nationalgridESO

System Operability Framework
Whole system short circuit levels

Great Britain's transition to a low carbon economy is leading to a decline in transmission short circuit levels. Short circuit levels on the distribution networks are increasing driven by growth in distributed generation and demand. This report looks at how these two trends interact and their net effect on the whole system.

Over the next decade, we expect to see a decline in synchronous generation capacity in the transmission system and an increase in non-synchronous generation such as wind and solar connected, to the whole system. Synchronous generators are the primary contributors to short circuit level (SCL) in the transmission network. As their numbers decline, the transmission short circuit levels will reduce. SCL is important in ensuring safe and stable operation of the network.

Figure 1 shows a sample transmission system area with declining short circuit level over the next decade. In 2018, 50% of the year is spent at 17.5 kA or less; however, in 2027, 50% of the year is spent at 12.5 kA or less.

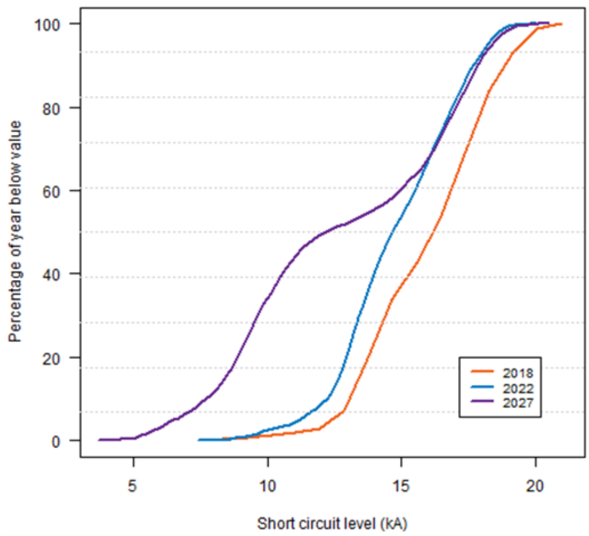

Figure 1: SCL for a sample transmission area for analysis

This report, in collaboration with Distribution Network Owners (DNOs), has assessed the impact of declining transmission SCL on the distribution networks by comparing maximum and minimum SCL contribution from distributed non-synchronous generation.

The key findings are:

- the decline in transmission SCL will lead to a reduction in the minimum distribution SCL
- at times of peak demand, maximum SCL in the distribution networks will increase due to growth in demand and distributed generation
- the proportional contribution of transmission SCL towards maximum distribution SCL will decrease
- the proportional contribution of distribution SCL towards maximum and minimum transmission SCL will increase
- the variation of SCL within a day and within a year will require moving away from using a peak or an average infeed value for analysis
- existing inverter based technologies are not reliable in providing sustained levels of fault current and should not be included as contributing when assessing for minimum current settings for protection operation

Network owners and operators need to work together to understand the network changes that will occur over the next decade and the impact on minimum short circuit levels at both transmission and distribution levels. Standards need to be updated to provide guidance on minimum network conditions.

This report has been delivered by National Grid ESO, Electricity North West Limited, SP Energy Networks and Western Power Distribution in collaboration, and has been supported by the Electricity Networks Association's (ENA's) Open Networks project.

SP ENERGY NETWORKS

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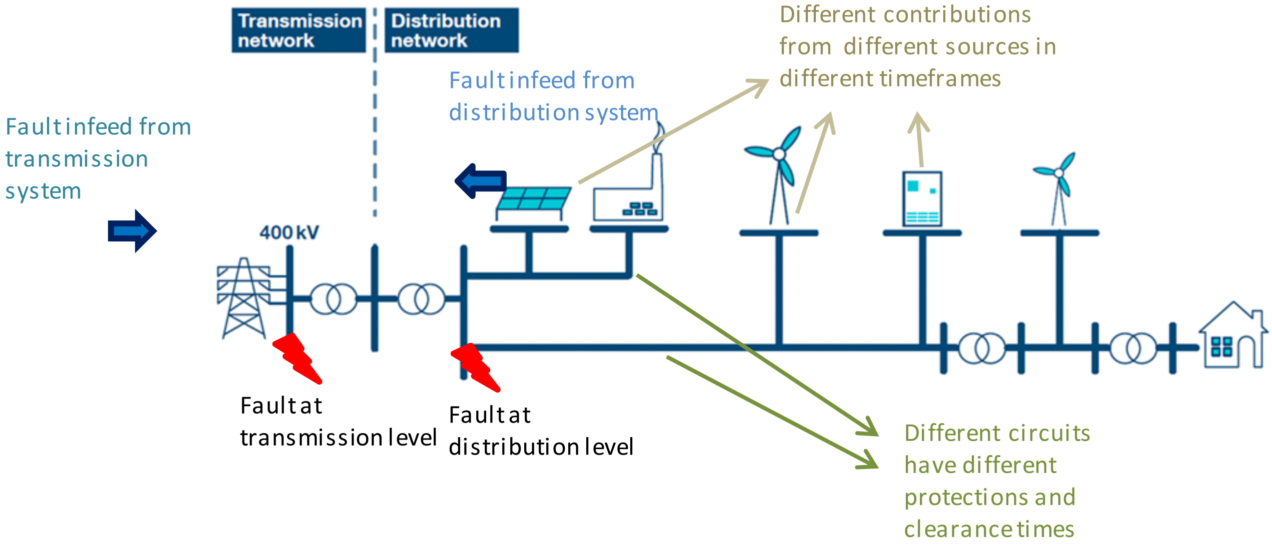
Background

Figure 2: View of transmission - distribution fault infeeds



Network short circuit levels

Figure 2 illustrates short circuit fault current contribution from different parts of the system, for transmission and distribution system faults. For faults on either system, there is short circuit fault current contribution from both systems. The level of fault current contribution depends on various factors. For example; fault location, type and connection of generation technology, network voltages and network configuration.

Historically much of the short circuit level contribution to distribution networks has come from the transmission side. Transmission system short circuit levels are predominantly provided by large synchronous generators. With the increase in non-synchronous generation, the transmission system is expected to operate at lower SCL more frequently across many regions.

Distribution systems are expected to see an increase in demand and distributed generation which will increase the contribution to the maximum short circuit levels from within the distribution system.

Both maximum and minimum short circuit levels are an important consideration for protection design and operation. Maximum short circuit levels, determined by initial peak currents, drive network investments and operational guidance (such as network running arrangements). For ongoing system stability and to ensure safe network operation, minimum levels of short circuit level are considered.

Protection systems

Protection systems are designed to detect and safely isolate faulty equipment on the power systems quickly, limiting the fault effect upon the wider system. As they safeguard people and equipment, they need to be very reliable, and their design and settings are highly dependent on the detection of short circuit level in the network. If the potential short circuit level is too low, then the fault may go undetected. There are different operational principles for different protection systems, explained in Table 1.

Table 1: Protection system types

Overcurrent protection	Compares the current to a fixed threshold. If the current is higher than the setting, the relay will trip.
Distance protection	Compares the impedance at the relay point with the reach impedance. If the measured impedance is lower than the reach impedance, the relay will trip.
Differential protection	Compares the current infeed and outfeed across a circuit or zone. If the difference between them is different to bias current settings, the relay will trip.

High Voltage Direct Current (HVDC)

In order for High Voltage Direct Current to be used by the power system it must be converted to Alternating Current (AC) through the switching of valves or thyristors at a rate which matches the behaviour of the power system. The valves then commutate to transfer power from HVDC to the AC power system, or vice-versa.

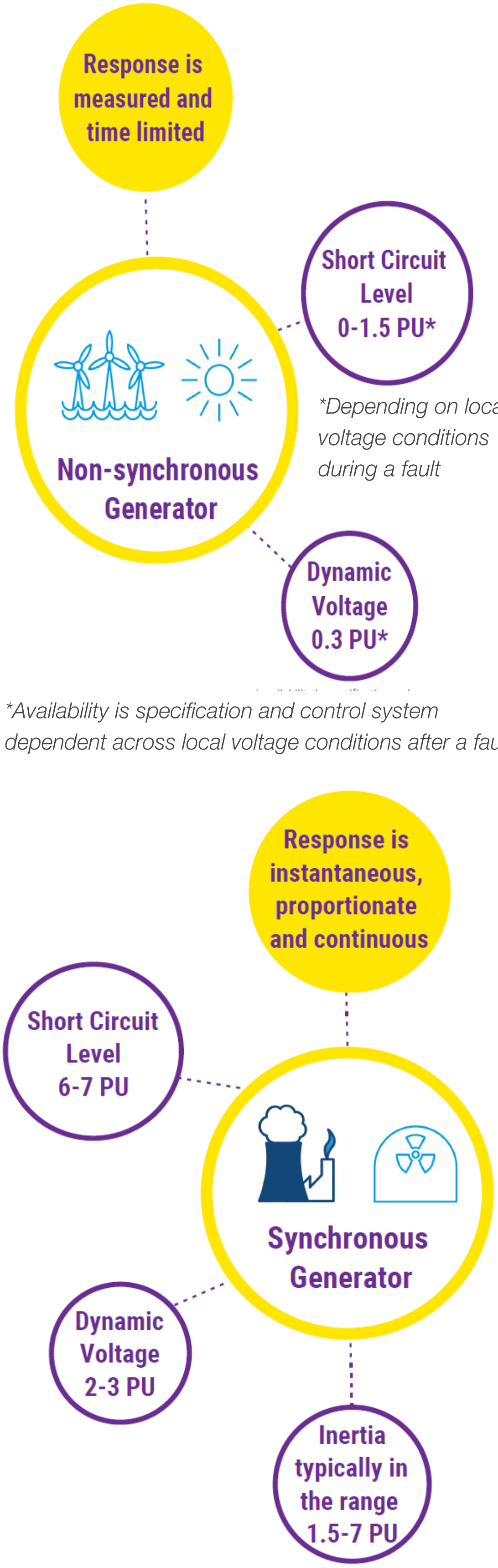
During a fault or other disturbance, the voltage of the power system can vary rapidly. The extent to which voltage can vary is related to the SCL. Higher SCL means less voltage variation is seen by the HVDC system. To maintain commutation, the stability of HVDC connections are often expressed as a ratio between the SCL and the power rating of the converter. Commutation failure can occur if the commutation achieving the desired power transfer across a valve or thyristor cannot complete before voltage reversal. This affects the pattern of the next valve switching. In this instance, HVDC current source converters will block and disconnect due to commutation failure.

With a decline in short circuit level, maintaining the necessary short circuit ratio becomes more challenging. All non-synchronous generation, including HVDC converters are equipped with Phase Locked Loop (PLL) controllers which synchronise their power produced to the power system. The PLL may lose track of system phase during low fault level conditions. Given that the local voltage is more prone to distortion at lower SCL, this could lead to wider system instability. Modes of HVDC commutation failures and impact of PLL controllers due to low SCL have been discussed in previous SOF documents.

Inverter short circuit level contribution

Inverter based technologies are limited by the short term converter capability (which are typically limited to no more than 1.5 pu) and do not provide sustained levels of short circuit current in the timescales for operation protection [3][4]. At transmission level, protection systems are expected to operate close to 100-140 ms after a fault. This time could be longer for distribution systems depending on their configurations. At 100 ms, the synchronous generation is still providing sustained short circuit current (around 3-5 pu), but non-synchronous generation is providing negligible short circuit current. Figure 3 summarises properties of non-synchronous and synchronous generation.

Figure 3: Properties of synchronous and non-synchronous generators



Short circuit current levels decay over a period of time. They decline from initial peak levels in a period known as the sub-transient period (within 50 ms of the fault occurring). For network investment where the ability to withstand a high sub-transient short circuit level is important (for example in the rating of power system equipment), the peak contribution possible from an inverter based plant needs to be included. For the consideration of minimum protection settings, stability and availability of non-synchronous technologies (short circuit level around 100 ms), contribution from an inverter based plant would be expected to be negligible. The fault infeed is closely related to the retained voltage during faults. In weaker systems (such as a transmission system with low SCL), there is less confidence of short circuit level contribution from inverter based technologies within a short period of fault (less than 100 ms).

Any new inverter based plant connecting to transmission or distribution networks after 1st April 2018 subjected to Requirements for Generator (RfG) must provide a certain level of reactive support during and after the fault [5].

Methodology

In this report, the year round impact of transmission fault levels on generic distribution networks over the next decade is assessed. The assumptions are detailed below and additional information is provided in Appendix C.

Transmission – distribution network configurations

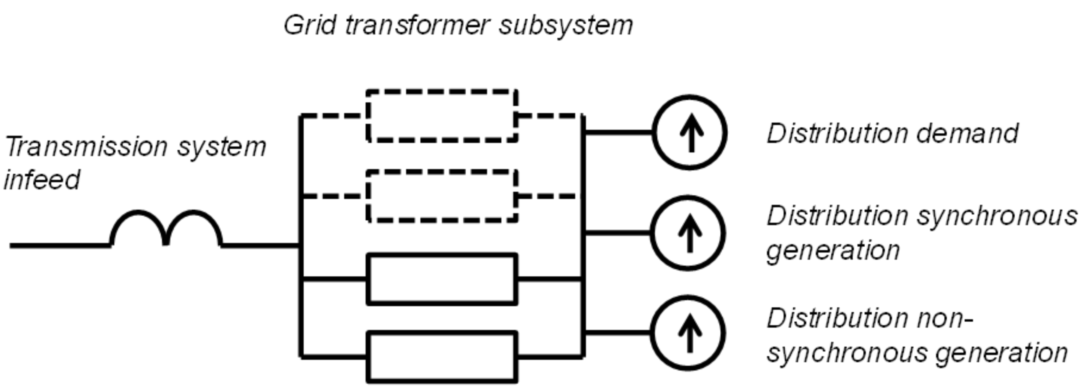
Four generic network configurations are considered:

- 400/132 kV 4 SGTs
- 275/33 kV 2 SGTs
- 400/66 kV 2 SGTs
- 132/33 kV 2 SGTs

Model

The scenarios are run in an impedance based model with the topology shown in Figure 4.

Figure 4: Model topology



Short circuit level results are determined as root mean square (RMS) values at both the transmission and distribution busbars on either side of the grid transformer subsystem. Distribution demand, synchronous generation and non-synchronous generation are all modelled as equivalent current sources feeding into the distribution busbar.

Transmission short circuit levels

Year round transmission system short circuit levels for a sample area with high non-synchronous generation growth are considered. These are generated by considering year-round transmission generation and demand dispatch, and regional network impedances. Three sample years have been chosen (2018, 2022, 2027).

Distributed generation

Considering existing distributed generation scenarios for each generic Grid Supply Point (GSP) network. The analysis is calibrated against the maximum short circuit level, in kA, expected on existing equivalent GSP networks. The growth in non-synchronous generation is calculated by considering existing demand and generation, and additional capacity available.

Demand

Demand for each network configuration is formed by considering normalised time series profiles of typical GSPs and their firm capacity. Short circuit level contribution from demand is considered as 1 pu per MVA of demand at the low voltage busbar of the GSP. The short circuit level contribution from demand is considered to stay the same across all three years.

Infeeds from distribution connected generation

We have considered fault current infeeds from distributed synchronous generation to be 5 pu per MVA at the low voltage busbar of the GSP.

For non-synchronous generation, two values of fault infeeds are considered :

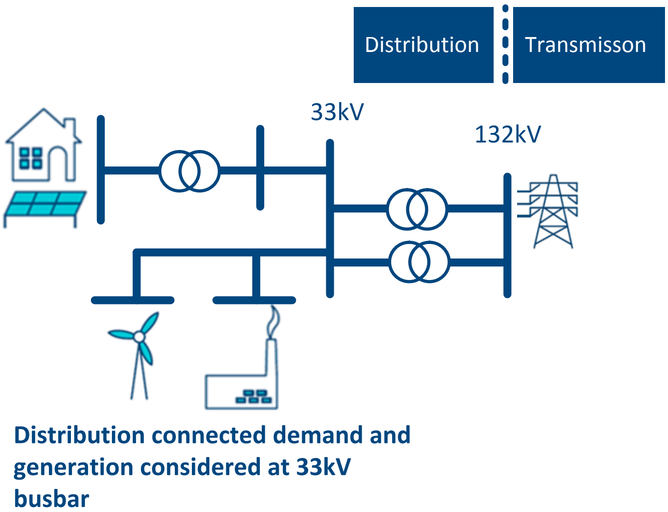
- minimum infeed of 0 pu which is relevant for minimum protection settings
- maximum infeed of 1.5 pu which is relevant for asset ratings

Distribution short circuit levels

The total short circuit level seen at the distribution busbar is calculated by summing transmission fault infeeds, demand infeeds, and distributed generation infeed. This is all subjected to transmission-distribution network impedances.

Assessment

Figure 5: 132/33kV network diagram



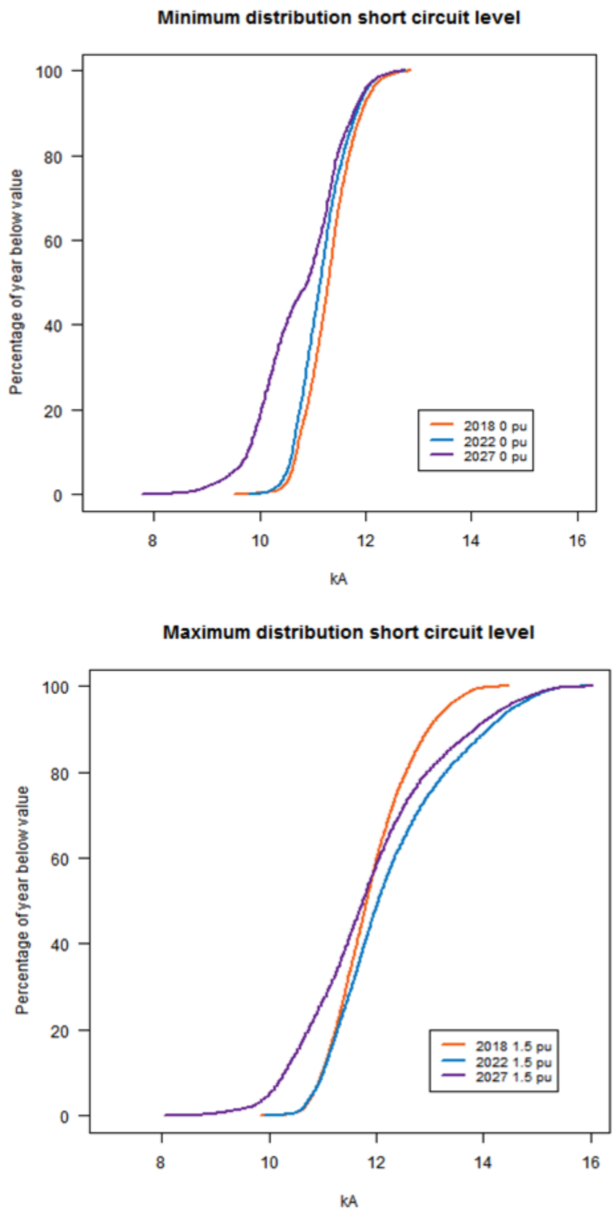
Results of the 132/33 kV sample network Figure 5 are discussed in this section. Additional results are provided in Appendix C.

- There is a reduction in minimum SCL in 2027 compared to 2018 due to negligible fault infeed consideration from non-synchronous generation (0 pu fault infeed for protection operation)
- There is an increase in maximum SCL in 2027 compared to 2018 due to significant fault infeed consideration from non-synchronous generation (1.5 pu fault infeed for asset ratings)

Impact of non-synchronous generation on short circuit level at distribution level

Figure 6 shows the maximum and minimum distribution fault levels. The maximum short circuit levels consider 1.5 pu fault current infeed from non-synchronous generation. The minimum short circuit levels consider 0 pu fault current infeed. The fault current contribution from converter based technologies is generally limited around 1.5 pu. This contribution is short-lived within the transient timeframe and defines our maximum contribution. Protection systems are not expected to see this short-lived contribution. The fault current contribution from converter based technologies is negligible for the operation of protection systems. Hence 0 pu contribution for consideration of minimum protection settings. This defines our minimum short circuit level contribution of 0 pu.

Figure 6: Minimum and maximum distribution SCL



For maximum short circuit levels in 2027, we see a range of 8 – 16 kA, which has increased from 2018 (10 – 14.5 kA). In 2027, a wider range of transmission short circuit levels are seen at lower values, over longer periods, compared to 2018. This is combined with the growth of distributed generation which results in the increased range of maximum distribution level short circuit levels.

Similarly, for minimum fault levels, in 2027 the range has increased towards the lower end compared to 2018. There is also more time being spent on lower values in 2027 (40% of time at 10.5kA or less) compared to 2018 (40% of time at 11kA or less). These changes are primarily being driven by the behaviour of year-round transmission short circuit levels which are due to less running of conventional synchronous generation in the future.

- Proportional contribution of transmission system towards maximum distribution short circuit level is decreasing
- Proportional contribution of transmission system towards minimum distribution short circuit level roughly stays the same

Impact of transmission short circuit level on distribution network

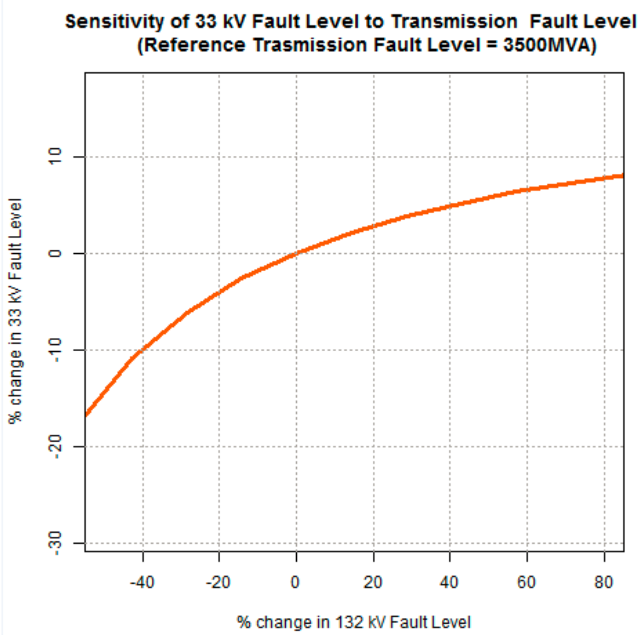
Figure 7 shows how the percentage of distribution fault level that comes from the transmission network varies over the next decade.

With the growth in distributed generation and a decline in transmission fault levels, the proportion of contribution from the transmission system towards maximum distribution fault levels is decreasing, shown by the dotted lines.

The proportional contribution from transmission to distribution for minimum fault levels on the distribution network roughly stays the same. Approximately 70% - 95% of fault infeeds seen by the distribution networks come from synchronous generation connected to the transmission system.

The impact of the decline of transmission upon distribution system fault levels is moderated by the impedance of the grid transformers. For a typical 132/33 kV site, decrease of 50% on the 132 kV transmission fault level results in a 15% decrease at 33kV distribution level (Figure 8).

Figure 8: Distribution SCL sensitivity



- Proportional contribution from distribution systems towards both maximum and minimum transmission SCL is increasing

Figure 7: SCL contribution from transmission network

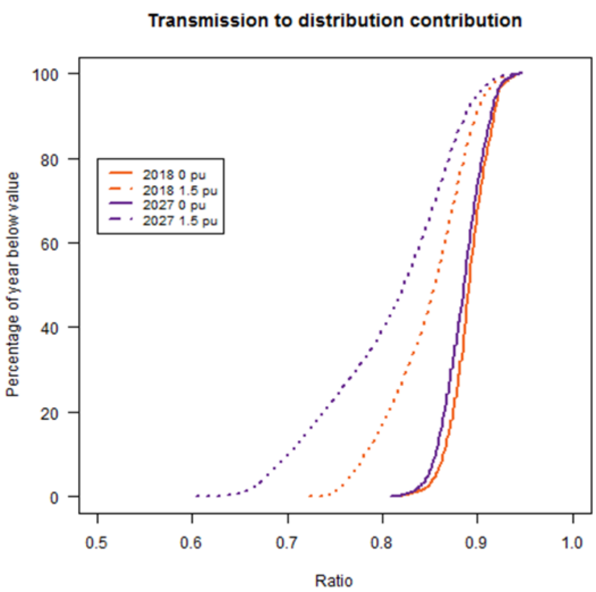
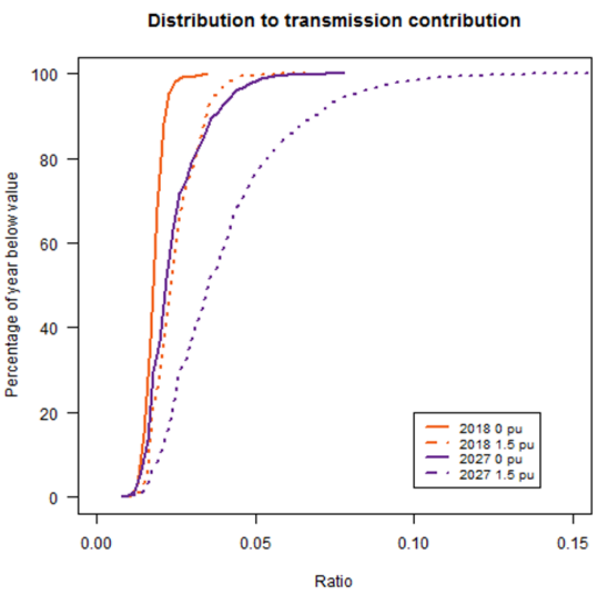


Figure 9: SCL contribution from distribution network



Impact of distribution short circuit level on transmission network

Figure 9 shows how the percentage of transmission fault level that comes from the distribution network varies over the next decade.

With the growth in distributed generation, the maximum fault level contribution from distribution to transmission is increasing, as shown by the dotted lines in Figure 8. For minimum fault levels on **distribution networks**, **the** contribution from distribution to transmission is increasing, shown by the shift in 2027. With growth in demand and distributed generation, the transmission system will see slightly increasing fault infeeds from the distribution networks both for maximum and minimum periods.

- Minimum and maximum short circuit levels vary within a day and from one season to another

Seasonal variations in maximum and minimum short circuit levels

Figure 10 and Figure 11 show within day variations in transmission and distribution short circuit level for summer and winter respectively.

As expected, the transmission fault levels shown by *T 2018* and *T 2027* are higher in winter compared to summer. This is due to higher demand and generation at transmission level. In winter and summer, low transmission fault levels are observed between midnight and early morning. This is due to low demand periods. This declines in 2027 compared to 2018. This is because of the slight reduction in the minimum distribution short circuit level for those minimum periods. These minimum fault levels observed on the distribution network follow distribution demand and transmission fault current infeeds. However, the magnitude of the reduction is limited by the impedance of the transformers.

Figure 10: Summer SCL variation

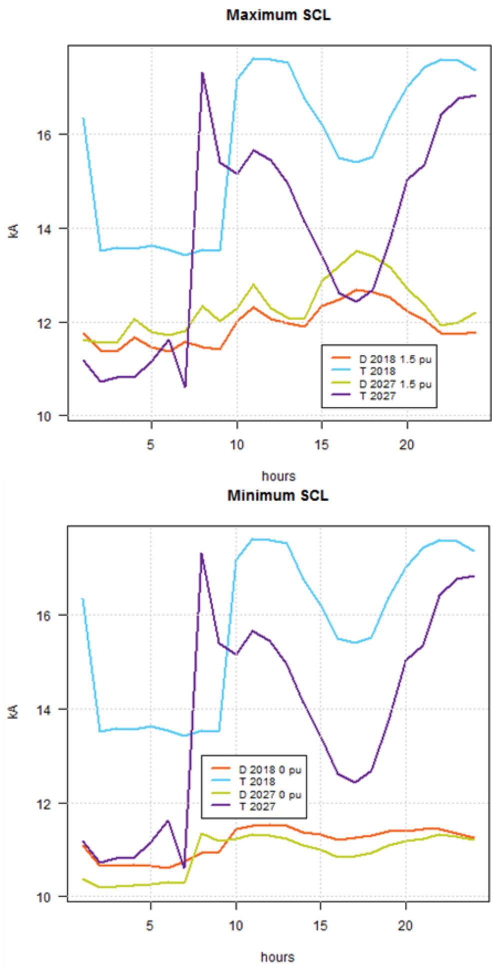
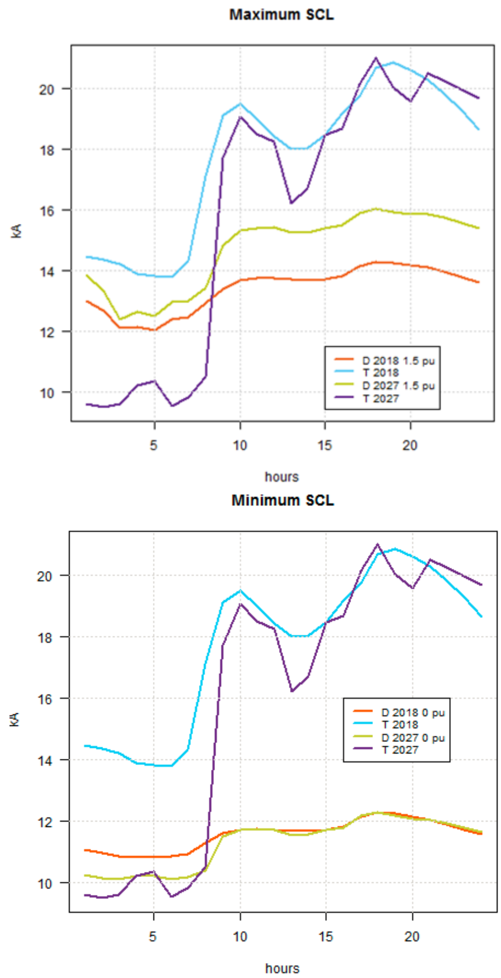


Figure 11: Winter SCL variation



Conclusions

With generation and demand changes over the next decade, transmission system short circuit levels are expected to stay at low levels for longer periods. This report analyses the generic impact of year round variations in transmission short circuit levels on the distribution networks.

The conclusions are:

- the decline in transmission SCL will lead to reduction in the minimum distribution SCL
- at times of peak demand, maximum SCL in the distribution networks will increase due to growth in demand and distributed generation
- the proportional contribution of transmission SCL towards maximum distribution SCL will decrease
- the proportional contribution of transmission SCL towards minimum distribution SCL will roughly stay the same
- the proportional contribution of distribution SCL towards maximum and minimum transmission SCL will increase
- the variation of SCL within a day and within a year will require moving away from using a peak or an average infeed value for analysis
- existing inverter based technologies are not reliable in providing sustained levels of fault current and should not be included as contributing when assessing for minimum current settings for protection operation

The analysis also shows that distribution short circuit levels will become more important to the transmission system in the future. There is need for enhanced understanding of how transmission and distribution networks perform and interact in varying year round conditions, most importantly in minimum network conditions. The existing industry guidelines such as Engineering Recommendation G74 are focused on peak network conditions. The existing data exchanges between transmission and distribution networks also focus on peak network conditions. With the European demand connection code, there will be an obligation for transmission owners to publish minimum SCL occurrence for year ahead. This provides further opportunity to improve existing standards to consider minimum conditions. With more inverter based plants rapidly replacing synchronous generation in the future, there is a need to enhance standards to provide guidance on minimum network conditions. This analysis recommends that network owners and operators need to better understand analysis of minimum network conditions and the impact on minimum short circuit levels both at transmission and distribution levels.

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Appendix A: Case study on a sample GSP network

To understand variation of short circuit level at different voltage levels, we have carried out analysis on a sample GSP network within the Western Power Distribution area. This network has different levels of distributed generation (DG) at different voltage levels. We have studied this network against a winter peak dataset.

The network consists of two incoming 400kV circuits and 1.2GW of transmission connected generation. The 400/132 kV GSP feeds four 132/33kV substations (A, B, C & D) all of which have varying amounts of DG of different technologies (shown in Table A1). Fault level for each busbar is based on a three-phase fault.

Contribution of transmission short circuit level to distribution faults

For peak transmission short circuit level and a fault at 132kV GSP busbar, we observe that the transmission contribution towards the 132kV distribution short circuit level is 96% without DG (4% provided by distribution network lower than 132kV) transmission contribution towards the 132kV distribution short circuit level is reduced to 85% with DG (15% provided by distribution network lower than 132kV).

Reduction in transmission short circuit level

For a reduction in the transmission fault current of 52%, we observe that the reduction of 18% on the 132kV short circuit level diminishes further down in the distribution network.

The reduction in transmission fault current is considered by switching off 1.2GW of transmission generation and one of the 400KV circuits. The change in fault level at each busbar for the reduction in transmission short circuit level is shown in Table A2 .

Reduction in distribution short circuit level

For a reduction in distribution fault current, the reduction in short circuit level is greatest on the lower voltage network (up to 26% reduction on 33kV busbars) compared to higher voltages (3% reduction on the 400kV busbar).

The variation is considered by looking at the maximum fault level with all available DG switched in, and the minimum with all DG switched out. The change in fault level at each busbar for the reduction in DG is shown in Table A3.

Figure A1: Sample case study network

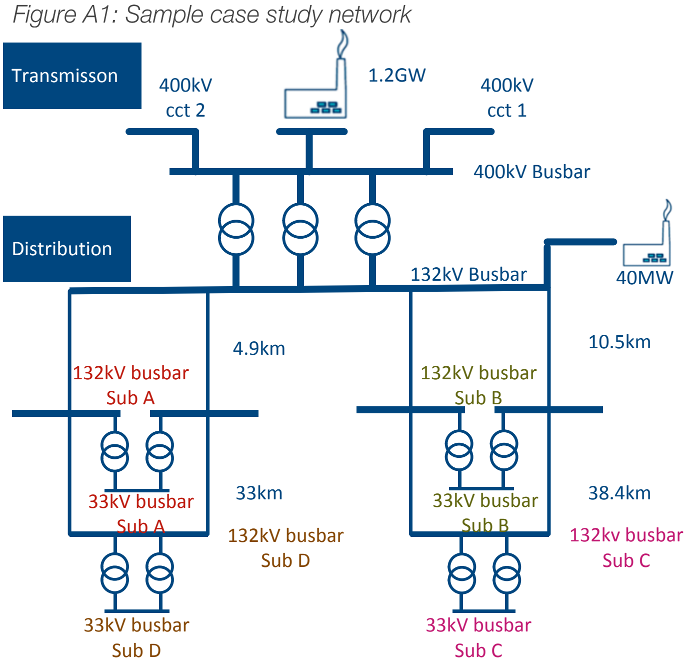


Table A1

	Total Gen (MW)	Solar	Wind	Other
A	50	14%	37%	49%
B	3.5	17%	57%	26%
C	60	82%	4%	14%
D	20	70%	0%	30%

Table A2

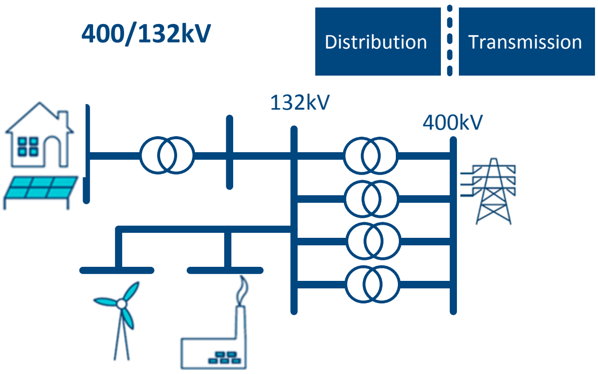
Substation	Busbar Voltage (kV)	% change in fault level
GSP	400	-53%
GSP	132	-18%
A	132	-14%
A	33	-4%
D	132	-8%
D	33	-3%
B	132	-11%
B	33	-4%
C	132	-7%
C	33	-3%

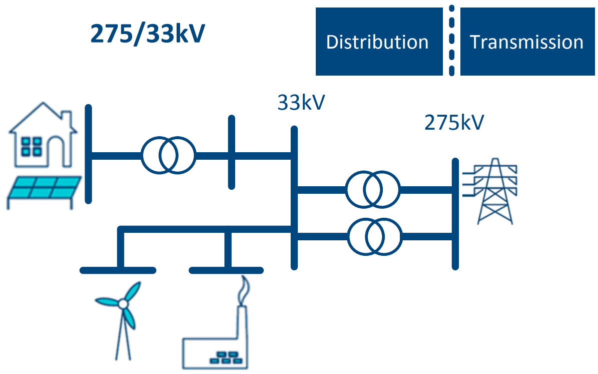
Table A3

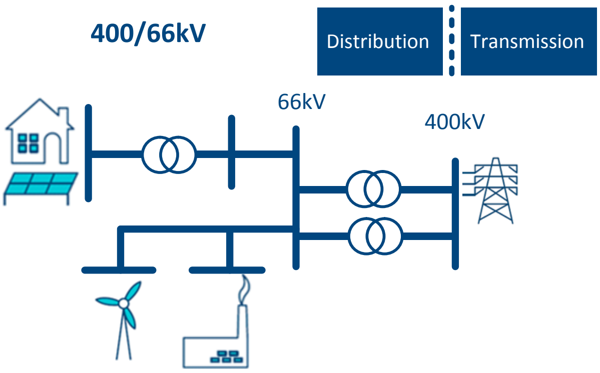
Substation	Busbar Voltage (kV)	% change in fault level
GSP	400	-3%
GSP	132	-13%
A	132	-11%
A	33	-26%
D	132	-9%
D	33	-11%
B	132	-10%
B	33	-9%
C	132	-12%
C	33	-20%

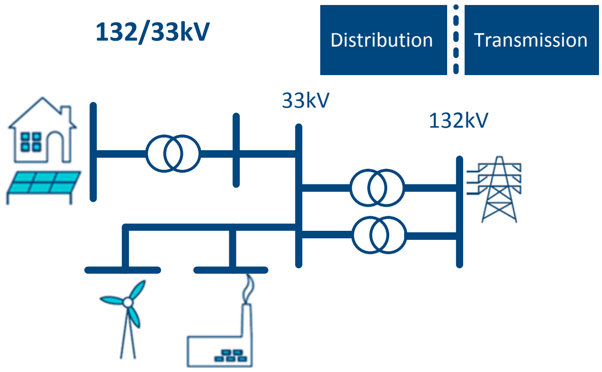
Appendix B: Assumptions

Transmission – distribution network configurations

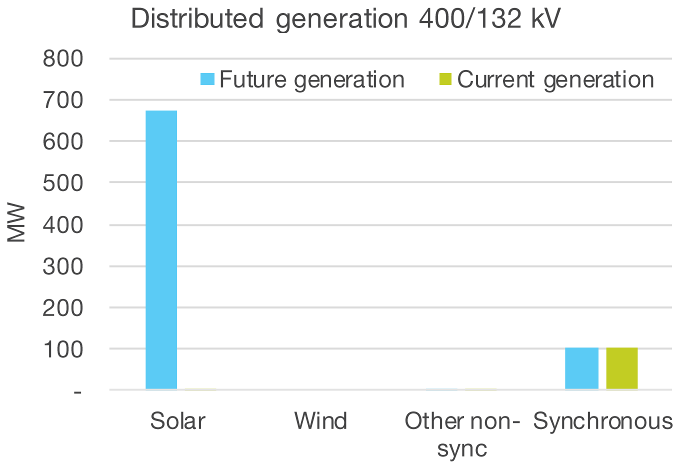


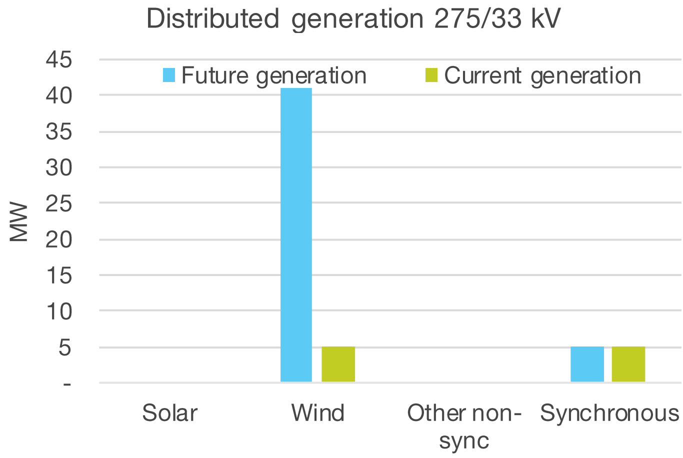


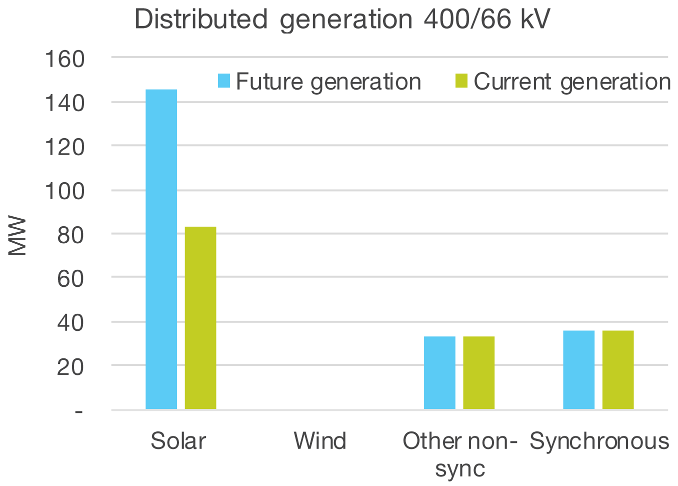


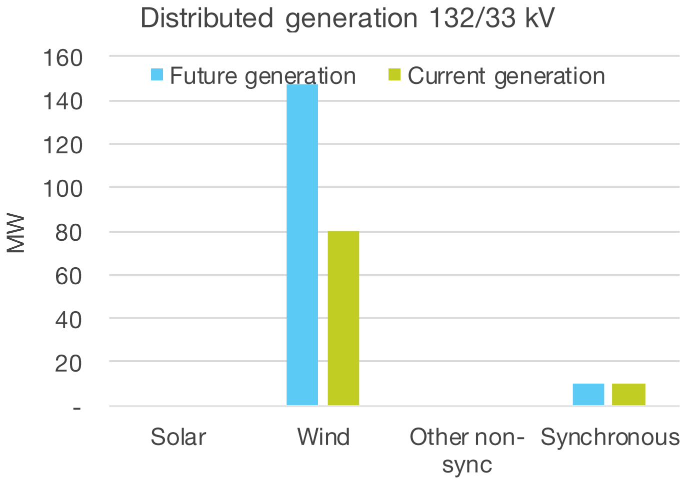


Distributed generation





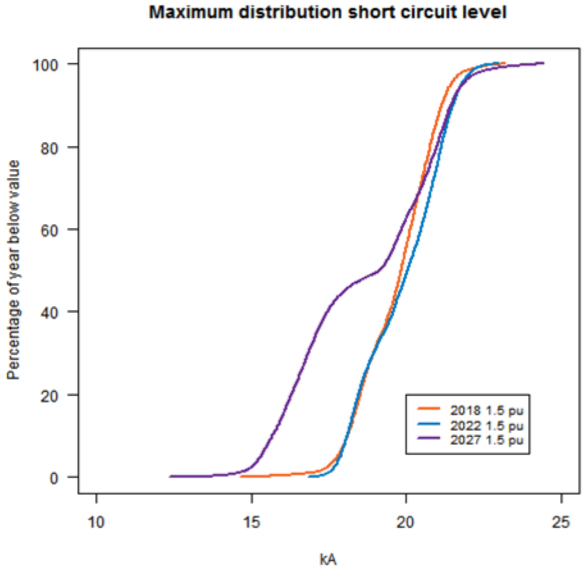


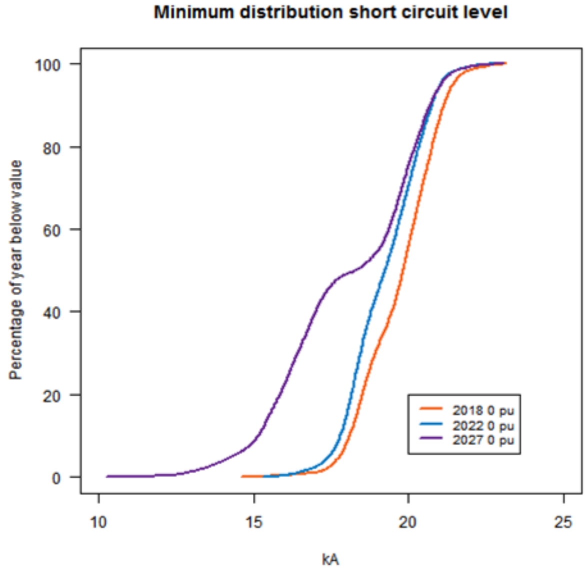


Appendix C: Additional results and analysis

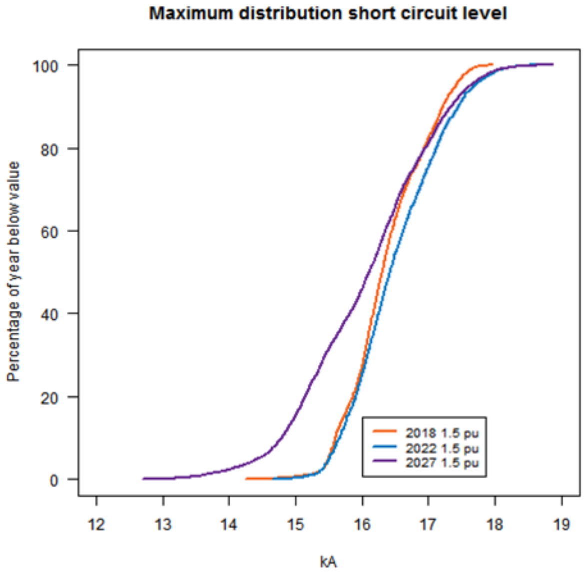
Distribution short circuit levels

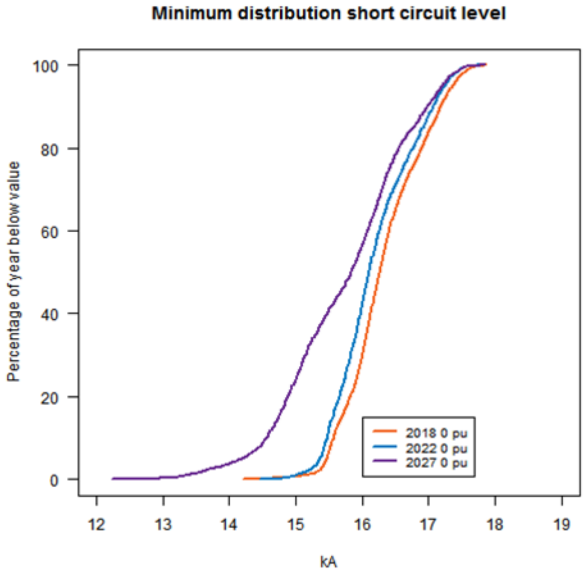
400/132 kV



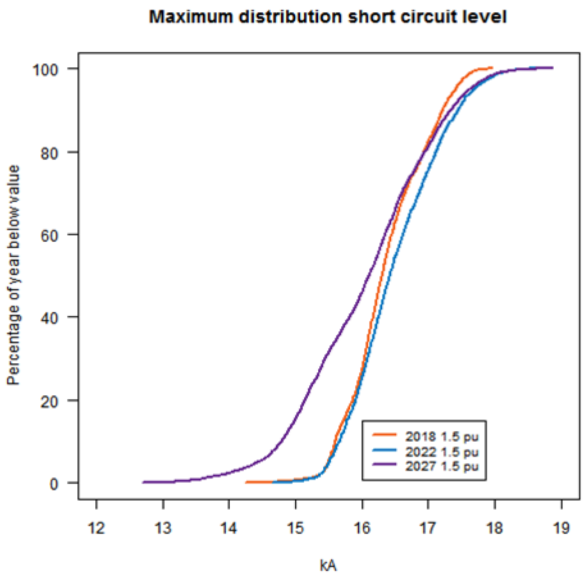


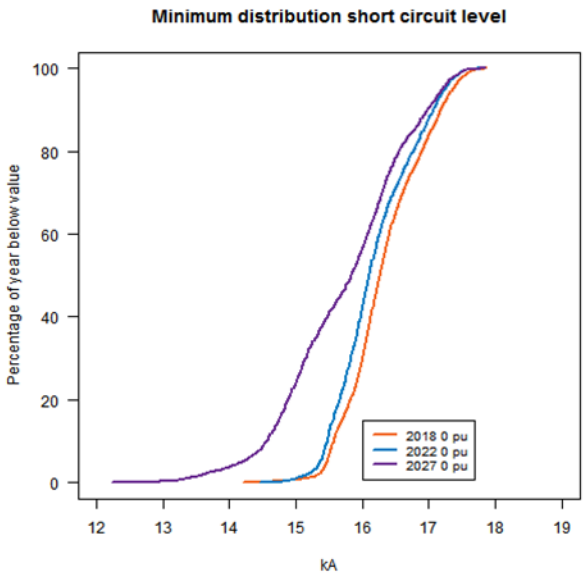
275/33 kV





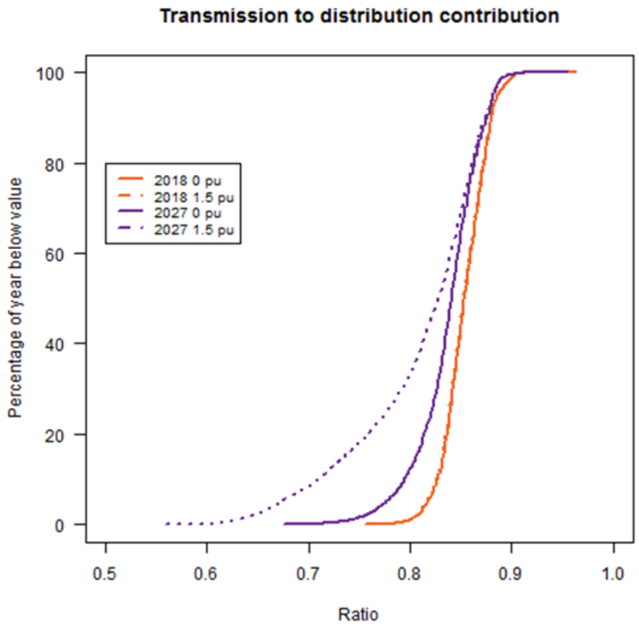
400/66 kV



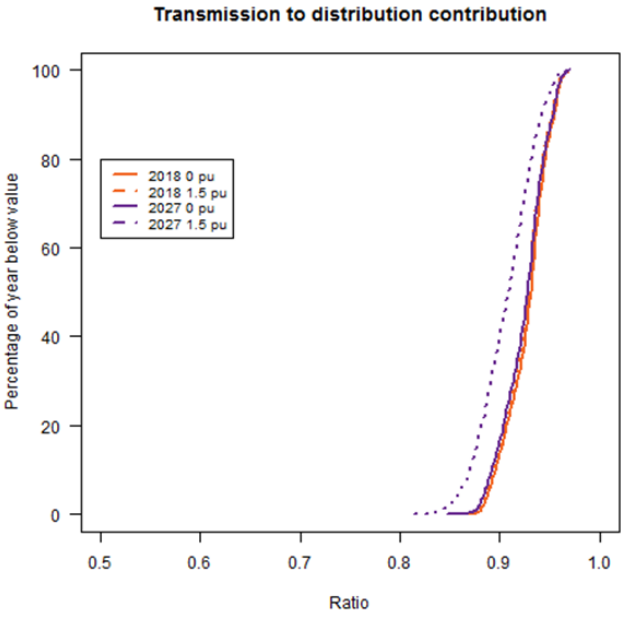


Transmission to distribution contribution

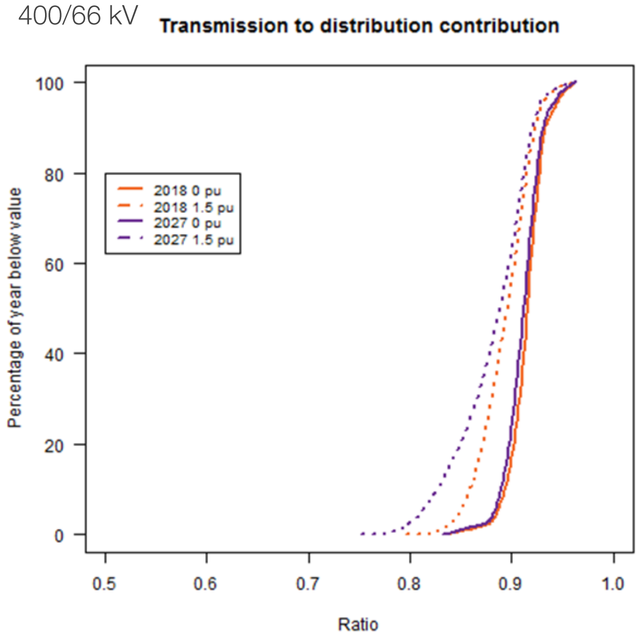
400/132 kV



275/33 kV

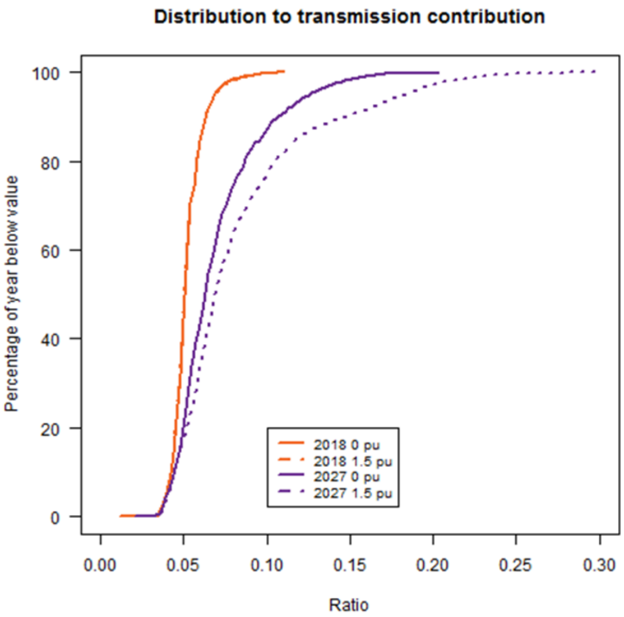


400/66 kV

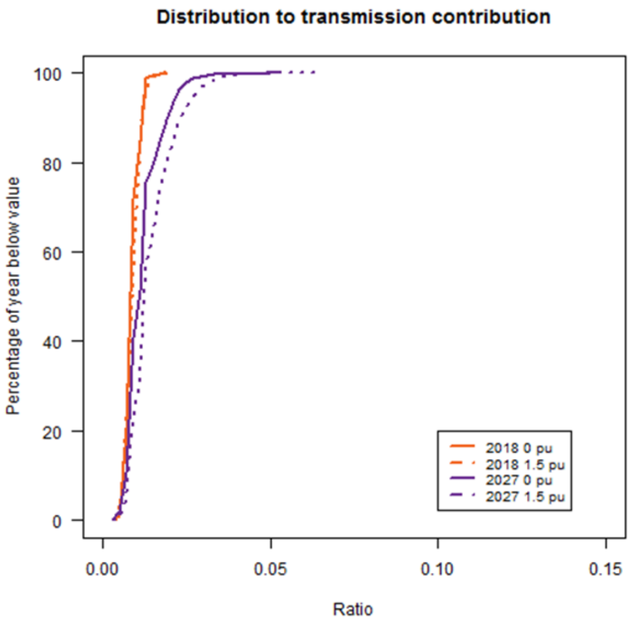


Distribution to transmission contribution

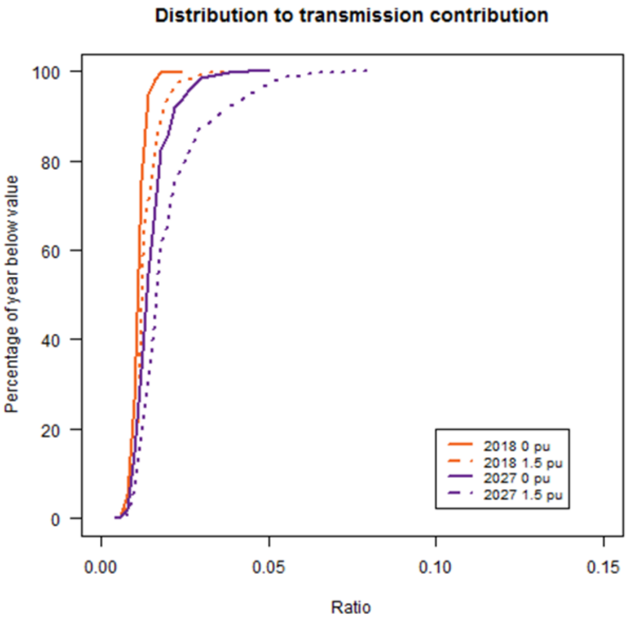
400/132 kV



275/33 kV

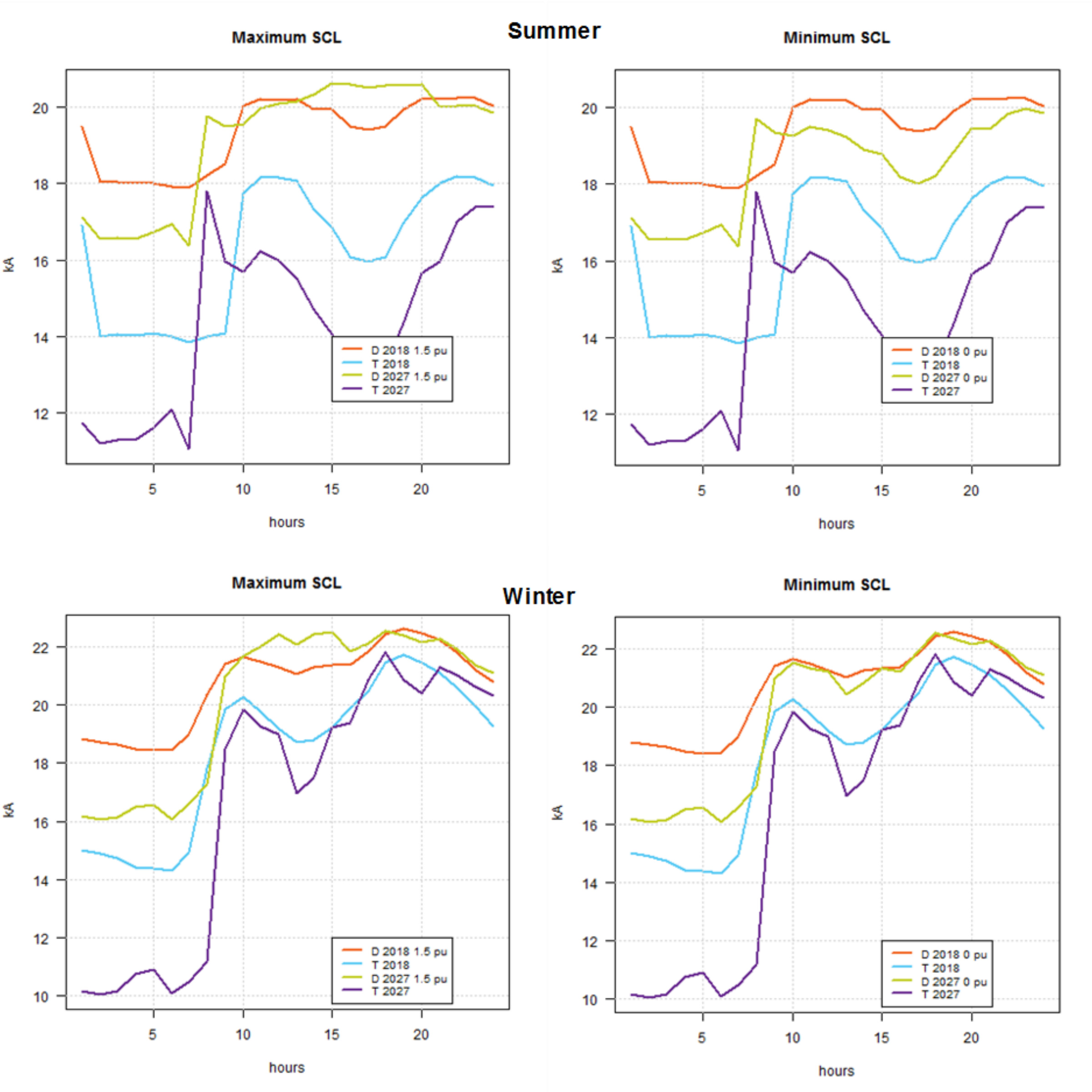


400/132 kV

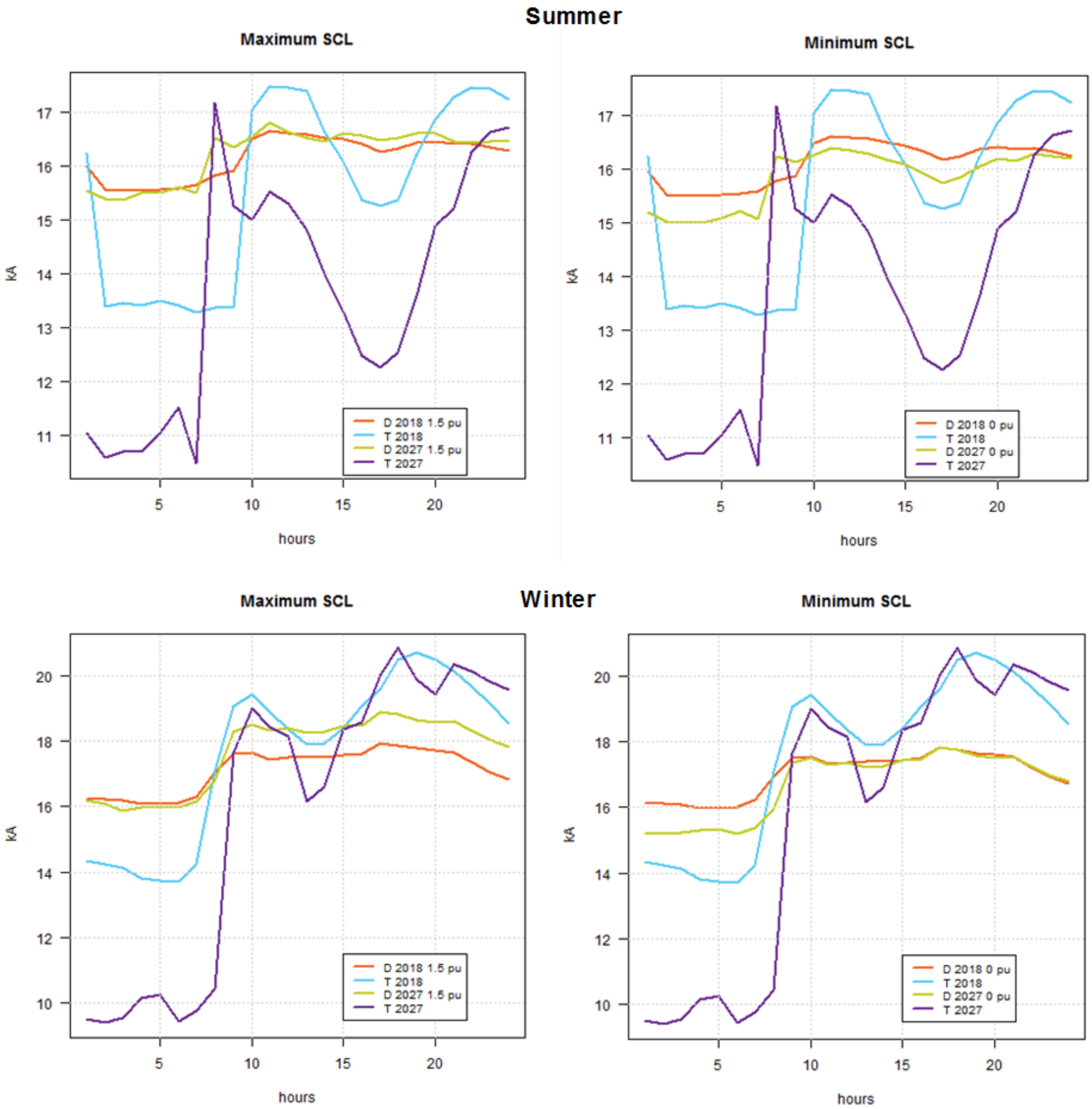


Seasonal variation for minimum distribution SCL

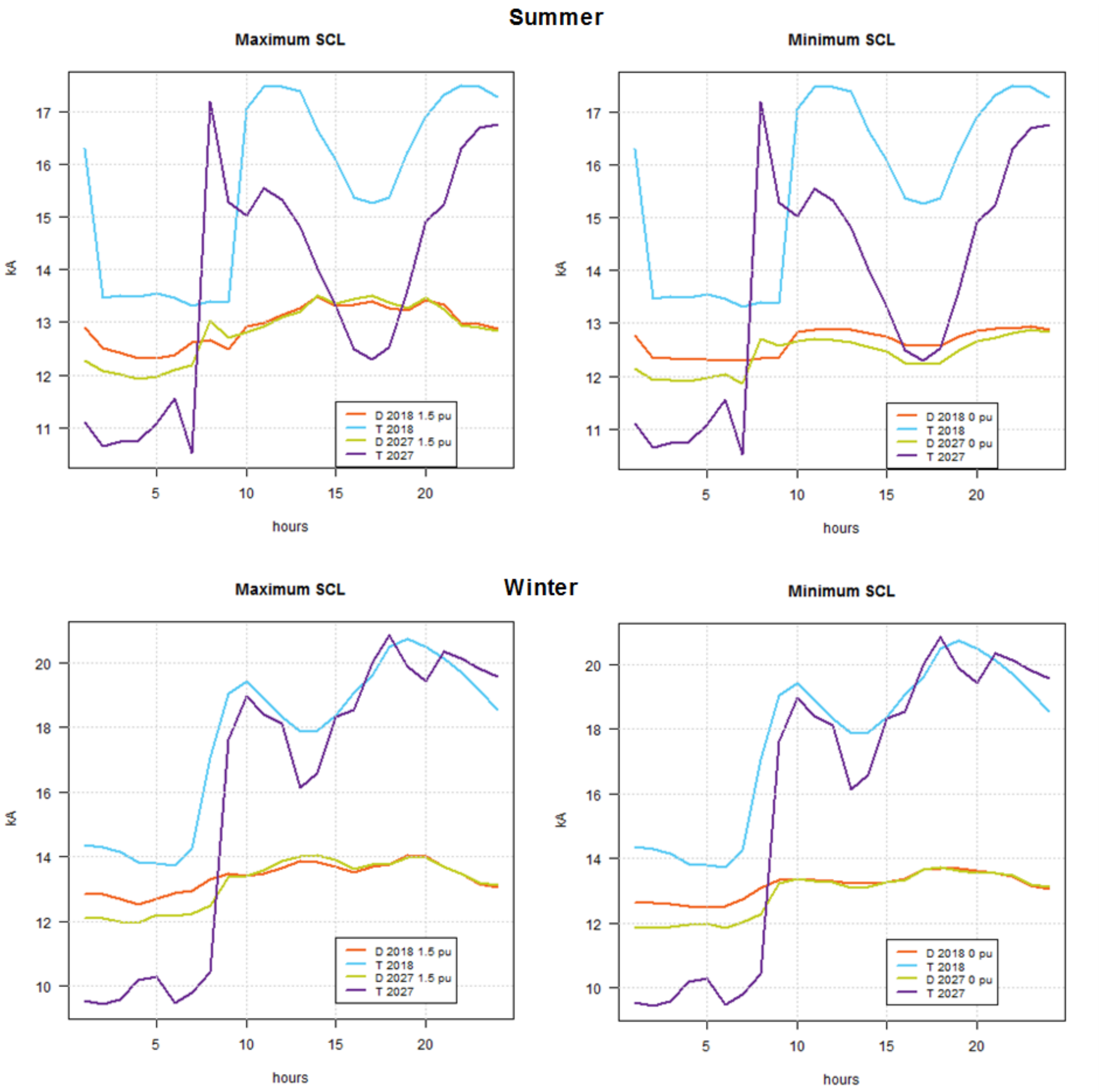
400/132 kV



275/33 kV


Summer
Maximum SCL
Minimum SCL
kA
hours
D 2018 1.5 pu
T 2018
D 2027 1.5 pu
T 2027
D 2018 0 pu
T 2018
D 2027 0 pu
T 2027
Winter
Maximum SCL
Minimum SCL
kA
hours
D 2018 1.5 pu
T 2018
D 2027 1.5 pu
T 2027
D 2018 0 pu
T 2018
D 2027 0 pu
T 2027

400/66 kV


Summer
Maximum SCL
Minimum SCL
Winter
Maximum SCL
Minimum SCL
kA
hours
D 2018 1.5 pu
T 2018
D 2027 1.5 pu
T 2027
D 2018 0 pu
T 2018
D 2027 0 pu
T 2027

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Continuing the conversation

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