# SOFT-OPEN POINTS FOR MEDIUM VOLTAGE NETWORKS – A CASE STUDY

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## *ABSTRACT*

*Using soft-open points (SOP), the load flow and fault behaviour of a distribution network can be decoupled. This is appealing when addressing the impact of distributed infeeds. This paper introduces two possible control strategies for an SOP: the switch and the PQ modes.*

*The addition of an SOP to two illustrative MV networks (urban and rural) is investigated: the SOP can contribute to reduce voltage variation and peak grid component loadings in both situations. As a consequence of the higher voltage variations in the rural example network, a voltage controlled mode or PQ controlled mode appears more appealing to this situation. An SOP with a reduced rating can also contribute to a partial improvement: when the SOP is used to reduce voltage variations and grid component overloading to a given quality standard, only the excessive variation or overload needs to be compensated.*

*The paper presents a modelling framework that will be used in a demonstration project where a reduced scale SOP will be deployed into a real network.*

## INTRODUCTION

The soft-open point (SOP) is a power electronic device that has been proposed and studied with the purpose to permit a meshed (or closed-loop) operation of radially operated distribution networks, i.e. open loops [1], [2]. As shown in Figure 1, a normally closed SOP represents a way to decouple load flows and fault currents:

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

The expected advantage of using SOPs is the increased operational flexibility and hosting capacity for renewable energy producers with minimal influence on existing protection and automation systems. A limited number of demonstrations of the normally open SOP has taken place essentially for normally open systems in LV networks.

This work will report on case studies investigating the anticipated advantages of normally closed systems in MV and its potential use in MV network reinforcements. The studies are also used in order to establish a specification of the SOP and its control.

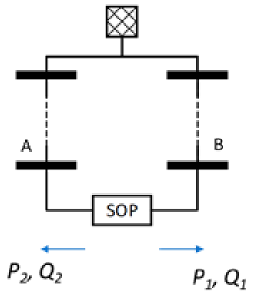

*Figure 1: Illustration of an MV network with an SOP.*

## CONTROL AND MODELLING OF THE SOP

### SOP model

The basic functionality of the SOP can be achieved using various principles including fast mechanical switches, semiconductor switches (possibly in combination with classic mechanical breakers) and full converter architectures. The latter offer the highest degree of freedom, indeed at the highest cost. Figure 2 shows the model of an SOP with back-to-back AC/DC converters used in this study: the power flow is controlled using two back-to-back converters connected to the network using transformers.

The converter and the networks have been simulated using DigSilent PowerFactory.

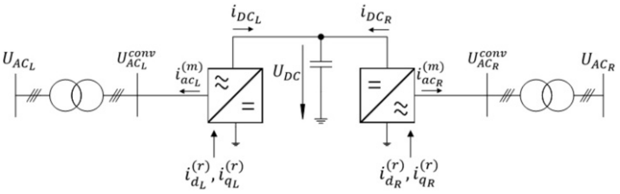

*Figure 2: Simplified model of an SOP for MV applications.*

## Possible control architecture

Two control modes for the SOP have been investigated [3]:

- The PQ mode directly controls the active and reactive power transit through the SOP. This is probably most attractive in active network schemes where communication is available and an optimisation of the distribution network is run remotely.
- The switch mode controls the voltage difference across the SOP: in closed mode the difference is controlled to zero and in open mode, the current is controlled to zero. This mode does not rely on communication or optimisation.

Figure 3 shows the control structure which has been implemented in the SOP model: in the PQ mode, reference values for the active and reactive power are passed to the SOP controller which contains an inner control loop. These references could e.g. be generated by an optimisation tool for losses minimization or voltage control. In the switch mode, the AC voltage amplitudes and phases at the SOP terminals are measured. The SOP controller generates d- and q-axis current references in order to minimise the voltage difference across the terminals to zero.

The rating of the SOP converters will limit the possible power transfer. Thus the SOP will change from switch mode to saturated mode as soon as the current amplitude reaches the converter's rated current. In this event, priority can be given to either the d- or q-axis current. This is relevant to situations of high loads or faults in the network. Figure 4 illustrates the closing of an SOP in switch mode: after the close command at t = 0.5s, the voltage magnitude and angle differences Δϕ and ΔU are reduced to zero.

## CASE STUDY IN AN URBAN NETWORK

### Effect on voltages and line loading

The proposed SOP structure has been tested in simulations for two distinct MV networks with two feeders operated radially before the addition of an SOP. Figure 5 shows the topology of the urban MV (21 kV) network (presently operated radially) used in this study. An SOP has been placed at the current normally open sectioning point. The loads are approximated by feeder demand reallocation (of the measurement at the primary substation), and a DG infeed of 3.5 MW is modelled at the node to the left of the SOP.

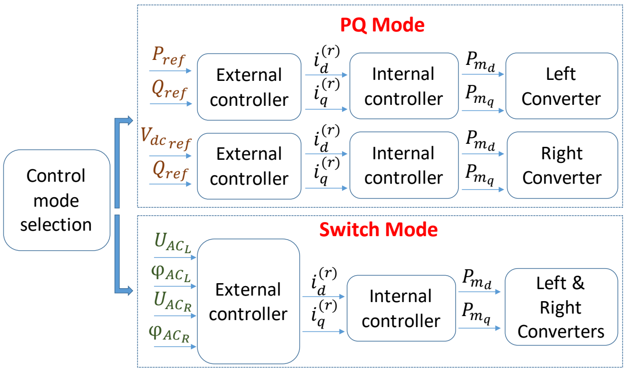

*Figure 3: Possible control modes and structure of an SOP.*

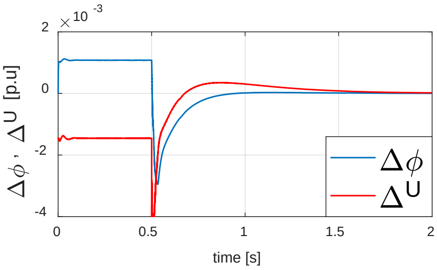

*Figure 4: Voltage magnitude and angle difference between the SOP terminals after a "close" command.*

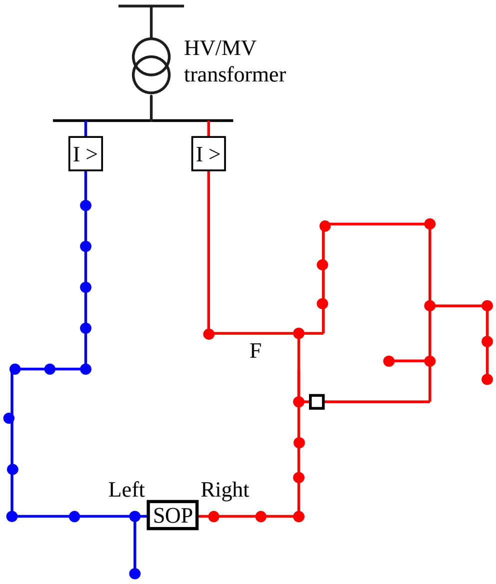

*Figure 5: Topology of the urban MV network studied.*

Figure 6 shows the voltage variations in the MV network (simulation) and the underlying LV networks (estimation) with and without an SOP and with an SOP of reduced rating. The extreme voltages have been determined by using representative extreme values of consumption and generation. In an open loop, any additional injection of power or consumption would necessarily flow through one feeder while in closed loop operation the additional load flow would be split across the two feeders. For this reason, the expected voltage variation is smaller in closed loop operation, especially when the load or generation variation is not balanced along the loop. This is for example the case in the urban network studied here. The voltage variations have been computed for several ratings of the SOP. The percentages in Figure 6 indicate the ratio between the current rating of the SOP and the current requirement for a fully closed loop operation of the network. When the SOP is closed, the reduced variation of the load flows in each part of the MV loop results in a lower variation of the voltage. If this power transfer is limited by the SOP rating, the effect on the voltage profile is also limited. For this study case, the SOP decreases the maximal voltage variation by 0.6%, which could correspond to 1.2…1.8% in the connected LV networks according to [4] and [5].

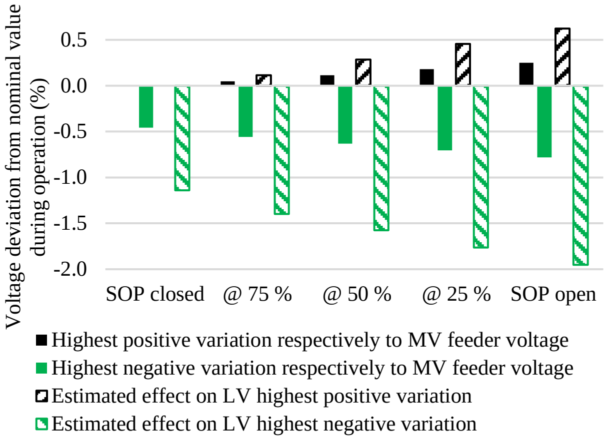

*Figure 6: Effect of the SOP on voltage variations (highest variation), depending on the SOP rating limitations*

## Fault behaviour

During a fault, the behaviour of the system is of course influenced by the presence of the SOP. The objective of the SOP operation is to detect faults fast enough in order to interrupt the SOP current (which is not the total fault current) within the first half-wave after the fault occurrence, i.e. within 5 ms. This is much faster than the action time and the time delay of the overcurrent protections typically used in radial MV networks. Thus the short-circuit levels are only marginally influenced and protection settings of already installed devices do not need to be adjusted (or at least the protection concept can be maintained as it is).

The behaviour of the SOP during a short-circuit is illustrated in Figure 7 for a resistive fault at the location marked "F" in Figure 5. Figure 7 shows the current and voltage magnitudes $i_{ac}$ and $U_{ac}$ as well as the active and reactive current components (the suffixes L and R refer to the right respectively left terminal of the SOP):

$$i_{P_{L,R}} = \frac{P_{L,R}}{U^{conv}_{AC_{L,R}}} \qquad \text{and} \qquad i_{Q_{L,R}} = \frac{Q_{L,R}}{U^{conv}_{AC_{L,R}}}$$

where:

$$P_{L,R} = U^{conv}_{d_{L,R}} \cdot i^{(m)}_{d_{L,R}} + U^{conv}_{q_{L,R}} \cdot i^{(m)}_{q_{L,R}}$$

$$Q_{L,R} = U^{conv}_{q_{L,R}} \cdot i^{(m)}_{d_{L,R}} - U^{conv}_{d_{L,R}} \cdot i^{(m)}_{q_{L,R}}$$

The fault duration in these simulations is only 400 ms since the operation of the existing protection system is not discussed here. The behaviour after a fault will depend on the action of the existing fault detection and isolation principles. The remaining fault current is interrupted by existing breakers and/or fuses. The SOP is therefore not used to interrupt fault currents and it is not used to inject fault currents above its nominal current.

The simulations have been made with either d- or q-axis current priority, which is of course only relevant in case the current exceeds the rating of the SOP converters. In the case of a fault, the currents and voltages are linked by the impedance of the faulted feeder section and therefore there is no relevant difference implied by the selection of the control strategy.

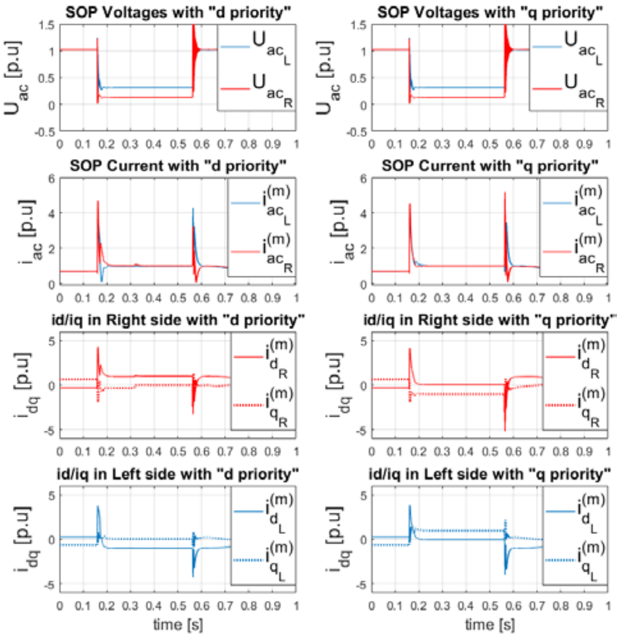

*Figure 7: Voltage and current Signals during a short-circuit at fault location F in Figure 2 with a fault impedance $R_f = 0.3\ \Omega$*

As expected, the continuous fault current of the converters is small as compared to rotating machines and network feeders.

## Rating limitation

A high rating of the SOP is desirable in order to limit the voltage variation in the network by meshing the system with no restriction in a manner comparable to a mechanical disconnector. This would however lead to inadequate size and cost of the SOP. Sizing the SOP requires a comparison between the effect of different SOP ratings on network quality descriptors, e.g. voltage variations during operation and maximum grid component loadings. Figure 6 shows such a comparison: the maximum and minimum voltages (at the location with the highest variation) have been calculated for several ratings of the SOP. If the SOP reaches its maximum loading, it will continue operation in saturated mode, which means that a residual voltage difference between its terminals will remain. This variation is smaller than in an open loop and therefore it can still permit to operate the network within set limits of voltage variation. Figure 8 shows an example of different operation states of the SOP in the urban MV network of this study: at the beginning the SOP is closed and the current required to establish a closed switch state is below the rated current. At t = 0.4 s the SOP loading increases beyond the rated current and thus a residual voltage difference establishes. Then (t = 0.9 s) the SOP loading is reduced and at t = 2 s the load flow is reversed. In this example the controller gives priority to the d-axis current, which is more effective for voltage control in grids with relatively high R/X ratios.

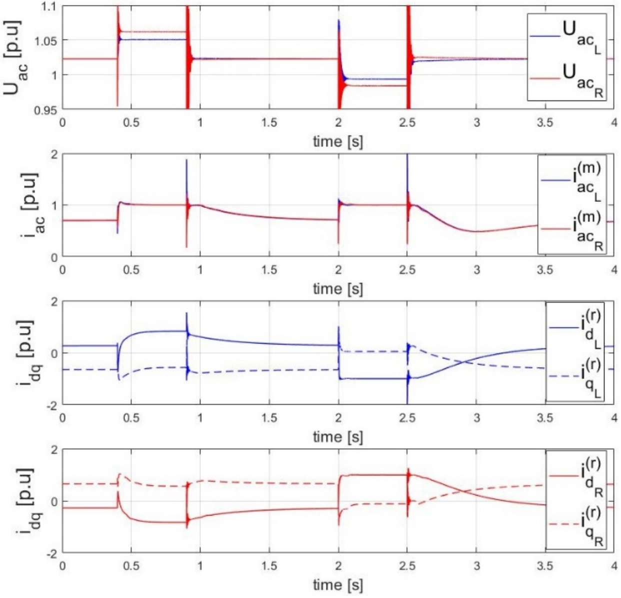

*Figure 8: Example of voltages and currents at the SOP terminals for both power flow directions with and without saturation.*

The simulations presented here lead to the conclusion that the switch mode appears to be acceptable for the case of an urban network: the voltage variations are reduced as a consequence of the better reparation of the load flows induced by the addition of distributed infeeds.

## CASE STUDY IN A RURAL NETWORK

The second case study network investigated in this work is a rural MV (18 kV) network illustrated in Figure 9. Two possible loops within that network are highlighted. These loops are currently closed during operation, which has required additional efforts e.g. in terms of protection systems as compared to the standard radial operation. The use of SOPs as an alternative to this non-standard approach is investigated in this study for the purple loop. For each loop, three possible locations for the SOP have been considered:

- the midpoint of the path represented by the loop, where the distance to the primary substation is equivalent on both sides of the SOP ("Geo middle")
- the impedance centre, where the impedance to the primary substation is equivalent on both sides of the SOP ("Z middle")
- the point with the highest voltage variation in operation ("ΔV max"). This variation is the difference between the highest and lowest voltages arising from different load and generation scenarios.

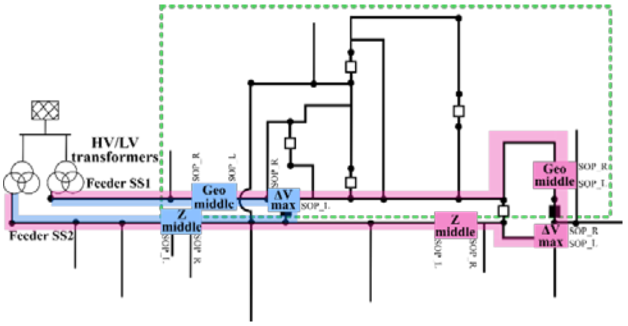

*Figure 9: Topology of the rural MV network studied*

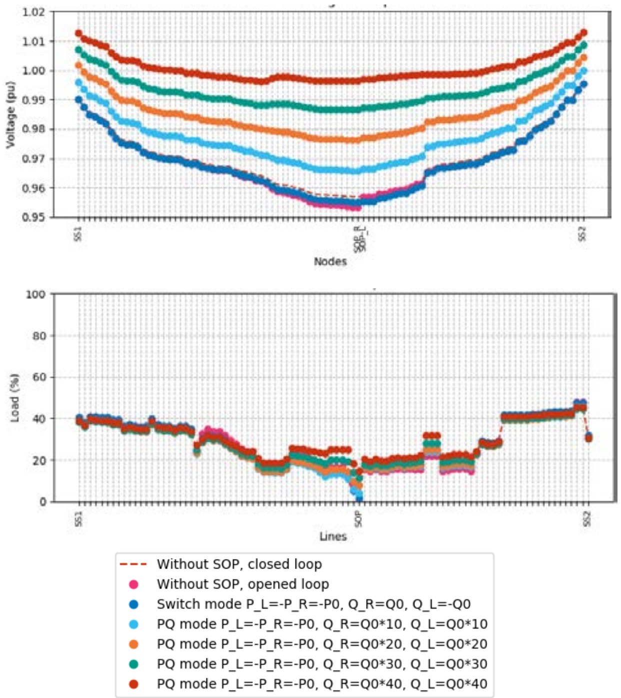

*Figure 10: Voltage and loading distribution in the purple loop shown in Figure 9 for different control strategies of the SOP.*

Figure 10 illustrates the effect of an SOP at the "ΔV max" location in the purple loop of the rural network. The node voltages and line currents for the segments in the loop are shown for a typical load situation. The nodes SOP_L and SOP_R represent the SOP terminals. The active power at each terminal, $P_L$ and $P_R$ respectively are always of opposite signs (when losses are neglected). The voltage distribution along the feeders exhibits less voltage drops in cases with a closed SOP and the maximum line loading is reduced as well. With the SOP closed, the voltage difference between the left and right terminals of the SOP is zero (unless the power flow is high enough to cause saturation of the SOP). In addition to the switch mode, the effect of injecting additional reactive power in PQ mode is shown: this case corresponds to all cases where the reactive power at both terminals are unequal: in this case the SOP additionally acts as a STATCOM ($Q_0$ represents the reactive power required for a closed switch operation). The result is a shift of the voltages in the entire loop. However, the values of $Q_R$ and $Q_L$ required to influence the voltage are substantial.

Table I summarizes the key effects of SOPs at two locations in the two loops in comparison with the situation without an SOP. The voltage variations and grid component maximum loading can be reduced as expected.

The magnitude of this reduction is of course dependent on the considered scenario. In order to evaluate the benefits of the SOP for the entire network, an improvement index taking into account voltage variations and cable loading is used. The improvement index is calculated according to the following steps ($U_m$: node voltage; $I_m$: line loading; $U_n$ and $I_n$: nominal values):

$$Index_{\Delta U} = \frac{1}{N}\sum_{i=0}^{N}\left(\frac{\frac{|U_{m,i} - U_n|}{U_n} * 100}{3}\right)^2$$

$$\Delta I_{cable,j} = \begin{cases} 2 * \frac{I_{m,j}}{I_n}\ for\ \frac{I_{m,j}}{I_n} \geq 0.5 \\ 0\ for\ \frac{I_{m,j}}{I_n} < 0.5 \end{cases}$$

$$Index_{Icable} = \frac{1}{N}\sum_{j=0}^{N} \Delta I_{cable,j}$$

$$II = 6 - \frac{5}{2}(Index_{Icable} + Index_{\Delta U})$$

*Table I: Effect of the SOP on the studied network for two possible SOP locations of the purple loop.*

| | **Closed loop, no SOP** | **Open loop** | **SOP at "Z middle"** | **SOP at "ΔV Max"** |
|---|---|---|---|---|
| **Min. Voltage (p.u.)** | 0.95 | 0.952 | 0.99 | 0.99 |
| **Max loading** | 47.11% | 47.11% | 45.35% | 45.54% |
| **Improvement Index** | - | - | 107.68% | 109.22% |
| **Apparent power transit (kVA)** | - | - | 2300 | 1796 |

The improvement achieved with the "ΔV max" location is highest and it is remarkable that this can be achieved with a smaller apparent power transit in the SOP.

Considering the case illustrated here, PQ control seems more appealing to the situation of a rural network: reactive power injections have a substantial impact on the voltage variation in this situation. As a next step, mixed approaches will be implemented as additional SOP control strategies.

## CONCLUDING REMARKS

Based on the simulations and laboratory tests discussed above, it is planned to deploy a test system into the LV network. An initial prototype has been tested and demonstrated in a laboratory setup [6]. A low voltage device is planned in the REeL ("réseau en équilibre local") project, a demonstration project carried out by Romande Energie in partnership with an academic consortium [7]. This project will also include contributions on new fault detection and location principles which are essential to the successful implementation of new FDIR strategies.

Since the achievable improvement of the network quality indicators will differ for each application, the selection of the MV networks with the highest improvement potential using SOPs will also need to be addressed. In a second step, detailed studies for the subsequent deployment of an SOP system into the MV network will continue.

## ACKNOWLEDGEMENTS

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