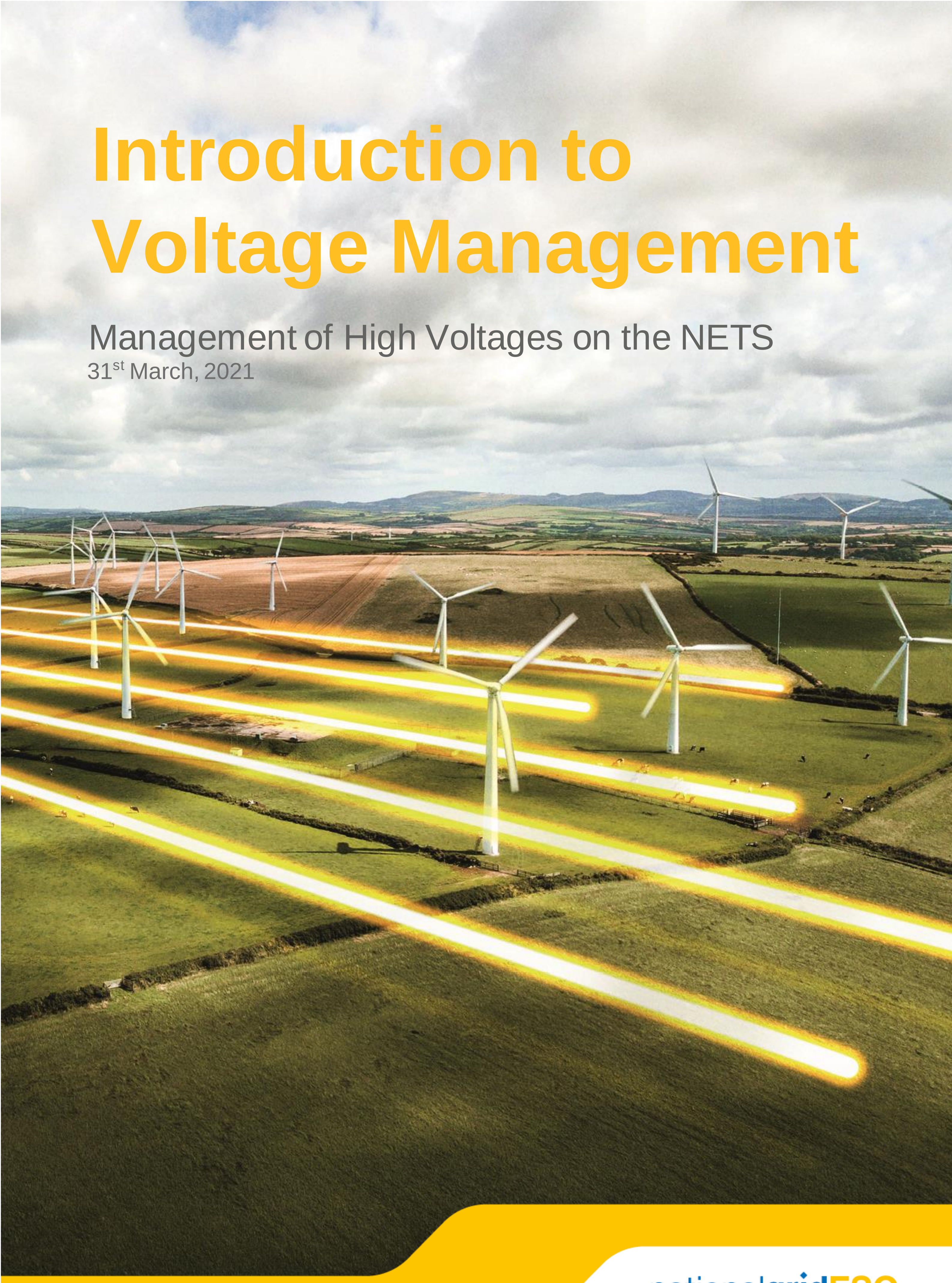
Introduction to Voltage Management

Management of High Voltages on the NETS

31st March, 2021



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Contents

Introduction

This document aims to present an overview of voltage control on the National Electricity Transmission System, and how voltages are managed.

Management of system voltages is a complex topic, from management of steady state voltages through to post fault transient stability and voltage stability. However, this document is mainly concerned with the explanation of how management of reactive power and voltage go hand in hand and how this is managed in real time.

There are a number of important considerations in management of reactive power that will be dealt with:

- How reactive power influences system voltage
- Management of reactive power is very locational
- Reactive power requirements can vary widely depending on system flows and topology

What Influences System Voltage

To demonstrate how system voltage is influenced by reactive power flows, an overview is given in the following section on the circuit theory behind flows on an AC power system.

What is reactive power

Reactive power is unique to AC power systems and arises due to the exchange of energy between charging and discharging of electric and magnetic fields in components of the transmission system, with no net real power gain or loss. Due to the behaviour of current flows in inductors and capacitors, when an alternating voltage is applied to the terminals, the current waveform in these elements is 90° out of phase to the voltage waveform (the real component of power is where the current is in phase with the voltage waveform), and this leads to the concept that reactive power is 90° out of phase to real power.

There is therefore a trigonometric relationship between real and reactive power, with the overall magnitude of the two components being called the apparent power, denoted *S*.

$$S = \sqrt{P^2 + Q^2}$$

This can be represented as a phasor diagram, Figure 1.

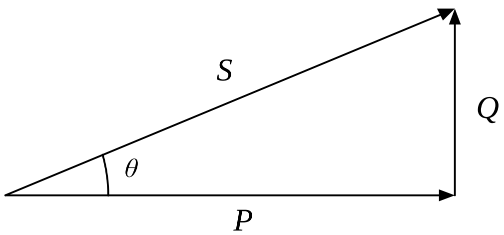

Figure 1 - Apparent, Real and Reactive Power Relationship

The active power is the component that does the useful work: it makes light bulbs emit light, turns motors, produces heat, charges batteries, etc. whereas the reactive power doesn't do any useful work. However, the transmission system must be designed to transmit the resultant apparent power. This gives rise to the familiar glass of beer analogy, where the real power is the liquid in the beer glass, the reactive power is the head on the beer, and the apparent power being the combination of the two, and the total measure that is paid for (Figure 2).

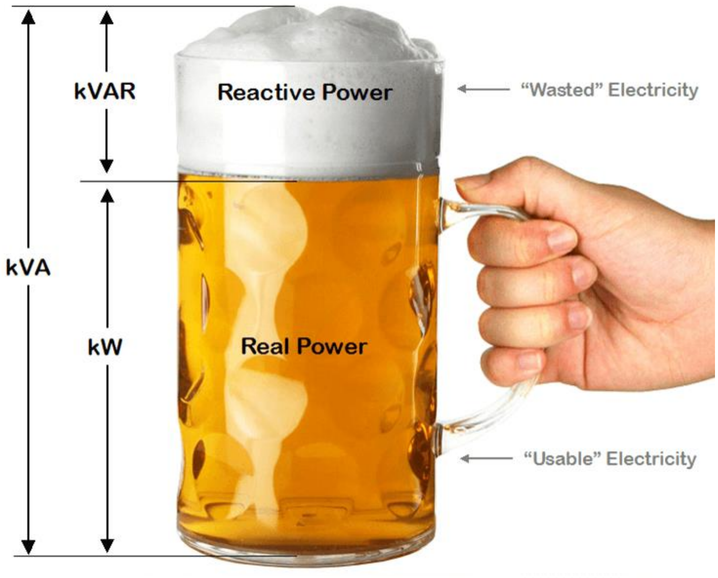

Figure 2 - Complex Power / Glass of Beer Analogy

However, reactive power is important for the overall stable operation of a power system, as equipment such as induction machines require reactive power for their correct operation (to form magnetic fields), and reactive power management is vital for voltage management on the transmission system.

A few other concepts are derived from this relationship too:

The power factor is the ratio of real to apparent power:

$$pf = \frac{P}{S}$$

And this is also the cosine of angle θ.

The ratio of reactive to real power (Q/P ratio) is another useful method of denoting the power factor, and this is also the tangent of angle θ.

The role of reactive power in voltage management

In an AC transmission system, high voltages are used to transmit power over long distances. Why use high voltages? From a simplistic view, this allows the transmission of high powers at low currents, reducing the heating losses in the transmission system. When looking at a DC system, the power, P, dissipated in a circuit can be calculated from the current and voltage:

$$P = I\,V$$

Therefore, for an increase voltage, the same power can be transmitted at a proportionally lower value of current. When a current is passed through a resistance, the power lost in the circuit can be found from Ohm's law

$$P_{losses} = I^2 R$$

Thus, reducing the current used to transmit power results in the losses reducing by the square of the reduction in current.

The above represent a DC based system, though when moving this to an AC system, the power flows across the network are determined by the impedance of the transmission line, which is the combined effect of both the resistance and the reactance of the transmission line. The physics governing the flow of power are such that the difference in the voltage angle between the two ends of the line determines the flow of real power, and the difference in voltage magnitude determines the flow of reactive power.

Considering a simple two bus system, Figure 3, the voltages at either end of a line (the sending end voltage V_S and receiving end voltage V_R) are given by complex phasors as per the diagram. Here we assume that resistance is negligible (which is reasonable for a transmission system, where typically X >> R)

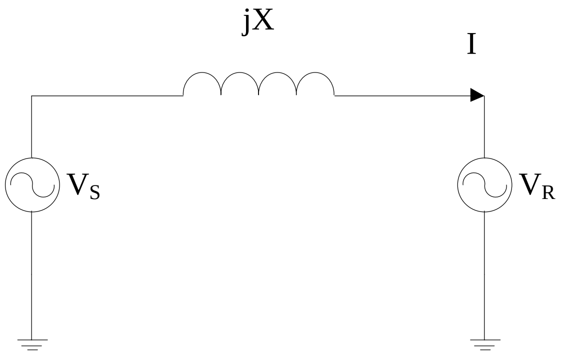

Figure 3 - Simple 2 bus system

X is the inductive reactance of the line and I is the current flowing. In the phasor diagram in Figure 4, we assume that V_R is the reference voltage at 0°, and V_S leads V_R

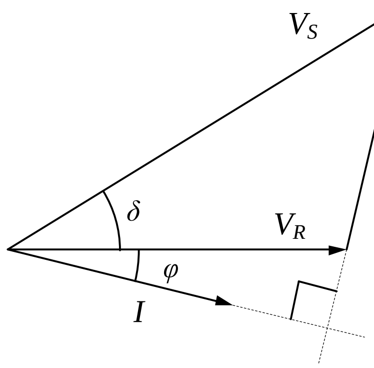

Figure 4 - Phasor diagram for simple 2 bus system

Using basic circuit theory, we can state that:

$$I = \frac{V_S - V_R}{jX}$$

$$= \frac{V_S}{X}\sin(\delta) - j(V_S\cos(\delta) - V_R)$$

At the receiving end, the complex power is given by the voltage multiplied by the complex conjugate of the current:

$$S_R = V_R I^*$$

$$= \frac{V_S V_R}{X}\sin(\delta) + j\left[\frac{V_S V_R}{X}\cos(\delta) - \frac{V_R^2}{X}\right]$$

The complex power can also be expressed as

$$S_R = P_R + jQ_R$$

Therefore

$$P_R = \frac{V_S V_R}{X}\sin(\delta)$$

$$Q_R = \frac{V_S V_R}{X}\cos(\delta) - \frac{V_R^2}{X}$$

Some further simplifying assumptions can be made:

- $V_R \sim V_S \sim V$ (with a difference of ΔV between them)
- The load angle, $\delta \sim 0$ (or very close to 0) then $\sin(\delta) \sim \delta$ and $\cos(\delta) \sim 1$

Giving the approximations of:

$$P_R \approx \frac{V^2}{X}\delta$$

$$Q_R \approx \frac{V}{X}\Delta V$$

This demonstrates that an excess of reactive power (positive Q_R) leads to an increase in system voltage, and a dearth of reactive power (negative Q_R) leads to a decrease in system voltage

This behaviour can also be exploited to change system voltages, by changing the reactive power balance at a node to increase or decrease system voltages.

The behaviour of the transmission system

The components of the transmission system can also act as significant sources and sinks of reactive power, unlike real power.

Transformers, overhead lines and cables all have a series self-inductance, which acts as a sink of reactive power when they have a load current flowing through them. We typically express the impedance that the inductance presents to the flow of current as the reactance, X_L. X_L is given in ohms, and is quoted at the system frequency:

$$X_L = 2\pi f L$$

The reactive losses are analogous to real power losses, and are expressed as such:

$$Q_{loss} = I^2 X_L$$

As would be expected, reactive power losses on the system tend to be much higher during periods of high demand.

Additionally, cables and overhead lines also have capacitance to ground and between phases, due to the electric fields that they generate. Normally cables have a much larger electrical capacitance due to their construction.

Capacitors act at a source of reactive power, and therefore increase system voltages. This is often called the reactive gain of the network, and it is proportional to the square of the voltage. Similarly to inductance, capacitance can be expressed as a reactance, X_C, though to make calculations easier, it can also be expressed as susceptance, B:

$$X_C = \frac{1}{(2\pi f C)}$$

$$B = \frac{1}{X_C}$$

The reactive power injection from a capacitor is related to the applied voltage squared:

$$Q_{gain} = BV^2$$

$$Q_{gain} = \frac{V^2}{X_C}$$

An important outcome of the above discussions concerning the reactive behaviour of the system elements is the balance between the gain and losses.

Typically, the system voltage is held close to nominal (1 per unit voltage) and therefore a simplification can be made that Q_{gain} for a line is fixed. However, the reactive losses will vary with the load on the line. Therefore, a transmission line can act as a sink of reactive power where the load is sufficiently high, and $Q_{loss} > Q_{gain}$, yet it will act as a source of reactive power where the load on the line is low and $Q_{gain} > Q_{loss}$. The point at which the two balance each other out is called the natural loading, or surge impedance loading of the transmission line.

The surge impedance (also called the characteristic impedance) of a transmission line is derived from transmission line analysis, and for a lossless line is expressed as:

$$Z_0 = \sqrt{\frac{L}{C}}$$

The surge impedance loading (SIL) is defined as the power loading at which reactive power is neither absorbed nor produced, and can be calculated from:

$$SIL = \frac{V^2}{Z_0}$$

In per unit terms, this can be calculated from the impedance and susceptance:

$$Z_{0(pu)} = \sqrt{\frac{X}{B}}$$

$$SIL_{pu} = \frac{1}{Z_{0(pu)}}$$

Where the load on the line is less than the SIL, the line will generate reactive power (and increase the system voltage) and when the line is greater than the SIL, the line will absorb reactive power (and decrease the system voltage).

It can also be demonstrated that the surge impedance loading for an overhead line is much lower than that for a cable, as the capacitance of a cable is much greater than the capacitance of an overhead line. For example, a typical overhead line has a SIL of 600 MW, whereas a cable will have a SIL of 3500 MW (in which case, the rating of the cable may be such that the load on the cable can never be greater than the SIL and therefore it will always generate reactive power). This is an important result, and NGESO will exploit this phenomenon overnight (when transmission system loadings are low) by switching out circuits with high capacitive gain to reduce system voltages.

Reactors and capacitors

The discussions in the preceding section have demonstrated that inductors and capacitors are capable of absorbing and injecting reactive power. These devices are therefore installed by transmission owners to assist with voltage control on the transmission system.

Shunt connected reactors decrease the reactive power balance at the connected node, and therefore reduce the system voltage and shunt connected capacitors increase the reactive power balance at the connected node and therefore increase the system voltage.

Demand and generation

The role of the transmission system was historically to facilitate the bulk transfer of power from large, decentralised generation to load centres, over long distances. However, the role of the transmission system is moving away from this model. Both demand and generation have an influence on system voltages and changes observed in the last 10-15 years have made voltage management more challenging.

Demand

Demand, by its nature has a real and reactive component. Historically, the demand taken from the transmission system was heavily inductive (absorbing reactive power), due to the nature of the connected load. However, over the last 10-15 years, there has been a dramatic reduction in reactive power demand, with DNO demand becoming largely capacitive (a net injector of reactive power).

Figure 5 gives a plot of reactive power demands on the GB transmission system for the last 15 years, showing the general declining trend.

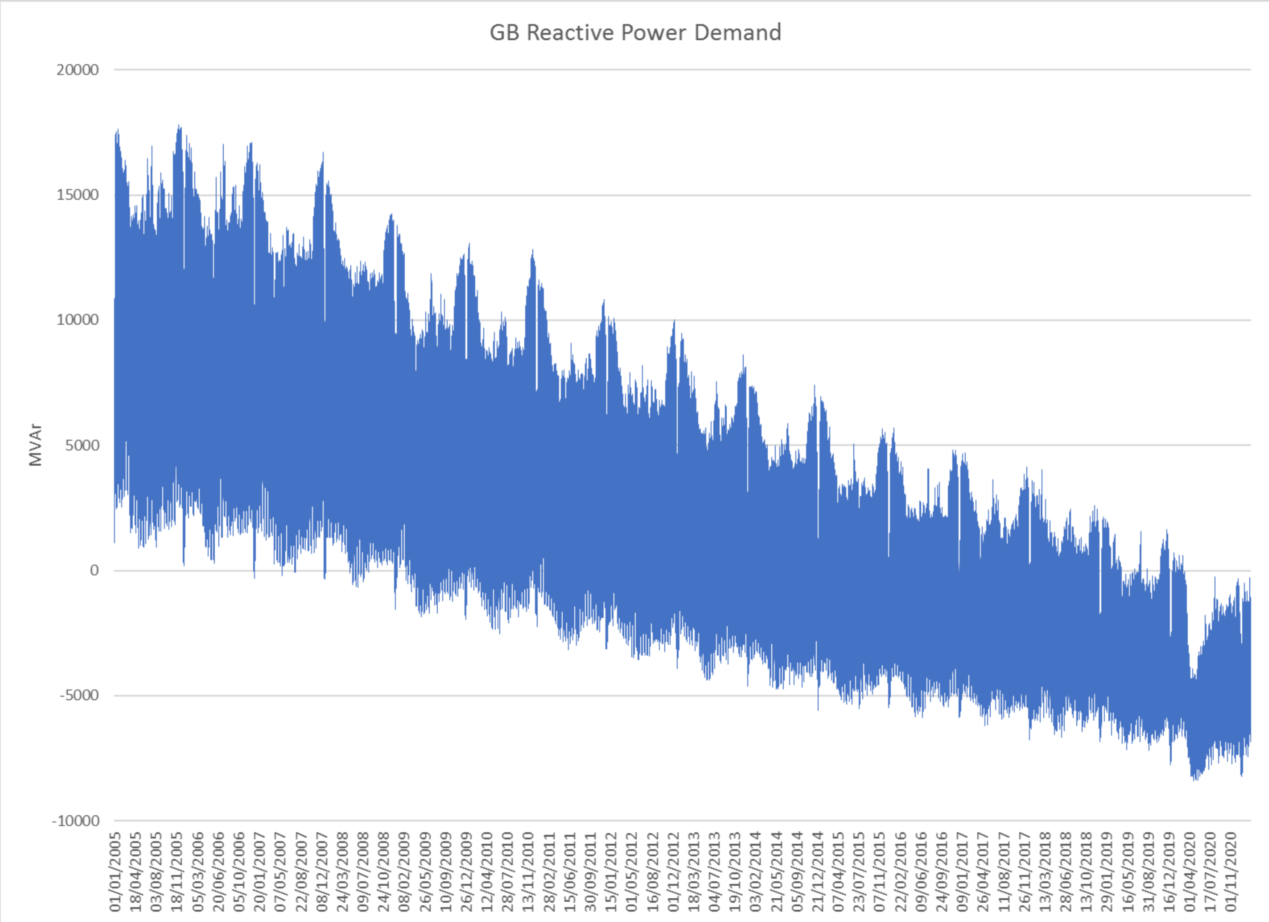

Figure 5 - GB Reactive Power Demand from 2005

This tends to exacerbate overnight voltage management problems, as the system loading is low, with the system gain dominating as described above, and the additional reactive power injection from distribution networks increases voltages on the transmission system further.

Generation

Historically, generators connected to the transmission system were large, steam turbine driven synchronous machines. These were connected throughout the system (generally close to the major fuel sources), and were capable of providing a large reactive power range. Also, where lack of reactive capability for management of voltages was identified in an area, it was (and still is to an extent) possible to access that generation through the Balancing Mechanism and in doing so, gain access to their reactive power range. Modern sources of generation are inherently less flexible (onshore and offshore wind generation, solar PV generation, etc.), or embedded within distribution networks. This means they either do not have the requirement to provide a reactive power service or their reactive power range cannot be accessed through the BM when they are not generating (due to the nature of their energy source – wind and solar PV do not run from a store of fuel). Several of these sources of generation are also connected to the extremities of the system and are therefore not capable of managing voltages across large parts of the system.

Locational Aspects

Another major challenge of voltage control is the locational nature of the requirements.

We have seen in the preceding sections that items of transmission plant can both generate and absorb reactive power, depending on the applied voltage and current flow. These effects, along with the highly-meshed structure of a transmission system tend to make the impact of reactive power localised.

This can be related back to the relationship between reactive power and differences in voltage magnitude and the reactive gain.

By meshing the transmission system, the overall impedance of the system, X_L, is reduced, as multiple X_L in parallel will have an equivalent impedance lower than the smallest X_L. Therefore, if the system consisted of purely series reactance, then the system voltage would tend to move together. However, when considering the capacitive gain of a meshed system, increasing the number of circuits increases the overall gain of the system, as the line capacitances are shunt connected and when capacitors are connected in parallel, the equivalent capacitance is the sum of the parallel capacitors.

This has the overall impact of lessening the effect of reactive absorption or injection at a location on the overall voltage profile. This can be described by an effectiveness, whose value is calculated thus:

- The reactive power requirement to meet a voltage target at a node (node A) is calculated;
- A known size of reactive power compensation is applied at an adjacent node (node B);
- The change in reactive power requirement at node A is noted;
- The effectiveness at node B is calculated from:

$$Effectiveness\ (\%) = \frac{Orignal\ requirement\ at\ node\ A - Resulting\ requirement\ at\ node\ A}{Size\ of\ compensation\ at\ node\ B} \times 100\%$$

This is best demonstrated with an example.

The system shown in Figure 6 supplies demands at Node D and Node C.

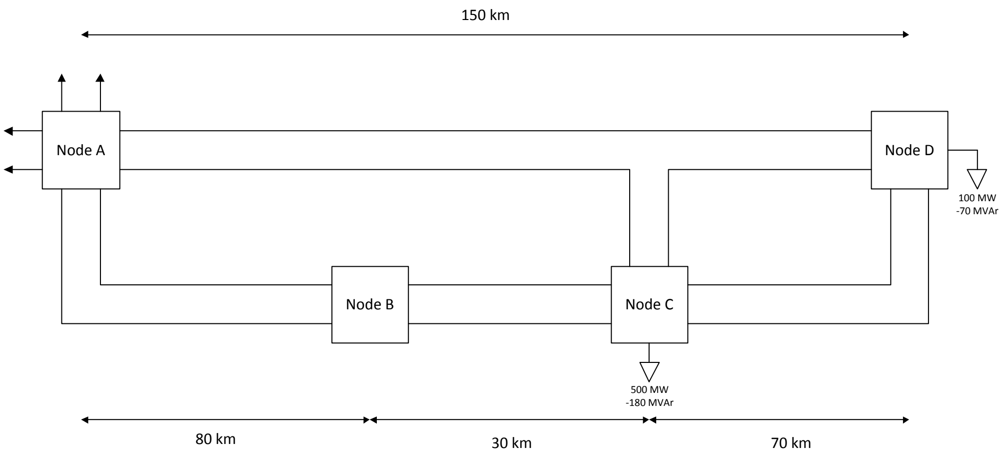

Figure 6 - Simple, example system

In order to maintain nominal system voltages at Node D overnight, power system studies show that approximately 260 MVAr of reactive power absorption is required at Node D. To evaluate the effectiveness of reactive power absorption at Nodes B & C, 100 MVAr reactors are placed at those nodes in turn. It is assumed that Node A has a fixed voltage.

At Node B, introducing a 100 MVAr reactor reduces the requirement at Node D to 228 MVAr to maintain nominal system volts, giving an effectiveness value for Node B (Eff_B)of:

$$Eff_B = \frac{260 - 228}{100}$$

$$Eff_B = 0.32\ or\ 32\%$$

At Node C, introducing a 100 MVAr reactor reduces the requirement at Node D to 208 MVAr to maintain nominal system volts, giving an effectiveness of:

$$Eff_C = \frac{260 - 208}{100}$$

$$Eff_C = 0.52 \; or \; 52\%$$

This is illustrated in Figure 7, demonstrating that effectiveness decreases the further away from the reference site the compensation is located.

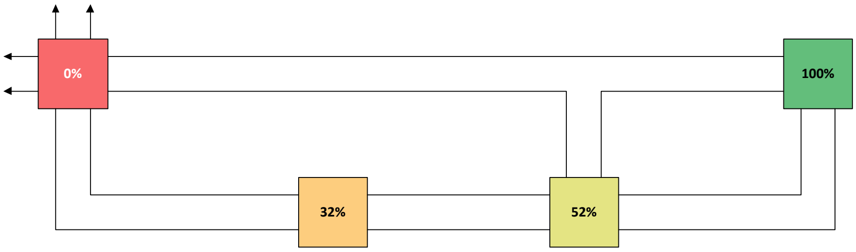

Figure 7 - Reactive power effectiveness values for the example system

This can be further extended to show the MVAr requirements at these nodes to maintain the voltage at Node D at nominal without any additional compensation there:

$$Q_B = \frac{Q_D}{Eff_B}$$

$$Q_B = \frac{260}{0.32}$$

$$Q_B = 812.5 \; MVAr$$

Carrying out the same exercise at Node C gives a value of $Q_C = 500 \; MVAr$.

When applying these to the simple network, it can be seen from Figure 8 that the voltage at Node D does indeed resolve to nominal. However, this drops the voltage at the compensated nodes below nominal.

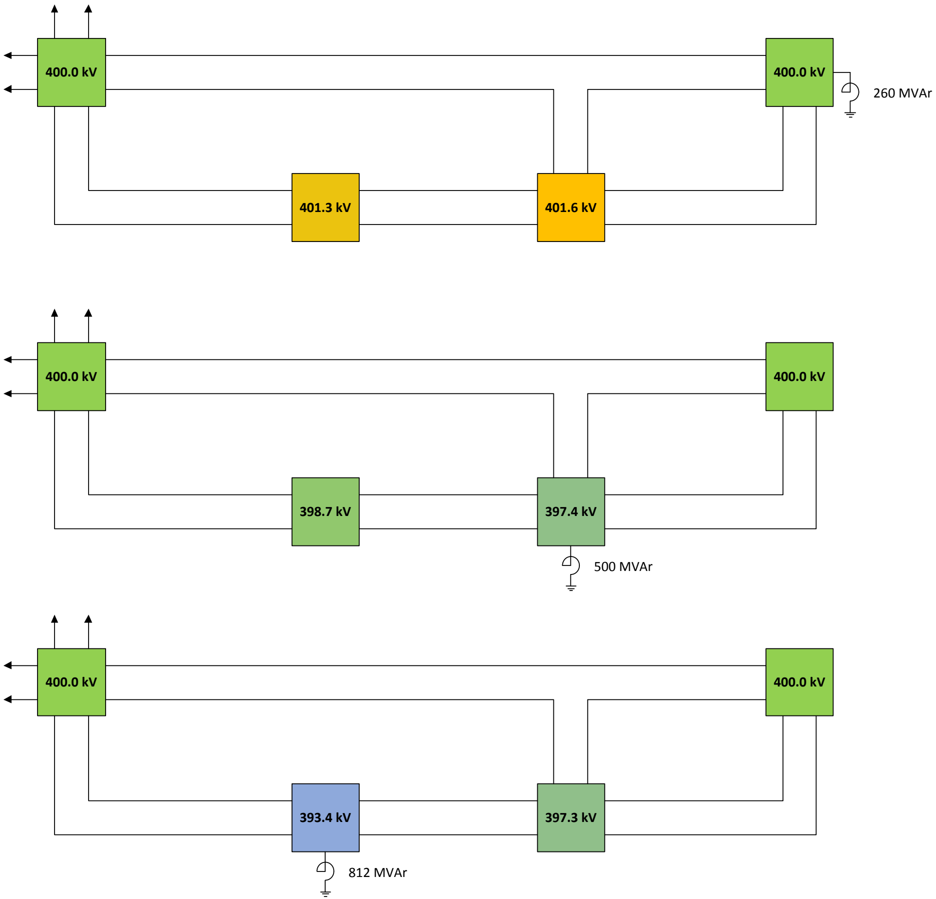

Figure 8 - Resultant voltages following application of shunt reactors at each node

This may not be acceptable following faults on the network, as it may give rise to unacceptable voltage step changes at customer interfaces, or voltage collapse. Therefore, more detailed studies would be required to determine the preferred mix of locations and compensation sizes to compensate the network.

Note also, that the above example demonstrates the process of identifying effectiveness values for an *intact system*. It is likely that differing effectiveness values would be calculated during planned outages and following fault outages (single circuit faults, double circuit faults, etc.) which could give rise to higher voltages and disconnect reactive compensation from the site(s) with the high voltage.

How do we manage high voltages

The previous section outlined the theoretical behaviour of system voltages with changes in reactive power flows on the system.

This section aims to cover the practicalities of managing voltages, and is principally concerned with the management of high voltages, as this has become an increasing operability challenge over the last ten years.

High voltages tend to manifest themselves when demand is low overnight (both real and reactive power demand). This then requires a reduced level of generation to meet that demand, along with reduced flows on the system.

This section aims to set out the process by which voltages are managed and how this translates in to an additional reactive power requirement.

Why worry about high voltages?

The simple answer to this is that NGESO's transmission licence requires NGESO to operate the NETS within the relevant standards, which are:

- The NETS SQSS
- The Grid Code
- The Electricity Safety, Quality and Continuity Regulations

Whilst these codify the requirements and place an obligation on NGESO to operate the system within defined limits, the overriding reason for not exceeding voltage levels is to ensure the safe operation of the system. If equipment is operated outside its design rating, then there is a risk that that equipment could be damaged. Additionally, that damage could happen in a destructive way, putting the safety of those in the vicinity of that equipment at risk.

General Methodology

The operational criteria set out in the NETS SQSS require the system to be operated within the limits set out there, under the prevailing system conditions, and then also within limits following a fault outage of various items of equipment.

Initially, system studies will be carried out to determine how best to manage system voltages with the forecast prevailing system conditions.

To minimise the cost of operating the system, generally TO assets are the first option to be used for voltage control. This allows voltages to be managed whilst preserving the dynamic reactive power reserves available on synchronous machines and any dynamic capability available from non-synchronous generators and offshore transmission networks. This may involve:

- Switching out shunt capacitors and switching in shunt reactors
- Adjusting targets on TO SVCs, STACOMs and/or synchronous compensators

Where flows on the system are forecast to be low and system security can be maintained, circuits which have a significant reactive power gain may be switched out to reduce the system voltage. Initially cable circuits around conurbations such as London will be switched out, especially where there are parallel circuits. Though other circuits across the transmission system may be switched out taking in to account the switching arrangements, outage pattern, equipment limitations and system security.

Reactive power contributions from generators will then be adjusted to increase their reactive power imports, taking in to account their reactive power capability and any redeclarations, whilst leaving a margin to ensure that there are dynamic reserves available. This then helps to lower the voltage system wide, reducing the overall system gain (recalling the previous discussions on reactive power gain).

If the above options have been exhausted, then it may be necessary to investigate the use of additional voltage control circuits, or to run additional generation to ensure that voltages can be maintained within limits.

The next step is to simulate fault outages on the transmission system and interrogate the results to see where post-fault voltage limits may be exceeded.

If limits are exceeded, then options are investigated to manage the post fault voltages. These may involve the looking at options described above, and they will typically be required pre-fault. However, the SQSS voltage standard does give allowance at 400 kV to take actions within 15 minutes to reduce voltages below 420 kV.

However, where operational actions are exhausted, or unavailable it may be necessary to use BM reactive power providers pre-fault to manage post-fault voltages.

This process allows the reactive requirement in an area to be identified. In the absence of a diverse range of commercial providers of reactive power, this is typically expressed as the number of BM providers required in an area to ensure voltage compliance.

It should be noted that this outlines the general methodology that is adopted for management of voltages. The process is run at intervals across timescales from 12 weeks ahead of real time to allow any challenging periods to be identified. If particular issues are identified in an area, then other options may be explored, such as moving outages or tendering for commercial services.

The studies that are carried out above also aim to investigate the system under worst case conditions – that is, conditions that could lead to higher system voltages. Closer to real time, as the generation and demand forecasts become more accurate, the plan can be refined. Additional options can also be used in real time to assist with voltage management as required:

- Transformer tap stagger
  This increases reactive losses in parallel connected transformers by operating them on different taps to force the circulation of reactive power in the transformer;
- Simultaneous tap changing of generator transformers
  This is a process that allows a system wide change in the voltage profile to be achieved without eroding reactive power reserves on the synchronous machines;

Worked Example

The following outlines a worked example to demonstrate the process outlined above. This is based on a generic scenario and may not be representative of actual system conditions.

Throughout the diagrams in the following sections, the following colour scheme is used to indicate the voltages at each node.

	400 kV	275 kV
	≥ 420 kV	≥ 300 kV
	≥ 415 kV, < 420 kV	≥ 294 kV, < 300 kV
	≥ 410 kV, < 415 kV	≥ 288 kV, < 294 kV
	≥ 405 kV, < 410 kV	≥ 281 kV, < 288 kV
	≥ 400 kV, < 405 kV	≥ 275 kV, < 281 kV

Step 1 – The intact network

Initially, assess the state of the voltage profile in a relevant area, taking in to consideration the available transmission plant and the forecast generation profile.

With the correct demand profile loaded, and the network is set up to reflect anticipated conditions (or possibly wort case conditions, depending on the time frame), a load flow study is run, and the system voltage profile obtained. Figure 9 shows the resultant voltage profile.

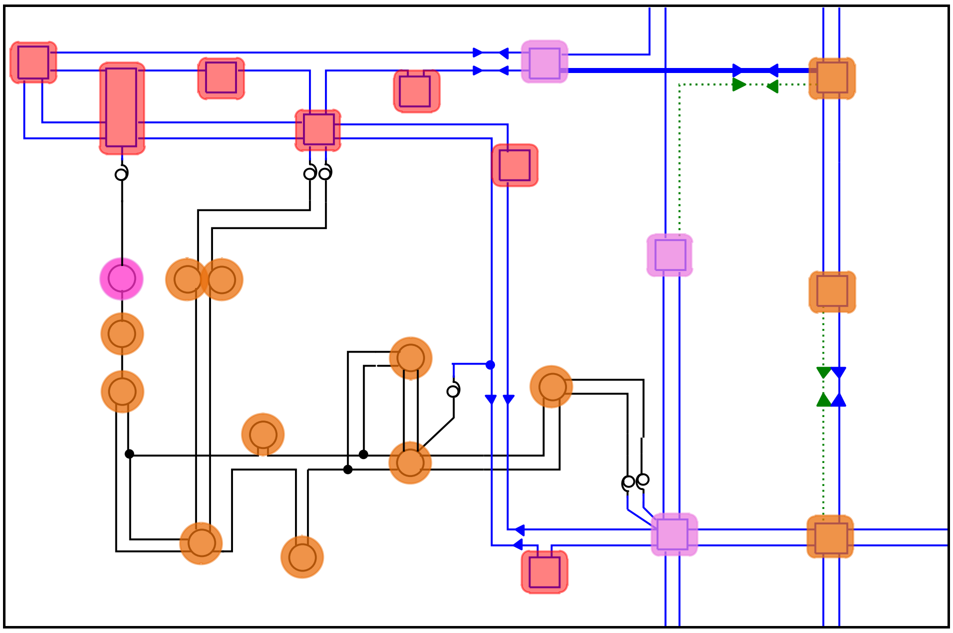

Figure 9 - Intact system, with observed steady state voltage levels

It can be seen from the diagram that several nodes have voltages in excess of 420 kV[1], therefore, action needs to be taken to resolve this situation.

Absorbing 220 MVAr at the node shown in Figure 10 is enough to solve this situation, and bring voltages within operational limits. It may be that other nodes are more effective, and therefore consideration is normally given to a different range of options to try and resolve any voltage issue. In this situation, though, the indicated node is the most effective.

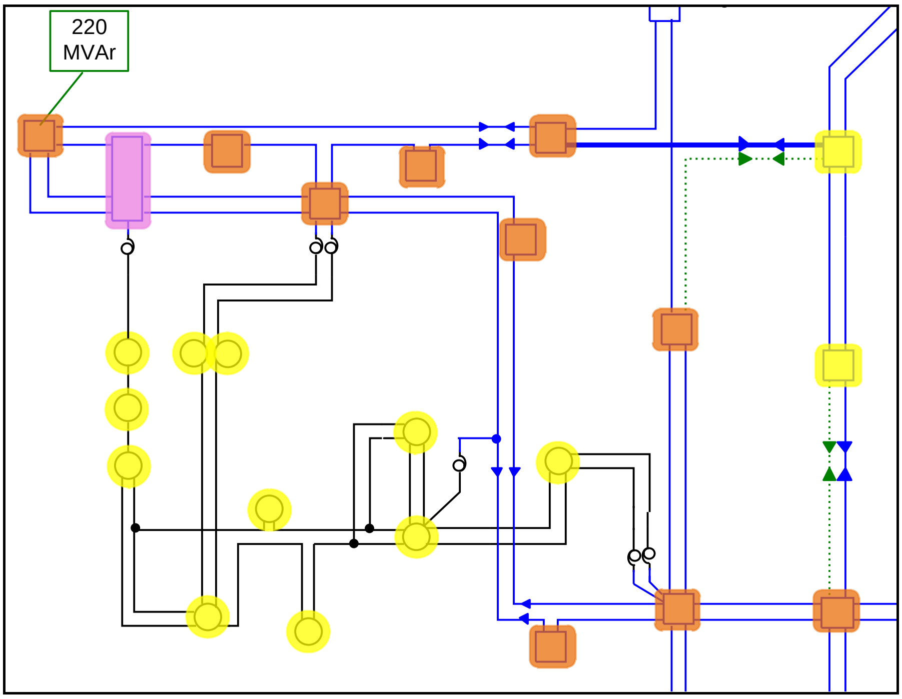

Figure 10 - Intact system with reactive power absorption as indicated

[1] 420 kV is the upper operational limit on the 400 kV network, as specified in the NETS SQSS. Voltages up to 440 kV are allowed, though for no more than 15 minutes.

Step 2 – Contingency Analysis

The next step is to analyse voltages following contingencies. Again, the standards to which the network needs to be operated specify that voltages need to remain within certain limits following fault outages of certain items of equipment.

Therefore, using the study that was set up to look at the steady state, pre-fault voltages, contingencies are simulated and the results interrogated to identify potential problems. Figure 11 demonstrates that the worst fault identified is a busbar fault at the indicated node, which gives high voltages (>420 kV) at various nodes on the network (note that the red dashed lines indicate circuits that trip as a result of the busbar fault). Again, the limit for voltages post contingency on the 400 kV network is 420 kV[2].

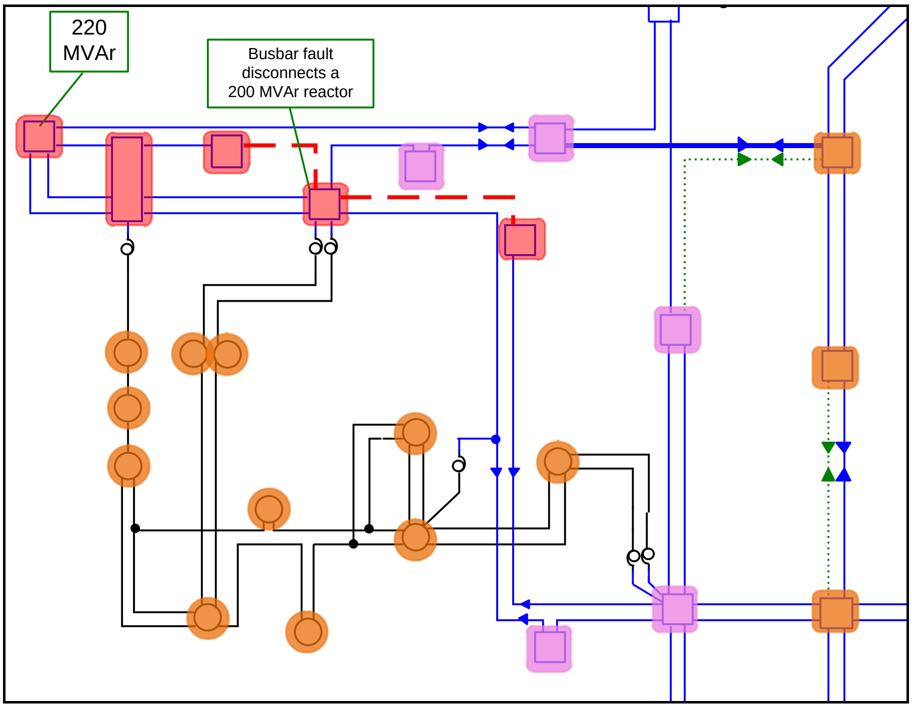

Figure 11 - Observed voltage levels following the indicated fault outage

To try and resolve this, various options are considered within the local network. The first set of options are to try and use additional reactive absorption at various locations as shown in Figure 12, Figure 13 and Figure 14.

[2] The NETS SQSS does allow this to rise to 440 kV post-contingency, though for no more than 15 minutes, similarly to the steady state limits.

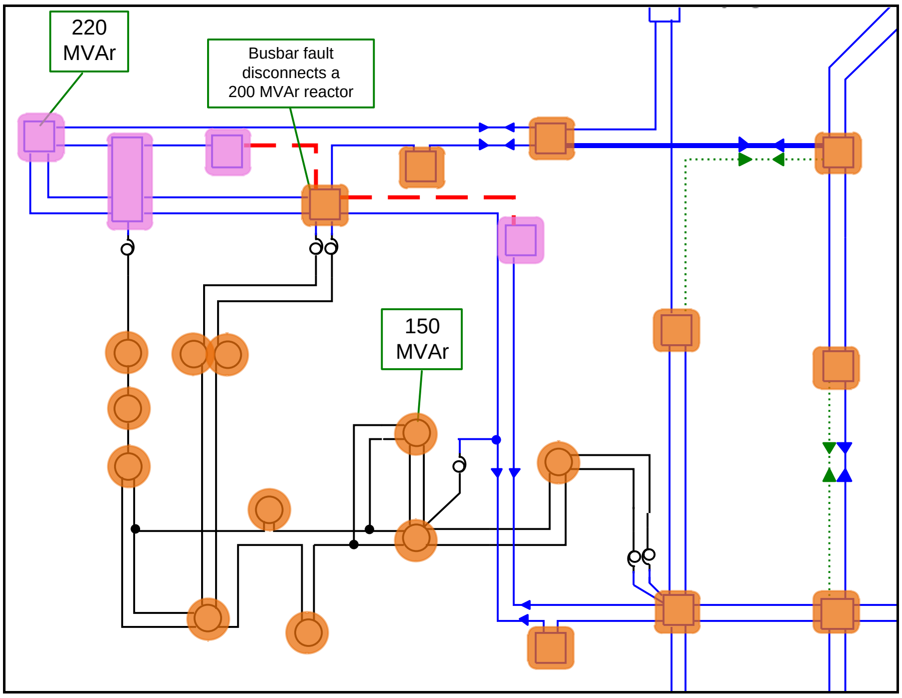

Figure 12 - Observed voltages following the indicated fault outage with additional reactive power absorption as shown

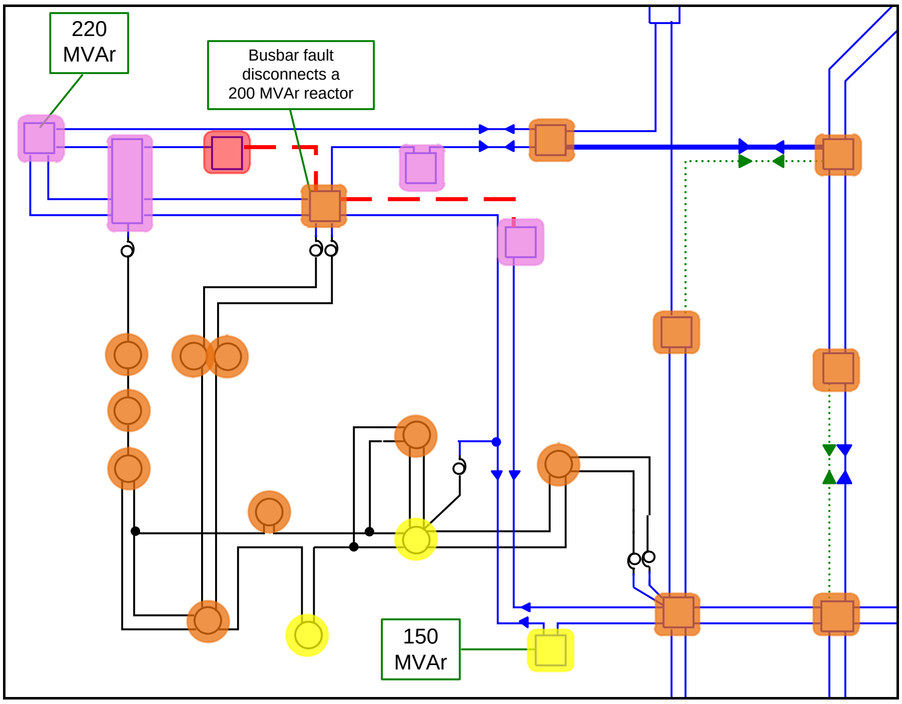

Figure 13 - Observed voltages following the indicated fault outage with additional reactive power absorption as shown

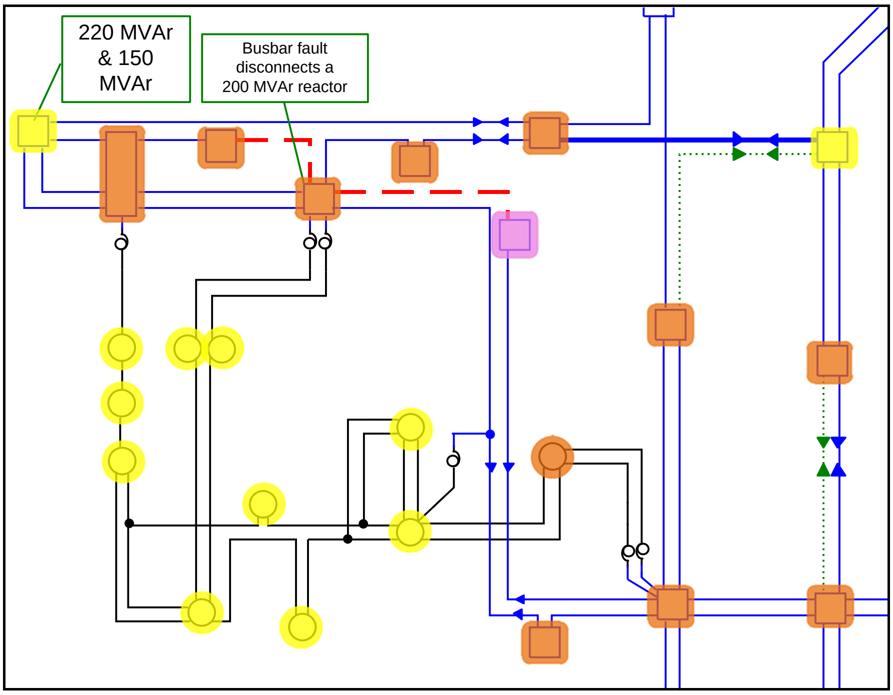

Figure 14 - Observed voltages following the indicated fault outage with additional reactive power absorption as shown

Having tried the above options, with varying levels of impact, further options are then considered, such as switching out high gain circuits, as shown in Figure 15.

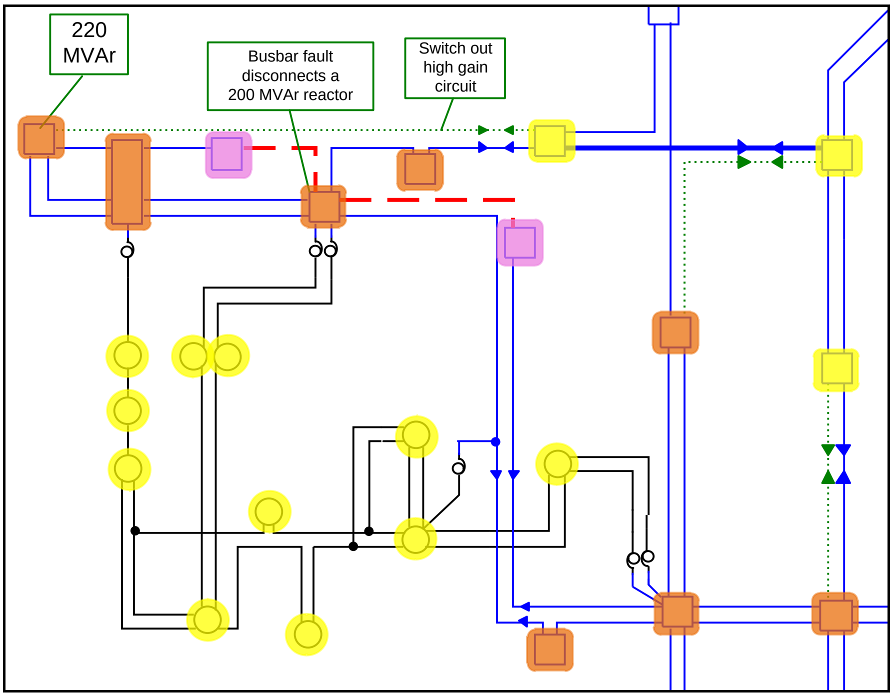

Figure 15 - Observed voltages following the indicated fault outage with high gain circuit switched out

Step 3 – Recheck Contingencies

Having been through the preceding steps, and arrived at a solution that maintains voltage in standards, both pre-fault and flowing the worst contingency, the next step is to check contingencies again.

This is an important step, as due to the locational nature of the effects of reactive power, solving the worst contingency may not solve high voltages for all contingencies in an area. Therefore, if high voltages are observed following other contingencies, then it is necessary to repeat steps 2 and 3 until all high voltages are resolved, and an optimal combination of options arrived at. To achieve this, it may be necessary to test different combinations of options.

Definition of Reactive Power Requirement

Using the above process, for different regions of the transmission system, the regional reactive power requirement can be defined. This is typically expressed as a number of reactive power providers that are required within an area to achieve a compliant voltage profile.

This will normally be for a fixed scenario, based on anticipated system conditions, or worst case conditions (low system flows and low real and reactive power demand).

Version Control

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