AN ALGORITHM FOR SOFT OPEN POINTS TO SOLVE THERMAL AND VOLTAGE CONSTRAINTS IN LOW VOLTAGE DISTRIBUTION NETWORKS

Nathaniel BOTTRELL
Imperial College London – UK
nathaniel.bottrell@imperial.ac.uk

Tim GREEN
Imperial College London – UK
t.green@imperial.ac.uk

Peter LANG
UK Power Networks – UK
peter.lang@ukpowernetworks.co.uk

ABSTRACT

Thermal and voltage constraints in the low voltage network (0.4 kV) may become more prevalent if increases in load or increases in distributed generation occur. Typically, constraints in the distribution network are solved by replacing the transformer, replacing the feeders, or installing a new substation. One solution to avoid these costly reinforcements is to utilise power electronics. The UK Power Networks project called Flexible Urban Networks – Low Voltage (FUN-LV) explored the use of connecting multiple feeders with power electronics. This paper reports on the design of the control algorithm and demonstrates the operation by presenting field trial results.

INTRODUCTION

Generation in the distribution network causes the voltage to rise and this phenomenon limits the amount of generation that can be connected. The electrification of loads such as heat pumps and electric vehicles is likely to increase the peak load. This may cause excessive power flows to occur and low voltages at the end of feeders.

Voltage constraints may be solved by changing the tap of the secondary-side of the distribution transformer. This may solve one feeder but it could cause a new voltage constraint on another feeder. Excessive power flows may be solved by meshing the network to allow multiple transformers to share the loads. However, this increases the fault current, which could then exceed the protection rating of existing equipment. Reinforcing the network is another solution for solving network constraints. However, this can be costly and cause disruption to the local area. Power electronic solutions have been proposed in the literature as solutions for voltage constraints [1] and thermal constraints [2]. These devices are able to support the voltage on one feeder without directly affecting the voltage on the other feeders, not significantly increase the fault current and may be able to defer reinforcements.

UK Power Networks explored the use of power electronics in the project Flexible Urban Networks Low Voltage (FUN-LV). The aim of the project was to increase latent capacity in the low voltage network by allowing or performing transformer equalisation between secondary (distribution) substations. The project was awarded funding under Ofgems's Low Carbon Networks Fund. UK Power Networks led the project, with partners including Ricardo Energy & Environment, Imperial Consultants Ltd, GE Grid Solutions (UK) and CGI UK. The project trialled three types of power electronic devices. (1) Circuit Breakers and Link Box switches (provided by EA Technology Ltd), (2) dual-terminal 2-port Soft Open Points (SOP), and (3) multi-terminal 3-port SOPs (both SOP Methods provided by Turbo Power Systems).

This paper describes the SOP technology and the algorithm designed to enable the SOP to solve thermal and voltage constraints. Field trial results presented in this paper demonstrate correct operation of the algorithm.

SOFT OPEN POINTS

SOPs connect feeders through power electronic devices (PEDs) at the normally open points in the distribution network. These devices consist of multiple voltage source inverters (VSIs) which share a common DC bus. SOPs in simulation on an example 11 kV network showed that the amount of distributed generation could be increased without exceeding thermal or voltage limits and therefore without the need for reinforcement [3].

In a typical SOP, each port (which is a single VSI) may have three or four ways. Distribution networks of 11 kV and higher are typically three wire systems (three ways) and the low voltage (0.4 kV) networks are typically four wire (four ways). Ports with three ways will only be able to control positive sequence and negative sequence current and ports with four ways will be able to control positive, negative and zero sequence currents.

The dual-terminal (back-to-back) and multi-terminal PED were considered in FUN-LV and shown in Fig. 1. Each port of the SOP had three ways and the SOP included a separate common VSI used to control the neutral currents. The neutral conductor of each feeder connected to the SOP, was connected to the common neutral VSI. The common neutral conductor enabled the SOP to supply neutral current into the network and effectively allowed each port to have four ways. However due to the coupling of the neutral conductors for each feeder, the SOP was not able to control which neutral conductor would carry the neutral current from the SOP.

The SOP controlled real power from one port to another port and independently controlled reactive power for each port. If there is no storage or generation attached to the DC bus, then the sum of the real power for each of the terminals (two for the dual-terminal and three for the multi-terminal) will be equal to the losses associated with the converter including any ancillary supplies used for the control and cooling. If the converter was ideal and lossless, then the real power summed at the terminals would be equal to zero. The DC bus provided galvanic isolation, which prevented fault current passing from one feeder to another feeder.

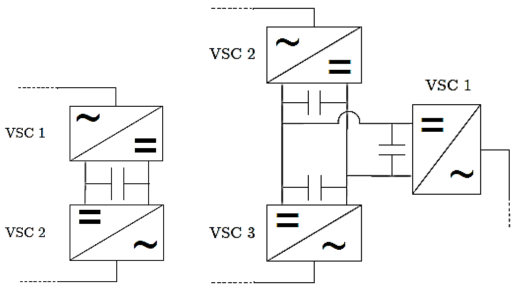

Fig. 1. The dual-terminal and multi-terminal SOP that was trialled in FUN-LV

One of the VSIs in the SOP regulated the DC bus voltage and acted as the slack bus. This VSI ensured that the total real power transfer of the SOP was equal to the losses of the SOP. Other VSIs (one for the dual-terminal and two for the multi-terminal) controlled real power. Each VSI independently controlled reactive power.

SOP ALGORITHM

This paper describes the operation of the algorithm when the SOP was placed in the modes transformer equalisation and voltage support. Power factor correction and unbalance compensation were also developed but are not discussed.

The aim of transformer equalisation was to balance the transformer loading according to the capacity of the transformer. Real power was used to move the load from one transformer to another. For example, consider a network with a SOP where one transformer is at 50 % utilisation and the other transformer is at 100 % utilisation. For the two transformers to operate at 75 % utilisation load is increased on the transformer at 50 % utilisation and load is decreased on the transformer at 100 % utilisation. By sharing the load latent capacity in the network is released which can enable the connection of more load to the transformer that previously operated at 100 % utilisation.

In voltage support mode, when the voltage was high the SOP would act as a load by importing real power to reduce the voltage. When the voltage was low, the SOP would act as a generator by exporting real power to increase the voltage. Real power was used because low-voltage cables have a low X:R ratio and are more sensitive to real power than to reactive power.

Architecture

The SOP included a low-level controller, which used a digital signal processor (DSP), and a high-level supervisory algorithm, which used a programmable logic controller (PLC). The low-level controller computed the DC bus controller and the PQ controllers. The supervisory algorithm processed measurement information from remote and local sensors. This received information enabled a balanced three-phase real power set point to be calculated for each of the ports (two ports for the dual-terminal and three ports for the multi-terminal SOP). The VSI selected to control the DC bus voltage did not required a P set point. However, calculating the P set points for each port allowed any of the three VSI to operate as the DC bus controller without the need to inform the supervisory algorithm. The low-level controller operated at 5 kHz (once every 0.0002 s) and the supervisory algorithm operated at 0.1 Hz (once every 10 seconds).

Measurements Received by the SOP

The supervisory algorithm received measurements of RMS voltage from the substation-bus bars. RMS current, real power, reactive power from both the secondary side of the transformer and the feeder that connected to the SOP at the connection of the feeder to the substation-bus bars. These measurements were not local and required remote sensors and a communications link. The supervisory algorithm also received local measurements of voltage, current, real power and reactive power from the terminals of the SOP. All measurements were single phase and the supervisory algorithm received a data point for each phase of the three-phase network.

The supervisory algorithm updated the set point every 10 seconds (6 times a minute). Local measurement data was received every 10 second and remote measurement data received every minute. To increase the performance of the algorithm a simple estimation algorithm estimated the remote measurement values for the time intervals without measurement data. This was achieved by assuming that any change in real and reactive power at the SOP was also observed at the feeder connection to the substation and the transformer. For example, if the transformer measurement for real power was 100 kW of load, the feeder measurement was 50 kW and the change in SOP output for the new set point was 10 kW of generation, then the estimated transformer real power would be 90 kW (100 kW – 10 kW) and feeder would be 40 kW (50 kW – 10 kW). Voltage at the remote measurement was assumed not to change and this parameter was updated every minute. The estimated current was calculated from the previously measured voltage, the estimated real power and estimated reactive power.

Integral with Hysteresis Algorithm

Each support function had associated set and reset thresholds, which the user programmed during the commissioning of the SOP. The thresholds determined when the SOP should and should not be providing support. When the condition for the set-threshold was satisfied, the SOP increased its output using a constant ramp (integral) function. When the condition for the reset-threshold was satisfied, the SOP decreased its output using a constant ramp (integral) function until the SOP output was zero. When neither the set nor reset thresholds were satisfied the SOP then held its output (next set point is equal to the previous set point). Fig. 2 shows an example of voltage support. The set-threshold was satisfied when the voltage was above the set-threshold and the reset-threshold was satisfied when the voltage was below the reset-threshold.

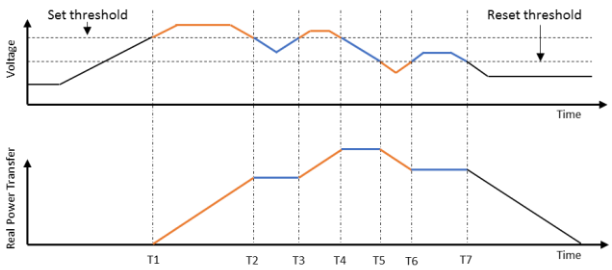

Fig. 2. Diagram showing the operating principle of the algorithm. Top graph shows the voltage as measured by the SOP and the bottom graph shows the output of the SOP in response to the voltage measurement.

Before T1: At T=0 the SOP was transferring zero power. The voltage at the terminal of the SOP was below the set-threshold and subsequently the SOP output remained in the same state and transferred no power. **At T1:** Voltage measured at the terminal of the SOP surpasses the set-threshold and the SOP responds by transferring real power. Real power increased at a constant rate and continued to ramp-up output (integral function) until the voltage was less than the set-threshold. **At T2:** Voltage was below the set threshold but above the reset-threshold. Subsequently the output of the SOP was held (previous set point equal to next set point). **At T3:** Voltage rises above the set-threshold and subsequently the SOP starts to ramp the real power transfer. **At T4:** Voltage again falls below the set-threshold but was above the reset-threshold. The SOP subsequently held its output. **At T5:** Voltage falls before the reset-threshold and the SOP reduced its output at a continuous ramp-rate (integral function). **At T6:** Voltage increased above the reset-threshold but below the set-threshold. Output of the SOP held constant. **At T7:** Voltage falls below the reset-threshold and the SOP reduced its output at a continuous ramp-rate (integral function) until the output of the SOP returned to zero.

Protection Features

Asset Guarding

Asset guarding was designed to protect the network from the operation of the SOP and prevent the SOP from causing the current at the feeder, current at the transformer and voltage at the terminal of the SOP from being outside of their operating limits.

When a port of the SOP was exporting power (acting as a generator), asset guarding would operate when the voltage was greater than the maximum voltage threshold or when the reverse current in the feeder or transformer was greater than their respective maximum reverse current ratings. If the feeder or transformer was loaded (not reverse current flow) and the current was greater than the maximum current rating, then asset guarding would not operate because the SOP would not be causing this network condition and support from the SOP would be required to solve the thermal constraint.

When a port of the SOP was importing power (acting as load on the feeder), asset guarding would operate when the voltage was less than the minimum asset-guarding voltage or when the load current on the feeder was greater than the maximum current rating.

Input Data Range Check

The supervisory algorithm performed a check to ensure that each measurement data point was in range and received within a certain time. Measurement data that failed the range check and latency check caused an error and the algorithm subsequently ignored this measurement. All support functions associated with this measurement were then disabled. Mal-operation of the supervisory algorithm could result if the next set point was calculated from incorrect measurement data. There was no provision to check that the real power and reactive power measurements agreed with the current and voltage measurements.

Support Functions

Transformer Equalisation

Transformer equalisation balanced the loading between two substations for the dual-terminal SOP and three substations for the multi-terminal SOP. A minimum of two ports must be enabled for this feature to operate. For the dual-terminal device this was both ports and for the multi-terminal device the third port may be disabled or operate in another support mode.

The real power measurement was normalised with respect to the rating of the transformer by calculating the utilisation. This was defined as the sum of the real power demand for each phase of the transformer divided by the transformer rating as shown in equation (1). The rating of the transformer was programmed during the installation of the SOP.

$$U_{Tx} = \frac{P_{L1}+P_{L2}+P_{L3}}{Transformer\ Rating} \quad (1)$$

Total utilisation, shown in equation (2), calculated the combined utilisation of the transformer at each port enabled in transformer equalisation mode. This calculated value is different from the mean of the transformer utilisations.

$$T_{Tx} = \frac{\Sigma(P_{L1}+P_{L2}+P_{L3})}{\Sigma(Transformer\ Ratings)} \quad (2)$$

For each port enabled, the difference between the transformer utilisation U_{Tx} and the total utilisation T_{Tx} was calculated. The calculation defined positive values for when the transformer utilisation was greater than the total utilisation (over-utilised) and negative for when the transformer utilisation was less than the total utilisation (under-utilised).

If two transformers had the same rating, then when one port satisfied the over-utilised set-threshold, the other port would satisfy the under-utilised set-threshold. The SOP would act as a load to increase the load of the under-utilised transformer and act as a generator to decrease the load of the over-utilised transformer. However, if the transformer ratings were different or if the transformers were being equalised across three ports. Then then the situation could occur where only one port or only two of the three ports satisfied either an under-utilised or an over utilised set-threshold. In this situation, the algorithm would solve the port with the triggered threshold. The other ports (or two ports for the multi-terminal SOP) would apply the reverse power set points. For example, if Port A required 10 kW of load, then the set point for Port B and Port C would be 5 kW of generation each. This insured that the requirement for the real power across the SOP to sum to zero was satisfied (excluding losses).

Voltage Support

The SOP received the voltage measurement for each phase and for each port. For upper-voltage support, the SOP used the maximum voltage of the three phases and for lower-voltage support, the SOP used the minimum voltage of the three phases. This enabled the SOP to support unbalanced voltage and ensure that each phase satisfied either the upper voltage or lower voltage set-threshold. If both the lower voltage threshold and the upper voltage threshold were triggered for different phases on the same port, then the SOP would not be able to respond and subsequently would not operate.

If two ports satisfied the upper-voltage set-threshold and one port satisfied the lower-voltage set-threshold, then the algorithm would import on two ports to solve the high voltage and export on the other port to solve the lower-voltage constraint. If only one port satisfied a set-threshold, then the algorithm would export or import power to solve that condition and apply the reverse power set point to all other enabled ports. The algorithm would ensure that the real power across the SOP to summed to zero.

FIELD TRIAL RESULTS

Transformer Equalisation

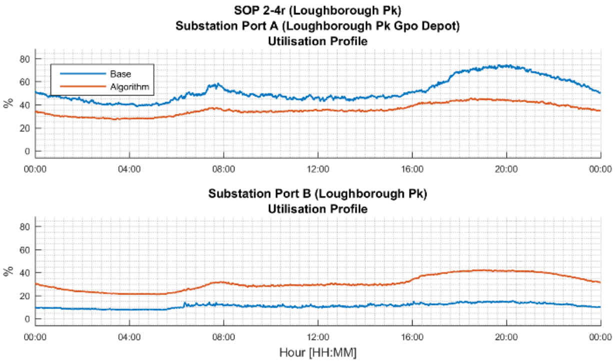

Fig. 3. Utilisation profile for when the SOP was in operation (algorithm) and when the SOP was not in operation (base) for a dual-terminal SOP.

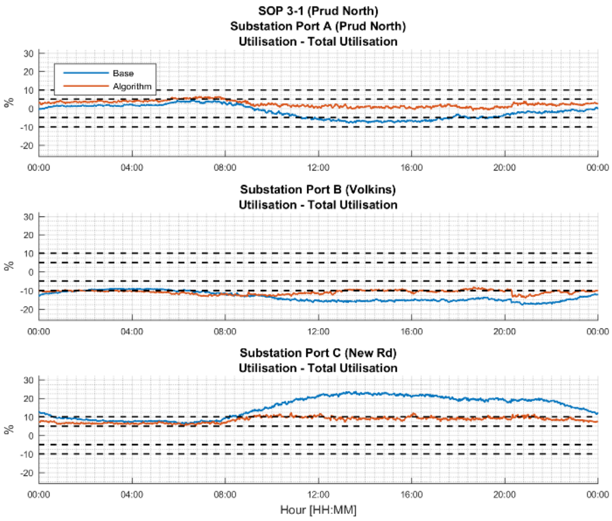

Fig. 4. Utilisation minus total utilisation demonstrating the algorithm set-threshold and reset-threshold for a multi-terminal SOP in transformer equalisation. The dotted lines indicates the set-thresholds and reset-thresholds.

Fig. 3 shows the transformer utilisation for SOP 2-4r for when the algorithm was in operation and when the algorithm was not in operation. The algorithm reduced the utilisation of the heavily loaded transformer at Port A and increased the utilisation on Port B. More load could now be connected to Port A without needing to increase the capacity of the transformer.

Fig. 4 shows the difference between the utilisation (equation (1)) the total utilisation (equations (2)) for each of the three ports of SOP 3-1. The algorithm has increased the loading for the transformers connected to Port A and Port B and reduced the loading connected to Port C. The difference between the utilisation and the total utilisation was at the set-threshold of 10 % difference. Substation A was less than the reset value because this was the solution such that the power transfer between all three sites was equal to zero.

Voltage Support

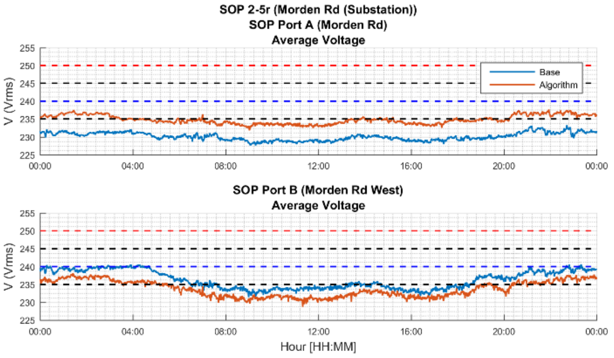

Fig. 5. The SOP supporting the voltage for a dual-terminal device. The maximum voltage for asset guarding was set to 250 V; the set-threshold was set to 245 V for the upper-voltage and 235 V for the lower-voltage. The reset-thresholds were set to 240 V.

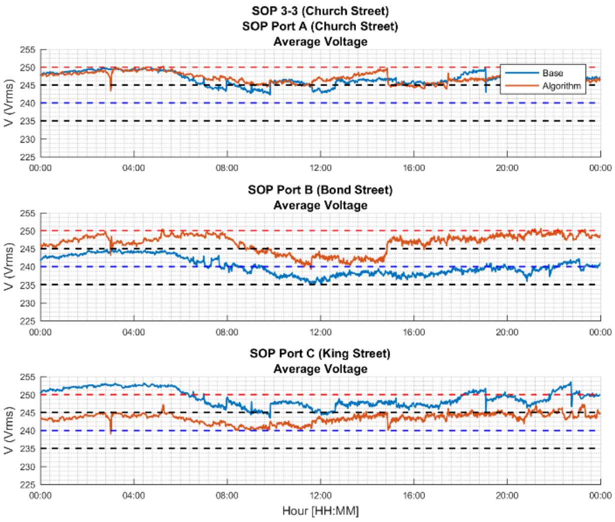

Fig. 6. The SOP supporting the voltage for a multi-terminal device. Port B and Port C was operating in voltage support mode.

Fig. 5 shows when SOP 2.5r was placed into voltage support mode. The algorithm increased the voltage at Port A and reduced the voltage at Port B. When the SOP was initialised, the voltage at Port A was less than the lower-voltage set- threshold (support required) and the voltage at Port B was between the upper set-threshold and lower set-threshold (no support required). As expected, the SOP supported the port where the set-threshold had been triggered. The SOP exported on Port A to increase the voltage. To maintain the power sum of zero across the SOP, Port B imported real power. This caused the voltage at Port B to reduce. The algorithm expected the voltage on Port B to reduce, ignored the lower-voltage set-threshold and used the low voltage asset-guarding threshold. Power transfer across the SOP would now reduce if the voltage went below 218 V.

Fig. 6 shows a multi-terminal SOP placed into voltage support for Port B and Port C. Port A was located with a short cable to the transformer, and voltage support disabled for this port. The algorithm would have used this port to support the other two ports until the measurement reached the asset-guarding limit (indicated by the red dotted line). The voltage at Port C was greater than the set-threshold and the SOP increased the load on this feeder and successfully reduced the voltage. Port A and Port B ensured that the real power of the SOP summed to zero. Subsequently the voltage at Port B increased to near the asset-guarding limit, which happened to be above the set-threshold. Voltage equalisation between Port B and Port C may have provided a better solution.

CONCLUSIONS

This paper has described the SOP algorithm developed for the UK Power Networks led project FUN-LV. Field trial examples provided evidence to demonstrate the operation of the SOP in a distribution network. Transformer equalisation successfully released capacity and voltage support locally increased or decreased the voltage at the end of the feeder.

Acknowledgments

This project has been dependant on the valuable contributions of all of the project partners and suppliers. In particular, the contributions of Claire Newton, Simon Terry and Cliff Walton (all of Ricardo Energy & Environment) and Thazi Edwards (UK Power Networks) have been critical. Additional acknowledgement is also made of the Ofgem Low Carbon Networks Fund without which the project would not have been possible.

REFERENCES

[1] T. Frost, P. D. Mitcheson and T. C. Green, "Power electronic voltage regulation in LV distribution networks," *2015 IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Aachen, 2015, pp. 1-7.

[2] W. Cao, J. Wu and N. Jenkins, "Feeder load balancing in MV distribution networks using soft normally-open points," *IEEE PES Innovative Smart Grid Technologies, Europe*, Istanbul, 2014, pp. 1-6.

[3] J. M. Bloemink and T. C. Green, "Benefits of Distribution-Level Power Electronics for Supporting Distributed Generation Growth," in *IEEE Transactions on Power Delivery*, vol. 28, no. 2, pp. 911-919, April 2013