EirGrid

INVESTIGATION INTO MITIGATION TECHNIQUES FOR 400/220KV CABLE ISSUES

FINAL REPORT

EIRGRID PSP022

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Contents

1 INTRODUCTION

EirGrid engaged London Power Associates (LPA) to investigate techniques for mitigating issues arising from the installation of high voltage underground cables on the Irish Transmission System..

The objective of this project is to produce an updated investigation report into the mitigation techniques for the issues arising from the proposed deployment of 220/400 kV cables in the Irish transmission network.

The report will categorise the mitigation against the issues that they may resolve, track history of the applied use of the mitigation and grade the relative risk of reliance of each mitigation technique.

The report will also address the details of the dynamic response of devices proposed as well as any impact on steady-state behaviour at the fundamental 50Hz frequency.

Any associated benefits by introducing proposed mitigation techniques, such as the provision of reactive power compensation etc. and the associated costs, have been listed.

The project has been delivered in two parts:

> Part A: An international review of mitigation techniques for previously identified issues such as voltage rise, temporary overvoltages and resonance, and
>
> Part B: Reviewing the implications of applicability of the mitigation techniques in Ireland via two different individual transmission circuit projects, a radial and meshed application.

The GridWest[1] and GridLink[2] projects have been selected respectively for this appraisal.

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[1] EirGrid GridWest Project Brochure, http://www.eirgridprojects.com/media/Grid_West_Project_Information_Brochure_Summer_2014.pdf

[2] GridWest Initial Report, EirGrid, http://www.eirgridprojects.com/media/Stage%201%20Report.pdf

2 PREVIOUS WORK

As part of the scope of works for this investigation EirGrid has provided a number of international references and EirGrid commissioned work, related to the interconnection of Northern Ireland and Ireland which covers similar issues[3], cable investigations for offshore application [4] and has been active in EEUG[5] and CIGRE on this subject. This work is referenced throughout this investigation.

In this regard EirGrid have been notably involved in:

Cigre 556 – "Power System Technical Performance Issues Related to the Application of Long HVAC Cables"[6]

Cigre 568 – " Transformer Energization in Power Systems – A study Guide"[7]

Cigre 569 – "Resonance and Ferroresonance in Power Networks"[8]

And as a partner, in the support and development of:

SINTEF "Electromagnetic Transients in future Power Systems"[9]

Most notably of their own publically available works in 2009 EirGrid & NIE commissioned a report from TEPCO to examine the technical issues relating to the integration of underground cables. [10]

The conclusions of this report are given below:

The results of this thorough study concluded that with regards to the long cable network an attention must be paid to lower frequency phenomena such as temporary and steady-state overvoltages. The slow-front overvoltage is not a concern for the safe operation of the network because of the decay in the cable and large capacitance of the cable.

For example, dominant frequency components contained in the energisation overvoltage is not determined by the propagation time of the overvoltage as is often discussed in the textbooks that deal with surge analysis. They are rather determined by parallel resonance frequencies and are often very low due to the compensation.

Severe overvoltages were found in the parallel resonance overvoltage analysis in studies Part 1 and 2. Both of them exceeded the withstand overvoltage of a typical 400 kV surge arrester.

The magnitude of the overvoltage found in Part 1 is at a level in which there is no solution except operational countermeasures. In contrast, manufacturers will be able to develop a surge arrester that can withstand the overvoltages found in Part 2.

It will, however, lead to higher protective levels ensured by the surge arrester, which may affect the insulation design of other equipment.

These additional costs need to be evaluated by manufacturers. Finally, it will of course affect the total insulation coordination studied by the utilities.

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[3] EirGrid – North-South 400kV Interconnection Development – http://www.eirgridprojects.com/media/North%20South%20Preferred%20Project%20Solution%20Report_Final.pdf

[4] *EirGrid Offshore Grid Study* http://www.eirgrid.com/media/EirGrid%20Offshore%20Grid%20Study.pdf

[5] EEUG – Assessing Network Reinforcement Options – Preferred Project Solutions Report

[6] Cigre Document 556, Working Group C4.502, Power System Technical Performance Issues Related to the Application of Long HVAC Cables, October 2013

[7] Cigre document 568, Working Group C4.307, February 2014 "Transformer Energization in Power Systems: A study Guide"

[8] Cigre document 569, Working Group C4.307, February 2014 "Resonance and Ferroresonance in Power Networks"

[9] http://www.sintef.no/Projectweb/EMTransients/

[10] "Contract CA209:Assessment of the Technical Issues relating to Significant Amounts of EHV Underground Cable in the All-island Electricity Transmission System", TEPCO , 2009

In Part 1, the overvoltage that exceeded SIWV was found also in the load shedding analysis when a lower compensation ratio was adopted. Overall, Part 1 studies exhibited severer results compared to Part 2 or 3 studies.

It is mainly due to the weak system around Aghada, Cahir, and Kilkenny, which limited the propagation of the overvoltage. Another contributing factor was the fact that Part 1 studies had more freedom in terms of choosing study parameters.

Generally speaking, temporary overvoltages, such as the resonance overvoltages and the overvoltages caused by load shedding are low probability phenomenon.

Only certain, particular network operating conditions can yield such a severe overvoltage that they would lead to equipment failure.

Evaluating a low-probability high-consequence risk is difficult but must be done when installing cables.

The risks may be avoided via carefully prepared operational countermeasures, but unfortunately it will be a major burden for system analysts.

3 OBJECTIVE

From the previous work described in section 2 it is apparent that the integration of underground cables within the Irish transmission system may present some technical issues, specifically:

- Steady-State overvoltages
- Temporary Overvoltages (TOV)

Other issues related to the integration of cables are:

- Harmonic distortion
- Reactive power control
- Fault and protection issues

The objective of this report is to assess potential mitigation methods suitable for application in the Irish Transmission System.

Part A of the report is a review and assessment of technology and techniques utilised internationally

Part B of the report is an examination of the application of suitable techniques or technology for application on the Irish Transmission system based on the review in Part A.

The primary issue is avoidance and/or mitigation of Temporary Overvoltages (TOV).

The mitigation techniques will be examined to determine whether they can assist in avoiding the conditions where TOV becomes an issue by altering the system conditions or state such that unfavourable resonances at low harmonic frequencies are avoided.

From the previous work, it is recommended that specific low order harmonic resonances are avoided, particularly 2nd harmonic (100Hz) and 3rd harmonic (150Hz) as these are more difficult to mitigate than higher order harmonics and can cause difficulties in the setting and operation of control, protection and measurement equipment. The DC offset related to even harmonics may also contribute to saturation in motors and transformers.

Secondly, the mitigation techniques will be examined to assess the capability to reduce the effect of TOV if it cannot be avoided.

The mitigation of the other issues will also be considered.

4 PART A: INTERNATIONAL REVIEW

4.1 Issues related to 220/400 kV HVAC cables

There are many potential issues caused by introduction of HVAC underground cables to a power network. Adding cables adds complexity to the operation and design of the network – expand – OHL same issues but lesser impact.

The issues examined here are:

- Voltage rise and reactive power
- Fault level increase
- Self-excitation in synchronous generation
- Voltage Stability
- Temporary Overvoltages (TOV)
- Harmonics
- Zero-missing phenomenon
- Protection

4.1.1 Voltage Rise and Reactive Power[11]

The capacitive current of a cable depends on the applied voltage and the capacitance per unit length. At the critical cable length, the cable current rating is completely consumed by the capacitive current and no active power can flow through the cable. Shunt reactive power compensation installed along the cable route can correct this.

Reactive power surplus in any operating condition causes a power-frequency voltage rise, not only at the cable terminations but also at adjacent nodes in the grid.

In normal operating conditions, a voltage step of 3% is allowed while connecting or disconnecting a cable as described in the Transmission Planning Criteria.[12]

To keep voltages within acceptable margins, reactive power compensation is usually necessary.

This compensation can be achieved using shunt reactors, typically installed at both ends of a cable, and/or by the installation of Static Var Compensators.

The amount and location of shunt compensation influences the voltage profile along the cable.

Theoretically, uniformly distributed shunt compensation may produce the best voltage profile, but at a high cost. The external system also plays a role.

From Cigre Document 556:

The planning studies related to the reactive compensation of underground cables are similar to those carried out for long overhead line circuits.

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[11] Cigre Document 556, Working Group C4.502, Power System Technical Performance Issues Related to the Application of Long HVAC Cables, October 2013

[12] EirGrid Transmission Planning Criteria http://www.eirgrid.com/media/Transmission%20Planning%20Criteria.pdf

Due to the particular features of underground cables, some differences in the reactive compensation planning for overhead lines and cable circuits can be identified:

a) *Minimum length of circuit requiring shunt compensation.*

As a general rule, the shunt capacitance of an underground cable is in the order of 20 to 30 times the capacitance of an equivalent overhead line circuit.

Shunt compensation may need to be considered in underground circuits in the order of 20 to 30 times shorter than the equivalent overhead line.

b) *Degree of shunt compensation.*

Overhead lines are typically restricted to 60% to 80% shunt compensation due to risks of line resonance during open-phase conditions.

This phenomenon is caused by capacitive coupling between the disconnected phase and the remaining energized phases.

Given that there is no capacitive coupling between insulated cables, the restriction on low degree of shunt compensation does not apply.

Compensation degrees close to 100% are typical for underground cables.

In the case of mixed cable-overhead line circuits, inter-phase capacitive coupling will be present in the overhead line section.

A value between 60% and 100% can be chosen depending on the line/cable ratio.

c) *Voltage Rise*

Voltage rise at the receiving (open) end must not exceed the maximum continuous operative voltage (MCOV) or TOV capabilities of shunt reactors, surge arresters, or other equipment. The voltage rise is often higher in the presence of cables.

An estimate of the voltage rise due to the Ferranti Effect can be calculated using the following equation:

$$V_R = \frac{V_S}{1 - \omega^2 . \frac{C}{2} . L}$$

Where:

V_R is the voltage at the receiving end

V_S is the voltage at the sending end

C is the cable capacitance

L is the cable inductance.

The switching surges are overvoltages generally characterised by a high-frequency damped oscillatory phenomenon, superimposed on the fundamental power frequency voltage. These overvoltages are caused by switching operation on the EHV system (such as line opening or line energisation) or fault clearance.

4.1.2 Fault levels increase

Increased penetration of underground cable circuits in transmission systems can increase the fault levels, which could potentially have an adverse effect on switchgear duty and safety.

The application of a system fault causes a transient and a subsequent power frequency overvoltage. For effectively grounded systems, the maximum overvoltage is normally less than 1.4pu.

The duration is dependent on the protection systems used to detect and clear the fault condition. In the majority of cases, the fault condition with the resulting overvoltage lasts for only a few cycles.

Even in the rare case of a fault being cleared by backup protection (breaker fail condition), the overvoltage duration will normally be less than 1.5 sec.

The voltage waveform associated with the fault application usually is a sine wave. The exception to this would be systems where a fault is close to a transformer during which saturation of the transformer can cause waveform distortion.

4.1.3 Self-excitation in synchronous generators

This may occur when the machine's internal reactance is greater than the equivalent external reactance which is more likely to occur with a high penetration of UGC in the network.

This phenomenon can arise in the event of load rejection and system separation, or during a black-start restoration procedure. It can also arise due to the presence of capacitor banks and filters associated with HVDC. The self-excitation phenomenon can cause an uncontrolled voltage rise in the generator terminals, only limited by the saturation of the step-up transformer.

For shorter circuit lengths, underground cable increases the risk of this occurring when compared to overhead line.

Long transmission lines or cables connected in series with low impedance step-up transformers are prime candidates to cause this phenomenon. Self-excitation can occur both in hydro (salient pole) and thermal (round rotor) units, although it is more likely in thermal units due to their larger synchronous reactance.

4.1.4 Voltage stability issues

Underground cables (UGCs) provide more reactive power than an equivalent distance of overhead lines (OHLs).

Switched or variable shunt reactors associated with UGCs tend to provide more flexibility in reactive power control. However loss of these components could create voltage stability issues. Therefore it is necessary that these situations are considered in contingency analysis of the network. [13]

However, in the event of the cable being de-energised or tripped the loss of reactive power on the network may be significant causing potential voltage control issues.

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[13] Cigre Document 556, Working Group C4.502, Power System Technical Performance Issues Related to the Application of Long HVAC Cables, October 2013

4.1.5 Temporary Overvoltages (TOV)

IEEE Standard 1313.1-1996 defines temporary overvoltages as *"an oscillatory phase-to-ground or phase-to-phase overvoltage that is at a given location of relatively long duration (seconds, even minutes) and that is undamped or only weakly damped"*. They are characterised by the amplitude, the oscillation frequencies, the total duration, and the decrement.[14]

Overvoltage conditions can cause problems on a transmission system through:

- insulation failures, overheating or mis-operation.
- increasing the magnetic flux in the magnetic cores of equipment such as transformers and shunt reactors, which produces heat in the transformer cores, and can cause the equipment to fail.
- mis-operation of equipment such as surge arresters
- causing short circuits, or causing circuit breakers to fail interrupting power flow.

Resonance is a special concern with cables as they lower the system resonant frequencies.

Under normal switching conditions, transient voltages may be damped. However, where there is an excitation current at a resonant frequency, overvoltages may be sustained for several seconds, damaging protective devices such as surge arresters and other equipment.

In general system configuration, equipment characteristics, protection methods and operating procedures all affect TOV.

Common causes of TOV are:

- system faults
- load rejection
- line energisation
- line dropping/fault clearing, and reclosing
- transformer energisation.

There are special cases that merit detailed examination and are discussed in the following sections below.

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[14] Temporary Overvoltage Equipment Limits – Summary Report, K&R Consulting, LLC, for Northeast Utilities, December 17 2004, http://www.ct.gov/csc/lib/csc/docket_272/roc_report/ROC_App_B_TOV_Report.pdf

4.1.5.1 *TOV caused by parallel resonance*

On a system with long HVAC cables the inductance of the shunt reactors and the distributed capacitance of the cables form a parallel resonant circuit.

This is usually characterised by large impedance at the resonant frequencies.

Large current may circulate through the resonant inductance and capacitance producing higher transient voltages.

The most onerous condition is a long length of cable combined with a low system strength. Consideration of the length of cable in the design phase is key to avoiding issues in the this case.

4.1.5.2 *TOV caused by series resonance*

The series (leakage) reactance of a transformer can create a series resonance circuit with the capacitance of the cable.

The situation is characterised by lower impedance at the resonant frequency, which results in large harmonic current and high TOV.

4.1.5.3 *Switching Procedures which can create TOV*

1) Transformer Energisation (controllable)
2) Fault Removal (not controllable)
3) Load Rejection (not controllable)
4) Islanding (not controllable)

This may occur, for example, during single pole auto reclose events or single breaker maloperation on a transformer circuit or circuits connected to a long cable circuit causing overvoltages.

4.1.5.4 *TOV caused by Ferroresonance*

Ferroresonance is an interaction between capacitors and saturable iron-core reactance such as transformers.

When a transformer and cable become isolated, and the cable capacitance is in series with the transformer magnetising characteristic ferroresonance may occur causing effects similar to series resonance.

From Cigre document TB 569:[15]

In simplest terms, ferroresonance can be described as a non-linear oscillation arising from the interaction between an iron core inductance and a capacitor. ...
As with linear resonance, ferroresonant circuits can be either series or parallel, albeit only series configurations are typically encountered in transmission networks. It should be noted that parallel ferroresonant configurations are common in distribution systems with ungrounded or resonant neutral connections.

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[15] Cigre document 569, Working Group C4.307, February 2014 “Resonance and Ferroresonance in Power Networks”

4.1.6 TOV Withstand of Equipment on the Transmission System

This section is a review of the available information regarding the TOV withstand of equipment on the transmission system.

The impacts of the conditions described in the previous section define the level of overvoltages that may occur and which the network and its users equipment must be able to withstand.

To design the network effectively the equipment will need to be adequately rated to withstand the overvoltages experienced on the network. The availability of data relating to aspects other than fundamental frequency related capability can be limited. This can result in equipment that cannot be operated at full rating or potentially may fail in certain circumstances if design margins are not employed. Other alternatives may be the use of conditioning monitoring equipment with associated capital and manpower cost that still may not be sufficient. Understanding of the equipment capability is very important in designing the system to withstand longer-term TOV effects.

From the review it is apparent that the majority of material relating to equipment withstand is based on the fundamental frequency withstand as defined in the various international standards and grid codes.

The Insulation Coordination requirements for equipment on the Irish Transmission System are given in table CC.7.2.2.1 of the EirGrid Grid Code.[16]

However, the withstand of equipment related to TOV is discussed in the design of surge arresters and was also discussed in the evaluation of TOV mitigation in Southwest Connecticut, USA. Extracts from these sources are given below:

From Siemens "Fundamentals of Surge Arresters"[17]:

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[16] EirGrid – Grid Code version 5 - http://www.eirgrid.com/media/GridCodeVersion5.pdf

[17] http://www.energy.siemens.com/ru/pool/hq/power-transmission/high-voltage-products/surge-arresters-and-limiters/aboutus/Arrester_Book_Ed%20_3_en.pdf

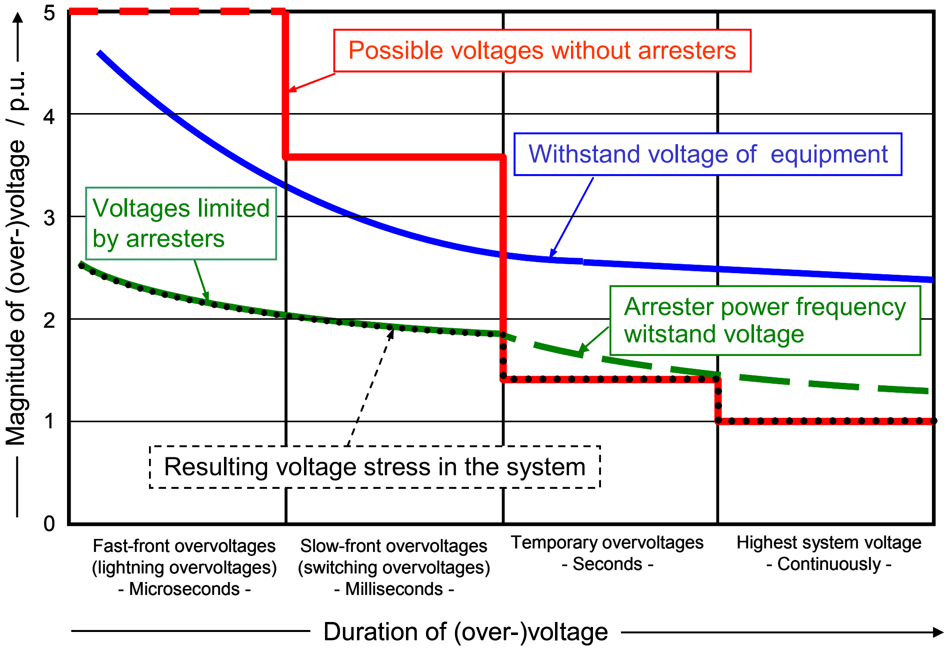

Fig. 1: Schematic representation of the magnitude of voltages and overvoltages in a high-voltage electrical power system versus duration of their appearance (1 p.u. = $\sqrt{2} \cdot U_s / \sqrt{3}$)

The time axis is roughly divided into the range of fast-front overvoltages (mainly lightning overvoltages) in the microsecond range, slow-front overvoltages (mainly switching overvoltages) in the millisecond range, temporary overvoltages in the second range – which are commonly cited by the abbreviation "TOV" – and finally the temporally unlimited highest continuous system operation voltage.

The voltage or overvoltage, which can be reached without the use of arresters, is a value of several p.u.

If instead, one considers the curve of the withstand voltage of equipment insulation, (here equipment means electrical devices such as power transformers) one notices that starting in the range of switching overvoltages, and especially for lightning overvoltages, the equipment insulation cannot withstand the occurring dielectric stresses.

At this point, the arresters intervene. While in operation, it is certain that the voltage that occurs at the terminal of the device – while maintaining an adequate safety margin – will stay below the withstand voltage.
Arresters' effect, therefore, involves lightning and switching overvoltages.

However, arresters cannot and are not expected to limit temporary overvoltages. They must instead be designed to withstand the continuous system operation voltage without sustaining damage.

This is shown in Figure 1 by the dotted part of the arrester curve on the right, in which the arrester – like any other device in the system – must demonstrate sufficient operational stability over and above likely voltage stress.

From Temporary Overvoltage Equipment Limits – Summary Report by K&R Consulting for Northeast Utilities[18],

To determine what problems the overvoltage conditions could cause, it is necessary to identify the equipment that is most vulnerable to such conditions.

Using IEEE standards and manufacturers' specifications, each piece of equipment on the system or planned for new construction was reviewed to identify existing TOV capabilities.

The withstand capacity of the electric transmission system was determined by finding the equipment with the lowest withstand capacities and determining if these withstand capabilities could be increased without causing other problems.

The equipment with the lowest TOV withstand limits are surge arresters and transformers.

IEEE Standard C57.00 contains transformer overvoltage withstand limits for lightning surges, switching surges and 60 cycle overvoltages.

The data in this standard can be used to estimate a transformer overvoltage withstand for short TOVs. The existing transformer TOV limits in per unit nominal system voltage were calculated using the safety margins defined in IEEE Standard C62.22.

The transformer TOV limits are shown below.

	2 cycles	*6 cycles*	*30 cycles*	*1 second*
345kV (900kV BIL)	*2.6*	*2.4*	*2.2*	*1.8*
115kV (350kV BIL)	*2.8*	*2.6*	*2.4*	*1.9*

Table 1 - Southwest Connecticut Transformer TOV Limits

Surge arresters are designed to prevent insulation flashover and equipment damage by limiting transient voltages between energized conductors and grounded components. Surge arresters are not designed to protect equipment from TOVs.

Arresters may be specified within a particular class by the Maximum Continuous Operating Voltage (MCOV). In applying arresters, it is critically important that the arrester MCOV rating be greater than the maximum continuous voltage to which the arrester is exposed at any time.

Arresters may also be specified by the "Duty Cycle Rating" which is the maximum voltage an arrester can successfully withstand after a series of discharge tests.

The Duty Cycle test procedure is defined in IEEE Standard C62.11.

For the purpose of this discussion, the remaining arrester rating parameters will be discussed in terms of MCOV in order to directly compare the arrester rating with the nominal system phase to ground voltage.

At MCOV the arrester current is less than a few milliamperes.

As the voltage across the arrester is increased to between 20% and 30% above the MCOV, the arrester resistance decreases and the arrester starts to conduct some current and absorb some thermal energy from the power system. This conduction process occurs quickly and the arrester may "turn on" and "turn off" in a fraction of a microsecond.

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[18] Temporary Overvoltage Equipment Limits – Summary Report, K&R Consulting, LLC, for Northeast Utilities, December 17 2004, http://www.ct.gov/csc/lib/csc/docket_272/roc_report/ROC_App_B_TOV_Report.pdf

For lightning and switching overvoltages, arresters may conduct and absorb all the energy from a particular waveshape in much less than one 60 Hz power frequency cycle (16.7 milliseconds).

In the case of a temporary overvoltage, the arrester will absorb energy from the system at each positive and negative voltage wave peak until the TOV decays to a level approaching the MCOV rating. It is this repeated operation of the arrester (twice every 60 Hz period) over an extended duration that will often cause a surge arrester to fail.

Manufacturers' data (from ABB – "EXLIM P") for arresters commonly used on the NU and UI transmission system indicate the arresters may fail if the following TOVs are exceeded:

	2 cycles	*6 cycles*	*30 cycles*	*1 second*
115kV (70kV MCOV)	*1.69*	*1.69*	*1.59*	*1.57*
345kV (209kV MCOV)	*1.62*	*1.58*	*1.52*	*1.50*

Table 2 - Typical (Existing) Southwest Connecticut Surge Arrester TOV Limits

The energy handling capability of an arrester depends on the amount of metal oxide material within the arrester.

A higher voltage arrester will have more standard 76 mm disks stacked in series to withstand the applied voltage.

A higher voltage arrester is capable of absorbing more energy than a lower voltage arrester of the same type.

A higher voltage arrester also withstands a higher voltage before it starts to conduct and absorb energy from the power system. For these two reasons, an acceptable engineering practice when arrester energy limits are a concern, is to increase the specified arrester's MCOV.

In certain locations where the existing surge arrester TOV limits are exceeded, the arresters may be replaced. The TOV limits for 84 kV MCOV and 235 kV MCOV arresters are shown below:

	2 cycles	*6 cycles*	*30 cycles*	*1 second*
115kV (84kV MCOV)	*2.03*	*1.98*	*1.92*	*1.89*
345kV (235kV MCOV)	*1.85*	*1.80*	*1.74*	*1.71*

Table 3 - Typical 84kV MCOV and 235kV MCOV Surge Arrester TOV Limits

Due to the higher voltage level (compared to line-to-ground voltage), the failure risk for the involved equipment (power transformer, eventually voltage transformers, compensation reactors) will increase.

It is absolutely recommended to carry out in-depth transient network analysis in advance and to calculate the failure costs for a worst-case scenario and to compare it with (low power) offline test costs and risks.

An alternative to increasing the arrester voltage rating is to add multiple parallel columns of matched arresters in the substations where excess TOV may exist. This alternative would limit the amount of TOV energy that propagates through the remainder of the transmission and distribution system.

EMTP transient modeling would be necessary to determine both the effectiveness of this approach and the amount of energy that would be absorbed by the arresters.

The arrester manufacturers would need to be involved with the design, testing, and installation of these custom matched high energy parallel arrester stacks.

It is not possible to simply connect various standard arresters in parallel in order to absorb the required amount of energy. The manufacturer must balance the individual discharge voltage of disks columns to ensure the multiple columns will share the energy from the overvoltage.

If two standard arresters of the same voltage rating are placed in parallel, it is likely that one of them will have a slightly lower discharge voltage than the other and, consequently, one arrester would absorb a disproportionately larger portion of any electrical surge.

This approach would result in a non-standard transmission component with unknown reliability.

This option of increasing arrester energy capability is not recommended for control of excess system TOV.

Recommendations:

- *Without replacing existing surge arresters, TOVs cannot exceed 1.6 per unit for more than 6 cycles without causing potential surge arrester failure. At locations where the TOVs exceed this limit, the MCOV of the surge arrester should be increased.*
- *Whenever arresters are replaced to increase TOV withstand capabilities, an insulation coordination study must be extended to the lower voltage side of the associated transformer. This may result in replacement of distribution equipment.*
- *Older transformers with lower BIL ratings, (900 kV @ 345 kV or 350 kV @ 115 kV) are at greatest risk for failure due to TOV events and insulation degradation. The dissolved gases in the insulation fluids in these transformers should be tested to determine if insulation has been degraded. Under the worst scenario, these transformers may have to be replaced.*

4.1.6.1 TOV Withstand of Cables

From Cigre document 556[19]:

In order to test the insulation performance of cables, lightning impulse voltages, switching impulse voltages and power frequency test voltages are applied to cables according to international and national standards.

IEC 62067 defines the test methods and requirements for XLPE cables and accessories for rated voltages above 150 kV up to 500 kV.

Typical power frequency withstand tests on cables in accordance with IEC 62067 are at 1.1pu to 1.4pu voltage for 15 minutes depending on the voltage level. Recent international practice has extended the level to 1.7pu and 60 minutes in many HV/EHV cable projects.

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[19] Cigre Document 556, Working Group C4.502, Power System Technical Performance Issues Related to the Application of Long HVAC Cables, October 2013

When a three-phase HV transformer with a fully insulated neutral is connected to a cable system, testing with AC phase-to-phase voltage becomes possible by grounding one phase, resulting in 1.7 U_0 *at both non-grounded phases and 1.0* U_0 *at the neutral.*[20]

This test method bears the risk of unpredictable transient overvoltages when switching such a transformer to the line. Of course, all general disadvantages of online tests apply also to phase-to-phase voltage tests.

4.1.6.2 Recent work

This section discusses possibilities for determining TOV acceptance criteria.

CIGRE Document 556 provides a preliminary theoretical methodology for evaluating the insulation performance of cables.

This testing is on the cable not on the cable system, which includes joints, transition box connections, sealing ends and other accessories. Testing of cable systems is usually at a lower voltage. AC Testing of cables post-installation can be logistically difficult; in particular, for long lengths, large equipments is needed to manage the required reactive power at the required testing voltage; as such the cables can be tested to a lower voltage depending on the equipment available. [21] Nonetheless, other equipment on the network is likely to have a lower withstand capability e.g. surge arresters.

This methodology is an attempt to define best practice and does not yet form part of an IEC or other international standard, although it may be strongly considered once a consensus with further cable manufacturers is reached.

With the voltage-time relationship, a severe temporary overvoltage can be evaluated to be within the insulation performance of cables and accessories when the following inequality is satisfied.

$$V^n \, x \, t \; \leq \; {V_{test}}^n \times t_{test}$$

Where

V and t are the level and the duration of temporary overvoltages

V_{test} *and* t_{test} *are the level and the duration of applied power frequency test voltages.*

n is a parameter that can generally be obtained from a cable manufacturer with typical values ranging from 9 to 15.

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[21] "After-Installation Testing of HV/EHV Extruded cable systems-Procedures and Experiences. U.Hermann, IPH Berlin (Germany),A.Kluge, R.Plath. Jicable07

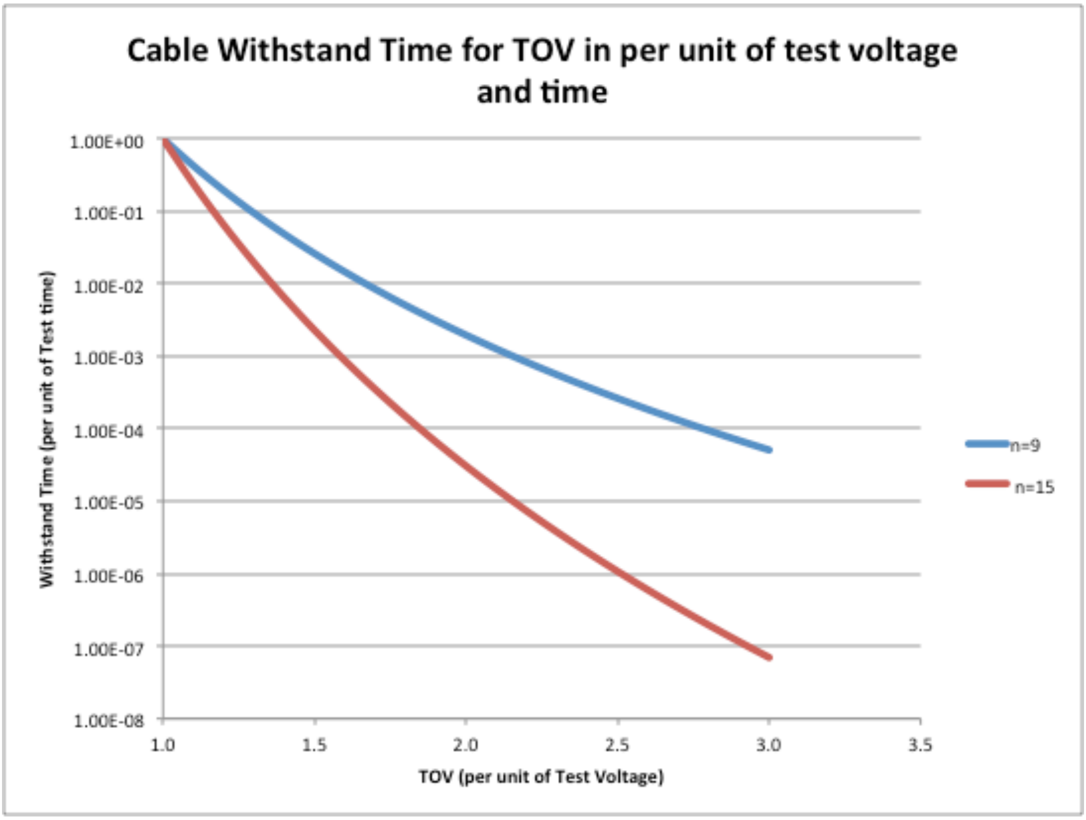

Figure 1 - Cable Withstand Time for TOV in per unit

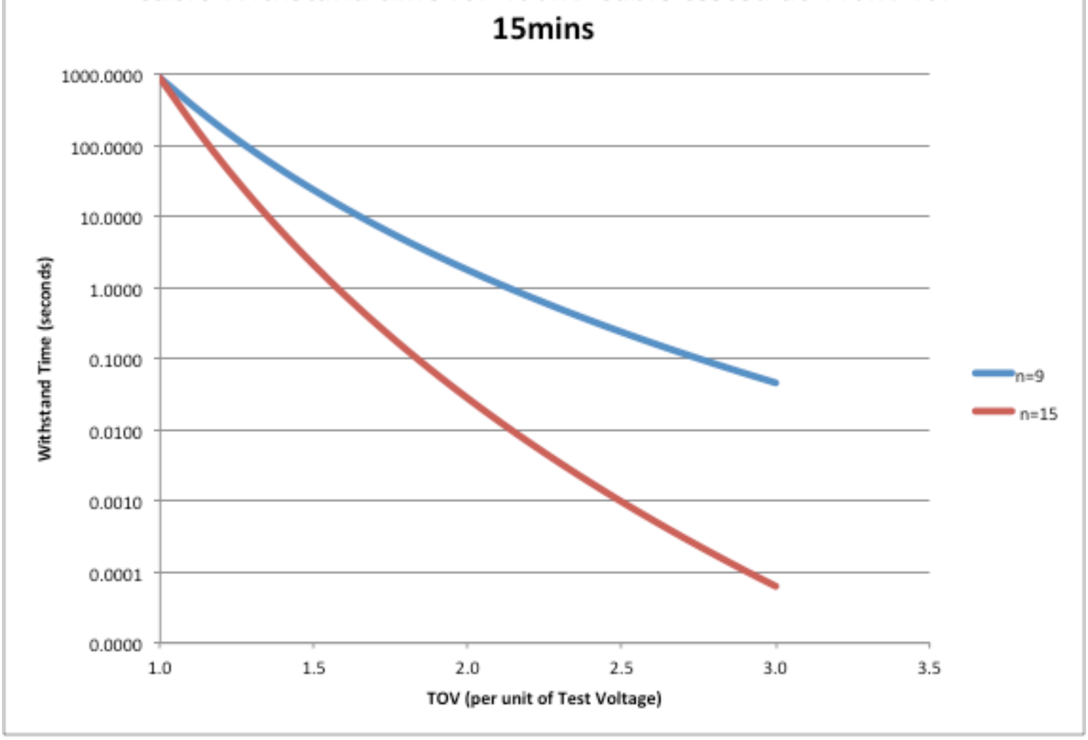

Figure 2 - Cable Withstand Time for a 400kV Cable

4.1.7 Harmonics[22]

The main intent in controlling harmonics is the maintenance of power quality, to operate within the Grid Code and Transmission Planning Criteria[23] and to avoid damage to user's equipment. EirGrid evaluates harmonic impact in accordance with IEC 61000-3-6.

Installation of cables and the associated large capacitance can cause amplification of harmonics due to resonances on the network and can change the harmonic impedance profile of the network, usually in a unfavourable manner.

Inductances and capacitances of power system components create series and parallel resonant frequency points. The number and frequency of these resonant points depend on the number, size and lumped or distributed nature of components, their electrical parameter values, and placement with respect to each other and the point of interest.

Switching operations can generate a wide spectrum of high-frequency voltage and current components, which may then trigger oscillations at system resonant frequencies, which will then lead to excessive harmonic distortions and overvoltages.

System resistances tend to dampen the oscillations. However due to higher capacitance values associate with cables, the resonant frequencies tend to be lower than without cables, and at lower frequencies the damping also tends to be lower.

Excessive harmonic distortion and overvoltages may result. System resistances tend to dampen the oscillations, especially at higher frequencies and greater distances from the disturbance.

Due to higher capacitance values associated with cables, the resonant frequencies tend to be lower than without cables, and at lower frequencies the damping also tends to be lower.

A system with cables will tend to have lower resonant frequencies, due to higher capacitance or line charging.

The first resonant harmonic order can be estimated by:

$$h = \sqrt{\frac{MVA_{sys}}{MVA_{cable}}}$$

Where :

MVA_{sys} is the system short circuit strength at the cable and

MVA_{cable} is the cable reactive power at nominal voltage.

Local shunt compensation can be added to MVA_{sys} increasing the first resonant frequency.

It must be pointed out that this formula neglects the capacitance of the existing network and therefore overestimates the frequency of the first parallel resonance.

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[22] Cigre Document 556, Working Group C4.502, Power System Technical Performance Issues Related to the Application of Long HVAC Cables, October 2013

[23] EirGrid Transmission Planning Criteria http://www.eirgrid.com/media/Transmission%20Planning%20Criteria.pdf

4.1.8 Zero-missing phenomenon[24]

ZERO-MISSING phenomenon is defined as an AC current not crossing zero value during several cycles. If a current does not cross zero value it is not possible to open the circuit breaker without risk of damage, except if the circuit breaker is designed to interrupt DC currents or open at a non-zero current value [1][2].

Because of the large capacitive reactive power of HVAC cables, shunt reactors are needed for power compensation. For unloaded cable systems, the shunt reactor current is almost in phase opposition to the current in the cable, reducing the amplitude of the resultant AC component through the circuit breaker. As the current in the shunt reactor has a transient DC component, the resulting current in the circuit breaker may have a DC component larger than its AC component. When this happens, the current passing through the circuit breaker does not cross zero until the DC component becomes smaller than the AC component.

During its energization the cable is unloaded, and the resistance of the system (cable+shunt reactor(s)) is very small. As a result, the DC component may take several seconds to be damped, period during which the circuit breaker cannot be opened.

If more than one shunt reactor is used to compensate for the reactive power, it is possible to synchronize their energization thus reducing the risks of zero-missing phenomenon occurring.

For zero-missing phenomenon to occur, a shunt reactor has to compensate more than 50% of the reactive power generated by the cable. When a cable is compensated by several shunt reactors, all with the same compensation level, it is necessary to have more than one connected to have zero-missing phenomenon (unless if it is necessary to compensate more than 100% of the generated reactive power).

When a shunt reactor compensates 50% of a cable's reactive power, the amplitude of its AC component is half of the amplitude of the cable's AC component. As these two currents are in phase opposition, the resulting current has an AC component whose amplitude is equal to that of the shunt reactor's current. The initial DC component is never larger than the amplitude of the shunt reactor AC component and in the worst case scenario the minimum peak value of the current is therefore zero.

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[24] **Methods to Minimize Zero-Missing Phenomenon ,** Silva, Filipe Miguel Faria da; Bak, Claus Leth; Gudmundsdottir, Unnur Stella; Wiechowski, W.; Knardrupgård, M. R.
Published in: I E E E Transactions on Power Delivery**, 10.1109/TPWRD.2010.2045010**

4.1.9 Protection issues

Protection action has the potential to:

- Change the network configuration such that the frequency response of the network moves to an unfavourable resonance condition which could result in resonant TOV or harmonic amplification
- Tripping, auto-reclosing or re-energisation of a network element could instigate a TOV event if the system resonance conditions are unfavourable

The introduction of cables onto the system can have the following effects on protection operation or design:

- Zero-missing phenomenon causing maloperation of circuit breakers (discussed in detail in section 4.1.7)
- Introduction of complexity in design for protection that requires linear impedance of circuits. E.g. if part of long circuit or ring is underground cable that is mostly overhead line then there is discontinuity in impedance that has to be taken into account in the protection system potentially resulting in additional protection equipment and complexity of zone coordination.
- Resonance conditions may require additional protection to cope with higher currents (in the case of series resonance) and voltages (in the case of parallel resonance).

4.2 Mitigation techniques

This section examines the techniques potentially available to mitigate the issues relating to the use of underground cables on a transmission system.

Each of the techniques can be useful for one or more of following:

- Avoiding issues
- Mitigation of the impact if the issue cannot be avoided
- Both avoidance and mitigation of the impact

Issues can be described as *controllable* or *non-controllable*.

Controllable issues are predictable and are potentially manageable by “designing out” the risk at the planning phase or by change in operational procedure.

An example of this is in mitigating a TOV caused by a switching event when the transmission system is in a particular configuration resulting in an unfavourable resonance condition. This could be managed by temporarily changing the system configuration prior to the switching event or by delaying the switching event until the system configuration has changed to a more favourable state.

An *uncontrollable* issue is not predictable and cannot be directly managed.

An example of this is the unexpected tripping of a circuit or other network element whilst the network is in an unfavourable resonance condition causing large TOV. In this event, the mitigation technique can only reduce the impact of the event after it has occurred.

Certain mitigation techniques will “cure” issues whilst others may reduce the risk of unfavourable events occurring.

Constraining the length of the cable to avoid resonant conditions could be considered a cure as certain issues are completely avoided.

The techniques to be examined are:

Mitigation Technique	Description
MT1	Management of existing reactive compensation equipment
MT2	Change of operating procedures
MT3	Modification of switching / energisation procedures
MT4	Adjustment of Cable Length
MT5	Surge Arresters
MT6	Shunt Capacitors
MT7	Shunt Reactors
MT8	Dynamic Reactive Compensation
MT9	Series Compensation
MT10	HVDC

Table 4 - List of Mitigation Techniques

4.2.1 Techniques available for controllable issues

4.2.1.1 Mitigation technique 1 (MT1): Management of existing reactive compensation equipment

Reconfiguration of the shunt reactive components on the network may alter the harmonic impedance characteristic such that unfavourable low order resonances are avoided.

4.2.1.2 MT2: Change of operating procedures

Severe TOVs can be prevented by introducing restrictions on system operations.

By examining the network conditions under which the cable may cause unfavourable network due to low order harmonic resonance or by energisation from a weak source, operational restrictions can be put in place to avoid these issues.

Although this is a valuable and viable mitigation it has to tempered by the number of restrictions or type of restrictions and their impact on the effective and reliable operation of the network. For example, other factors, either technically or due to the operational state of the network during a depleted network (i.e. outages in storms), may stop an operational sequence being possible or viable.

Other events that could be managed are to avoid issues:

- Transformer energisation to avoid resonant TOV excitation or ferroresonance.
- Black start (effectively energisation from a weak source)

4.2.1.3 MT3: Modification of switching / energisation procedures

Modifications to line and system switching procedures can also be an effective method of TOV control, avoiding events that initiate the TOV events by exciting an unfavourable resonance.

4.2.2 Techniques available for non-controllable issues

4.2.2.1 MT4: Adjusting the cable length

Introducing a large number of underground cables to a network adds capacitive reactance to the system. Greater capacitance increases the risk of low order harmonic resonance on transmission systems with lower fault levels.

Resonance conditions can cause TOVs that are unacceptable and could cause damage to network equipment.

However by reducing cable length, the risk of low harmonic order resonance can be reduced by shifting the resonant point to higher point on the frequency spectrum.

This concept is known as ‘system de-tuning’ and it is suggested by International standards [25]

This is the primary technique for TSOs to specifically mitigate TOV issues.

4.2.2.2 MT5: Surge arresters

Surge arresters of the zinc-oxide type provides an efficient means for overvoltage protection of cable systems. The arrester is placed at one or both ends of the cable which is to be protected. It is common practise to protect the cable by surge arresters at the overhead line side of the cable where cable is part of a series connected link with an overhead line (Siphon).

The voltage at the cable end where the surge arrester is connected will limit to the surge arrester protective level plus the voltage drop of the connecting leads. Sometimes it is necessary to provide surge arresters at both ends of the cable, if the opposite cable end could be disconnected (eg. Due to

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[25] IEC60071-2, pg.33

line tripping). However even with a surge arresters at the both ends, a higher voltage could occur inside the cable due to reflection. Special care should be made when specifying rated voltage and energy absorption capability of surge arresters

Surge arresters are usually used for protecting transformers, generators, motors, capacitors, traction vehicles, cables, and substations. They are designed to prevent insulation flashover and equipment damage by limiting transient voltages between energised conductors and grounded components. Surge arresters are not designed to protect equipment from longer term TOVs.

Arresters are specified within a particular class by the Maximum Continuous Operating Voltage (MCOV), which is greater than the maximum continuous voltage of the network. In the case of a TOV, the arrester will absorb energy from the system at each positive and negative voltage wave peak until the TOV decays to a level approaching the MCOV rating. It is this repeated operation of the arrester (twice every 50 Hz period) over an extended duration that will often case a surge arrester to fail.

With increased energy discharge capabilities and simplified design, the gapless metal oxide varistor technology offers more reliable unit with inherent protective characteristics.

As discussed above and in section 4.1.5.5 surge arresters are designed to mitigate short term voltage events and are not suitable for longer term TOV events.

4.2.2.3 MT6: Shunt capacitors

Mechanically switched capacitors are a simple but low-speed solution for voltage control and network stabilisation under heavy load conditions. Their utilisation has almost no effect on the short-circuit power but it increases the voltage at the point of connection. (eg. MSC).

Shunt capacitors can also be configured as a harmonic filter.

A harmonic filter is normally tuned to specific harmonic orders mitigating harmonic distortion and altering the harmonic impedance characteristic of the transmission network.

Extra damping can be provided at low order frequencies by the use of C-Type Filters or as they are sometimes known - Mechanically Switched Capacitor Damping Networks (MSCDNs).[26]

An MSCDN is a simple and effective compensation method for the grid. It will act as a filter for system harmonics and help to control voltage and reactive power. It can also provide some benefit for stability improvement due to the additional damping at low order frequencies.

The maximum size of the individual MSCDNs is determined by the Transmission Planning Criteria[27] requirement for a maximum voltage step of 3% for capacitor switching which is directly proportional to the system MVA fault level.

The primary intent of MSCDNs / C-Type Filters is for voltage control and reactive compensation and have not previously been used specifically for TOV mitigation.

As this equipment is tuned at low harmonic order there is a potential for interaction with other devices on the system that may cause unexpected, unfavourable conditions under non-intact network states.

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[26] The control of harmonic distortion on an EHV system by the use of capacitive damping networks, NM MacLeod, JJ Price, IW Whitlock, Conference: Harmonics And Quality of Power, 1998. Proceedings. 8th International Conference on, Volume: 2

[27] EirGrid Transmission Planning Criteria http://www.eirgrid.com/media/Transmission%20Planning%20Criteria.pdf

4.2.2.4 MT7: Shunt reactors .

Shunt reactors are used to compensate for capacitive reactive power generated by lightly loaded transmission lines or underground cables and for voltage control.

They are normally connected to a transformer tertiary winding but can also be directly connected on systems of up to 345 kV.

The reactance of the Shunt Reactor affects the harmonic impedance characteristic of the transmission system to which it is connected and can be useful in avoiding unfavourable resonance conditions if they are free to be switched at will.

Shunt reactors can be used for mitigating controllable TOV by making a grid asset safer before transformer energisation.

Development of the network and network re-configuration can make the prediction of resonant conditions a particularly complex analysis due to the large amount of unknowns. Shunt reactors required for reactive compensation may provide a benefit to management of resonant conditions in some cases and may have a negative impact in other cases. The installation of shunt reactors would be required to mitigate underground cable capacitance regardless of network conditions making coordination complex.

There are scenarios when shunt reactors may become sources of harmonic currents for example if they saturate. Special requirements may be necessary in these circumstance's

For example, if there is significant voltage unbalance on the system, even harmonics (which causes a DC offset) and/or resonance conditions around 100Hz, then saturation of the windings may occur causing harmonic current generation.

Additionally, the installation of shunt reactors may mitigate generator self-excitation by increasing the reactance external to the generators.

Overall, shunt reactors may be beneficial or detrimental depending on the design parameters both initially and over the lifetime of the equipment as the system develops. Therefore, careful evaluation and reviews are required.

4.2.2.5 MT8: Dynamic Reactive Compensation

Static Var Compensators (SVC) are a fast and reliable means of controlling steady-state voltage on transmission lines and system nodes and for providing support to the transmission system during and after faults.

SVCs provide reactive power (capacitive or inductive) in response to changing system conditions (e.g. voltage).

The reactive power is changed by switching or controlling reactive power elements connected to the secondary side of the transformer.

Each capacitor bank is switched ON and OFF by thyristor valves (TSC) and is effectively a very fast switching Shunt Capacitor that can be switched on and off with much greater frequency. Shunt Capacitors can typically only change state once every 5 or 10 minutes depending on which International Standard was used to design the capacitors.

Reactors can be either switched (TSR) or controlled (TCR) by thyristor valves. TCRs can provide any amount of reactive power within the designed reactive power range whereas TSCs can only be on or off.

A combination of TCRs, Fixed Capacitors and TSCs can provide a reactive power output at any point from full inductive to full capacitive very quickly with a response time that is appropriate for controlling steady-state and for supporting the transmission system during and after fault events. which are shorter duration than TOV.

Static Var Compensators perform the following tasks:

- Improvement in voltage quality
- Dynamic reactive power control
- Increase in system stability
- Damping of power oscillations
- Increase in power transfer capability
- Unbalance control.

STATic Synchronous COMpensators (STATCOM), which are also part of the FACTS device family, consist of a three-phase rectifier/inverter that can be shunt-connected to any system and to dynamically compensates the reactive power requirement of the system.

A STATCOM is a voltage-source converter that converts dc power into a power of variable amplitude and phase angle. By varying the amplitude and phase angle of the three-phase ac currents at its ac side, a STATCOM can supply a variable and precise amount of reactive power to the ac power system to which it is connected.

This feature can be used to ensure that the voltage across the ac power system connected to the STATCOM is maintained at the nominal value or to ensure that the power factor of a large industrial application is maintained at unity.

STATCOMs can provide the full dynamic reactive range for a wider voltage range than Static Var Compensators and can respond quicker but at the expense of higher capital cost and considerably higher losses.

The size of an individual SVC or STATCOM and the maximum change in Mvar output from an SVC is dictated by the maximum allowable voltage step in accordance with the Transmission

Planning Criteria.[28]

Therefore for a given system strength the maximum length of cable that can be mitigated by an SVC is limited by the same criteria.

SVCs are primarily designed for durations related to support during faults and post-fault support. To compensate for long duration TOV the SVC equipment would need to be rated accordingly which may be beyond the available technology.

The installation of multiple SVC or STATCOM units on a Transmission System may be problematic at low system fault levels due to control system interaction issues.

4.2.2.6 MT9: Series compensation devices

Series compensation is defined as insertion of reactive power elements in series with transmission lines.

The most common application is the fixed series capacitor (FSC). Thyristor-valve controlled systems (TCSC) and thyristor-valve protected systems (TPSC) may also be installed.[29]

Fixed Series Capacitor (FSC)

The simplest and most cost-effective type of series compensation is provided by FSCs. FSCs comprise the actual capacitor banks, and for protection purposes, parallel arresters (metal oxide varistors, MOVs), spark gaps and a bypass switch for isolation purposes.

Fixed series capacitor provides the following benefits:
- Increase in transmission capacity
- Reduction in transmission angle

Thyristor-Controlled Series Capacitor (TCSC)

Reactive power compensation by means of TCSCs can be adapted to a wide range of operating conditions. In this configuration, a TCR is connected in parallel to the capacitor bank. This allows to tune the overall system impedance of the TCSC according to the varying system operation conditions during dynamic disturbances.

Spark gaps and major part of the arresters can be omitted in this configuration. Additional benefits of thyristor-controlled series capacitor:
- Increase in system stability
- Damping of power oscillations (POD)
- Load flow control
- Mitigation of sub-synchronous torsional interaction (SSTI)

Thyristor-Protected Series Capacitor (TPSC)

An enhanced configuration of the FSC is the TPSC. In this case, high-power thyristors in combination with a current-limiting reactor are installed in parallel to the limiting series capacitors, and substitute the spark gap as well as the MOVs as protection devices. The protection of the power capacitor is performed by firing a bypass of the thyristors valves.

Due to the very short cooling-down times of the special thyristor valves, TPSCs can be quickly returned to service after a line fault, allowing the transmission lines to be utilized to their maximum

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[28] EirGrid Transmission Planning Criteria http://www.eirgrid.com/media/Transmission%20Planning%20Criteria.pdf

[29] http://www.energy.siemens.com/us/en/power-transmission/facts/series-compensation/

capacity. TPSCs are the first choice whenever transmission lines must be returned to maximum carrying capacity as quickly as possible after a failure.

By altering the effective impedance of the transmission line, series compensation may assist in avoiding unfavourable resonances and by provides some measure of reactive power and voltage control.

The introduction of Series Compensation can cause unfavourable interactions with existing generation at frequencies below the nominal system frequency (Sub-Synchronous Resonance phenomena) and may interact with other power electronic systems such as HVDC and windfarm controllers.

4.2.2.7 MT12: HVDC

The network cable connection can be replaced with an HVDC interconnector and transmitting via DC instead of AC. Therefore avoiding issues related to AC Cables.

During the last few decades, High-Voltage-Direct-Current (HVDC) transmission became the standard technology for power transmission over large distances (several 100 of km) and, hence, in particular for submarine connections.

AC transmission over such distances has excessive losses or is just technically unfeasible. An important advantage in the case of submarine DC connections is the significantly lighter design of the cables.

The capacitance in DC cable networks does not contribute to the total system capacitance since the cable capacitance is decoupled from the system with the HVDC converters on both ends of the cable.

This avoids issues relating to the resonance of the cable with the transmission system. HVDC systems can also provide voltage and reactive power control. HVDC systems can prevent the propagation of faults throughout the network by “blocking” the transmission of power very quickly.

However, an HVDC system requires converter stations at each of the transmission circuit to convert from AC to DC and vice-versa, which can have a considerable impact on the cost and space requirements of a project.

An HVDC solution avoids many of the technical challenges associated with power transfer by underground cable and the choice of technology (AC or DC) is most commonly determined by economic issues.[30]

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[30] CAVAN-TYRONE AND MEATH-CAVAN 400KV TRANSMISSION CIRCUITS, ALTERNATING CURRENT OVERHEAD AND UNDERGROUND, AND DIRECT CURRENT UNDERGROUND
Parson Brinkerhoff http://www.eirgridprojects.com/media/PB%20Power%20Report.pdf

4.3 Technical appraisal of mitigation techniques

For the technical appraisal of mitigation techniques five questions were posed :

Question 1- Is the mitigation technique theoretically effective?

Question 2- What is the worldwide experience on the application of the mitigation technology?

Question 3- What is the worldwide experience on the application of the technology for TOV mitigation?

Question 4- What are the consequences at the design phase of TOVs?

Question 5- What are the consequences at the operation and operational planning stage?

The following sections answer these questions for each mitigation technique described in section 4.2.

Mitigation Technique	Description
MT1	Management of existing reactive compensation equipment
MT2	Change of operating procedures
MT3	Modification of switching / energisation procedures
MT4	Adjustment of Cable Length
MT5	Surge Arresters
MT6	Shunt Capacitors
MT7	Shunt Reactors
MT8	Dynamic Reactive Compensation
MT9	Series Compensation
MT10	HVDC

Table 5 – List of Mitigation Techniques

4.3.1 *MT1:* Management of existing reactive compensation equipment

Question	**Answer**
Is the mitigation technique theoretically effective?	YES: Effective at helping to avoid resonance, control harmonic distortion and in voltage control NO: Does not reduce TOV magnitude or duration. May become ineffective over time. By adding a new cable to an existing network, the shunt capacitance of the network will increase. However by removing an existing shunt capacitance (one or several) from the network will keep the network shunt capacitance more or less at the same value. Therefore this is theoretically effective method for controlling harmonic and TOV resonance issues.
What is the worldwide experience on the application of the mitigation technology?	This is widely being used as a method of mitigating harmonic issues but has not been used a primary means of controlling TOV. It is normal TSO practice in Operation to switch off capacitors in light load periods, i.e. overnight, summer time, etc if not required for harmonic mitigation.
What is the worldwide experience on the application of the technology for TOV mitigation?	There is no widely available information regarding this technique has been applied for TOV mitigation.
What are the consequences at the design phase of TOVs?	There is no adverse effect on design phase as this is management of existing equipment.
What are the consequences at the operation and operational planning stage?	Shunt capacitor equipment that is specifically required for reactive compensation may not be suitable for resonance control as there may be limited freedom of switching in all network cases

Table 6 - MT1: Management of existing reactive compensation equipment

Long term development of the transmission system may negate the effectiveness of the solution as the resonance pattern may change over time negating the impact of the installed equipment for resonance mitigation purposes.

4.3.2 MT2: Change of operating procedures

Question	**Answer**
Is the mitigation technique theoretically effective?	YES: Configuring the system appropriately may avoid resonance conditions causing high TOV and/or harmonic issues[31]
What is the worldwide experience on the application of the mitigation technology?	Not applicable
What is the worldwide experience on the application of the technology for TOV mitigation?	Common practice for mitigating harmonic issues. No directly stated experience of mitigation of TOV.
What are the consequences at the design phase of TOVs?	New equipment and circuits may impact on the effectiveness of the method.
What are the consequences at the operation and operational planning stage?	Studies to assess network states likely to cause resonance issues. The ongoing study and manpower requirements to maintain an up to date evaluation of the effective configurations as the system develops are considerable.

Table 7 - MT2: Change of operating procedures

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[31] Elinfrastrukturudvalget (Denmark), Technical report on the future expansion and undergrounding of the electricity transmission grid – Summary, April 2008**.**

4.3.3 MT3: Modification of switching / energisation procedures[32]

Question	**Answer**
Is the mitigation technique theoretically effective	YES: Avoidance or reduction of events that can cause high TOV
What is the worldwide experience on the application of the mitigation technology?	Common practice for TSOs to avoid or minimise events causing TOV
What is the worldwide experience on the application of the technology for TOV mitigation?	Common practice for TSOs to avoid or minimise events causing TOV
What are the consequences at the design phase of TOVs?	Not applicable
What are the consequences at the operation and operational planning stage?	Studies to assess risk of events causing TOV and network state for risk of unfavourable resonances. As for MT2, the ongoing study and manpower requirements to maintain an up to date evaluation of the effective configurations as the system develops are considerable.

Table 8 - MT3: Modification of switching / energisation procedures

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[32] Denmarks Cable Policy Landsnet Annual meeting 2014 , March 20th 2014
Jens Møller Birkebæk Director, International Affairs
http://www.landsnet.is/library/Skrar/Landsnet/Upplysingatorg/Kynningarmal/Opinn-kynningarfundur-2014/06%20Landsnet%20Annual%20meeting%20%20-%20%20Danish%20cable%20policy%20ppt%20%20_Jens%20Møller%20Birkebæk_LOKA.pdf

4.3.4 MT4: Adjustment of Cable Length

Question	**Answer**
Is the mitigation technique theoretically effective?	YES : Avoids resonance conditions and reduces voltage regulation [33] The harmonic resonance point can be shifted as high as necessary by adjusting the cable length. This will be very effective to mitigate TOV and harmonic issues.
What is the worldwide experience on the application of the mitigation technology?	This is the primary technique for avoiding TOV issues relating to cables.
What is the worldwide experience on the application of the technology for TOV mitigation?	Common practice for avoiding voltage, reactive power and stability issues and is the primary technique for avoiding TOV due to cables.
What are the consequences at the design phase of TOVs?	Studies to assess optimal cable length to minimise technical risks
What are the consequences at the operation and operational planning stage?	Not applicable

Table 9 - MT4: Adjustment of Cable Length

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[33] Elinfrastrukturudvalget (Denmark), Technical report on the future expansion and undergrounding of the electricity transmission grid – Summary, April 2008.

4.3.5 MT5: Surge Arresters (SA) [34]

Question	**Answer**
Is the mitigation technique theoretically effective?	NO Not of use for longer duration voltage events. No effect on TOV avoidance.
What is the worldwide experience on the application of the mitigation technology?	Surge arresters are used worldwide as a protective device to save the expensive network equipment such as transformers, HVAC cables etc. from short duration transients and overvoltages. Not designed for TOV mitigation.
What is the worldwide experience on the application of the technology for TOV mitigation?	Very commonly used to mitigate short-term overvoltages caused by switchings operation and lightning but not for TOV .
What are the consequences at the design phase of TOVs?	Transient studies required to determine frequency of short term versus long term overvoltages that may be beyond the arrester capability. SA with higher TOV may be required with Insulation Coordination consequences on other nearby equipment.
What are the consequences at the operation and operational planning stage?	Long duration voltage events may cause the surge arresters to fail requiring maintenance or replacement.

Table 10 - MT5: Surge Arresters

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[34] Temporary Overvoltage Equipment Limits – Summary Report, K&R Consulting, LLC, for Northeast Utilities, December 17 2004, http://www.ct.gov/csc/lib/csc/docket_272/roc_report/ROC_App_B_TOV_Report.pdf

4.3.6 MT6: Shunt Capacitors

Question	Answer
Is the mitigation technique theoretically effective?	YES: Switching of Shunt Capacitors is effective for controlling voltage, reactive power and alters the resonance characteristic of the system. Shunt capacitors configured as C-Type filters or other types of filter can provide mitigation of harmonics and damping at lower harmonic orders reducing the impact of TOV.
What is the worldwide experience on the application of the mitigation technology?	Common practice for voltage, reactive power and harmonic control. Some use for low order harmonic filtering when configured as a C-Type filter (e.g. MSCDNs on UK transmission network).[35]
What is the worldwide experience on the application of the technology for TOV mitigation?	C-Type filters were considered for the Southwest Connecticut cable project[36] and rejected due to interaction issues
What are the consequences at the design phase of TOVs?	Studies to determine voltage, reactive power, harmonic requirements and assessment of resonance characteristic of system
What are the consequences at the operation and operational planning stage?	Ongoing studies and manpower to assess network states likely to cause resonance issues.

Table 11 - MT6: Shunt Capacitors

Long term development of the transmission system may negate the effectiveness of the solution as the resonance pattern may change over time negating the impact of the installed equipment for resonance mitigation purposes.

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[35] The control of harmonic distortion on an EHV system by the use of capacitive damping networks, NM MacLeod, JJ Price, IW Whitlock, Conference: Harmonics And Quality of Power, 1998. Proceedings. 8th International Conference on, Volume: 2

[36] Harmonic Impedance Study for Southwest Connecticut Phase II Alternatives, Authors: J.H.R. Enslin; R. A. Wakefield; Y. Hu; S. Eric, KEMA Inc, October 2004 http://www.ct.gov/csc/lib/csc/docket_272/kema_harmonic_analysis_report.pdf

4.3.7 MT7: Shunt Reactors

Question	**Answer**
Is the mitigation technique theoretically effective?	YES: Switching of Shunt Reactors is effective for controlling voltage, reactive power and alters the resonance characteristic of the system. Shunt reactors are also effective at mitigating the effects of cable capacitance
What is the worldwide experience on the application of the mitigation technology?	Common practice for voltage, reactive power and harmonic control and for mitigating the effects of the high capacitance associated with underground cables. Also effective for mitigating zero-missing phenomenon.
What is the worldwide experience on the application of the technology for TOV mitigation?	Common practice on nearly all major cable projects for reactive compensation not for mitigating TOV.
What are the consequences at the design phase of TOVs?	Studies to determine voltage, reactive power, harmonic requirements and assessment of resonance characteristic of system. Studies to determine magnitude of cable capacitance.
What are the consequences at the operation and operational planning stage?	Ongoing studies and manpower to assess network states likely to cause resonance issues

Table 12 - MT7: Shunt Reactors

Long term development of the transmission system may negate the effectiveness of the solution as the resonance pattern may change over time negating the impact of the installed equipment for resonance mitigation purposes.

4.3.8 MT8: Dynamic Reactive Compensation

Question	Answer
Is the mitigation technique theoretically effective?	YES: SVC and STATCOM dynamically control voltage and reactive power. Can respond to TOV events within the limits of the transmission planning criteria and limited by system strength.
What is the worldwide experience on the application of the mitigation technology?	Mature technology for fast voltage and reactive power control. Two transmission SVCs currently on Irish network (Letterkenny and Castlebar).[37] SVCs designed for steady-state voltage and fault support.
What is the worldwide experience on the application of the technology for TOV mitigation?	SVC for AUAS in Namibia installed to control synchronous resonance.[38] Not suitable for multiple units and presents a single point of failure.
What are the consequences at the design phase of TOVs?	Studies to determine voltage, reactive power, harmonic requirements and assessment of resonance characteristic of system. Complexity increases for multiple units and interaction may limit effectiveness
What are the consequences at the operation and operational planning stage?	High manpower resources overhead on setting, maintaining and ensuring correct operation. Possible interaction issues with other equipment. Not suitable for multiple units.

Table 13 - MT8: Dynamic Reactive Compensation

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[37] EirGrid – All-Island Ten Year Transmission Forecast Statement 2013, http://www.eirgrid.com/media/TenYearTransmissionForecastStatement2013.pdf

[38] *SVC for resonance control in NamPower electrical power system*, M. Halonen S. Rudin B. Thorvaldsson ABB Power Systems Västerås, Sweden, Udo Kleyenstüber NamPower Windhoek, Namibia, Septimus Boshoff R.U.P. Johannesburg, South Africa, Chris van der Merwe Trans- Africa projects Johannesburg, South Africa

4.3.9 MT9: Series Compensation

Question	Answer
Is the mitigation technique theoretically effective?	YES: Series compensation can help in altering the network resonance characteristic, voltage and reactive power control.[39]
What is the worldwide experience on the application of the mitigation technology?	Series compensation is a mature technology although not for this application
What is the worldwide experience on the application of the technology for TOV mitigation?	None
What are the consequences at the design phase of TOVs?	Studies to determine voltage, reactive power, harmonic requirements and assessment of resonance characteristic of system. May introduce sub-synchronous resonance (SSR) issues potentially damaging generation on the transmission system and causing interaction with existing HVDC and other power electronic controlled equipment (e.g. windfarms)
What are the consequences at the operation and operational planning stage?	Risk of SSR (as described above) requiring ongoing analysis and manpower to assesss suitability, configuration and effectiveness

Table 14 - MT9: Series Compensation

Long term development of the transmission system may negate the effectiveness of the solution as the resonance pattern may change over time negating the impact of the installed equipment for resonance mitigation purposes.

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[39] http://www.energy.siemens.com/us/en/power-transmission/facts/series-compensation/

4.3.10 MT10: HVDC

Question	Answer
Is the mitigation technique theoretically effective?	YES: Issues related to AC cables avoided by use of DC cables. HVDC also provides voltage and reactive power control.
What is the worldwide experience on the application of the mitigation technology?	Mature technology for line-commutated converters. Some commercial experience[40] for underground cable voltage-sourced converter based HVDC (e.g. MurrayLink)[41]
What is the worldwide experience on the application of the technology for TOV mitigation?	HVDC projects have been installed primarily to transmit bulk power over distance. TOV mitigation / avoidance is a benefit not a primary application.
What are the consequences at the design phase of TOVs?	TOV avoided.
What are the consequences at the operation and operational planning stage?	Potential interaction with existing HVDC schemes.

Table 15 - MT10: HVDC

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[40] Cigre B4_203_2010, HVDC VSC (HVDC light) transmission – operating experiences, http://www05.abb.com/global/scot/scot221.nsf/veritydisplay/973416ce4ddcd540c12578270057724b/$file/B4_03_2010%20HVDC%20VSC%20(HVDC%20light)%20transmission%20operating%20experiences.pdf

[41] Murraylink, The world's longest underground power transmission system, http://new.abb.com/systems/hvdc/references/murraylink

4.4 Summary of Key Issues

Mitigation Technique	**Description**	**Control / Mitigation of steady-state voltage and reactive power?**	**Avoidance of TOV?**	**Mitigation of TOV?**	**Avoidance / Mitigation of harmonic distortion?**
MT1	Management of existing reactive compensation equipment	Yes	Yes	No	Yes
MT2	Change of operating procedures	Yes	Yes	No	Yes
MT3	Modification of switching / energisation procedures	No	Yes	No	No
MT4	Adjustment of Cable Length	Yes	Yes	Yes	Yes
MT5	Surge Arresters	No	No	No	No
MT6	Shunt Capacitors	Yes	No	Yes	Yes
MT7	Shunt Reactors	Yes	Yes	No	Yes
MT8	Dynamic Reactive Compensation	Yes	No	Limited	No
MT9	Series Compensation	Yes	Yes	No	No
MT10	HVDC	Yes	Yes	Yes	No

Table 16 - Summary of Key Issues

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Orange cells indicate methods that may be theoretically effective but may be reduced in effectiveness over time due to network development or may be limited by transmission planning criteria or system strength

4.5 Application of Mitigation Techniques

4.5.1 National Grid, UK

As the GB power network stands today the reactive power flow can change rapidly. In order to respond quickly to such changes and maintain security and quality standards the need was for switched and dynamic compensation which can be easily relocated.

Large, mechanically switched capacitors with damping network (MSCDN) banks on the UK EHV (400 and 275 kV) systems have been installed various locations on the network.[42]

These devices are designed not produce any significant magnification of pre-existing harmonic distortion.
Examples are 2x225 Mvar MSCDN in Sundon and 2x225 Mvar MSCDN in Grendon. [43]

The National Grid System also has many Static Var Compensators (>25) and a STATCOM at East Claydon for voltage and reactive power control and stability.

This equipment is designed for reactive power control, steady-state voltage control and system fault support.

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[42] The control of harmonic distortion on an EHV system by the use of capacitive damping networks, NM MacLeod, JJ Price, IW Whitlock, Conference: Harmonics And Quality of Power, 1998. Proceedings. 8th International Conference on, Volume: 2

[43] National Grid Ten Year Statement, http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/Electricity-ten-year-statement/Current-statement/

4.5.2 South West Connecticut Phase II, USA[44]

KEMA performed an independent technical review of the Application to the Connecticut Siting Council (Council) for a Certificate for the construction of Phase II facilities and associated technical studies provided in supplemental filings.

As directed by the Council, KEMA investigated the maximum length of the proposed Phase II 345 kV line that could be installed underground, based solely on technical feasibility, rather than optimizing the system based on economics.

In addition, KEMA investigated several mitigation schemes to assess whether these schemes could extend the portion of the Phase II line that can be feasibly constructed underground.

KEMA examined two methods of mitigating the harmonic resonance performance of the base case system.

These include:
1) STATCOMs (also examined by the Applicant), and
2) Passive filtering using "C-type" filters.

Harmonic resonance results for the STATCOM application were similar to the results of the Applicant's studies. STATCOMs may be an effective mitigation method, but ISO New England is concerned about their complexity from an operational perspective.

KEMA's study results for passive filtering are encouraging. These results indicate that C-type filters, tuned to the 3rd harmonic, increase the frequency of the first major resonance point and significantly dampen higher frequency resonance peaks.

Such filters appear to provide a more effective mitigation approach than STATCOMs from a harmonic resonance perspective alone. Also, they are not as complex and will not negatively affect system operations.

RECOMMENDATIONS
Based on these study results, KEMA recommends:

- *An optimal application of C-Type filters, either alone or in the combination with one or two STATCOMs, should be developed. In so doing, the tuned C-Type filters should be optimized for specific substations and for the entire system.*
- *Transient analysis studies should be conducted, based on a detailed system model of the selected configuration.*

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[44] Harmonic Impedance Study for Southwest Connecticut Phase II Alternatives By **KEMA, Inc**. Authors: J.H.R. Enslin; R. A. Wakefield; Y. Hu; S. Eric

From the Final Report to the Siting Council: [45]

Although the addition of C-Type filters could improve the performance characteristics of an intact system under normal operating conditions, TOVs were worse under many contingent conditions with C-Type filters added to the system than without them.

It should be noted that virtually all system fault events which can produce a TOV result in the system operating in contingent situation with the faulted system element (e.g., line, cable, or transformer) necessarily removed from the system.

In addition, the C-Type filters can only be switched into the system when the capacitive MVARs they produce are needed and can be accepted by the system without excessively increasing the steady-state voltage. TNA results show that high TOVs can also occur for light load conditions where the C-Type filters cannot be used. Accordingly, the ROC Group does not support the use of C-Type filters as a generic resolution to TOV problems

The potential for TOVs on the electric system that would exceed the withstand capability of system elements limits the use of underground cable. An expanded SWCT system could not be considered reliable if TOVs exceeding the withstand capability of any of its elements were likely to occur under contingency conditions.

The capacitance associated with underground cables increases the potential for TOVs. The ROC Group has looked carefully at the magnitude of TOVs in a number of cases, with varying combinations of overhead and underground transmission lines and varying cable and electrical equipment technologies (such as synchronous condensers and C-Type filters) and under varying operating scenarios.

The linear length of underground cable in the TNA screening analyses ranged from 4 to 44 linear miles. Upon reviewing the TNA results, and considering the volatility of the system transient response and load composition variations, as well as various possible generator, capacitor, and reactor dispatches, the ROC Group has determined that the maximum length of underground cable that is technologically feasible for the Project is the 24 linear miles (48 circuit miles) of underground XLPE cable in Case 5.

In the judgment of the ROC group, the addition of more underground cable than the 48 circuit miles modeled in Case 5 would not enable the reliable operation of the SWCT electric system after the Bethel to Norwalk and Middletown to Norwalk Projects are complete, while still preserving some margin of operational safety to allow for present-day operations and future evolution of the SWCT system (which are likely to include generation retirements, re-powering or replacement, generator lead connections, capacitor bank installations to maintain local voltages, and 115- kV transmission line upgrades or 115-kV cable installation).

To make Case 5 technologically feasible, the Companies will have to make equipment changes on the existing system in order to increase the acceptable TOV level (measured on a "per unit" voltage basis). If TNA results indicate that a project configuration could expose the system to TOVs that exceed the capability of equipment to withstand TOVs, then that configuration would not provide adequate assurance of reliable operation of the electric system in SWCT.

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[45] ROC – Final Report to the Connecticut Siting Council
http://www.ct.gov/csc/lib/csc/docket_272/roc_report/final_roc_report_12-20-04.pdf

4.5.3 Transpower, New Zealand

Detailed analysis and review of use of technology for development of the Transmission System in New Zealand is given in the reports referenced in the footnotes.[46] [47] [48]

These reports show the considerations for use of reactive compensation (SVC, STATCOM and shunt reactive elements) for voltage and reactive power control and stability

As with National Grid (UK) this equipment is designed for reactive power control, steady-state voltage control and system fault support.

4.5.4 Denmark

Denmark has stated the long-term objective of completely undergrounding the transmission system as outlined in [49] [50]:

… the system-related challenges of using long AC cables in overhead line systems are linked to the fact that AC cables at high voltage levels reduce the so-called natural frequency of the electricity system considerably. This increases the risk of resonance oscillations occurring in the system.

This policy of fully undergrounding the transmission network is for voltage levels of 150kV and below, whereas higher voltages are evaluated on a case-by-case basis.

Resonance oscillations are critical because even a frequently occurring incident – such as the disconnection of a circuit breaker – may initiate the resonance oscillation, which in turn may result in other components being damaged or cutting out due to high and oscillating voltages. When several power lines and generators are disconnected from the grid in an uncontrolled manner, system security is reduced, and the risk of power failures is high.

Energinet have set up a research project to examine the following issues[51]

System related

- Optimisation of the 132 kV and 150 kV network structure.
- Protection concept for cables in the transmission network.
- Optimise the reactive compensation in the transmission network.
- Voltage stability analysis for the network and find the best solutions
- Transient studies – Find the dimensioning studies and the needed modelling detail.
- Black-Start study for the network according to the Cable Action Plan.

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[46] Transmission Augmentations into Auckland : Technical Analysis of Transpower's Proposal and Short Short-listed Alternatives Part I www.ea.govt.nz/dmsdocument/4716

[47] UPPER SOUTH ISLAND RELIABILITY MCP STAGE 1, ATTACHMENT A OPTIONS AND COSTING REPORT**,** Transpower New Zealand Limited June 2012 www.comcom.govt.**nz**/dmsdocument/1063

[48] UPPER SOUTH ISLAND RELIABILITY, MCP STAGE 1, ATTACHMENT B TECHNICAL ANALYSIS Transpower New Zealand Limited June 2012 www.comcom.govt.**nz**/dmsdocument/1064

[49] Technical report on the future expansion and undergrounding of the electricity transmission grid Summary April 2008 http://www.atvinnuvegaraduneyti.is/media/fylgigogn-raflinur-i-jord/5-Elinfrastrukturudvalget.pdf

[50] **Cable action plan,** 132 - 150 kV grids – March 2009 http://energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Om%20os/Cable%20Action%20Plan%20-%202008-2009.pdf

[51] **Denmarks Cable Policy Landsnet Annual meeting 2014,** March 20th 2014
Jens Møller Birkebæk Director, International Affairs,
http://www.landsnet.is/library/Skrar/Landsnet/Upplysingatorg/Kynningarmal/Opinn-kynningarfundur-2014/06%20Landsnet%20Annual%20meeting%20%20-%20%20Danish%20cable%20policy%20ppt%20%20_Jens%20Møller%20Birkebæk_LOKA.pdf

4.5.5 Nampower, Namibia[52] [53]

From “**SVC for resonance control in NamPower electrical power system**” and “**SVC for Mitigating 50 Hz Resonance of a Long 400 kV ac Interconnection**”:

The extension of the Namibian transmission system results in a near 50 Hz resonance.

To control the resonance a SVC was installed at Auas 400 kV substation.

A new control principle for controlling the resonance was developed and tested

…extreme high overvoltages appearing at Auas with a peak value in excess of 1.7 p.u. and a sustained TOV of over 1.5 p.u. is attesting to the severity of the problem. It is clear that as soon as the 50-Hz resonance is triggered, very high dynamic overvoltages appear with large time constant depending on the system load and generation conditions.

The full SVC rating of 250 Mvar inductive power needed for resonance control is provided by three TCR's with a fourth TCR always energized (hot redundant).

The SVC is designed for severe black start conditions including immediate resonance control at combined SVC & 400 kV line energization.

The resonance oscillation in Namibian system is observed in the controller as a low frequency oscillation superimposed on the DC level.

During energisation of the 400 kV line and at fault condition the capacitance in the line is charged, which can be seen as a large sudden change in active power.

The results shown in [the paper] show the 400 kV voltage rise during the energisation of the 400 kV line as well as the voltage controller output and the additional contribution by the resonance controller. It can clearly be seen that the overvoltage is kept to a minimum by the fast and effective additional signal from the resonance controller.

The maximum transient overvoltage measured during this test was consistent with the results obtained from the design digital simulation studies as well as the RTDS simulator studies.

The overall results of the system performance tests demonstrated that the NamPower system can be operated effectively and safely under extremely challenging and different network conditions with the Auas SVC in service

The striking analogy between the near 50-Hz resonance and voltage stability phenomena can in fact make them dual where one produces overvoltage while the other leads to voltage collapse. In fact this points to a common solution method for both problems by means of adequate reactive power compensation.

At present, the SVC technology is well established in the power transmission environment with some reasonable reliability and availability figures being achieved on the average.

However, classical approaches to the application of SVCs in utility networks are in principle focused on voltage control particularly voltage support against collapse.

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[52] **SVC for resonance control in NamPower electrical power system**, M. Halonen S. Rudin B. Thorvaldsson ABB Power Systems Västerås, Sweden , Udo Kleyenstüber NamPower Windhoek, Namibia, Septimus Boshoff R.U.P. Johannesburg, South Africa , Chris van der Merwe Trans- Africa projects Johannesburg, South Africa

[53] **SVC for Mitigating 50 Hz Resonance of a Long 400 kV ac Interconnection**
Dr. A. Hammad, Consultant, NOK Baden, Switzerland, S. Boshoff W.C. van der Merwe, C. van Dyk, W. Otto R.P.A. Trans-Africa projects Johannesburg, South Africa, U.H.E. Kleyenstüber, NamPower Windhoek, Namibia

In the NamPower system, however, the Auas SVC has multiple functions; many are unconventional, in the following priority order:

- *Control the near 50-Hz resonance*
- *Limit temporary overvoltages during 400-kV line energisation, system contingencies and post fault conditions*
- *Avoid voltage collapse and provide sufficient voltage stability margin*
- *Damp power oscillations on the 400 kV interconnection to Eskom.*

Moreover, the weak NamPower network conditions add various constraints such as low order harmonic resonances and harmonic current injection limitations.

This is the only example of the use of dynamic reactive compensation for synchronous resonance control.

The NamPower transmission system is highly dependant on the correct and continuous operation of this SVC.

Due to the nature of the compensation control, the use of multiple units performing this task on a smaller, meshed system would be extremely difficult due to the interaction of the units.

4.6 Suitability for Application on the Irish Transmission Network

Mitigation Technique	Cost	Installed Footprint	Established Technology?	Established Technique?	Suitable for Irish Application?
MT1 Management of existing reactive compensation equipment	Low	N/A	N/A	Yes	Yes
MT2 Change of operating procedures	Low	N/A	N/A	Yes	Yes
MT3 Modification of switching/energisation procedures	Low	N/A	N/A	Yes	Yes
MT4 Adjustment of cable length	Low	Variable	N/A	Yes	Yes
MT5 Surge Arresters	Medium	Small	Yes	No	No
MT6 Shunt Capacitors	Medium / High	Medium	Yes	Yes	Yes
MT7 Shunt Reactors	Medium / High	Medium	Yes	Yes	Yes
MT8 Dynamic Reactive Compensation	High	Medium	Yes	Yes	Yes
MT9 Series Compensation	High / Very High	Medium / Large	Yes	No	No
MT10 HVDC	Very High	Large	Yes	Yes	Possibly

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Orange cells indicate methods that may be theoretically effective but may be reduced in effectiveness over time due to network development or may be limited by transmission planning criteria or system strength

5 PART B: IRISH APPLICATION

5.1 Overview of Irish Transmission System[54]

From EirGrid's Ten Year Transmission Forecast Statement and Grid25 Strategy Documents:

Over the next 10 years, major changes to Ireland's electricity requirements are forecast in its fuel mix and in its fleet of power stations. Change will increasingly be driven by issues of energy and system security, competitiveness, climate change and by the desire to move away from imported fossil fuels.

In Ireland, renewable energy policy is driven by a binding European legal requirement to ensure that 16% of the country's total energy consumption is derived from Renewable Energy Sources by 2020.

In order to achieve this total energy target, the Irish government is aiming for (40%) renewable electricity (12%) renewable heat and (10%) renewable transport. In the electricity sector, it has been estimated that between 3,500 - 4,000 MW of installed wind generation will be required to meet circa 37% of electricity demand in 2020. The remaining 3% is expected to be sourced from hydro generation, bio-energy, renewable CHP.

Over the past two decades wind power generation in Ireland has increased from 6 MW (one wind farm) to 1,773 MW (159 wind farms) at the beginning of December 2012.

As of 1 December 2012, 82 wind farms totalling 1,477 MW had signed connection offers and committed to connecting to the transmission or distribution systems over the next few years with a total of 396 applications totalling 22,922 MW in the applications queue.

Since March 2013 the amount of contracted wind has increased significantly and it is expected that there will be sufficient renewable generation contracted to connect to the system to meet the 2020 renewable target.

The transmission system is a vital channel for supplying reliable, sustainable and renewable energy to Ireland's demand centres while promoting open competition within the sector. Reinforcing and upgrading the transmission system is required in order to maintain a robust electricity transmission system.

The capacity of the bulk transmission system, comprising circuits at 220 kV or higher, has remained largely unchanged in the last 20 years, a period that has seen a growth of 150% in the electricity demand. EirGrid calculates that to facilitate the necessary increase in renewable generation and to adequately meet the demands of the electricity customer, the capacity of the bulk transmission system will need to be doubled by 2025

In October 2008, EirGrid published GRID25[55]*, its strategy for the long-term development of the transmission system. GRID25 will provide transmission capacity for increased electricity demand, new conventional generators, increased interconnection and large amounts of renewable generation.*

Since the GRID25 strategy was developed significant progress has been made in optimising investment plans, in identifying new technical solutions, in building new transmission circuits and in uprating existing circuits.

An indicative analysis of the reactive power requirements for EirGrid was performed in 2012.[56]

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[54] EirGrid – All-Island Ten Year Transmission Forecast Statement 2013, http://www.eirgrid.com/media/TenYearTransmissionForecastStatement2013.pdf

[55] Grid25 "A Strategy for the Development of Ireland's Electricity Grid for a Sustainable and Competitive Future http://www.eirgrid.com/media/Grid%2025.pdf

[56] *EirGrid Offshore Cable Investigation* http://www.eirgrid.com/media/EirGrid%20Offshore%20Grid%20Study.pdf

5.2 Transmission System Operation

5.2.1 Voltage Step[57]

The permitted step voltage changes, as specified in the Transmission Planning Criteria, are:

- *The voltage step resulting from capacitor switching shall not exceed 3.0%*
- *For single contingencies, the maximum step change between pre- and post-contingency steady-state voltages shall be no more than 10%.*

The voltage at any point on the transmission system is determined by the reactive power output of the generating plant and of capacitors, reactors and SVC's, the tap position of each generator/system transformer, the electrical characteristics of the transmission and distribution systems, the level of system load and its power factor.

Voltage control is affected by dispatching generator reactive power, providing automatic voltage control on generators, altering transformer tap positions and the switching of shunt reactors, capacitors and SVCs.

5.2.2 Transmission Network Characteristics[58]

Below is data from the EirGrid 2013 Ten Year Forecast Statement for substations relevant to the Cable Projects described in the Cable Projects section.

Substation	**Voltage (kV)**	**Minimum Fault Level (MVA)**	**Maximum Fault Level (MVA)**
Dunstown	400	4919	6097
Dunstown	220	6745	8497
Bellacorrick	400	3118	3118
Flagford	400	1940	1940
Flagford	220	2744	3125
Great Island	220	3010	4916
Knockraha	220	4420	6630

Table 17 - Transmission Network Characteristics

Data is for Maximum and Minimum demand in 2019.

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[57] EirGrid Transmission Planning Criteria http://www.eirgrid.com/media/Transmission%20Planning%20Criteria.pdf

[58] EirGrid – All-Island Ten Year Transmission Forecast Statement 2013, http://www.eirgrid.com/media/TenYearTransmissionForecastStatement2013.pdf

5.3 Cable Projects in Ireland

5.3.1 The GridWest Project[59]

The Grid West project will deliver energy infrastructure to the west of Ireland

Ireland's national goal is to meet 40% of electricity consumption from renewable sources by 2020 – these include wind, wave and tidal energy. The existing transmission infrastructure in the region needs substantial investment to capture the west's increasing levels of renewable energy generation. This critical infrastructure will also allow the western region to attract the type of industry that requires a secure high-voltage power supply.

The western region is particularly rich in wind and wave renewable energy resources, as well as having potential for biomass and other renewable technologies. The current transmission infrastructure is not designed to accommodate the level of renewable energy planned for this region. The Grid West project is critical to connecting this resource to the national grid.

The Grid West project consists of a new high-capacity power connection, linking the north Mayo area to a strong point on the national grid.

GridWest is an approximately.100-115km transmission circuit project dependant of the technology applied overhead or underground cable respectively. The circuit project is required to connect collector station for approximately 450MW of generation to the transmission network.

This circuit will be operated nominally as radial circuit, however a normally open link to the local 110kV network at the collector station can be closed for network support in certain circumstances.

The longer-term development of other generating sources in the area could trigger this radial connection to become a part of the meshed network.

5.3.2 The GridLink Project[60]

The Grid Link Project represents the single largest project in the Grid25[61] strategy. It is required to reinforce the transmission network in the south-east of Ireland and to address a number of key drivers for the transmission network in that region, namely the integration of new renewable and conventional generation, ensuring security of supply in the south-east in order to support demand growth in the region and facilitating possible future interconnection with either Great Britain or France.

The drivers that mostly influence network capacity are the integration of generation and future interconnection along the south-east coast of Ireland with either Great Britain or France.

With regard to generation, there is approximately 1,600MW of renewable generation expected to connect to the electricity network in the south of the country as part of the Gate 3 process.

Together with existing renewable and conventional generation in the south of Ireland this will put the capacity of the existing network under pressure and create constraints. Similarly, future interconnection along the south-east coast in combination with the above mentioned existing and additional generation will also give rise to network capacity problems.

Constraints on the transmission network primarily result from the situation where, if any of the existing 220kV circuits between Cork, the south-east and Dublin are put out of service, the power that was flowing on the circuit prior to the outage transfers to the underlying parallel 110kV network. This would result in thermal overloads primarily on the existing 110kV circuits.

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[59] GridWest, EirGrid GridWest Project Brochure, http://www.eirgridprojects.com/media/Grid_West_Project_Information_Brochure_Summer_2014.pdf

[60] GridWest Initial Report, EirGrid, http://www.eirgridprojects.com/media/Stage%201%20Report.pdf

[61] Grid25 "A Strategy for the Development of Ireland's Electricity Grid for a Sustainable and Competitive Future http://www.eirgrid.com/media/Grid%2025.pdf

Even with the assumed completion of uprates of existing circuits (thereby maximising the potential of the existing network), the transmission network would not have sufficient capacity to cater for the power flow identified above.

The loss of existing 220kV circuits and/or existing 110kV circuits would also result in unacceptably low voltages and potentially widespread voltage collapse in the south-east resulting from large inter-regional flows introduced by the drivers. This problem is severe and widespread which indicates that additional circuits would be required to resolve the issue.

Therefore, because of the planned connections of large amounts of renewable generation, the need to ensure that demand in the south-east is securely supplied and the potential for a new interconnector connecting to the grid in the south-east, there is a need to reinforce the transmission network between Cork, the south-east and Dublin with additional high capacity circuits.

Gridlink is a transmission circuit project that will connect from a 400kV station, Dunstown, in the SW Dublin area to a 220kV station, Knockraha, in the Cork area (NE of Cork city).

The project is also required to support the Waterford area and for the purposes of this appraisal is assumed to be routed into a 220kV station, Great Island in Waterford effectively making the project two circuits, c.115km and c.130km in length.

5.4 Circuit Data

5.4.1 Cable Data[62]

Below is data from the ABB XLPE Land Cable User's Guide for cables appropriate for the projects described in the Cable Projects section.

Voltage (kV)	Conductor CSA (mm²)	Capacitance (µF/km)	Inductance		Susceptance (µS/km)	Q (Mvar/km)
			Trefoil (mH/km)	Flat (mH/km)		
220	1400	0.22	0.37	0.51	69.12	3.35
380	1200	0.18	0.40	0.53	56.55	9.05

Unshaded items are from the source documentation.

Shaded items are calculated from the data.

5.4.2 Transmission Line Data[63]

Below is data from the EirGrid 2013 Ten Year Forecast Statement for transmission lines relevant to the Cable Projects described in the Cable Projects section.

Voltage (kV)	Impedance (per unit on 100MVA base per km)		
	R	X	B
220	0.0001161	0.0008633	0.001305
380	0.0000192	0.000224	0.005048

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[62] ABB, XLPE Land Cable Systems User's Guide

[63] EirGrid – All-Island Ten Year Transmission Forecast Statement 2013, http://www.eirgrid.com/media/TenYearTransmissionForecastStatement2013.pdf

5.5 Mitigation Recommendations

This section will mainly focus on the mitigation of TOV, as there is little international experience in directly mitigating this aspect (as can be seen from Part A).

As will be seen the Irish Transmission system is already in state potentially vulnerable to resonant TOV and the impact of the installation of underground cables may be greatest in this area.

It is common practice for TSOs to try and avoid resonant conditions above 5th harmonic (250Hz) for harmonic distortion purposes due to prevalence of that harmonic given the ubiquity of power electronic converters and other devices generating that characteristic harmonic.

However, in some cases the Irish Transmission system is already below that point in which case it is recommend to remain above 3rd harmonic (150Hz), the next most prevalent harmonic.

5.5.1 Steady-State Voltage Control

Steady-state voltage rise is directly related to the length of the cable and system strength and can be mitigated by the following:

- Improving the system strength
- Reducing the length of cable
- Transformer Tap-changers
- Generator off-nominal power factor and voltage control
- Shunt reactors
- Static Var Compensation

Shunt reactors will directly mitigate the magnitude of the steady-state voltage rise and will also maximise the power capacity of the circuit by compensating for the capacitive absorption of the cable. The maximum individual size of shunt reactor is directly related to the system fault level and the allowable voltage step for switching of reactive compensation.

The GridWest project is used in the evaluation below as it has the lowest stated fault level and the use of the GridLink project with it’s two sections and multiple connection points would introduce complexity that would detract from the clarity of the results. However, the principles utilised on the GridWest project are directly applicable to each section, independently, of the GridLink project.

Assuming a combined cable and overhead line length of 130km the variation in reactive power for various splits of cable and overhead line and using the data given in sections 5.4.1 and 5.4.2 is as follows:

OHL Length km	UGC Length km	400 kV			220 kV		
		OHL [Mvar]	UGC [Mvar]	Total [Mvar]	OHL [Mvar]	UGC [Mvar]	Total [Mvar]
130	0	73	0	73	17	0	17
120	10	67	90	158	16	33	49
110	20	62	181	242	14	67	81
100	30	56	271	327	13	100	113
90	40	50	362	412	12	134	146
80	50	45	452	497	10	167	178
70	60	39	543	582	9	201	210
60	70	34	633	667	8	234	242
50	80	28	724	752	7	268	274
40	90	22	814	837	5	301	306
30	100	17	905	922	4	335	338
20	110	11	995	1006	3	368	371
10	120	6	1086	1091	1	401	403
0	130	0	1176	1176	0	435	435

Static Var Compensators (SVC) will also perform the same function dynamically. SVCs can respond to changes in voltage within one cycle but can also have a slow control loop that returns the voltage response of the SVC to nominal over a slower period to allow for the response of slower reacting items such as transformer tap-changers (say 5 minutes) or generator response.

Using generators for voltage control in this manner is not ideal for long periods as any operation that is not at nominal power factor or voltage reduces the real power capability of the generation.

5.5.2 Temporary Overvoltage

It can be seen from studies performed by EirGrid that introduction of long overhead lines and cables to the Irish Transmission system results in resonances at low harmonic frequencies.[64]

Using the equations in section 4.1.5 and the data given in sections 5.4.1 and 5.4.2 gives the following first-resonance point for various cable and overhead line lengths at various 220kV and 400kV system strengths as defined in section 5.2.2:

Cable Length km	OHL Length km	220kV			400kV	
		2744MVA Hz	3010MVA Hz	4420MVA Hz	1940MVA Hz	3118MVA Hz
0	130	259.2	271.3	327.9	275.4	342.1
10	120	232.8	243.6	294.2	183.0	226.4
20	110	213.3	223.2	269.3	147.6	182.0
30	100	198.1	207.2	249.9	127.8	157.0
40	90	185.9	194.4	234.3	114.7	140.5
50	80	175.7	183.7	221.3	105.3	128.6
60	70	167.1	174.7	210.4	98.2	119.5
70	60	159.8	167.0	200.9	92.5	112.2
80	50	153.4	160.3	192.7	87.9	106.3
90	40	147.7	154.3	185.4	84.0	101.3
100	30	142.7	149.0	179.0	80.8	97.1
110	20	138.2	144.3	173.2	77.9	93.5
120	10	134.1	140.0	167.9	75.5	90.3
130	0	130.4	136.1	163.2	73.3	87.4

Note: shunt reactors for cable compensation are included in the resonance calculation

As shown in the table above the low frequency resonance is unavoidable.

An indication of the maximum cable length based can be determined from the table above given selection of a minimum acceptable resonance point.

5.5.2.1 Avoidance of TOV

As discussed above, the avoidance of low order resonance on the Irish Transmission System is unlikely as the "natural" resonance is already low.

The addition of shunt reactors for steady-state voltage control may assist in slightly raising the resonant frequency (assuming an inductive transmission system at low order harmonics) but not to the extent where it is no longer an issue. Shunt reactors may also increase the risk of extra low order harmonic injections

Mechanically Switched Capacitor Damping Networks (MSCDN) will provide additional damping (resistance) at specific harmonic orders and can mitigate the magnitude of the resonant TOV to the point where it may be controlled by other means.[65] However, the extremely comprehensive evaluation on the Southwest Connection project in Connecticut[66] determined that the interaction of C_Type filters with other equipment on the network made this equipment unsuitable for application as TOV mitigation.

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[64] *EirGrid Offshore Grid Study* http://www.eirgrid.com/media/EirGrid%20Offshore%20Grid%20Study.pdf

[65] The control of harmonic distortion on an EHV system by the use of capacitive damping networks, NM MacLeod, JJ Price, IW Whitlock, Conference: Harmonics And Quality of Power, 1998. Proceedings. 8th International Conference on, Volume: 2

[66] ROC – Final Report to the Connecticut Siting Council http://www.ct.gov/csc/lib/csc/docket_272/roc_report/final_roc_report_12-20-04.pdf

On the same basis the addition of resistance to new equipment may improve the overall system damping, mitigating the magnitude of the resonant TOV. E.g. Transformers. Although this may come at the expense of higher system losses.

System re-configuration may also change the system resonance characteristic to a certain extent and it is possible that certain dangerous resonance points (e.g. integer harmonic cases) may be avoided by network switching.

Long term development of the transmission system may negate the effectiveness of the solution as the resonance pattern may change over time negating the impact of the installed equipment for resonance mitigation purposes.

5.5.2.2 Control of TOV

The magnitude and duration of the resonant TOV is such that the use of surge arresters would not be of benefit. This can be clearly seen in the Aghada-Kilkenny surge arrester absorption studies given in the TEPCO Report.[67]

Multiple column arresters may be of use for events of less than 1ms but the majority of the TOV events are likely to be significantly longer than this as discussed in section 4.3.5

SVCs and other FACTS devices such as STATCOM may be used to mitigate the TOV once it has occurred and mitigated as far as possible by system damping.

Typically an SVC can respond to a voltage event within one cycle that should control the voltage to within the required magnitude within the required withstand time as defined in section 4.1.5.

However, the SVC can be configured as individual switched items and/or elements with vernier control such as a Thyristor Controlled Reactor (TCR) providing a smoother response although the maximum step-change in overall reactive power response will remain the same.

SVCs have a variable slope parameter that can be coordinated with the system configuration to maximise effective response with the voltage step constraints.

The size of an individual SVC or STATCOM and the maximum change in Mvar output from an SVC is dictated by the maximum allowable voltage step in accordance with the Transmission Planning Criteria.[68]

Therefore for a given system strength the maximum length of cable that can be mitigated by an SVC is limited by the same criteria.

SVCs are primarily designed for durations related to support during faults and post-fault support. To compensate for long duration TOV the SVC equipment would need to be rated accordingly which may be beyond the available technology.

The installation of multiple SVC or STATCOM units on a Transmission System may be problematic at low system fault levels due to interaction issues. As the SVC control systems are required to be highly tuned to specific circumstances and system configurations it is unlikely that multiple units could be coordinated to mitigate the resonant overvoltages without interaction which could cause abnormal behaviour and results.

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[67] "Contract CA209:Assessment of the Technical Issues relating to Significant Amounts of EHV Underground Cable in the All-island Electricity Transmission System", TEPCO , 2009

[68] EirGrid Transmission Planning Criteria http://www.eirgrid.com/media/Transmission%20Planning%20Criteria.pdf

From [69] :

"The 330 MVAr dynamic range of the Auas SVC makes it one of the dominating devices in the NamPower network with the ability to control or blackout the network."

"The fact that the entire NamPower system depends on the successful, reliable and continuous operation of the Auas SVC presents special high demands on the design, quality, functionality and layout of the individual components and sub-systems as well as the SVC scheme as a whole. Furthermore, the Auas substation is relatively remote from technical support and is planned to be unmanned. Any outage time would, therefore, impact severely on the entire system "

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[69] **SVC for resonance control in NamPower electrical power system**, M. Halonen S. Rudin B. Thorvaldsson ABB Power Systems Västerås, Sweden , Udo Kleyenstüber NamPower Windhoek, Namibia, Septimus Boshoff R.U.P. Johannesburg, South Africa , Chris van der Merwe Trans- Africa projects Johannesburg, South Africa

6 OVERALL RECOMMENDATIONS

Summary
For development of the cable projects on the Irish Transmission System the following items will provide benefit in the control of steady-state voltage control, reactive power control and mitigation of resonant TOV:

- Restriction of cable length to avoid integer harmonic resonant conditions as it is recommended that specific low order harmonic resonances are avoided, particularly 2nd harmonic (100Hz) and 3rd harmonic (150Hz) as these are more difficult to mitigate than higher order harmonics and can cause difficulties in the setting and operation of control, protection and measurement equipment. .
- Use of shunt reactors to control steady-state voltage and to maximise cable capacity.
- Examination of system configuration to avoid dangerous resonant conditions where practical.
- Potential re-specification of future equipment to increase system damping at the expense of losses to mitigate resonant TOV.

Use of SVCs to control steady-state voltage, control reactive power and provide dynamic voltage control in the event of unavoidable resonant TOV.

The specific recommendations for mitigation of issues related to the integration of 400kV and 220kV underground cables are suggested as follows

6.1 Reactive Power Control

The following items are considered to be suitable for control of reactive power issues related to underground cables:

- Shunt Reactors
- Dynamic Reactive Compensation
- HVDC
- Limitation of cable length

6.2 Steady State Voltage Control

The following items are considered to be suitable for controlling steady-state voltage issues related to underground cables:

- Shunt Reactors
- Dynamic Reactive Compensation
- HVDC
- Limitation of cable length

6.3 Harmonic Distortion

The following items are considered to be suitable for permanently avoiding or mitigating harmonic resonance issues related to underground cables:

- HVDC
- Limitation of cable length
- Change of Operating Procedures

The following items are considered to be suitable for avoiding or mitigating harmonic resonance issues related to underground cables but may be limited by long term development of the transmission system which may negate the effectiveness of the solution as the resonance pattern may change over time negating the impact of the installed equipment for resonance mitigation purposes:

- Shunt Reactors / Capacitors
- Management of existing reactive compensation equipment

6.4 Temporary Overvoltage

The following items are considered to be suitable for avoiding or mitigating TOV resonance issues related to underground cables:

- HVDC
- Limitation of cable length
- Change of Operating Procedures
- Modification of Energisation / Switching Procedures

The following items are considered to be suitable for avoiding or mitigating TOV resonance issues related to underground cables but may be limited by transmission planning criteria, system strength and cable length:

- Dynamic Reactive Compensation
- Re-specification of future equipment (e.g. transformers) to provide additional system damping at the expense of system losses

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