacapri, Italy, 2016.