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REEL Demo – Romande Energie ELectric network in local balance Demonstrator

Deliverable: 6c2 Field test verification

Demo site: Chapelle

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[Fribourg/Yverdon, 27.03.2021]

1 Description of deliverable and goal

1.1 Executive summary

The 50 kVA SOP in Chappelle-sur-Moudon has been put into operation in February 2021. Before this, several simulations have been performed with different grid control modes. This report presents the operational experience gained with the SOP prototype and confirms the conclusions of the simulation phase of the project.

1.2 Research question

The objective of the activity covered by the work in this report is to answer the following question: Does the soft open point (SOP) prototype installed at Chappelle-sur-Moudon effectively improve the voltage variation and component loading compared to the reference situation before the addition of the SOP?

1.3 Comparison with other demonstrator activities

Another demonstration of a normally closed SOP by Alstom Grid under the UK's low carbon network fund has been discussed in previous deliverables. The SOP discussed in this report is normally closed and the converter designed for this application has a capability to control the neutral current, which effectively allows it to work under unbalanced conditions.

Also, the demonstration activity includes substantial effort in the protection and communication of the SOP, which has not been found in other demonstration activities.

1.4 Description

1.4.1 Modelling and simulation of the SOP performance

1.4.1.1 SOP principle

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, see e.g. 6c1 "Report on soft-open point deployment" and 6a1 "Preliminary study for soft-open point deployment into REEL Demonstrator".

Figure 1 shows the location of the SOP prototype discussed in this report: it interlinks two LV distribution networks in the village of Chappelle-sur-Moudon. The networks are each fed by a 250 kVA MV/LV distribution transformer.

Figure 1: Geographic map of the two LV networks (blue/purple) in Chappelle-sur-Moudon and the interconnecting MV cable (black). Schematic view of the SOP location 1 (red). Alternative locations 2…7 studied in this work.

1.4.1.2 Performance evaluation

The effect of the SOP prototype in the network will be quantified using a performance score (the lower the better) considering the voltage variations during operation, the maximum loading of cables and transformers as well as the network losses (including the SOP). This scoring is explained in this section.

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

1. Voltage index:

$$index_{\Delta u} = \frac{1}{n}\sum_{i=1}^{N}\left(\frac{\max_k\{u_{i,k}\} - \min_k\{u_{i,k}\}}{d_{\{max\}}}\right)^2 \qquad (eq.1)$$

Where:

$\boldsymbol{N}$	Total number of buses with loads connected
$\max_i\{\boldsymbol{u_{k,i}}\}$ $\min_i\{\boldsymbol{u_{k,i}}\}$	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 [1])

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:

$$index_{\Delta i_{\{cable\}}} = \frac{1}{M}\sum_{j=1}^{M}\Delta i_{\{cable\},j} \qquad (eq.2)$$

$$\Delta i_{\{cable\},j} = \begin{cases} \dfrac{\max_k\{I_{(m,j),k}\}}{\frac{I_{n,j}}{2}}, & \dfrac{\max_k\{I_{(m,j),k}\}}{I_{n,j}} \geq 0.5 \\ 0, & \dfrac{I_{m,j}}{I_{n,j}} < 0.5 \end{cases} \qquad (eq.3)$$

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:

$$index_{i_{TR\{max\}}} = \max_{i,k}\{i_{TR_{i,k}}\} \quad (eq.4)$$

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:

$$index_{losses} = \frac{1}{K}\sum_{k=1}^{K}\left(\gamma_k * \frac{P_{loss,tot,k}}{P_{load,tot,k}}\right) \quad (eq.5)$$

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:

$$score = \sum_{j=1}^{J}(\alpha_j * idx_j) \quad (eq.6)$$

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 indices 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:

$$idx = 1 - \left(\frac{index_{max} - index_{initial}}{\Delta max}\right) \quad (eq.7)$$

Where:

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

1.4.1.3 Methodology applied to simulations of the SOP in Chappelle-sur-Moudon

The size of the SOP prototype has been decided in previous studies in collaboration with HEIG-VD and Romande Energie. For this pilot project, an SOP of 50 [kVA] was built in order to be installed in a real LV network of Romande Energie. It will be used to interconnect two LV grids ("Chappelle" and "Champ-Monnet") that are fed by separate MV/LV transformers. These transformers have the same nominal power of 250 [kVA].

Once the size of the SOP was fixed, we tried to simulate its behaviour in different sites in order to make the link between “Chappelle” and “Champ-Monnet” LV grids.

These different feasible locations were discussed previously with Romande Energie in order to study the technical feasibility of the installation. Afterwards, seven locations were decided and simulations were made in order to compute the score of each grid control mode in these different locations.

For each simulation for a chosen location, a score was computed for each case study where the two LV grids are first connected through an ideal line which is later replaced by an SOP of 50 [kVA] that has different grid control modes as VOLTSAME (VOLTage SAME), TRABA (TRAnsformers BAlancing) and VSTB (Voltage profile Shifting & Transformers Balancing), introduced in [2].

These grid control modes have different objectives and use various inputs from intelligent measurement grid units in order to generate active and reactive power references (P^* and Q^*):

- VOLTSAME:
  This grid control mode will minimize the difference between voltage amplitudes at transformers and SOP terminals and in the same time, it will try tend the voltage magnitude profiles to 1 [p.u].
- TRBA:
  The objective of this algorithm will be to balance the active power between the MV/LV transformers in each LV grid.
- VSTB:
  This algorithm will combine the objectives of VOLTSAME and TABA.

A flow chart of each grid control mode is given in the Annex and further described in [2]. The simulated case studies are:

Initial state	The case where simulations are made with the existing network topology. This can be seen as a reference situation: if the score decreases for another case, an improvement is reached. Otherwise, the initial situation is preferable to the addition of an SOP.

Line	The case where simulations are made by connecting the studied LV grids through an ideal line.
VOLTSAME	The case where simulations are made by connecting the studied LV grids through an SOP having the VOLTSAME grid control mode.
TRABA	The case where simulations are made by connecting the studied LV grids through an SOP having the TRABA grid control mode.
VSTB	The case where simulations are made by connecting the studied LV grids through an SOP having the VSTB grid control mode.

It is worth to mention that scenarios used in each simulation were combining different load and production values and some further scenarios assume an increase of the total PV generation in the two LV grids (in our case an increase of 42.9[%]) in order to load at least one of the existing transformers up to 100 %.

We should note as well that the simulation of each scenario was executed using an AC Load Flow that performs calculations for a single-phase, positive sequence network representation. This implies the assumption that lines are three-phase in steady state sinusoidal, the power system is three-phase symmetrical in the current and balanced in the voltages and finally cables and lines have a symmetrical conductor placement structure.

Before computing the final score of each study case using (eq.6), we need to evaluate quantitatively the weighting factors α_i that will give a different weight for each normalized index.

This evaluation is based on a financial analysis where the cost of new cables, new transformers and grid losses are taken into account:

- Cost of new cables:
  As noticed from grid data, all lines in our studied LV grids are modelled as cables. The cables that would potentially be replaced are the ones lying between SOP and transformers' terminals. A three-wire conductor having a greater section will replace the existing cables.

We make the hypothesis that the cost of new cables will be equally divided between the evaluation of voltage and current indexes because we assume that increasing a cable section could decrease the conductor loading (related to current index) and in the same time improves the electrical network stability by enhancing the voltage profile in order to respect voltage constraints (related to voltage index).

- Cost of new transformers:
  This cost will consider the price of transformers that have an apparent nominal power that is a step higher than the ones already installed in the LV networks. The catalogue of prices for MV/LV transformers is taken from the same review [3] that is used to compute new cables' costs. This cost is used in the computation of the weighting factor that is related to the transformer index.
- Cost of grid losses:
  Many external factors will influence the computation of this cost:
  - Price of the a [kWh] of grid losses:
    In our simulations, this price was estimated to: $p_{loss,cost} = 0.05 \left[\frac{CHF}{kWh}\right]$
  - Annual interest rate: $r = 2\ [\%]$
  - Total lifetime of the replaced grid components:
    In our case study, this was estimated to: $T = 30\ [years]$

As this cost is evaluated in a time scale having a T duration, there is a need to compute the Net Present Value (NPV) of the cost of grid losses by using the equation (eq.8):

$$losses\ cost = \sum_{t=1}^{T-1} \left(\frac{annual\ losses \cdot p_{loss,cost}}{(1+r)^t} \right) \quad (eq.8)$$

With:

$$annual\ losses = \frac{1}{n} \sum_{i=1}^{n} p_{loss,i} \quad (eq.9)\ ;\ p_{loss} = \left(\frac{1}{K} \sum_{k=1}^{K} P_{loss,tot,k} \right) \cdot H \quad (eq.10)$$

Where:

losses cost	The total cost of grid losses in [CHF]

$\boldsymbol{annual\ losses}$	The mean value of annual losses in [kWh] between all case studies (i.e. initial state, line, VOLTSAME, TRABA, VSTB)
$\boldsymbol{p_{loss,i}}$	The mean value of annual losses in [kWh] between all scenarios for case study ”i”.
$\boldsymbol{n}$	The total simulated case studies
$\boldsymbol{P_{loss,tot,k}}$	The total grid losses in [kW] for the “k” scenario
$\boldsymbol{K}$	The total number of simulated scenarios
$\boldsymbol{p_{loss,cost}}$	Price of the a [kWh] of grid losses, assumed to be equal to 0.05 $\left[\frac{CHF}{kWh}\right]$
$\boldsymbol{T}$	Total lifetime of the replaced grid components, assumed to be equal to 30 $[years]$
$\boldsymbol{H}$	Total number of hours per year, which is equal to 8760 $[h]$
$\boldsymbol{r}$	Annual interest rate, fixed to 2 [%]

1.4.1.4 Simulation results:

After simulating all case studies and computing their scores using (eq.6), we obtain the results illustrated in Figure 2, for "location 1" and for an SOP with a size of 50 [kVA]. From this figure, we note that using an SOP with VSTB grid control mode, we have the smallest score comparing to the other algorithms (TRABA and VOLTSAME) and comparing to the remaining case studies (Initial state and Line). As mentioned in the previous chapter, the lowest the score the better the performance.

From these observations, we can conclude that the VSTB grid control mode will enhance the grid behaviour because comparing to the other case studies, it gives the best trade-off between the decrease of voltage amplitudes deviations, the cables and transformers loading and the grid losses.

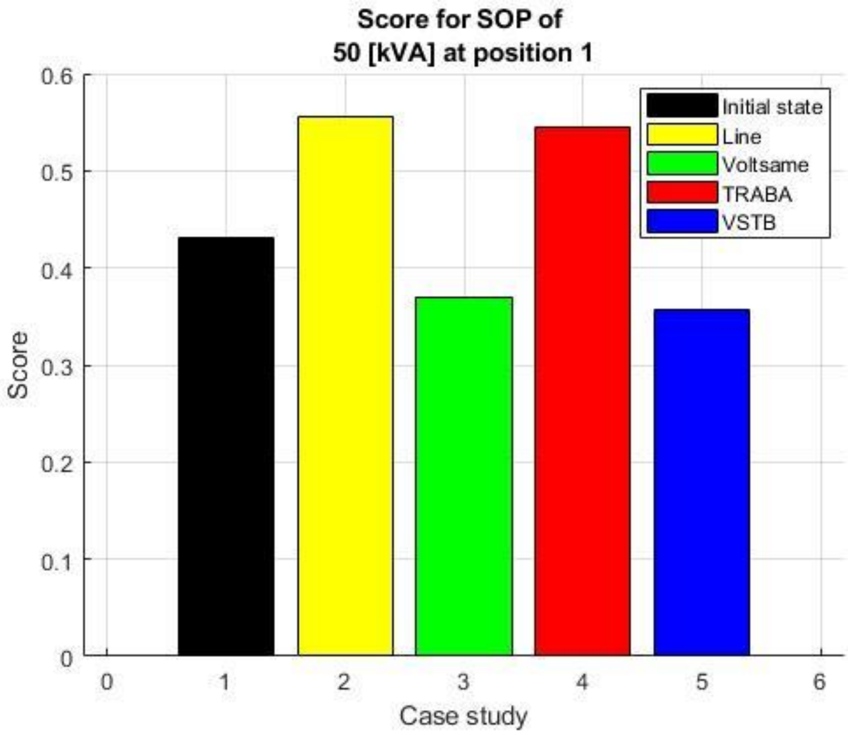


Figure 2: Score of different case studies for an SOP of 50 [kVA] at location 1

As the score normalization is different for a given size and a given location of SOP connection between the two studied LV grids, we need to find a new way in order to be able to compare the score of each case study in different potential locations of SOP installation.

In consequence, for a given size and site of SOP, we choose to compute the difference between the initial state and the remaining case studies where:

$$\Delta\ score\ of\ Line = score\ of\ initial\ state - score\ of\ Line$$

$$\Delta\ score\ of\ VOLTSAME = score\ of\ initial\ state - score\ of\ VOLTSAME$$

$$\Delta\ score\ of\ TRABA = score\ of\ initial\ state - score\ of\ TRABA$$

$$\Delta\ score\ of\ VSTB = score\ of\ initial\ state - score\ of\ VSTB$$

If the $\Delta\ score$ of the i^{th} case study is negative, this means that the corresponding case study has a higher score than the initial state and in consequence, it worsens the behaviour of the studied LV networks. By following the same logic, the $\Delta\ score$ of the i^{th} case study with the highest positive value will most improve the behaviour of the studied LV networks.

Figure 3 illustrates the $\Delta\ score$ of different case studies in different locations for an SOP of 50 [kVA].

From these results, we can observe that:

- The score of the "Line" case study has its best performance at the location 3.
- The score of the "VOLTSAME" case study has its best performance in location 5.
- The case study using the "TRABA" grid control mode will always worsen the LV networks behaviour independently of SOP sites.
- The score of the "VSTB" case study has its best performance at the location 1. It also has the highest $\Delta\ score$ value between all case studies at different SOP sites.

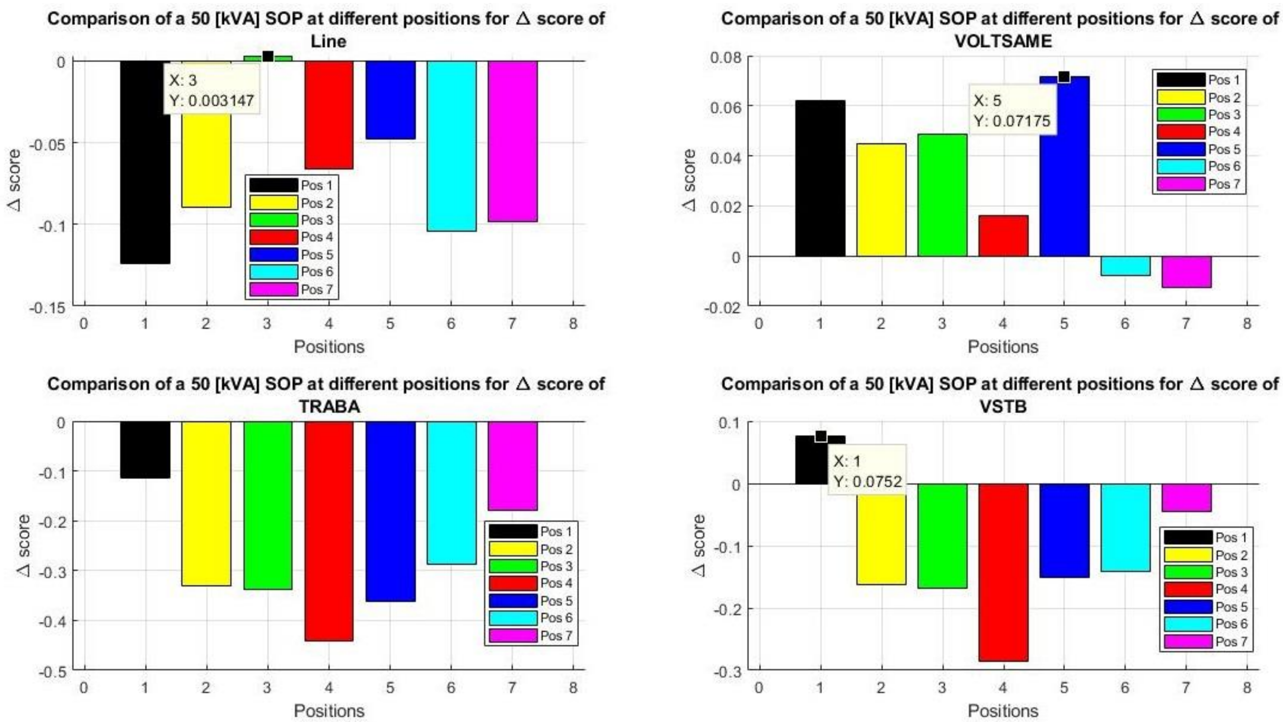


Figure 3: Comparison of different case studies for a 50 [kVA] SOP in different locations

From all these results, we can conclude that installing the SOP in location 1 (which represents the site chosen with Romande Energie to install the SOP prototype) and using the VSTB grid control mode, will improve the most the studied LV networks behaviour.

1.4.2 Field verification of the SOP performance

Figure 4 shows measurements of the active power at the two secondary substation transformers as well as the power transferred by the SOP. Four situations are presented in order to illustrate the operation of the SOP in the VSTB mode during its validation phase:

- Situation A: reference situation with an initial unbalance between the loading of the two transformers which is compensated by the SOP.
- Situation B: variation of the injected power of the PV panels due to scattered clouds imply that within a measurement interval (here 60 seconds), the imbalance between the loading of the two transformers can increase, although within acceptable limits.
- Situation C: in this case, the voltages are represented instead of the transformer loading. The Figure shows how the reactive power on the Champ-Monnet side of the SOP is adjusted over time from negative to positive in order to maintain the voltage at the SOP to a value such that the average between the SOP and transformer voltage is 1 p.u.
- Situation D: in the case of low PV infeed, the SOP is working at very low setpoints.

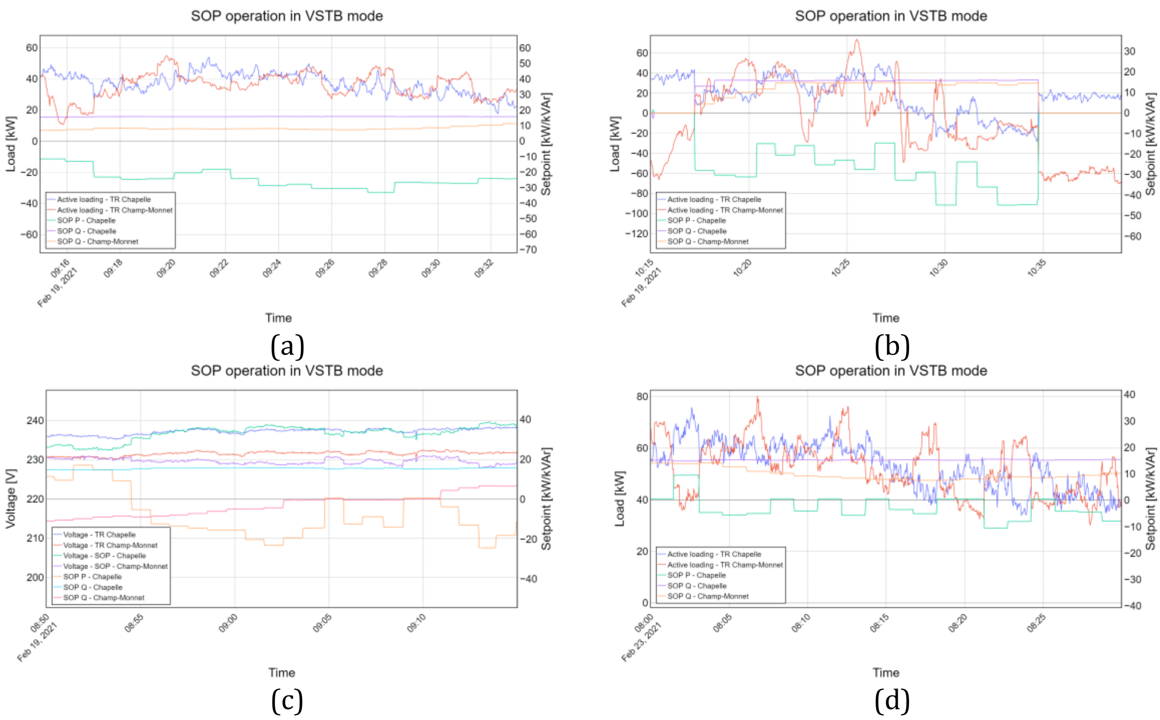
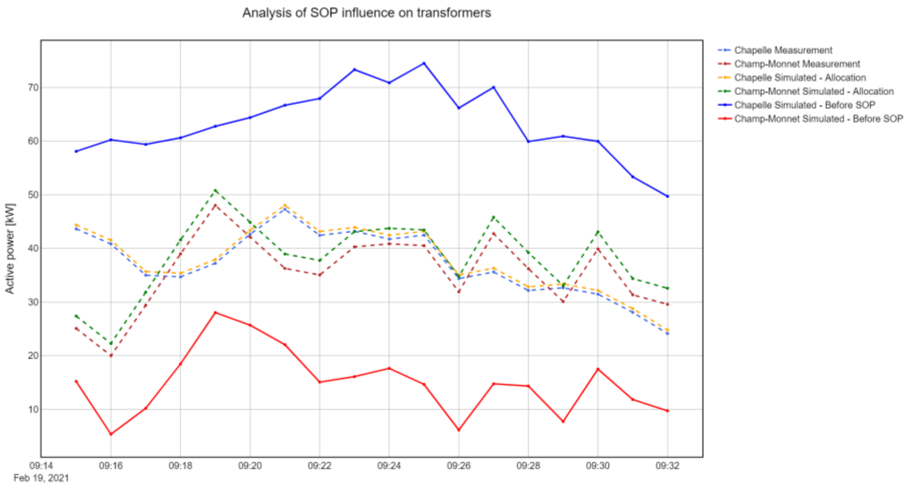


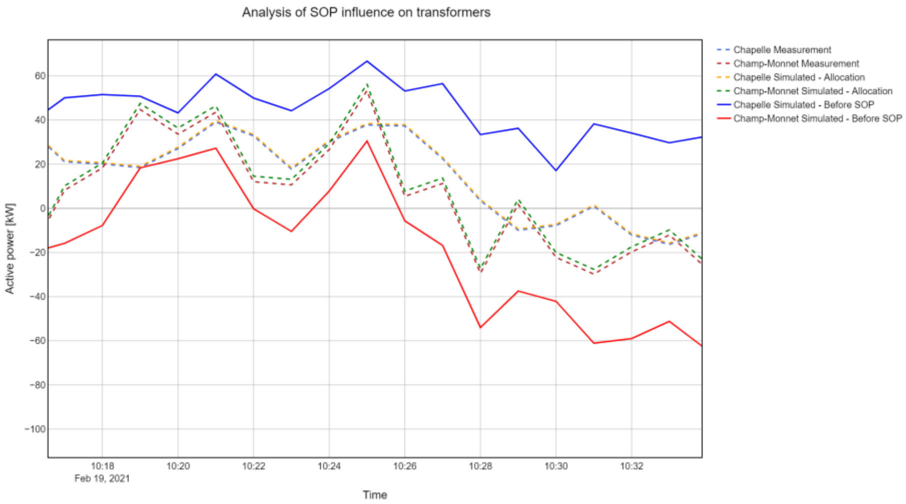
Figure 4: Illustration of the use of the SOP during normal grid operation

In order to illustrate the change implied by the use of the SOP, a simulation of the situation without the SOP has been made, by approximating the grid loading (load allocation) for the same period of time as shown in Figure 4. Figure 5 shows that the transformer loadings would have been different in that case ("Before SOP" curves in the figures). In order to check the simulation assumptions, the situation with the SOP is also simulated, using the same load allocation as for the case without the SOP ("Allocation" curves in the figures). The results confirm that the load allocation leads to results similar to the measurements. In particular, the following observations can be made for each situation:

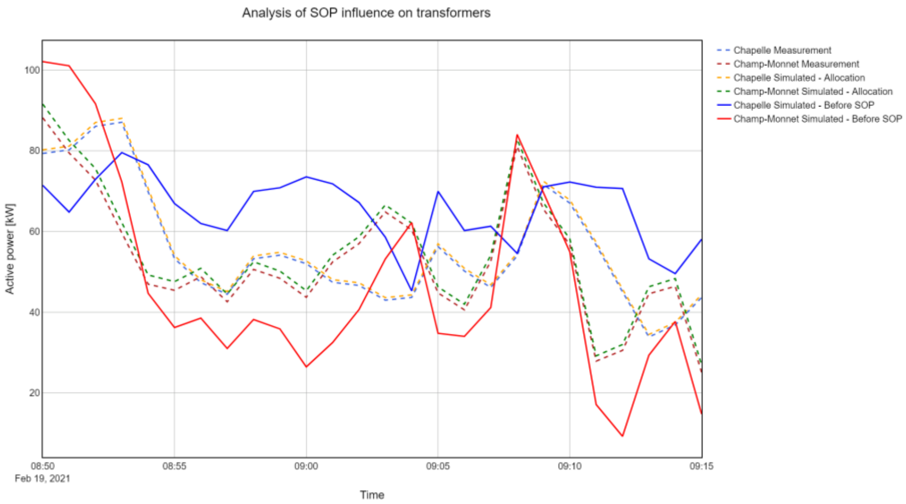
- Situation A: as expected, the peak load of the Chapelle transformer is largely reduced.
- Situation B: the reduction of the peak load is less impressive in this situation, but still exists.
- In situations C and D the active power in the SOP was close to zero. Hence there is no relevant effect on the transformer loadings. However in these cases, the voltages are still improved compared to the situation without an SOP.



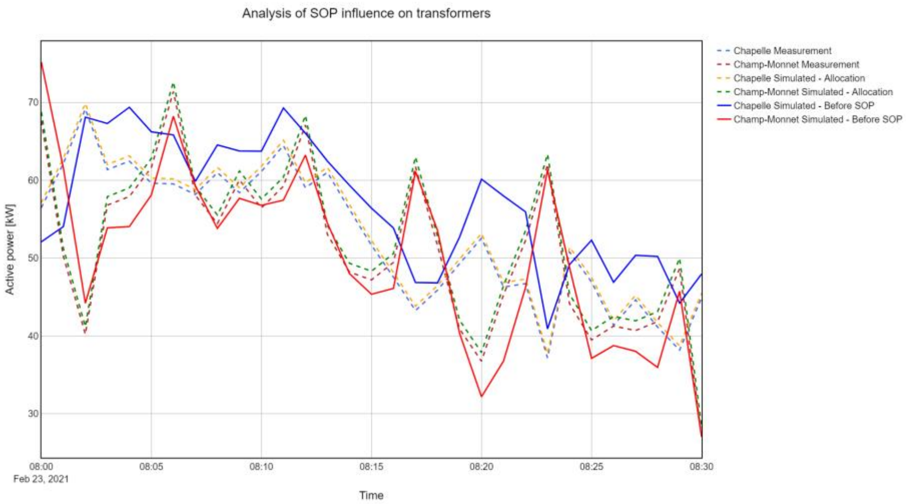
(a)



(b)



(c)



(d)

Figure 5: Simulation of the situation without the SOP

1.4.3 Preliminary conclusion and further work

A location for an SOP within the Chappelle-sur-Moudon LV distribution has been selected and the best grid control mode identified based on simulations. The initial operational evidence is that the SOP can contribute to improving the performance of a low voltage network with distributed generation. The next steps should focus on reducing the footprint and cost of the device in order to achieve competitiveness with alternative solutions.

2 Achievement of deliverable:

2.1 Date

1.9.2020: Simulations completed and SOP assembly in progress

4.2.2021: SOP in operation, operational data available

2.2 Demonstration of the deliverable

The SOP is actually installed at Chappelle-sur-Moudon and the data used for the field verification (section 0 of this report) is from real measurements.

3 Impact

The soft open point is one of the actuators installed in the Chappelle-sur-Moudon demonstration grid. Also, it interfaces the GridEye system that has been previously deployed within the REEL framework. The SOP prototype showcases the potential benefits of this principle, and it furthermore is part of the installed base of smart technologies that have the potential to interact in order to optimise the operation of distribution networks.

References

[1] {DACHCZ Verband der Netzbetreiber}, "Règles techniques pour l'évaluation des perturbations de réseaux," Association des entreprises électriques suisses, Aarau, Règles DACHCZ, 2007.

[2] P. Favre-Perrod, M. Allani, C. Bernasconi, E. Auberson, A. Demierre, M. Carpita*, et al.*, "6c1 Report on soft-open point deployment," 2020.

[3] {AES}, "Coûts standardisés," Association des entreprises électriques suisses, Aarau, Annexe à la recommandation pour l'évaluation des réseaux de distribution, 2007.

Annex

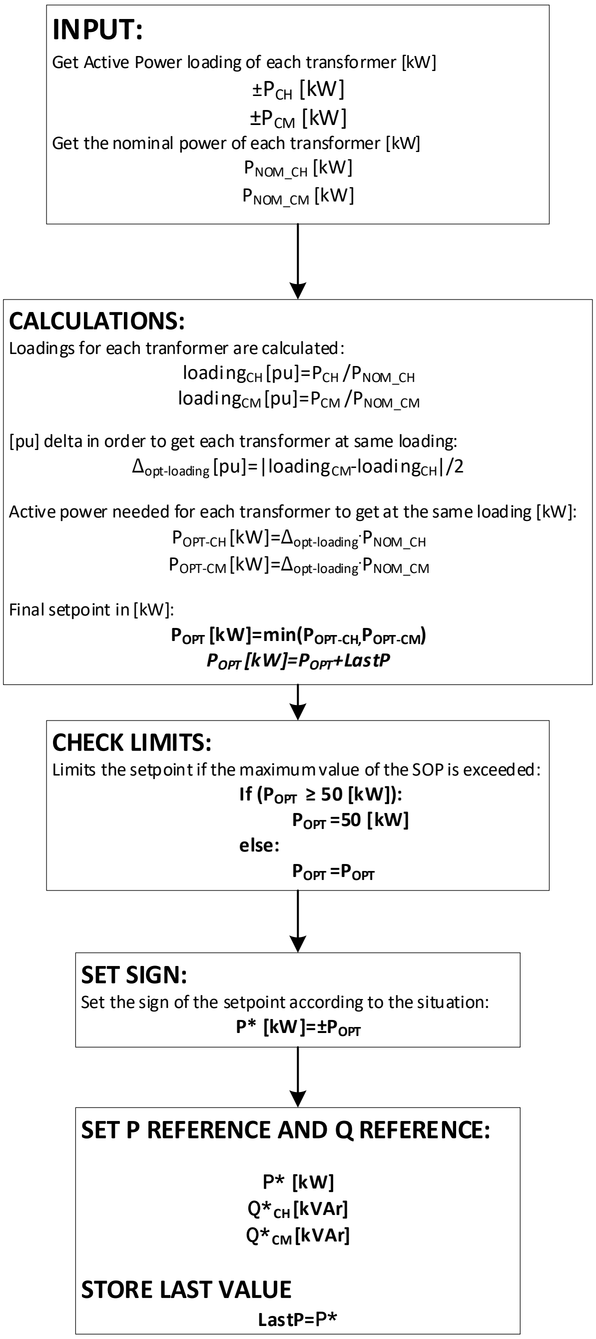


Figure 6: Flow Chart of TRABA

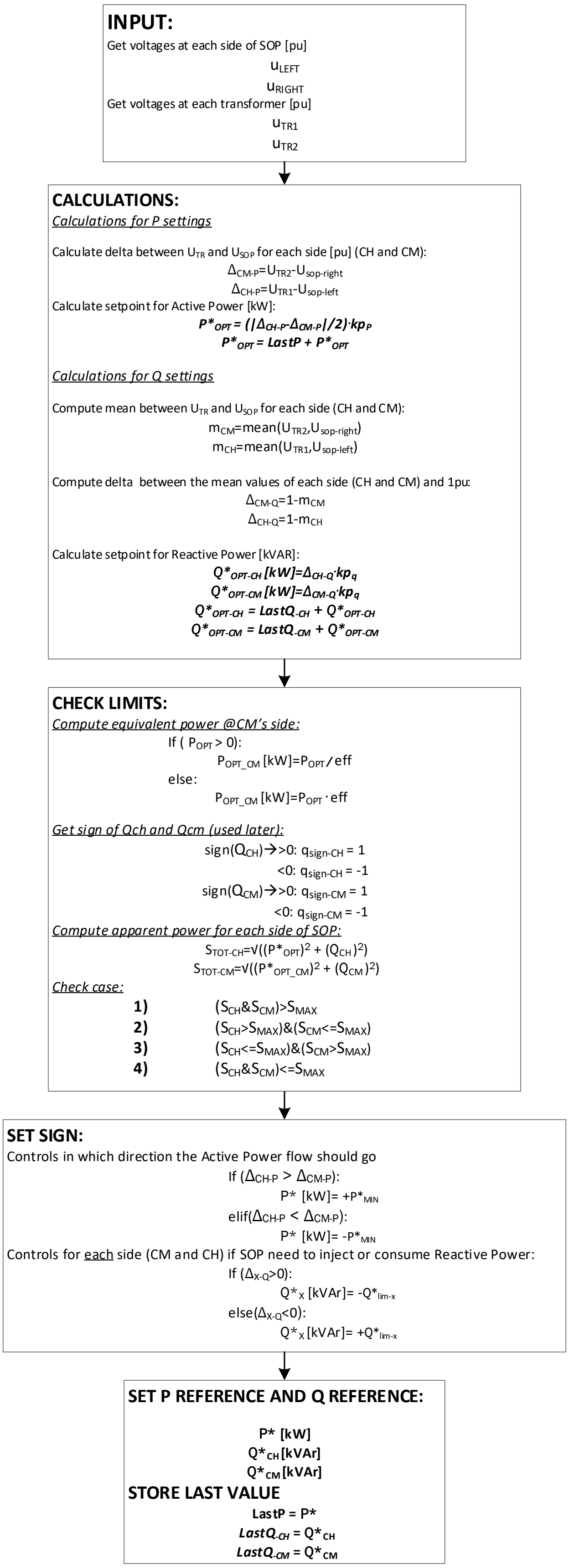


Figure 7: Flow Chart of VOLTSAME

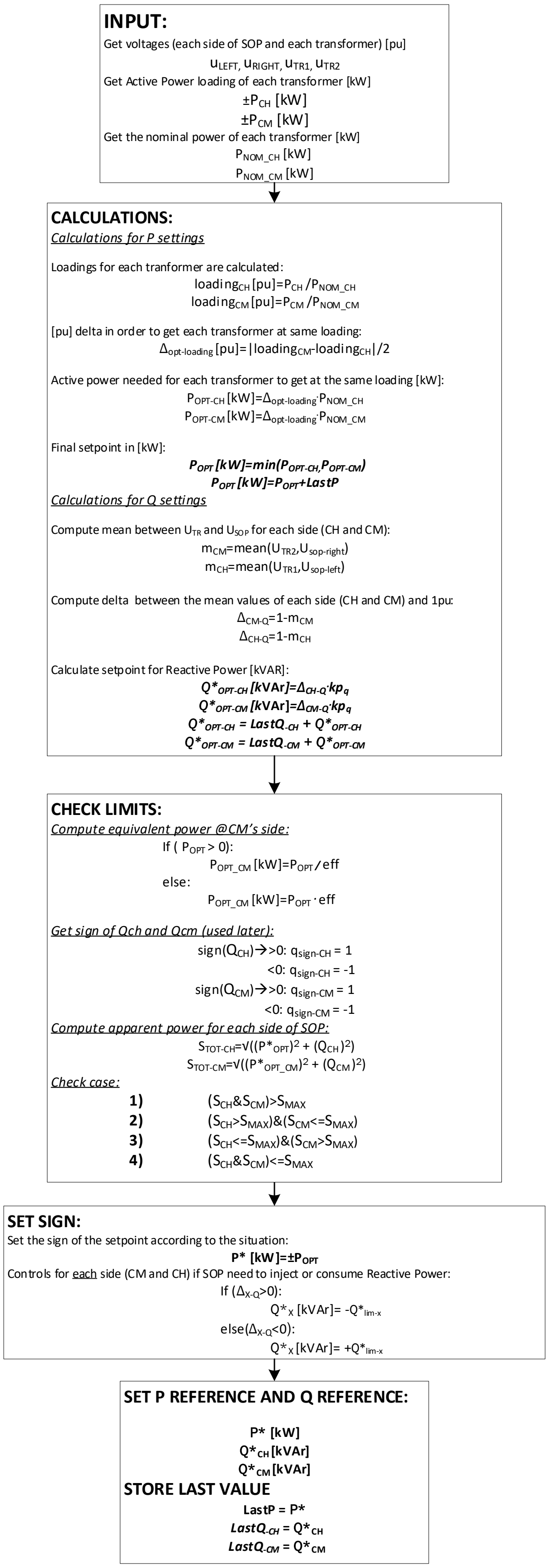


Figure 8: Flow Chart of VSTB