D-Suite

Control Algorithm: Control Architecture and Performance

Future Networks

ABOUT REPORT

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REPORT PROGRESS

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1/3/24	V 1.0	First version.
18/3/24	V 1.1	Updated executive summary and formatting for ENA SNP.

Executive summary

This report presents the control architecture which has been developed to facilitate network-level control of power electronic devices within low voltage distribution network as part of the Alpha phase of the D-Suite Strategic Innovation Fund project. The control architecture maps out the key elements of the control system and the data and power flows required for its realisation. The control architecture consists of three control modes:

Offline Schedule mode makes use of forecast and historical data to determine the operation of the devices in advance (day ahead, or seasonally where appropriate). This approach also acts as a fail-safe for other modes in the event of loss of communication.

Real-Time mode tracks network congestion using live measurements available locally to the D-Suite device. If operational limits of the network are breached, the control setpoints for the D-Suite devices can be updated using these measurements. This can increase the utilization of D-Suite device capacity where congestion forecasts are less accurate.

Main Control uses live measurements to calculate operating points for D-Suite devices in real-time via a centralized optimization platform, enabling coordination of multiple devices where there are complex interactions (for example, in interconnected networks).

The control objectives and actions are identified within the report, and these are mapped onto the devices with recommended control modes in each case. The set points can be calculated using either rule-based or optimisation approaches, and the advantages and disadvantages of each are discussed.

The report demonstrates the control scheme on two case studies, one using Real-Time mode to control a D-STATCOM mitigating current unbalance, and another using Offline Schedule control to manage both bulk power transfer and imbalance correction using two D-SOPs. In both cases, optimisation and rule-based approaches are compared demonstrating the trade-off between operating costs and complexity.

The work conducted in the Alpha phase has a number of key learnings, leading to recommendations to take forward into the Beta phase.

- Evaluating the three control types in the control architecture highlights that, for most applications, centralized Main Control is not required. If this approach can be avoided, it will be possible to integrate D-Suite into a DNO's network and internal processes with many fewer interactions and therefore lower risk and resource requirements.

  D-Suite Beta recommendation: it is suggested to avoid Main Control approach in the Beta phase, focussing on rule-based control methods instead. Main Control can be considered a future option as D-Suite rolls at a wider scale.

- The use of Real-Time control is necessary to increase the utilization of D-Suite devices for providing network capacity when there is substantial uncertainty in congestion forecasts, as can be the case for activities such as phase current unbalance mitigation. Offline Scheduled control is effective when control actions are highly predictable (e.g., mitigating congestion during an evening peak).

  D-Suite Beta recommendation: consider demonstration case studies which allow for a comparison of Real-Time and Offline Scheduled control in network trials.

- The roll-out of LV monitoring at secondary substations represents an opportunity for D-Suite devices to provide real-time control without requiring additional monitoring points to be installed. Similarly, the use of Smart Meter infrastructure also represents an opportunity to schedule and assess the impact of voltage control actions.

  D-Suite Beta recommendation: ensure data pipelines are be set up to leverage both smart meter and LV monitoring data sources in network-level control actions.

- This report been developed to mirror the requirements for a formal network-level control tendering as required in Beta. It is therefore suggested that this report form the basis of the network-level tender document in Beta, with this leverage reducing the risk and complexity of the control development.

  D-Suite Beta recommendation: develop control tendering using findings from D-Suite Alpha phase.

Glossary

CUF	Current unbalance factor
DNO	Distribution Network Operator
D-SOP	D-Suite Soft Open Point
D-ST	D-Suite Smart Transformer
D-STATCOM	D-Suite Static compensator
HV	High voltage
LV	Low voltage
MC	Main Control
OS	Offline Scheduled control
PED	Power electronic device
PF	Power factor
RT	Real Time control
SIF	Strategic Innovation Fund
SPD	SP Distribution (service area)
SPM	SP Manweb (service area)
Th-F	Thermal congestion - feeder level
Th-SS	Thermal congestion - substation level
VM	Voltage magnitude congestion
VUB	Voltage unbalance congestion

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1. Introduction

As energy systems transition towards net zero, distribution network operators (DNOs) must maintain adequate network capacity to supply demand whilst maintaining power quality and appropriate levels of service. Capacity constraints limit the power transfer capabilities of power distribution networks. This includes maintaining thermal constraints of assets (e.g., transformers, cables or overhead lines), maintaining safe operating voltages for both customers and assets, and also ensuring high levels of power quality (e.g., voltage unbalance) to enable high utilization of sensitive loads. Should uptake of low carbon technologies (such as electric vehicles and heat pumps) follow projections necessary to meet the UK government's carbon budgets, it has been estimated that up to £64 bn will need to be invested by 2050 to reinforce LV distribution networks alone.

The D-Suite project aims to provide a suite of power electronic device (PED)-based solutions that can be installed by a DNO at low voltage to address congestion. Such an approach maximises the utilization of existing network assets, removing or deferring the need for upgrades. For example, if the demand across the two sides of a normally open link box (i.e., a normally open point, NOP) varies with time, then the utilization of both sides of the feeder can be increased by transferring power through a PED-based Soft Open Point, or D-SOP.

In this report, a proposed control scheme is developed for three D-Suite devices: the smart transformer (D-ST), the static compensator (D-STATCOM), and the D-SOP. Each device can provide multiple services and congestion mitigation mechanisms for the DNO. Therefore, a general overall control scheme is developed that has potential to provide all of the services required of the D-Suite devices. Operation during normal and emergency (failsafe) conditions are considered, as well as variation in operation in radial versus interconnected topologies. Rule-based approaches are proposed as an approach for controlling most D-Suite device functionality, and two case studies demonstrate good performance as compared to a full-information, optimal controller.

1.1. The D-Suite Solution

The three D-Suite devices considered in this report (D-ST, D-STATCOM, D-SOP) can address some or all of: voltage magnitude (VM) congestion, thermal congestion on feeders (Th-F), thermal congestion in substation transformers (Th-SS), and voltage unbalance (VUB). Therefore, they have potential to mitigate congestion caused by low carbon technologies. In this section, we briefly introduce these technologies to highlight the main congestion issues they can address.

1.1.1. D-STATCOM

A D-STATCOM is a PED that consists of a three- or four-leg power converter connected in shunt to the individual phases of the LV distribution system (Figure 1.1). By controlling the currents injections from each leg of the D-STATCOM, the powers flowing in each phase of the network can be adjusted. A D-STATCOM can also inject balanced reactive power to adjust voltages. In contrast to transmission-connected STATCOM devices, the D-STATCOM is primarily envisioned as a device for providing steady-state congestion mitigation, rather than dynamic voltage control. This is because dynamic voltage stability is not a major concern in distribution networks, and because phase unbalance is much more likely in distribution (as the aggregation effects seen at higher voltages are not as applicable at LV).

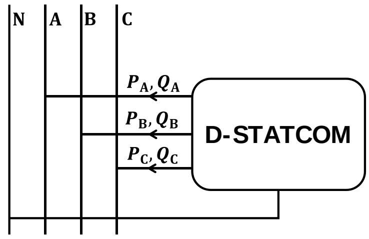


Figure 1.1 The D-STATCOM can inject active and reactive power into a network subject to current and power balance constraints within the device. Both balanced and unbalance current injections are possible, with the neutral wire enabling injection of zero sequence current.

1.1.2. D-SOP

A D-SOP is a PED constructed of back-to-back converters (Figure 1.2), and is conventionally installed in-place of a normally open link box. As compared to a STATCOM, it has increased flexibility as it can allow active power to be transferred between feeders. As with the STATCOM, the neutral connection enables increased flexibility for the converter when injecting unbalanced powers into the active phase legs A, B, C.

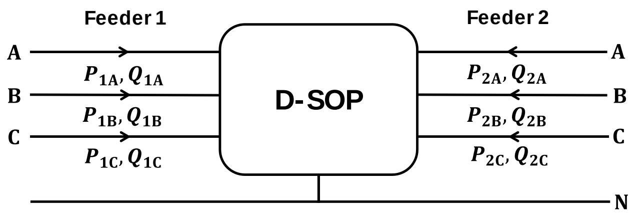


Figure 1.2 Distributed Soft Open Point (D-SOP). As with the D-STATCOM, the D-SOP can inject arbitrary active and reactive powers into the phases of each feeder, but can also transfer active power between feeders.

1.1.3. D-ST

The D-ST is the most complex of the D-Suite devices. As with the D-SOP, the power electronics are constructed of a back-to-back PED. In contrast, however, these devices are connected in a shunt-series configuration, as shown in Figure 1.3, with a series transformer enabling a partially rated PED to inject a voltage V which can be used to adjust the voltages and currents on the secondary side of a distribution transformer. The active and reactive power P, Q is required to inject the voltage from the series converter.

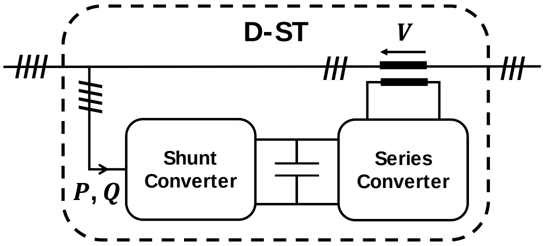


Figure 1.3 Distributed Smart Transformer (D-ST) has a shunt-series connection to enable a voltage injection (V) across a series transformer, enabling voltage magnitudes in the network to be controlled. Active and reactive powers (P, Q) are drawn to enable the voltage injection. As with the D-SOP and D-STATCOM, the voltage and power injections can be unbalanced (not shown for simplicity).

2. Control Architecture

This section presents a control architecture, which comprises a unified structure and device-specific rules which will enable D-Suite devices to mitigate a network congestion. In particular, it presents:

- The three types of control that can be implemented to mitigate congestion, depending on the available measurements (either real-time or historic) and whether the D-Suite device is connected to a radial or interconnected network.
- The actions D-Suite devices do or not take when there is loss of communication channels when the control is implemented.
- How is the control implemented: where may the measurements points be placed with respect to the D-Suite device and how information flows to enable control setpoints to be determined (to be passed to lower-level control loops used by the power electronics).

2.1. General Control Architecture

This section introduces the general control scheme for each control type (Offline Scheduled (OS), Real-Time (RT), and Main Control (MC)), and presents the steps used implement the offline and the real time control approaches.

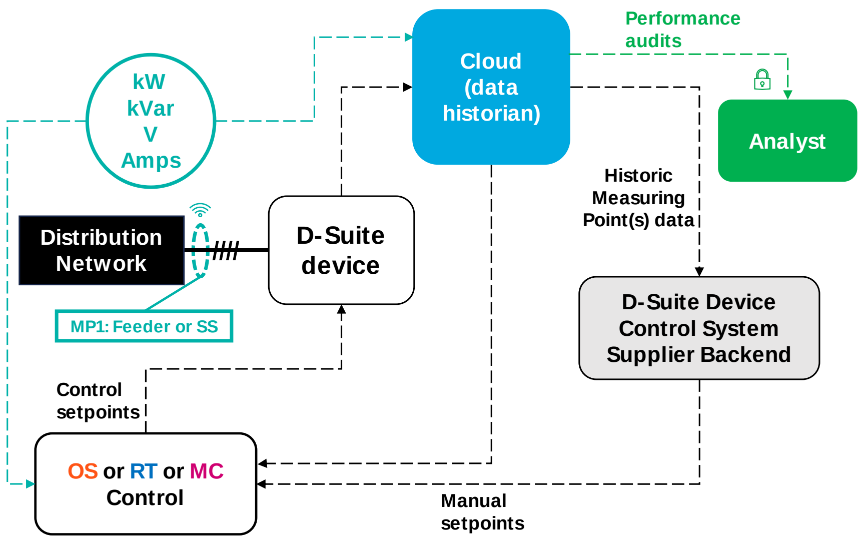


Figure 2.1 Proposed D-Suite device control system schematic. The D-Suite device (D-STATCOM, D-SOP or D-ST), is controlled using one of three control modes (OS, RT or MC). This controller can use measurement points (MPs) directly, or historic data from MPs (and smart meters) from the Cloud. Manual setpoints can also be set from D-Suite Device Control System Supplier's backend. Performance audits can be carried out by an analyst by considering measured utilization and measurements from the system.

For control implementation there are three main components which receive, store, or send data. These are the cloud (data historian), the measuring points (MP) across the network, and the D-Suite device controller, which may perform OS, RT or MC control. The management of the control system is performed by the control system supplier backend to an agreed policy, and performance audits will be available from the cloud (data historian) to the analysts through a secure communication channel.

The functions and communication flows of these points and entities are as follows.

- D-Suite device controller
  The D-Suite device controller performs OS, RT or MC control. When operating under normal operating conditions (i.e., with all communication channels open), the controller performs the highest-level control that is available. In the event of loss of communications, the control system operates under 'emergency (failsafe) operating mode': the D-Suite device will move down the control approach hierarchy, eventually following pre-determined set points (i.e., using OS control).

- Measuring Points
  Measurements will be taken from DNO-owned measurement devices installed in the network. These may be legacy measurements, or telemetry installed specifically for D-Suite control. Typically, these devices will report active and reactive power flows per phase (kW, kVar), voltage magnitudes (V) and currents (Amps). Each of those measurements will be made on a per-phase basis.

- Cloud (data historian)
  The Cloud will act as a data historian. It will receive and store data from the measuring points, as well as the scheduled and measured control actions taken by the D-Suite device. The data stored in the cloud will be accessible to the D-Suite device, control system supplier's backend, and to SPEN or third-party analysts.

- D-Suite device Control System Supplier Backend
  The control system supplier should provide a backend such that appropriate data can be taken from the Cloud, analysed, and then manual set points sent to the D-Suite device controller as required.

- Analysts
  Control analysts will have access to all historic data to perform performance audits.

2.2. D-Suite Device Control Approaches

Depending on the nature of the congestion and the configuration of the network, D-Suite devices may be controlled using one or more types of control. These are the offline scheduled control, the local real-time control or the centralised main control, as described in Figure 2.2. (Control objectives and control modes for D-Suite devices are outlined in Section 2.4.)

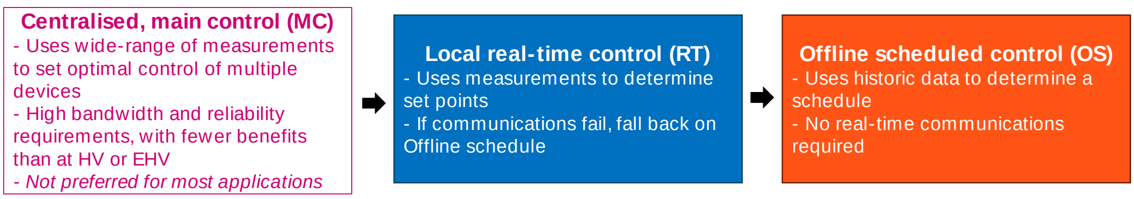


Figure 2.2 Hierarchy of control from most sophisticated to most robust, covering centralised main control (MC), local real time control (RT) and offline scheduled control (OS). Most D-Suite functionality can be achieved using only RT or OS control, and so MC is not preferred for most D-Suite applications.

2.2.1. Offline Scheduled (OS) Control Approach

OS control aims to define the D-Suite device set points in advance using historic data. Offline scheduled control does not rely on real time measurements, and therefore can be implemented even when there is a loss of communication channels between the measurement points, the Cloud (data historian), and D-Suite Device Controller.

Figure 2.3 outlines a general, detailed overview of this approach, showing how a forecasted network state can be used to develop a D-Suite device day-ahead schedule. The load and generation are forecast based on information that is available from the cloud (data historian). The day-ahead schedule is also then available to the control system supplier backend, or for inspection by analysts.

Note that, in many cases, a seasonal scheduling approach could also be feasible. This could be possible, for example, when congestion is at a predictable peak time period, is well-defined and there are no additional challenges of D-Suite device interactions.

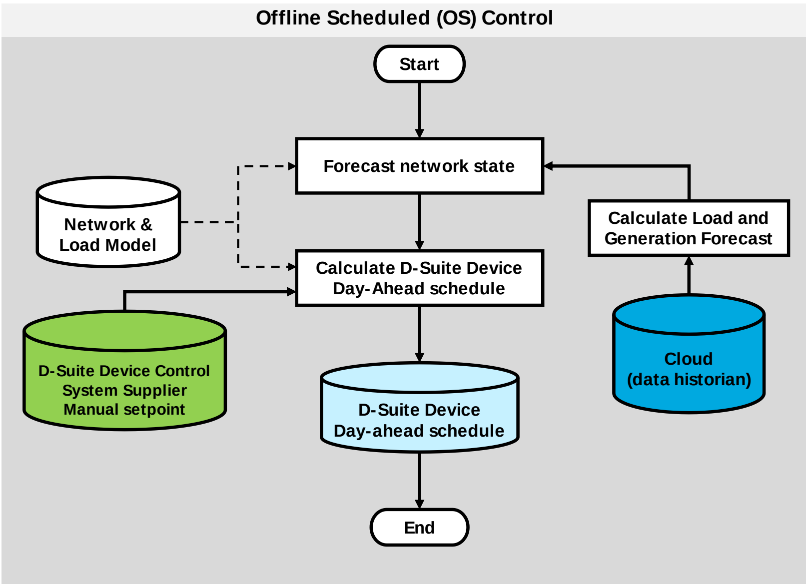


Figure 2.3. Offline Scheduled control general scheme for determining the day-ahead schedule. To calculate the D-Suite Device day-ahead schedule, the forecasted network state, the network and load models, and any manual setpoints from control system supplier may be used. If congestion is highly predictable, a weekly or even seasonal schedule can also be determined, improving predictability.

Ideally, OS scheduling is undertaken using a rule-based approach. Rule-based approaches use the known mechanisms of D-Suite congestion mitigation to choose a device operating pattern based on measured congestion levels. Alternatively, more sophisticated numerical routines (e.g., formal optimization-based approaches) could be used, although the increased complexity of these systems should be avoided unless there is a clear advantage to them (e.g., this operation could significantly reduce device losses or increase D-Suite device utilization).

Figure 2.4 shows a potential implementation of an OS control scheme for a D-STATCOM for providing power factor mitigation. If the load with a poor power factor has a predictable or constant load profile and the congestion profile at the transformer follows a standard profile (as determined using measurement point MP1), then the D-STATCOM can inject reactive power during periods of high demand to mitigate congestion at the transformer.

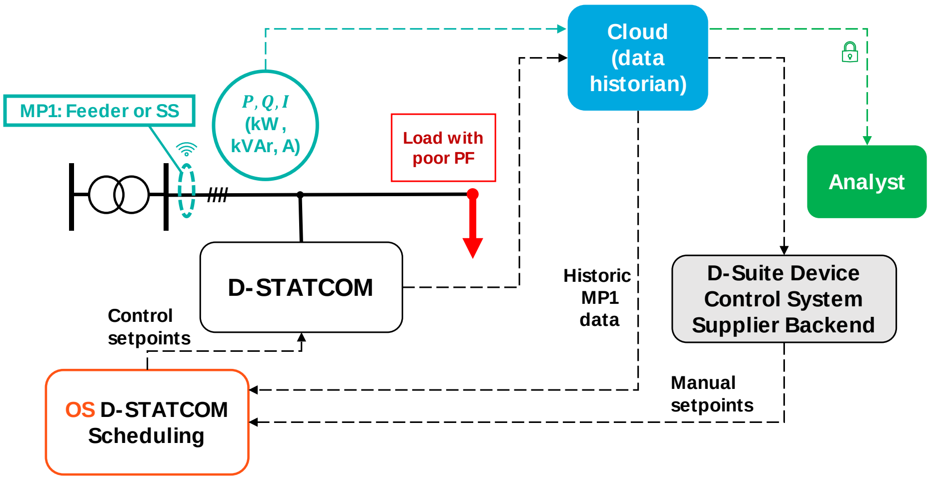


Figure 2.4 – D-STATCOM example control architecture Implementation for offline scheduled approach. Control mode: Power Factor correction. The D-STATCOM receives control setpoints from the controller which performs the OS schedule, whose control actions are also shared with the cloud (data historian). Feeder (or substation - SS) real/reactive power (P, Q), and current (I) measurements are available for the scheduler through the cloud. The controller receives information from the Cloud and the Control System Supplier Backend.

2.2.2. Local Real Time (RT) Control Approach

RT control uses real-time feedback from measurements installed in the LV network to determine the control set points of the D-Suite device. It is required when D-Suite devices deal with congestion that has a significant element of uncertainty associated with it, making congestion forecasts challenging or inaccurate. When this is the case, it will lead to increased utilization of the D-Suite devices as compared to a scheduled approach. As in OS control, RT control may be implemented using either a rule-based or an optimisation-based approach, with rule-based approaches preferred. It is assumed that a day-ahead schedule is determined, as with OS-based control, which will be used as a default schedule (which may be no injections).

Figure 2.5 shows a general implementation of such a control scheme. As compared to the OS scheduling approach (Figure 2.3), there is an additional decision made prior to setting the D-Suite device set point, based on the actual measured network state. Specifically, if the day-ahead schedule is deemed not to result in any congestion issues, then the D-Suite Device set point from the Control System Supplier is implemented. If it is deemed that there are congestion issues, then a new D-Suite Device set point is calculated using the network and load models and the day-ahead schedule. As with OS control, Analysts will be able to securely implement performance audits of the control process.

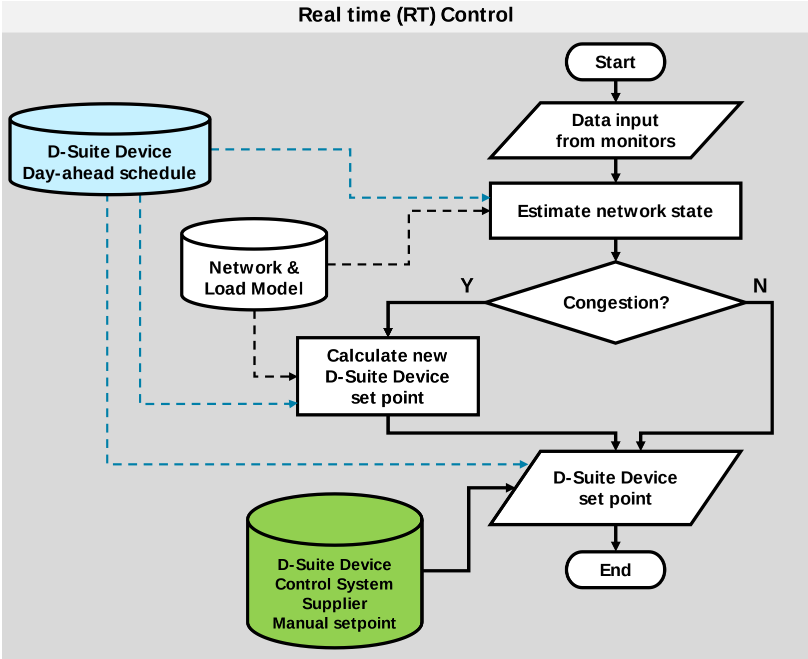


Figure 2.5 - Flow chart: Real time control. A D-Suite Device setpoint is calculated in case of a congestion. This process uses monitor data, and estimates network data according to the day-ahead schedule and the network and load models.

An example of this control architecture is shown in Figure 2.6. A D-SOP is operating in OS mode, and MPs 1 and 2 are providing data to ensure this does not lead to network constraints being violated. If the demand deviates significantly from the forecast, resulting in network congestion, then the D-SOP will switch to RT mode and new setpoints will be calculated based on the real-time measurements.

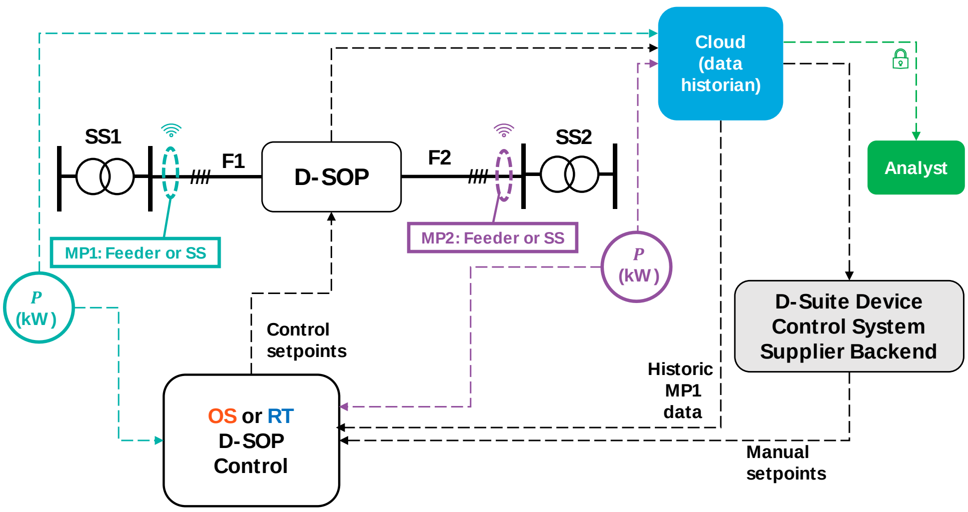


Figure 2.6 D-SOP example control architecture Implementation for RT control. The D-SOP is controlling active power injections for thermal congestion mitigation. If the OS schedule mitigates congestion accurately it is used; if real-time measurements show further congestion mitigation is required, the controller updates the setpoint from the RT scheduling algorithm.

2.2.3. Main Control (MC) Approach

MC control is used when the highest performance operation of a D-Suite device is required, when the control actions of D-Suite devices have strong interactions, or when a wider range of measurements are required to ensure correct operation of a D-Suite device. MC requires a more complex control implementation, and uses a wide range of measurements to control multiple devices. An optimization-based approach is used to schedule devices to ensure the highest performance of D-Suite devices.

An example of a device which would likely require the use of MC control is the use of a D-ST within an interconnected LV network, because the injection of a voltage results in a circulating current through the HV/LV system (Figure 2.7). Such a system would require measurements at a number of substations to ensure that the circulating current is supporting congestion management and not inadvertently overloading any other feeders or substation transformers.

It is envisioned that D-Suite will evolve using local control only in Beta phase. However, future work could investigate MC control approaches more comprehensively once D-Suite devices have been proven as a concept.

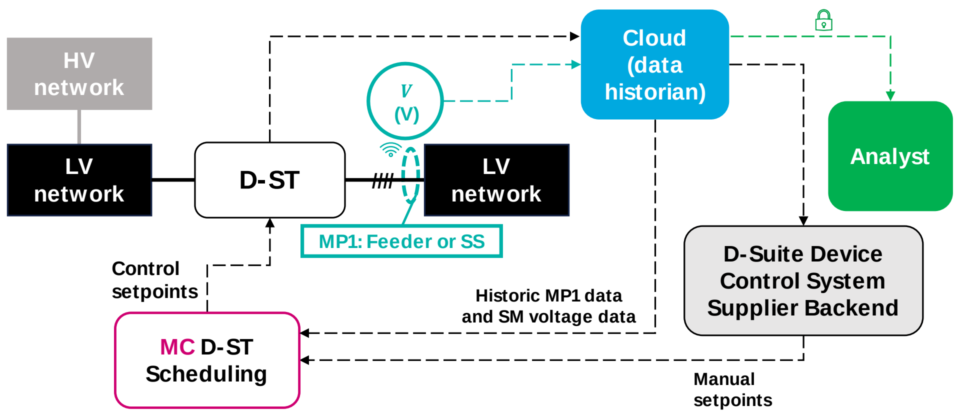


Figure 2.7 D-ST device between interconnected networks. An example of a potential use of the main control (MC) approach.

2.3. Operating under Adverse Conditions

To maintain good operation of D-Suite devices under adverse conditions (e.g., loss of communications), an emergency operation mode is required. For this purpose, it is proposed that D-Suite devices will transition to an OS scheduled approach.

The control types presented above use information that is acquired through local and central communication channels. In the event these channels fail to pass on information, due to a fault for example, the D-Suite device(s) will operate as planned in the offline scheduled control (which doesn't require real time information). This will be referred to as 'emergency (failsafe)' operation mode.

Figure 2.8 shows the control architecture for real time (RT) control using a D-STATCOM for current unbalance factor mitigation (CUF) under emergency (failsafe) operating mode. Real time measurements cannot be obtained due to loss of communication with the cloud, and so the D-STATCOM operates as planned in OS control.

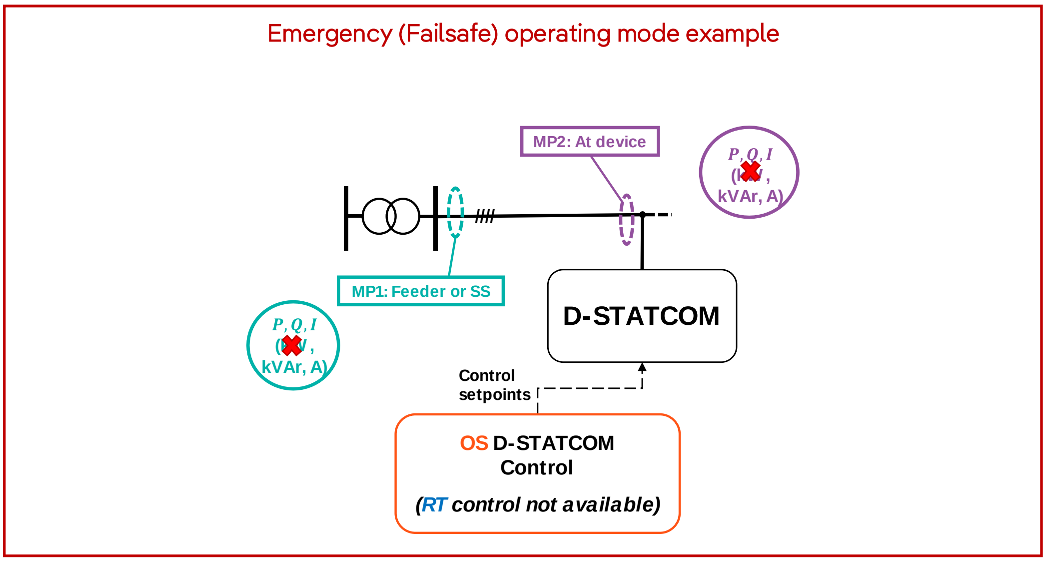


Figure 2.8. If there is a loss of communications, the D-Suite device moves to the emergency (failsafe) operating mode, where the D-Suite device operates under its schedule. This example shows this for a RT control approach for a D-STATCOM operating for an current unbalance mitigation control mode.

2.4. Control objectives

Four types of congestion present in LV distribution networks can be addressed:

- Thermal feeder (Th-F)
- Thermal substation (Th-SS)
- Voltage unbalance (VUB)
- Voltage magnitude (VM)

Depending on the cause and type of the congestion, the control objectives of D-Suite devices can vary. Nine different operating characteristics have been identified as providing a technical benefit, as follows.

- Current unbalance mitigation
- Reactive power injection for voltage control
- Power factor correction
- Negative sequence current injection
- Bulk power transfer for voltage or thermal congestion
- Voltage optimization (load-demand sensitivity)
- Voltage magnitude constraint violation mitigation
- Feeder load balancing
- Loss reduction

Appendix B (section 5.2) maps these control objectives to each of the D-Suite devices, and presents which control type may be most appropriate to address each congestion (OS, RT or MC) for radial and interconnected networks. The control variables for D-STATCOM, D-SOP and D-ST devices, whose value must be chosen by the scheduling algorithms, are presented in Table 2.1.

Table 2.1 D-Suite Devices: Control variable summary.

Technology	Control variables
D-STATCOM	▪ Active power injections per phase ▪ Reactive power injections per phase
D-SOP	▪ Active power injections per feeder per phase ▪ Reactive power injections per feeder per phase
D-ST	▪ Active and reactive power injections per phase (as for D-STATCOM) ▪ Voltage magnitudes and angles per phase

3. Control Performance

This section presents two case studies which demonstrate the capabilities of the proposed control scheme and quantify the benefits of different levels of complexity within the control design. These cases are picked as two of the six networks considered in the Alpha phase (Table 3.1).

In general, there are many different criteria that can be used to assess control system performance. Here, we focus on successful congestion mitigation (i.e., the ability to clear congestion as required), and the cost to deliver this in terms of total PED losses[1]. To enable an assessment of the proposed rule-based approaches, a full information, optimisation-based mathematical model has been developed for benchmarking. This model is described in Appendix A (Section 5.1) of this report.

Section 3.1 presents the first case study, exploring the benefits of using D-Suite devices to mitigate a thermal Transformer congestion in a rural network using RT control. Section 3.2 collects the second case study explores the benefits of using multiple D-Suite devices to mitigate thermal Feeder congestion on a suburban network using OS control.

*Table 3.1 Summary of basic properties of the six networks studied in detail. The network ID represents the service area (as SP Manweb, SPM or SP Distribution, SPD) and the type of network (as urban, U; suburban, Sl or rural, R). Per-demand demand is for the "Leading The Way" (LTW) future energy scenario. *For interconnected networks, only the rating of a single transformer is given.*

NTWK. ID	NO. CUSTOMERS	NO. FEEDERS	TOPOLOGY	TX RATING, KVA	2040 PER-CUSTOMER DEMAND (LTW), KW	FIRST CONGESTION YEAR (LTW SCNRO.)
SPM-U	283	4	Intrcntcd.	500*	2..37	2040
SPD-U	1260	6	Radial	1000	2.03	2023
SPM-S	1125	5	Intrcntcd.	500*	1.83	2040
SPD-S	453	5	Radial	750	2.20	2032
SPM-R	36	3	Radial	200	3.01	2040
SPD-R	24	2	Radial	50	3.33	2025

[1] A 95% efficient power converter of 100 kVA running throughout the year will result in 43.7 MWh losses/yr. At a cost of £40/MWh, this results in £1750/yr, or a present value of £26,652 over 20 years (considering a discount rate of 3.5%).

3.1. D-STATCOM – Addressing thermal congestion at substation (Control type: RT)

This section presents a case study in which RT control is implemented to address thermal congestion at a substation transformer using a D-STATCOM. Results show both the rule-based and optimisation-based approach control schemes described above.

The network used is a rural radial distribution network ('SPD-R') with D-STATCOM located as shown in Figure 3.1, using forecasted demand for the year 2035 in a winter day. Feeder and Transformer capacity are shown in the table below. A D-STATCOM of 30 kVA capacity is used (Table 3.2).

Table 3.2 D-STATCOM disturbance case study information.

CASE STUDY INFORMATION	
Network | Type	SPD-R | Radial
Demand Year | Season	2035 | Winter
No. of Feeders | Capacity	2 | 137 kVA, 225 kVA
No. of Transformers | Capacity	1 | 50 kVA
D-Suite Device | No. of Devices | Capacity	D-STATCOM | 1 | 30 kVA

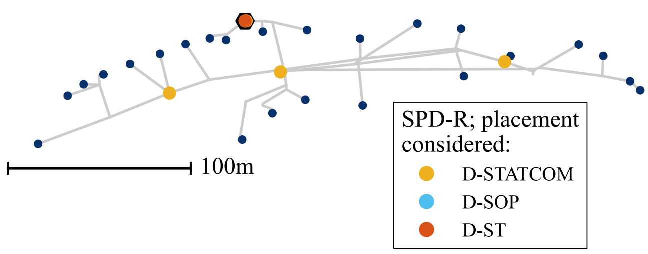
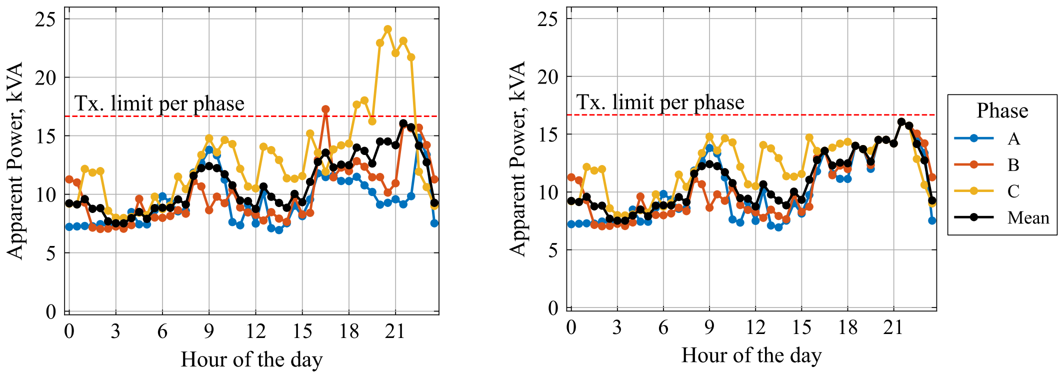


Figure 3.1 Rural radial network case study, showing the location of the D-STATCOM. Any of the four D-STATCOM locations could be used for congestion mitigation in this case study; no D-ST or D-SOP devices are installed.

With the state of the network before adding a D-Suite device, the Transformer would be overloaded at around 18:00 on a Winter peak day with the expected demand of 2035, as shown in **Error! Reference source not found.** (A). To avoid the Transformer thermal congestion, a D-STATCOM can be connected in the network and controlled using an RT mode (following Table 5.1). Using the proposed rule-based approach, the congestion can be mitigated (as shown in **Figure 3.2**); the Transformer capacity in phase 3 that was exceeding the upper kVA limit has been avoided using the D-STATCOM injections displayed in Figure 3.4.



(A): BEFORE D-SUITE MITIGATION

(B): AFTER D-SUITE CONGESTION MITIGATION

Figure 3.2 Transformer loading before and after the use of the D-STATCOM, demonstrating how D-Suite enables congestion mitigation to be achieved via rule-based control of the D-STATCOM active power injections.

To implement a basic rule-based approach, the active powers for phases A, B, C and any D-STATCOM device active injections, are measured at the congested transformer. The day-ahead schedule is assumed to have value zero, due to challenges accurately forecasting unbalance. Then, the loading of the underlying asset is calculated (i.e., the power that would be seen without congestion mitigation from the D-STATCOM). Using that underlying asset loading, the unbalance power injection vector is calculated within the capacity of the D-STATCOM device, which is then injected into the network.

These injections solve the network congestion but, as shown in Figure 3.4, this basic rule-based control over-uses the D-Suite device (e.g., the unbalance is mitigated even over the middle of the night when congestion is low). This results in unnecessary losses due to the PED throughout the day.

To counter this, the proposed rule-based approach includes a thresholding function, as plotted in **Figure 3.3**.. The value of the thresholding function is multiplied by the unbalance injection vector to yield the control sent to the D-STATCOM. For this case study, a the thresholding function is set as follows:

1. If all phase loadings are less than 90%, the D-STATCOM does not inject any power.
2. If the asset phase loading is between 90% and 100%, then the threshold multiplier linearly increases between 90% and 100%. (For example, if the asset loading is 95%, a 50% thresholding value, as 95% is 50% of the distance between 90% and 100%).
3. If the loading is greater than 100%, then the multiplier will be 100%.

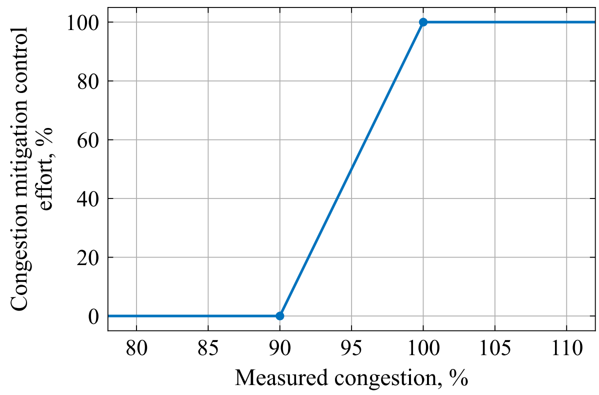
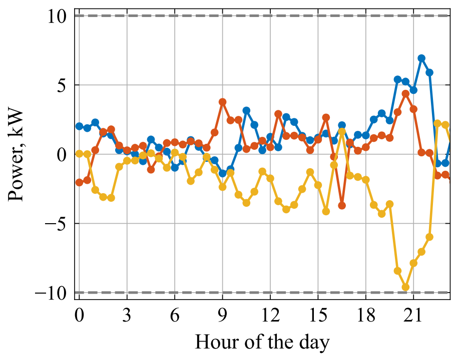
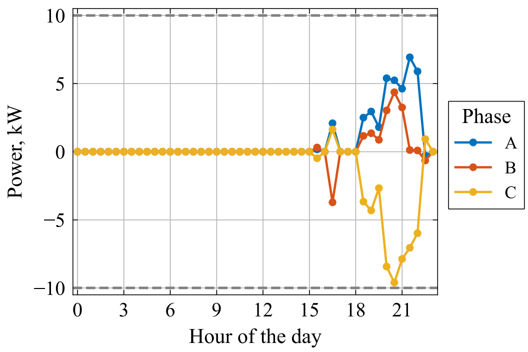


Figure 3.3 Thresholding function used to reduce D-STATCOM current unbalance mitigation during periods when congestion is low, to reduce system losses. Other thresholding functions could be used if they provide better performance.

The effect of thresholding is to only use the D-STATCOM to mitigate congestion when required, rather than throughout the day (and is performing the role of the 'Congestion' decision diamond in Figure 2.5). The output of this approach is shown in Figure 3.4, showing that there are no power injections before 15:00, due to the threshold.



(A): RULE-BASED, NO THRESHOLDING



(B): RULE-BASED, WITH THRESHOLDING

Figure 3.4 D-STATCOM real power injections per phase for the RT rule-based approach. Left – (A) : Without thresholding, indicating an overutilisation of the device (i.e., injecting unbalanced currents even when there is no congestion). Right- (B): With Thresholding, indicating a more efficient operation of the D-STATCOM.

The optimisation-based results are shown below in Figure 3.5, and represent the D-STATCOM injections when using an optimal control with perfect information, and may be used as a reference. The mathematical model formulation used in this case study for the optimisation-based approach is outlined in Appendix 5.1.

The rule-based approach which uses a threshold (Figure 3.4, right plot) delivers similar power injections to the optimisation-based approach, which indicates it may be a method which combines the simplicity of the no-threshold rule-based approach with the efficiency of the optimisation-based approach. This can be seem clearly considering the daily losses for the three methods (Table 3.3).

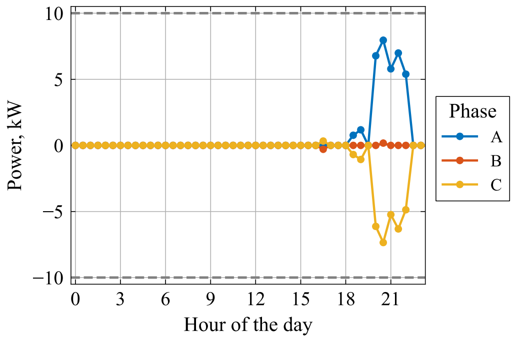


Figure 3.5 Optimisation-based approach: D-STATCOM real power injections per phase when using an optimal, perfect information approach, showing even more efficient device utilization than the rule-based control with thresholding (and therefore lower losses).

Table 3.3 Network losses for each control implementation approach, showing that the rule-based control with threshold results in good performance as compared to the full-information optimisation approach.

Methodology / Approach	Device losses, kWh
Full-information optimisation	1.68
Rule-based (with threshold)	2.74
Rule-base (no threshold)	6.55

3.2. D-SOP - Addressing feeder thermal congestion mitigation using multiple devices (Control type: OS)

This section presents a second case study in which OS control on a suburban distribution network ('SPD-S') where there is thermal congestion on two feeders on a peak winter's day in 2035. In the case study of this section, two D-SOP devices of 60 kVA and 90 kVA capacity are connected in the network to demonstrate the potential to mitigate congestion seen on this day. The network has five (5) Feeders and one Transformer with the capacities shown in Table 3.4 below. The location of the D-SOP devices in the network is shown in Figure 3.6.

Table 3.4 D-SOP case study information with OS type control.

CASE STUDY INFORMATION	
Network | Type	SPD-S | Radial
Demand Year | Season	2035 | Winter
No. of Feeders | Capacity	5 | 330 Amps
No. of Transformers | Capacity	1 | 500 kVA
D-Suite Device | No. of Devices | Capacity	D-SOP | 2 | 60 kVA, 90kVA

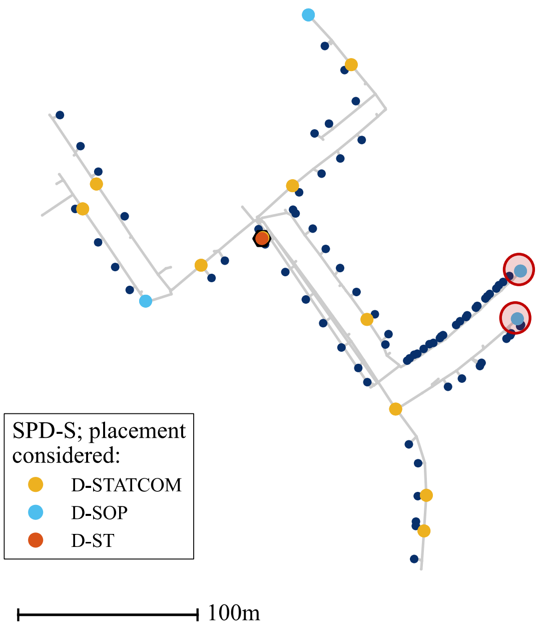


Figure 3.6 SPD-S suburban radial network case study. The location of the two D-SOP devices are highlighted with red circles; no other candidate D-Suite devices are installed.

Before adding the D-Suite devices, two out of five Feeders' capacity would be insufficient for demand year 2035 (Figure 3.7). In Feeder 1 this can be seen for phase B, whilst for Feeder 4 this occurs on phases A and C, all around 18:00. The congestion is following a typical domestic load profile pattern. As such, congestion mitigation during the evening peak will be well-suited to addressing this congestion. The proposed schedule for two D-SOPs is shown in Figure 3.8 to provide this service.

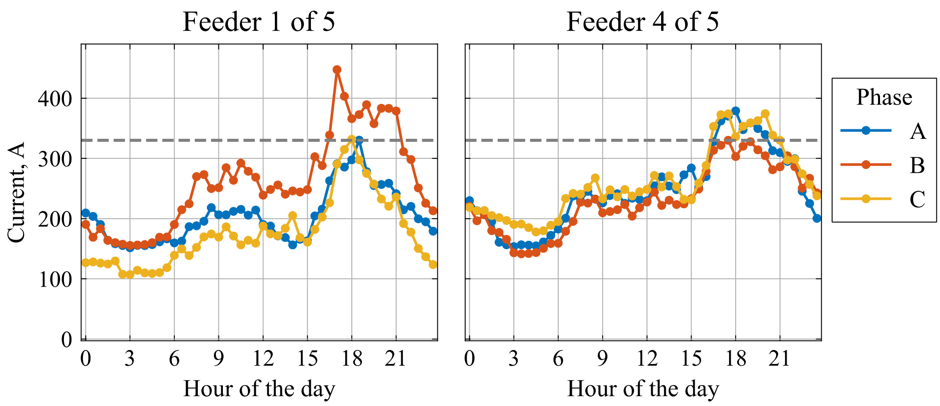


Figure 3.7 Per-phase feeder currents, for demand year 2035, prior to congestion mitigation. Feeder capacity is exceeded in both feeders through the evening.

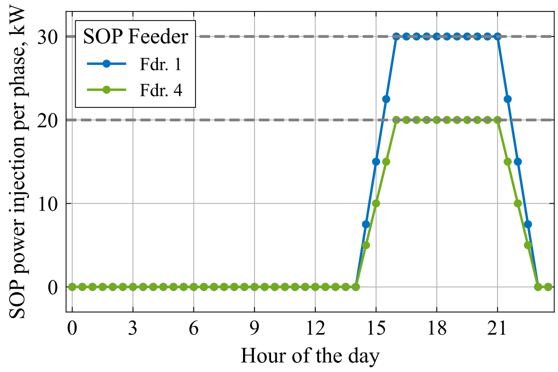


Figure 3.8 Rule-based control power injections for the two feeders with congestion, aiming to reduce congestion during the evening peak. All phases of the SOP inject the same active power and no reactive power.

Figure 3.9 shows the currents in each feeder after the D-SOP power injections using the OS schedules. The maximum phase current on each feeder no longer crosses its maximum normal ampere rating.

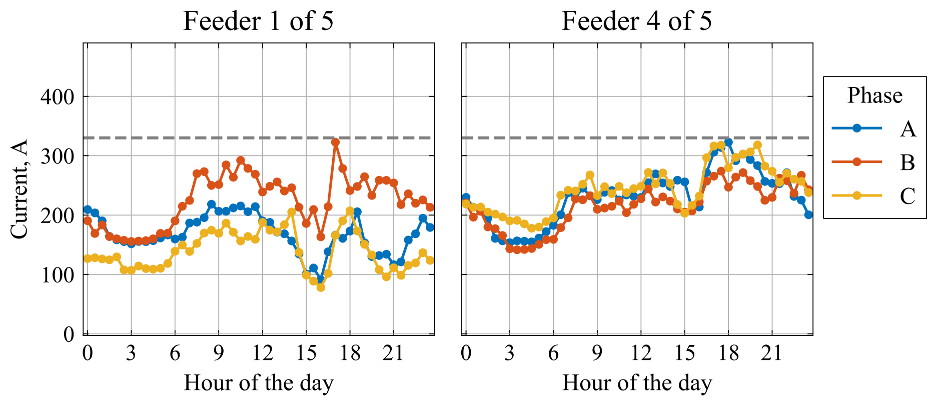


Figure 3.9 Feeder loading after using D-SOPs for two feeders, demonstrating that the scheduled control effectively addresses congestion on both feeders.

Whilst in the rule-based approach all phases of the D-SOP are utilised equally, in the optimisation-based based approach the first D-SOP injects kW power in phase B (left plot in Figure 3.10), whilst the second D-SOP injects kW power in phases A and C (right plot in Figure 3.10). This difference in the power injections between the rule-based and optimisation-based approaches is expected, because the optimisation-based approach has access to real-time measurements.

In this case, the per-day losses are much lower for the optimisation-based approach as compared to the rule-based approach (Table 3.5). Nevertheless, the OS-based scheduling has much simpler communication requirements and results in much more predictable power flows on the network, and has a similar utilization of the D-SOPs.

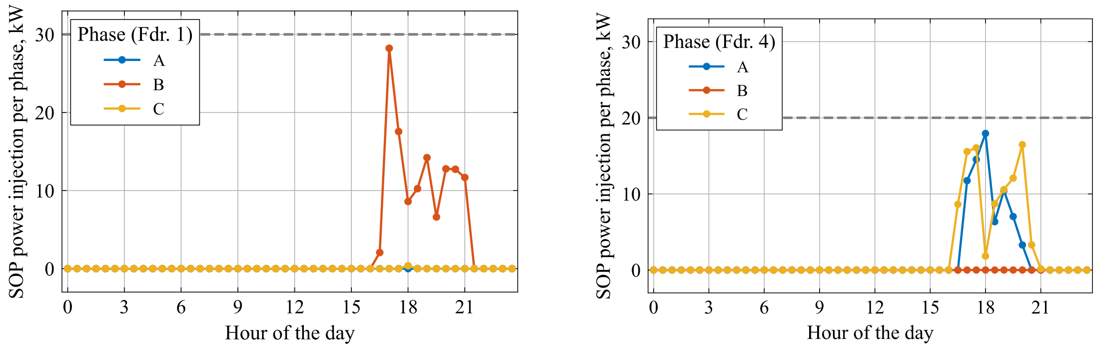


Figure 3.10 Optimisation-based approach: Optimal D-SOP power injections for each feeder. As compared to scheduled OS control, injections are only

Table 3.5 Network losses for each control implementation approach, highlighting that the offline schedule tends to have much higher device losses over the course of the day.

Methodology / Approach	Device losses, kWh
Full information optimisation	14.5
Rule-based OS schedule	105.0

4. Conclusions

This report has presented the architecture developed to control power-electronic devices installed in LV distribution networks as part of the D-Suite project. A general control architecture was presented, defining three main control modes, the key elements of the control system, and the data and communication flows required to deliver control. The control objectives and operating modes were shown, and mapped to the three D-Suite devices: the D-STATCOM, D-SOP, and D-ST.

The control architecture has been designed to deliver a trade-off between performance, complexity, and robustness. The devices can take optimised or rule-based action based on real-time measurements when these are available. To ensure that safe and secure operation is not put at risk following a lack of communication, an emergency failsafe mode has also been designed in which the devices revert to following a pre-determined operating schedule.

The performance of the control scheme – and relative performance of two of the control modes – were demonstrated using two case studies. In the first of these, a D-STATCOM was addressing thermal overload by reducing current unbalance in RT control mode. Three control approaches were compared: optimised, rule based, and rule-based with thresholding. All three schemes were able to successfully relieve the network constraint. While the optimised control gave the best performance in terms of operating cost, the rule-based approach with thresholding gave only a small reduction in performance. The second case study demonstrated the application of a D-SOP to mitigate thermal constraints in OS control mode. Both the rule-based and optimal control were able to alleviate the constraints. The rule-based control did so with more power injections, and therefore a higher operating cost, but also demonstrated a more robust and predictable approach.

5. Appendices

5.1. Appendix A: Optimisation-based approach: Model formulation

The optimisation-based approach calculates the schedule of the D-Suite Devices using formal mathematical optimisation approaches. To build an optimization which is interpretable and can use off-the-shelf solvers, the power flow Jacobian is constructed (in terms of voltage phasor sensitivities with respect to power injections). This is built using network parameters obtained from NAVI, output in the OpenDSS .dss format. The Jacobian allows for current phasors to be determined (via multiplication with primitive admittance matrices for branch elements) and subsequently network losses and powers. The main output of the optimisation-based methodology are the active and reactive injections of the D-Suite device, but this approach will also provide congestion and power flow variables (as shown as 'Inputs' and 'Outputs' in Figure 5.1).

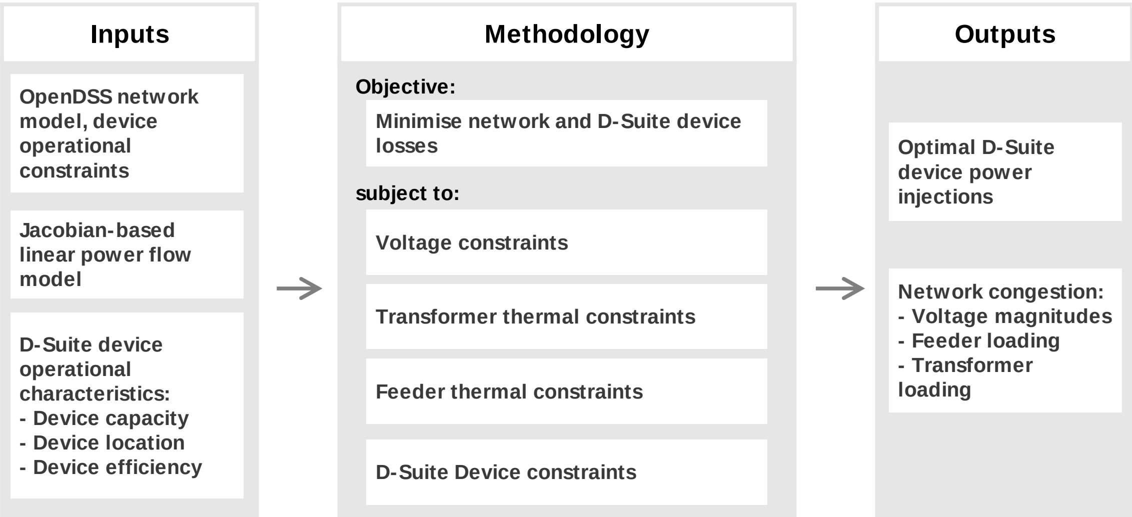


Figure 5.1 Optimisation-based methodology. ***Left box:*** *The inputs for this process are OpenDSS and power flow Jacobian results, and the D-Suite device operational limits.* ***Centre box:*** *The optimisation methodology, were the network and device losses are minimised given a set of voltage, transformer, feeder and device constraints.* ***Right box:*** *The outputs of the methodology, which include the D-Suite device power injections, the transformer and feeder loadings, resultant power flows, voltage magnitudes and congestion information.*

The mathematical formulation of the case studies of Section 3 3.1is shown below, has been coded in MATLAB 2023a and is solved using the MOSEK solver using the YALMIP toolbox. Model constraints are shown in green, and model descriptions is plain text colour. The model is formulated as a second order cone program (SOCP), and therefore a convex problem, with conic relaxations of the losses of each leg of the power converters, and for the quadratic the network losses. The relaxation gap was found to be small in both case studies of this report, with the absolute value of the relaxation gap for both network losses and PED losses less than $9.2\times 10^{-6}\%$ at all timesteps (on the per-unit base of the PED capacity). Therefore, the results of the optimisation problems calculated in case studies are considered to be numerically exact.

Objective function:

$$\min\ y^T \Lambda\, y + \lambda^T y + c_\lambda + \sum_{i\in\{1,\cdots,N_{Dev}\cdot\varphi\}} P_{Dev,\,Loss}(i)$$

where,
- y is the D-Suite device injections
- Λ, λ and c_λ are quadratic loss coefficients calculated for the network, determined via the power flow Jacobian method.
- $P_{Dev,\,Loss}$ represents the losses of the D-Suite devices.

Subject to:

Voltage constraints:

$$V = Ky + c_K$$

$$V_{min} \leq V \leq V_{max}$$

where,
- V is the matrix of voltage magnitudes
- K and c_K are the linear injection-voltage sensitivity parameters
- V_{min} and V_{max} represent that minimum and maximum voltage magnitudes limits respectively.

Transformer constraints:

$$S_{Tx} = W_{Tx} y + c_{W,Tx}$$

$$S_{Tx}(i)^2 + S_{Tx}(i+\varphi)^2 \leq S_{Tx,\,max}(i)^2, \forall i \in \{1,\cdots,\varphi\}$$

where,
- S_{Tx} are the transformer kVA powers per phase
- $W_{Tx,\,Jac}$, $c_{W_{Tx}}$ are linear injection-power sensitivity parameters (based on scaling current sensitivity matrices according to a nominal voltage)
- $S_{Tx,\,max}$ represents the Transformer maximum kVA capacity.

Feeder constraints:

$$I_{fdr} = W_{fdr,\,Jac} y + c_{W_{fdr}}{}^T$$

$$I_{fdr}(i)^2 + I_{fdr}(i+\varphi)^2 \leq I_{fdr,\,max}(i)^2, \forall i \in \{1,\cdots,N_{Fdrs}\cdot\varphi\}$$

where,
- I_{fdr} is the feeder(s) current per phase
- $W_{fdr,\,Jac}$, $c_{W_{fdr}}$ are linear injection-current sensitivity parameters
- $I_{fdr,\,max}$ represents the feeder(s) maximum kVA capacity.

D-Suite device constraints:

$$y(i)^2 + y(i+\varphi)^2 \leq S_{Dev,\,max}(i)^2, \forall i \in \{1,\cdots,N_{Dev}\cdot\varphi\}$$

$$y(i)^2 + y(i+N_{Dev}\cdot\varphi)^2 \leq S_{Dev,\,max}(i)^2, \forall i \in \{1,\cdots,N_{Dev}\cdot\varphi\}$$

$$P_{Dev,\,Loss}(i) \geq \xi \cdot \sqrt{y(i)^2 + y(i+N_{Dev}\cdot\varphi)^2}$$

$$\sum_{i\in\{1,\cdots,\varphi\}} P_{\text{Dev, Loss}}(i) + \sum_{i\in\{1,\cdots,\varphi\}} y(i) = 0$$

where,
- $S_{\text{Dev, max}}$ is the maximum kVA capacity of the D-Suite device(s)
- φ represents how many connections each device has with the network. For a D-STATCOM φ is always set to 3.
- ξ represents the D-STATCOM losses. A value of 5% is used for the case study of this report.

5.2. Appendix B: Control Modes and Nominal Scheduling Approaches

This section maps the set of control objectives presented in section 2.4 to each of the D-Suite devices, and presents which control type (offline scheduled (OS), real time (RT), or main control (MC)) may be most appropriate to address a set congestions for radial and interconnected networks.

Table 5.1. D-STATCOM - Control objectives addressed per control type.

	D-STATCOM CONTROL MODE			
	Current unbalance mitigation	Inject balanced reactive power for voltage control	Power factor correction	Inject negative sequence current
Congestion addressed:	Th-SS, Th-F	VM	Th-SS, Th-F	VUB
Control mode, Radial	RT	OS	OS	OS
Control mode, Interconnected	RT	OS or RT	OS	OS

Table 5.2. D-SOP - Control objectives addressed per control type.

	D-SOP CONTROL MODE				
	Current unbalance mitigation	Inject balanced reactive power for voltage control	Bulk power transfer for voltage or thermal congestion	Power factor correction	Inject negative sequence current
Congestion addressed:	Th-SS, Th-F	VM	Th-SS, Th-F	VUB	
Control mode, Radial	RT	OS	OS or RT	OS	OS
Control mode, Interconnected	RT	OS or RT	OS or RT	OS	OS

Table 5.3 D-ST - Control objectives addressed per control type.

	D-ST CONTROL MODE		
	Voltage optimization (load-demand sensitivity)	Voltage – magnitude constraint violation mitigation	Feeder load balancing
Congestion addressed:	Th-SS, Th-F	VM	Th-SS, Th-F
Control mode, Radial	OS	OS	N/A
Control mode, Interconnected	N/A	N/A	RT or MC

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