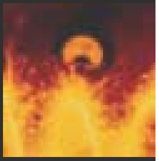
Harmonic Impedance Study for Southwest Connecticut Phase II Alternatives

By **KEMA, Inc**.

Authors: J.H.R. Enslin; R. A. Wakefield; Y. Hu; S. Eric

October 18, 2004



KEMA Inc. T&D Consulting, 3801 Lake Boone Trail, Suite 200
Raleigh, NC 27607, Phone: 919 256-0839, Fax: 919 256-0844

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EXECUTIVE SUMMARY AND CONCLUSIONS

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.

A new system model was developed, based on data provided by the Applicant. This model was used to evaluate the different system alternatives from a harmonic resonance point of view. In evaluating the study results obtained, the desirability of having a first resonance point in excess of the 3rd harmonic was used as one measure of acceptability.

BASE CASE RESULTS

KEMA studied the new Base Case system (Applicant/ISO-NE Study Case 5) with 24 miles of undergrounding using XLPE cables and compared its harmonic resonance performance with that of the approved Phase I system. KEMA also investigated extending the undergrounding with XLPE cable along the Devon to Beseck corridor. The results for the Phase II Base Case are comparable and consistent with harmonic scan results performed by the Applicant and their consultants.

MITIGATION

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.

ADDITIONAL UNDERGROUNDING

With regard to increased undergrounding between Devon and Beseck, KEMA's results confirm that harmonic resonance peaks moves lower as the amount of additional undergrounding increases. However, the results also indicate that passive filtering would be effective in mitigating these negative effects, especially for additional undergrounding in the 10-20 mile range. Based on these results alone, if effective mitigation is employed, additional undergrounding of up to 20 miles along the proposed corridor from Devon north to Beseck would be technologically feasible. Undergrounding of the entire Devon to Beseck corridor appears to be a risky choice from a reliability perspective, because system resonance points below the third harmonic may occur.

RECOMMENDATIONS

Based on these study results, KEMA recommends:

1. 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.
2. Transient analysis studies should be conducted, based on a detailed system model of the selected configuration.

1 INTRODUCTION

1.1 Scope of Services Provided

KEMA, Inc. has conducted an harmonic analysis of the Northeast Utilities (NU) 345 kV transmission system to evaluate different cable and line options in Southwestern Connecticut (SWCT).

1.1.1 CT SITING COUNCIL'S OBJECTIVE

The State of Connecticut, Connecticut Siting Council (CTSC) requested an independent technical review of an application to the Council for a Certificate of Environmental Compatibility and Public Need (Certificate) for the construction of a new 345 kV electric transmission line facility and associated facilities between Scovill Rock Switching Station and Norwalk Substation, which includes the reconstruction of portions of the existing 115 kV and 345 kV electric transmission lines, pursuant to Connecticut General Stat. §16-50v(2)9(f). The Council engaged the services of KEMA Inc. (KEMA) to assist the Council.

1.1.2 CONSULTING SCOPE OF WORK

KEMA performed an independent technical review of the application to the Council for a Certificate for the construction of the 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 has investigated several mitigation schemes to assess whether these schemes could extend the portion of the Phase II line that can be feasibly constructed underground.

1.1.3 REQUIRED INFORMATION AND SYSTEM MODELS

KEMA reviewed the technical part of the application for a certificate of environmental compatibility and public need (Application) for Phase II, the technical studies provided in the supplemental filings, expert testimony on directly related technical issues, and relevant hearing documents. In addition, KEMA reviewed all related data responses provided by the parties involved.

To independently investigate the feasibility and technical suitability of options to install high voltage electric transmission lines underground, KEMA requested from the Applicant the load flow and harmonic and transient studies that justified the proposed alternative, accompanied with the underlying assumptions, and all the models used for load flow and switching transient and harmonic studies.

Because the Applicant's consultant was unwilling to supply the related harmonic and transient study models, a new 368-bus model was developed using data provided by the Applicant. This model was used to evaluate the harmonic resonance performance of alternative system designs. Harmonic results were obtained for the approved Phase I project, Phase II alternatives with and without mitigation, and various cases that included additional undergrounding beyond that proposed in the original Application. In evaluating the study results obtained, the desirability of having a first resonance point in excess of the 3rd harmonic was used as one measure of acceptability.

No detailed harmonic performance criteria, or acceptable system operating conditions were obtained from the Applicant. It was only indicated that the first resonance frequency should be higher than the 3rd harmonic number. Based on our past experience and on our knowledge of NEPOOL and the Connecticut System, we evaluated the approved Phase I project against the different Phase II alternatives and developed recommendations on mitigation methods and transmission undergrounding.

1.2 Background of Southwestern Connecticut Project

The electric reliability in Southwestern Connecticut (SWCT) has been a concern for several years, particularly during summer heavy load conditions. Inadequate local generation and transmission congestion in SWCT make the region vulnerable to reliability problems when demands are higher than expected or generating units or transmission lines serving the area are unavailable. As owners of the SWCT transmission system, the Applicant has proposed to the Council and to the Independent System Operator of New England (ISO-NE) specific measures to improve the transmission system and reduce the possibility of future outages.

A two-phase expansion has been proposed to upgrade the 345 kV transmission network in SWCT. Phase I consists of a double circuit 345 kV cable between the existing Plumtree 345kV substation and a new Norwalk 345 kV substation. This phase was previously approved by the Connecticut Siting Council. [2]. Phase II is described in "Docket 272 - Connecticut Light and Power Company and United Illuminating Company application for a new 345-kV electric transmission line between Scovill Rock Switching Station in Middletown and Norwalk Substation in Norwalk" [1]. Phase II extends the 345 kV network by adding the Beseck 345 kV substation between Southington and Devon, and constructing a 345 kV transmission line from Beseck to Norwalk, via Devon and Singer (Pequonnock).

The proposed Phase II Middletown to Norwalk project would serve the whole SWCT region, which is defined for power supply purposes to include all or portions of 54 municipalities in the central and southwestern portions of Connecticut. By completing the 345-kV transmission loop in SWCT, this Phase II Project is intended to address the long-term reliability requirements of this region and its major load centers.

In the process of studying Phase II, some reliability concerns have been raised concerning the system's harmonic resonance performance, and this report addresses these concerns.

1.3 Study Approach

In conducting this harmonic study, KEMA used the following approach:

1. KEMA investigated, solely from a system harmonic performance perspective, the maximum length of underground 345 kV cable for the Phase II Project. Harmonic studies were performed using a SWCT system model, developed with data provided by the Applicant.

2. The studies were performed using the computer program PowerFactory from DIgSILENT. PowerFactory integrates all required functions and combines reliable and flexible system modeling capabilities with state-of-the-art algorithms and a common integrated database concept. All the studies were done under converged load flow operating conditions. The effects of different load levels were also investigated.

3. Data sources for KEMA model development include:

a. Basic existing system configuration, as represented in the ASPEN file provided by the Applicant.
b. System loadings and dispatch from the PSS/E (power flow) files provided by the Applicant.
c. Phase I and Phase II line and cable configurations and component data provided by the Applicant.

Harmonic frequency scans were made for Phases I and II at key 345 kV and 115 kV substations. Tables and graphs that compare the different network configurations were developed from the data associated with the harmonic scans.

1.4 Workplan and Simulation Conditions

1. In this study we calculated the harmonic frequency scans at key buses for the following system alternatives:
   (a) Phase I [2], according to the original application with two High-Pressure Fluid-Filled (HPFF) and some sections of cross-linked polyethylene insulated (XLPE) power cables.

   (b) An adapted version of Phase I, with a single HPFF cable connected, and another installed, but removed from service, as proposed in the Applicant's Summer of 2004 studies.
   (c) A revised Phase II proposal called "Study Case 5", using XLPE cables between Norwalk and Devon.
   (d) A revised Phase II proposal, based on Study Case 5, with additions up to 40 miles of XLPE cables installed from Devon going north toward Beseck, as an alternative to the proposed overhead construction on this corridor.

2. Based on the above-mentioned alternatives some mitigation techniques were examined, especially to determine the maximum possible underground cable length. These include the following:
   (a) Reactive power compensation using STATCOM installations in place of capacitor bank installations at some substations. The STATCOMs are also sized to replace the shunt reactors required for voltage regulation on the capacitor terminations, as applicable from a load-flow point of view.
   (b) C-Type passive filter capacitors to increase the low frequency points of harmonic resonance on the system and to damp the effects of higher-frequency resonances. Here also the shunt reactive power compensation was done using the C-Type Filters in place of the larger capacitor bank installations at some substations.

3. The harmonic impedance for the defined cases is calculated over the first 15 harmonics for key 345 kV and 115 kV substations.

4. The following results are presented in this report:
   (a) Harmonic impedance { **Z**(h) } per study case, plotted over the full frequency range.
   (b) Tables of harmonic resonance points and the associated impedance and damping.
   (c) Harmonic impedance graphs, combining the results from the different cases in (a).

2 ANALYSIS OF HARMONIC DISTORTION IN NETWORKS

This section describes some fundamentals of harmonic performance (and resonances) in electrical networks. Although the aspects of harmonics are investigated in this report in relation to HV cable networks, resonance and harmonics are common phenomenon in all electrical networks [6]. For any circuit, a resonance may be calculated where both capacitors and reactors are present in the network. Further, there is the possibility of either series or parallel resonance, depending on the configuration of the network. Based on these parallel and series resonances, the harmonic voltages and currents are amplified in the system, resulting in higher than expected harmonic emissions in the system.

2.1 Harmonic Distortion, Impedance, Compatibility and Immunity

In general, problems with the harmonic distortion can be described in terms of the following concepts:

- A disturbance source which produce harmonic current emissions
- A component or equipment which cannot deliver its required performance because it is not immune to the harmonic distortion in the voltage (harmonic victim)
- The impedance link between the disturbance current source and victim equipment.
- Resonance between different L and C components can increase the distortion levels in the network due to a large increase in the impedance link.

In any electrical network the disturbance source can be those customers who generate harmonic current emissions with consequences to the network voltage. The inrush currents associated with transformer switching, can also provide a disturbance source. It is also possible that a circuit breaker cannot operate correctly because it is not immune to the harmonic voltage distortion and therefore affects the whole system. The link between a disturbance source and a component is the high impedance (at the harmonic frequency) of the network.

For an electrical system that performs well, the emission of distortion will be sufficient below the immunity of possible “harmonic victims”. The reason for a system disruption can now be classified in three aspects:

- The level of emission of a distorting source is too high (this means higher than the level of immunity for a harmonic victim.
- The level of immunity of a harmonic victim is too low (this means lower than the expected level of immunity)
- The link (impedance of the network and the connected network components) is causing a higher level of emission (resonance) that gets higher than the level of immunity.

It is clear from this discussion that in order to have a harmonic problem, both the emission level of the distorting source and the immunity level of the possible victims should be considered. It is also important to note that a compatibility level should be defined for a specific system that provides an adequate margin between the emission level and immunity level so that minimum harmonic problems occur on the system. This compatibility level can be defined in terms of maximum harmonic current levels and maximum voltage harmonic levels. These compatibility levels can also be defined in terms of the harmonic voltage amplification levels, where the system impedance is compared between two different network configurations, for example with capacitors or cables in and out of service.

2.2 Harmonic Current Sources

Most harmonic sources penetrate the transmission network from all the different lower-level connected individual loads. Such loads commonly have some non-linear portion continuously producing harmonic currents on a steady-state basis. These harmonic currents are propagating through the system. Some currents cancel each other or are reduced, while others are amplified due to the different phase relationships between them.

Within the high voltage transmission network, non-ideal network components may also contribute to harmonic currents. These may also be generated on a steady-state basis or may exist on the system for a short period of time during switching. The two main sources of harmonic currents considered here are converter loads penetrating from the lower levels and the in-rush currents generated during the energization of power transformers.

Other non-linear loads that produce large amounts of distortion are arc-furnaces, arc-welders, fluorescent lighting and magnetic saturation in power transformers.

2.2.1 CHARACTERISTIC HARMONIC SOURCES FROM POWER CONVERTERS

Non-linear electrical loads, normally the consequence of power control equipment, are known to be the major sources of power network distortion. Because these loads are generally highly efficient, both their numbers and capacities increased enormously during the last number of years, and will follow this trend for the time to come. The technique of phase-angle control in supply commutated thyristor converters, is by far the most extensively used technique to control vast amounts of power in electric power systems. These power converters do inject currents, known as characteristic harmonic (5th, 7th, 11th 13th, .. etc.) currents into the power network under steady state conditions and reduced amounts of uncharacteristic harmonic currents (other harmonic and inter-harmonic numbers) under dynamic operating conditions. These phase-controlled converters form the largest single source of distortion in power systems.

Injected harmonic currents are generated in all the distributed non-linear converter loads, added at the different substations and penetrating into the transmission system. Some of these harmonic currents are however naturally compensated by means of phase shifts due to distribution and transmission networks, transformers, capacitors etc., throughout the system. However not all the currents are compensated and some penetrate through the network up to the 115 kV and 345 kV transmission networks. They however still have mainly the characteristic 5th, 7th, 11th, 13th, etc., harmonic nature.

Due to non-ideal converter and transformer configurations small values of 3rd, 9th and other triplet current harmonics, are also generated by phase-controlled and other non-linear loads. These triplet harmonics are however minimized by the star-delta connections of step-down transformers, resulting in minimal penetration of these triplet harmonics to high voltage transmission levels.

2.2.2 HARMONIC SOURCES DURING TRANSFORMER ENERGIZATION

The harmonic currents generated at the sub-station busbar due to the energization of a transformer are not of a steady-state nature as discussed in the previous paragraph, but exist only during the in-rush current time of 0.2 to 0.5 seconds. Normally these harmonic currents have high second order (2nd) and some third (3rd) order values during the energization time.

Most power transformers are not designed with a margin between normal flux peaks and the saturation limits to avoid saturating under energization, and so the core will almost certainly saturate during this first half-cycle of voltage. During core saturation, the magnetizing current with large 3rd harmonic levels will rise to a value easily exceeding twice its normal peak. This current will also have large even harmonic (especially 2nd) components due to this core saturation. The magnitude of the inrush current strongly depends on the exact time that electrical connection to the source is made. If the transformer has some residual magnetism in its core, before the switching moment, the inrush could be even more severe.

These second order (2nd) and third (3rd) order harmonic currents results in some harmonic voltages associated with the system impedance at these harmonic numbers, but they are normally well damped and no high overvoltage transient will result.

2.2.3 KEY HARMONICS CONSIDERED FOR THIS STUDY

For the purpose of this study the key harmonics are defined as being the characteristic harmonics (5th, 7th, 11th, 13th, etc.) and the 2nd and 3rd for concerns by the Applicant in connection with the energization of transformers.

2.3 Mechanisms of Series and Parallel Resonance

When analyzing the effects of distortion in power systems there are so many factors to be considered that it can become a detailed study of its own. Some effects of distortion are, however, very important and stand out as primary problem areas; they are described here. One of these serious effects is the principle of resonance of the equivalent network reactance at harmonic frequencies.

The principles are described here in terms of the SWCT system shunt capacitor and cable capacitances, and equivalent source impedances. Shunt capacitors and cable charging capacitances affect the system resonance dramatically and should be considered in the design of such a projects. The charging capacitance associated with the HV cables and shunt capacitors are normally seen as an equivalent capacitance C in parallel with the system, while the network series line, generator and transformer impedances, normally inductive, are seen as an equivalent series reactance L. The load and resistance of the line, transformers and cables are seen as the equivalent R or damping in the system. When analyzing the resonance phenomenon in this HV system, characteristic harmonic currents generated from the converters and the energization of a HV transformer are considered. In the case of the in-rush currents from the transformers, some unbalance currents may be generated for short periods of times generating some 2nd and 3rd harmonic currents into the system.

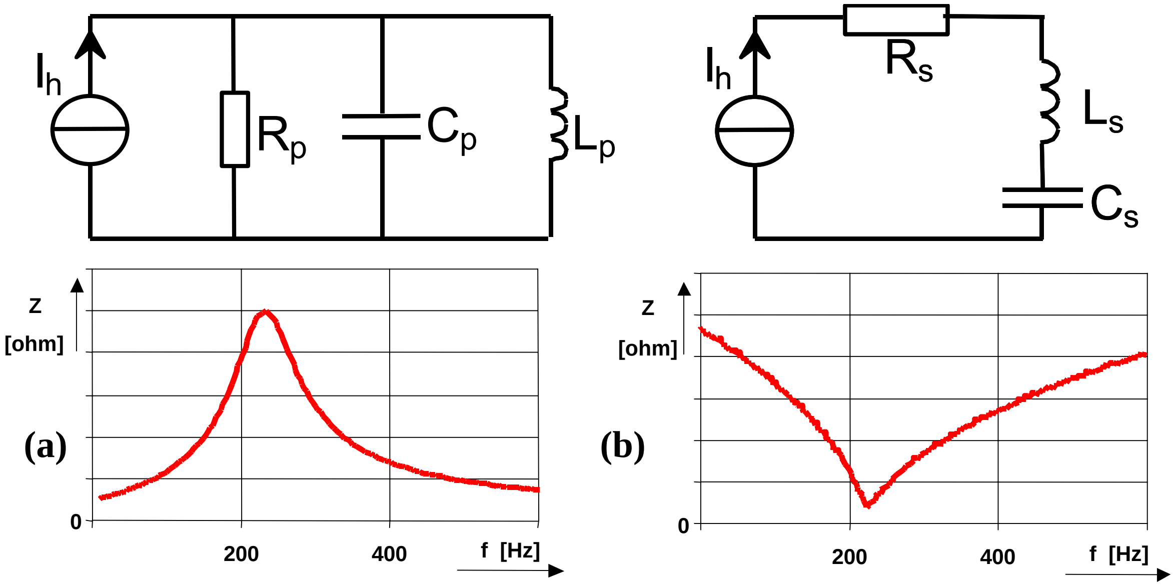


Figure 1: Mechanisms of Parallel (a) and Series (b) Resonance

Resonance phenomena are shown in Figure 1, and can be divided into the following:

- **Parallel Resonance** (Figure 1(a)) of the parallel network capacitance C_p (cable charging capacitance and capacitor banks) and the supply inductance L_p (transformer leakage, generators, lines and cable). A parallel resonance is characterized as a high impedance to the flow of harmonic currents at the resonance frequency. This parallel resonance is initiated by distortion generated <u>internally,</u> i.e. within the load connection point. In this case a in-rush current associated with the switching transformer or distorting converter load can be assumed to be the generating source current I_h. In this case the impedance at the

resonance is high, resulting in higher voltage distortion at the Point of Common Coupling (PCC), or where the equipment and load is connected.
- **Series Resonance** (Figure 1(b)) of the equivalent network capacitance C_s, and the supply reactance L_s, is resulting from externally generated or injected distortion from other parts of the system. A series resonance is characterized as low impedance for harmonic currents at the resonance frequency. In this case the background supply voltage distortion is the mechanism. In this case the impedance at the resonance is low, resulting in higher current distortion through the load, cable capacitance or capacitor bank installations.

In practice these two phenomenon are linked in one circuit and both increased levels in the voltage and current distortions are practically measured. For high voltage networks normally limited background voltage distortion exists and mainly locally generated distortion affecting the system in a parallel resonance is considered. In HV networks with large HVDC links and large capacitor bank installations the series resonance is important for capacitor bank and filter loading considerations.

System loading (active and reactive) can have a significant effect on the system frequency response, especially at lower frequency resonance points. In most cases the load is connected via a step-down transformer, represented by a series reactance and resistance in the circuit. At low frequencies the transformer series reactance is small compared to the load impedance, but at higher frequencies this reactance becomes large compared to the load, thus decoupling the load from the system impedance. The active portion of the system load affects mainly the system damping at lower resonance frequencies.

The series and parallel resonance can simply be calculated at the frequency f_r, in the following equation:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where f_r is the resonance frequency, L and C the equivalent reactance and capacitance in the series or parallel network.

If one of the current harmonics generated by the inrush current of a transformer or other local harmonic current source (parallel resonance mechanism) corresponds with the parallel resonance frequency, very high resonance voltages, damped only by the associated network and load resistances, will occur on the network voltage at PCC. This may have operational effects on the network and other equipment connected to the PCC. Furthermore, this resonance can be even more severe if the power network is weak, i.e. L is large, which results in a lower frequency resonance. The load is in parallel to the network resistance connected through a step-down transformer in the parallel resonance case, and may have a smaller effect on the damping than the line and cable resistance.

When one of the harmonics present in the network background distortion (series resonance mechanism) corresponds with the series resonance frequency, high resonance currents will flow in the network, damped only by the associated network resistance.

2.4 Generalized AC System Harmonic Impedance

Harmonic impedance of the network can be determined by different methods. In most cases mainly the inductive line impedances and the charging capacitance of the cable networks and reactive power compensation capacitor banks, influence the harmonic impedance. These two main reactive components (L and C) determine possible resonant points in the network. In the simplest form the resonant frequency is determined as shown in the following simple equation derived from Equation 1:

$$f_r = f_1 \sqrt{\frac{S_{SC}}{Q}} \qquad \textbf{(2)}$$

Where f_1 is the fundamental network frequency, S_{SC} the short-circuit power in MVA, at the point of connection, and Q the total amount of capacitive reactive power in MVAr of the charging capacitors cable network ($Q = \frac{1}{2}CV^2$).

In this simple equation no information on the network damping is available. In practical networks, resistive damping in the lines, transformers and loads, limits the resonance and harmonic impedance amplification to 3 – 10 times above the characteristic network impedance, Z_o.

$Z_0 = h\, Z_1$, and

$Z_h \,/\, Z_0 \le 3 \; to \; 10$, the typical harmonic impedance amplification ratio **(3)**

With Z_0 - characteristic network impedance in Ω;
Z_1 - harmonic impedance at fundamental frequency;
Z_h - harmonic impedance at a specific harmonic, h;
h - harmonic number, 1, 2, 3, 4, 5, ….

If the calculated resonance according to equation 2 is near to one of the key harmonics (2nd, 3rd, 5th, 7th, 11th, 13th …) of the source, the potential for problems should be evaluated further. As a first step the system impedance at the characteristic harmonic should be calculated. From this impedance together with the harmonic source current the voltage magnitude can be calculated at each characteristic harmonic.

In practical harmonic analyses studies, this harmonic impedance is calculated with software programs based on a specific network configuration using frequency scans and harmonic flow analysis.

2.5 Amplification of Harmonic Voltages

As discussed above, capacitor banks and cable charging capacitances affect the harmonic impedance when they are added or removed from the network. Therefore the frequency and damping of the resonance peaks move on the basis of the capacitors switched in or out. This may affect the amplification of some harmonic voltages. The harmonic amplification can be plotted in terms of the calculated network impedance, $\mathbf{Z}_{net}$, and the impedance of the capacitor bank or cable charging capacitance, $\mathbf{Z}_C$, (see Figure 2).

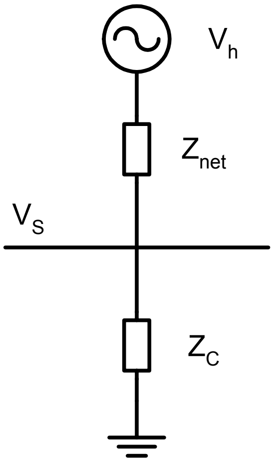


Figure 2: System Representation for Calculating the Harmonic Voltage Amplification

The amplification ration of the voltage harmonic is the absolute value of the complex impedance ratio:

$$\frac{Z_C}{Z_C + Z_{net}} \tag{4}$$

Z_C : Harmonic impedance of a capacitor or cable
Z_{net} : Harmonic impedance without the capacitor and / or cable
V_h : Harmonic voltage in the network
V_s : Resulting harmonic voltage at the substation with cable and / or capacitor

Based on this equation, the amplification of the voltage at a specific harmonic number can be calculated, taking the charging or shunt capacitor out of service and adding it back into the network.

The harmonic impedance Z_h, and characteristic impedance Z_0, according to equation 3, is plotted in Figure 3. From the previous discussion it is clear that where the harmonic impedance Z_h, is above the characteristic impedance Z_0, harmonic voltage amplification will be result with the same injected harmonic current source, and harmonic voltage damping will occur where the harmonic impedance Z_h, is below the characteristic impedance Z_0.

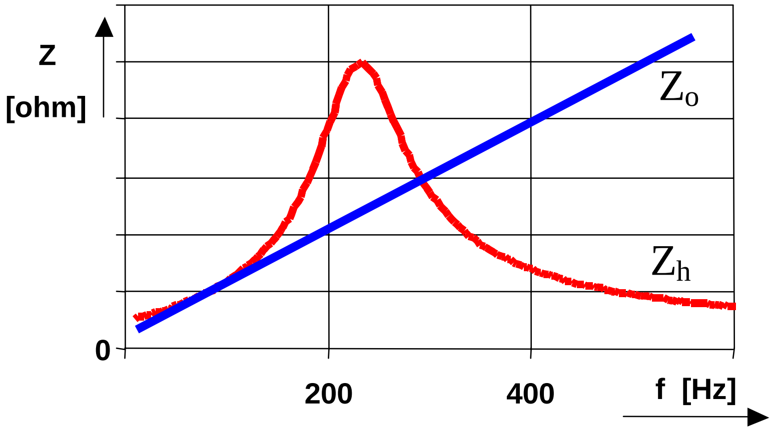


Figure 3: Harmonic System Impedance and Harmonic Voltage Amplification

2.6 Harmonic Voltage Measurements

In order to evaluate the impacts of a new project on the harmonic performance of a system some harmonic measurements should be undertaken at the key substations before the project commences [12]. This gives some indications on the existing levels of background voltage distortion and characteristic harmonic sources on the system. This will also provide some key mitigation options if some harmonic levels are approaching the IEEE-519 limits [9]. Care should be taken that the high voltage harmonic measurements are done with a high quality, high bandwidth voltage divider [6,12]. Normally capacitive voltage transformer (CVT) dividers give large erroneous results at harmonic frequencies.

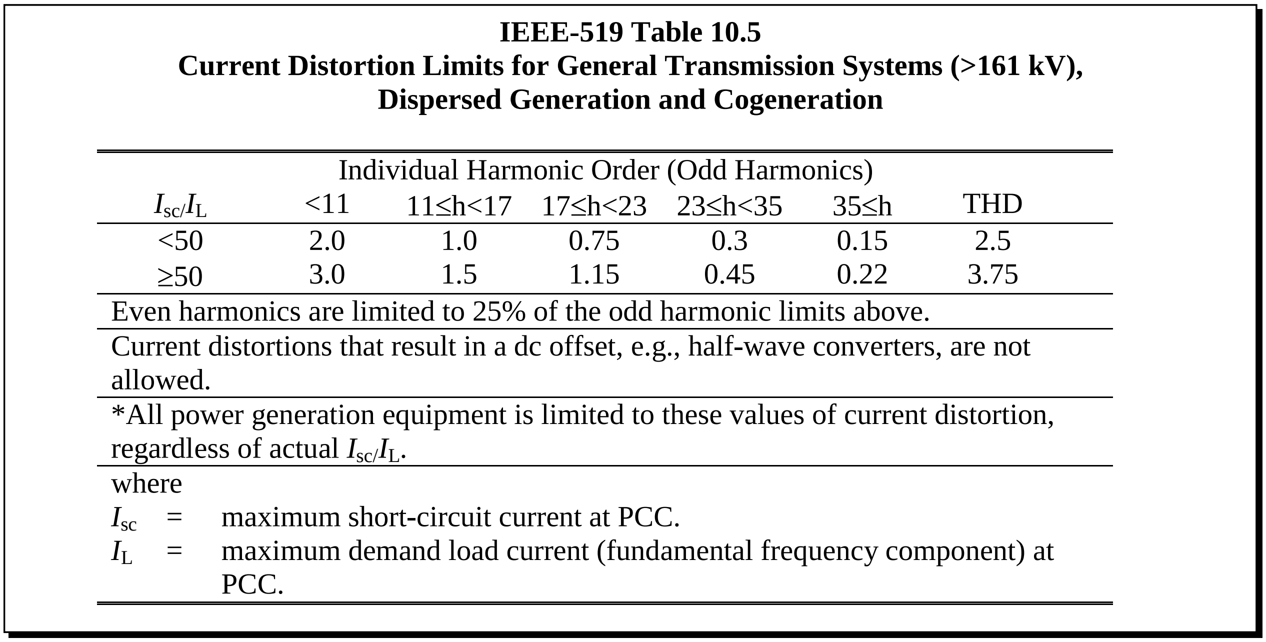
These results can then be included as background harmonic voltage distortion in the harmonic impedance calculations to determine the expected voltage distortion levels for a specific network configuration. These results can then be compared to the IEEE-519 or other harmonic standard to determine acceptable harmonic performance for a specific design.

2.7 Harmonic System Compatibility Requirements

It is clear from the above-mentioned discussion, a harmonic problem occurs when both the level of the distortion generated by the harmonic source and the immunity level of possible victims are considered to overlap. Based on the harmonic measurements and knowledge of the system characteristics in terms of harmonic currents, the compatibility requirements should be derived for the specific system. It is important to note that the compatibility level in terms of harmonic sources and voltage amplification should be defined for a specific system in order to have a clear system requirement. If no compatibility level is defined, the IEEE recommended design practice considering harmonic distortion, IEEE 519-1992: “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems” [9], may be used as a guideline.

2.7.1 IEEE-519 RECOMMENDED HARMONIC PERFORMANCE REQUIREMENTS

The IEEE-519-1992 recommended practice provides some limits for harmonic currents that may be generated. These are specified at different voltage levels and equivalent source impedance or short-circuit levels (I_{sc}). The harmonic current limits that are relevant for this HV system is shown in the IEEE-519 Table 10.5 [9].



IEEE-519 Table 10.5
Current Distortion Limits for General Transmission Systems (>161 kV), Dispersed Generation and Cogeneration

	Individual Harmonic Order (Odd Harmonics)					
I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	THD
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where
I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

Figure 4: Harmonic Current Limits for Transmission Systems, according to IEEE-519 [9]

If these current harmonic limits are exceeded at some sub-station or PCC locations, the following mitigation steps, according to IEEE-519, should be followed by the utility:

- Identify high harmonic current generating customers through measurements and analysis and require these customers to install harmonic filters or other measures to limit the harmonic currents.
- Install passive or active filters to limit the harmonic currents at the point of harmonic generation, if no specific customer contributed significantly to the distortion levels.
- Install a new feeder, thus strengthening the system (higher short-circuit levels) in that location.

Based on the amount of injected current harmonics, system strength and system resonance, the voltage distortion will vary. Limits of acceptable voltage distortion for this system is also specified in the IEEE-519 Guideline relevant for this HV system, shown in Table 11.1 [9]:

IEEE-519 Table 11.1
Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is a HVDC terminal that will attenuate by the time it is tapped for a user.

Figure 5: Harmonic Voltage Limits for HV Transmission Networks [9]

Based on the harmonic impedance at the specific location and the injected current harmonics, through ohm's law the voltage will be distorted. The IEEE-519 is normally specified as the maximum limits, but utilities may have their own, more stringent, harmonic performance requirements in order to have some margin in terms of the total system performance.

2.7.2 HARMONIC VOLTAGE AMPLIFICATION LIMITS

In addition to the harmonic current and voltage limits specified above according to IEEE-519, some utilities require that the amplification factor, defined in Figure 2 and further described in Figure 3, is limited per harmonic voltage. An example of such a limit is shown in Table 1 [12,5].

Table 1: Typical Harmonic Voltage Amplification Limits

Harmonic Order No	Maximum permissible harmonic voltage amplification at a specific sub-station busbar due to a parallel resonance
2	≤ 1.3
3	≤ 1.2
4 and 6	≤ 1.3
5	≤ 1.0
≥ 7 ≤ 49	≤ 1.0

This table provides information on the harmonic voltage amplification allowed on the system. It is for this reason also important to evaluate the system damping at the specific harmonic number. If the harmonic impedance is lower than the characteristic impedance, see blue line Figure 1, then no significant amplification of the specific harmonic voltage will result (Thus amplification harmonic voltage lower than 1.0). If the impedance at the specific harmonic number is higher than the characteristic harmonic (see blue line Figure 1 as an example), the amplification at the harmonic impedance may be higher than 1.0.

For this study KEMA has also used the system damping and harmonic impedance at a specific characteristic harmonic frequency as measure of acceptable harmonic performance, and not only the harmonic number.

3 NETWORK MODELING CONSIDERATIONS

3.1 Description of Network Model

The Applicant supplied the main Connecticut 345 and 115 kV network in ASPEN format. Furthermore the full regional transmission system model was supplied in PSS/E format. The full ASPEN model was converted to DIgSILENT, Power Factory version 13.1. The planned Phase I and Phase II network upgrade extensions on the 345 kV and 115 kV systems were modeled directly in the PowerFactory model, using the Applicants data provided in the discovery process. The harmonic impedance calculations were done using PowerFactory after a solved load flow was obtained for each alternative.

This ASPEN model and interactive data requests between KEMA and the Applicant were used to develop the Phase I and Phase II models used in the harmonic analysis.

3.2 Generator Dispatch

Table 2 describes the generators included in the original ASPEN file, and the modified status provided for the Middletown to Norwalk (M/N) project, which indicates the generators that are on or off during the light and minimum local generator dispatch conditions. Because the maximum generator dispatch is not a limiting condition in terms of harmonic resonance, this dispatch scenario was not considered in this study. The study cases considered here were based on real solved load flow conditions, therefore some of the capacitor allocation and minimum dispatch configurations could not be calculated and are considered not to be realistic operating conditions.

Table 2: Light and Minimum Local Generator Dispatch

Generator	V_n [kV]	ID	ST	Light Dispatch	Minimum Dispatch	Notes
MILLSTON U2	22.8	1		In-service	In-service	
MILLSTON U3	22.8	1		In-service	In-service	
RESCO	115	1		In-service	In-service	
ROCKY RVR U1	13.8	1		In-service	Not-in-service	
ROCKY RVR U2	13.8	1		In-service	Not-in-service	
ROCKY RVR U3	13.8	1		In-service	Not-in-service	
STEVENSON	6.9	1		Not-in-service	Not-in-service	
NORWALK	27.6	1		Not-in-service	Not-in-service	
BULLS BRIDGE	27.6	1		In-service	In-service	
FORESTVIL A1	13.8	1		In-service	Not-in-service	
Brdgphbr 2	18.4	1		Not-in-service	Not-in-service	
Brdgphbr 3	20.2	1		In-service	Not-in-service	

Brdgphbr jet	13.68	1	Not-in-service	Not-in-service	
COSCOBGEN	13.8	1	Not-in-service	Not-in-service	
COSCOBGEN	13.8	2	Not-in-service	Not-in-service	
COSCOBGEN	13.8	3	Not-in-service	Not-in-service	
E. DEVON 11U	13.8	1	Not-in-service	Not-in-service	
E. DEVON 12U	13.8	1	Not-in-service	Not-in-service	
E. DEVON 13U	13.8	1	Not-in-service	Not-in-service	
E. DEVON 14U	13.8	1	Not-in-service	Not-in-service	
English	13.68	8	Not-in-service	Not-in-service	
English	13.68	7	Not-in-service	Not-in-service	
ESHOREGEN	13.8	1	In-service	Not-in-service	
G1/G2	13.8	1	Not-in-service	Not-in-service	WALLNGFRDSUB
G3/G4	13.8	1	Not-in-service	Not-in-service	WALLNGFRDSUB
G5	13.8	1	Not-in-service	Not-in-service	WALLNGFRDSUB
GT1 (11)	16.0	1	Not-in-service	Not-in-service	BRGPRT ENERG
GT2 (12)	16.0	1	Not-in-service	Not-in-service	BRGPRT ENERG
Middletown 4	22.0	1	Not-in-service	Not-in-service	
Milford 1	20.9	1	In-service	Not-in-service	
Milford 2	20.9	1	Not-in-service	Not-in-service	
One	21.0	1	Not-in-service	Not-in-service	MERIDEN GEN
Shepaug Gen	13.8	1	In-service	Not-in-service	
So Norwalk a	4.8	1	Not-in-service	Not-in-service	
So Norwalk b	4.8	1	Not-in-service	Not-in-service	
So Norwalk g	13.8	1	Not-in-service	Not-in-service	
ST1 (10)	16.0	1	Not-in-service	Not-in-service	BRGPRT ENERG
Temp Gen	13.8	1	Not-in-service	Not-in-service	WATERSIDE
Temp Gen	13.8	2	Not-in-service	Not-in-service	WATERSIDE
Temp Gen	13.8	3	Not-in-service	Not-in-service	WATERSIDE
Three	21.0	1	Not-in-service	Not-in-service	MERIDEN GEN
Two	21.0	1	Not-in-service	Not-in-service	MERIDEN GEN
Unit 10	13.8	1	Not-in-service	Not-in-service	E. DEVON RING 2
Unit 6J-10	13.8	1	In-service	Not-in-service	NORWALK HARB
Unit 6J-1	17.1	1	Not-in-service	Not-in-service	NORWALK HARB
Unit 6J-2	19.0	1	Not-in-service	Not-in-service	NORWALK HARB
Unit 7	13.2	1	Not-in-service	Not-in-service	E. DEVON RING 2
Unit 8	13.2	1	Not-in-service	Not-in-service	E. DEVON RING 2
Walrecgen	4.16	1	Not-in-service	Not-in-service	WALREC
Total Generators In			**13**	**4**	

3.3 Capacitor Dispatch

The different capacitor dispatch configurations are shown in the next section. The capacitors are required to perform voltage support, especially under the light and minimum generator dispatch with high system loading.

3.4 Comparison of Short Circuit Values

As indicated before, the original ASPEN file was converted to PowerFactory. Some refinements were made to the PowerFactory model and short circuit calculations were performed on both models and compared. The fault currents were checked to validate the developed model. Northeast Utilities (NU) provided fault currents from their ASPEN model with all generators online. With the generators all online, three-line-to-ground faults were simulated at various buses in PowerFactory. The short circuit results at the 345 kV and 115 kV busses show a better than 3.5% comparison between the ASPEN and PowerFactory models, before Phase I and Phase II sections were added.

3.5 HPFF and XLPE Cable Data for Phase I and Phase II

KEMA has performed a harmonic system resonance study of the XLPE cable and overhead line alternative in the Beseck to Norwalk 345 kV transmission project (Phase II) that is proposed in SWCT. In this study the total of 15.5 miles of two parallel XLPE cables between Norwalk and Singer and 8.2 miles of two parallel cables between Singer and Devon were represented as 3000 kcmil XLPE cables (Parameters provided by NU). The approved 20.5 miles Phase I project, major part of it using two parallel 2500 kcmil HPFF cables between Plumtree and Norwalk, with short 1750 kcmil XLPE cable sections, was also considered in this study (Parameters provided by NU). The changes to the 115 kV cable sections for Phase I were also considered as provided by NU. In some of the study cases, one of the two HPFF cables in the Phase I section was removed.

The charging capacitance of the 3000 kcmil XLPE cables is approximately 60% of that of the 2500 kcmil HPFF cables. The Applicant provided the cable parameters for the different Phase I and Phase II cable configurations. These parameters were used to represent the 3000 kcmil XLPE cable and 2500 kcmil HPFF cables with sections listed below:

1. Plumtree to Norwalk – Phase I: 20.5 miles of overhead lines, and two parallel 9.7 mile, 2500 kcmil HPFF cable sections, and two short, parallel 1750 kcmil XLPE cable sections.

2. Norwalk to Singer – Phase II: Two parallel 15.5 mile sections of 3000 kcmil XLPE cables.

3. Singer to Devon – Phase II: Two parallel 8.2 mile sections of 3000 kcmil XLPE cables.

4. Devon to Beseck –Three parallel sections of 1750 kcmil XLPE cables of varying lengths up to 40 miles.

For the studies of additional undergrounding, 3 parallel cables were assumed. The same cable parameters assumed for the Phase I XLPE sections were used for this section, as well. The shunt reactors on both sides of the XLPE cable sections, similar to the sunt reactors between Norwalk and Devon are included at 10 mile intervals. Four different study cases were considered:

- 10 miles of XLPE cable from Devon toward Beseck, with the rest overhead line.
- 15 miles of XLPE cable from Devon toward Beseck, with the rest overhead line.
- 20 miles of XLPE cable from Devon toward Beseck, with the rest overhead line.
- 40 miles of XLPE cable from Devon to Beseck, with no overhead line.

3.6 Modeling Considerations for Specific Components

The model was developed using the "Guide for assessing the network harmonic impedance" produced by the CIGRé working group CC02 [3] as guidelines. In all the simulations only the lower order harmonic resonances were considered (< 1000 Hz). For this reason, the skin effect was not modeled in any of the components. This may effect mainly the damping of the different resonance peaks, especially the higher resonance damping values.

3.6.1 MODELING CONSIDERATIONS FOR GENERATORS

All generators were included in the model as supplied by the Applicant. The generator models include the sub-transient reactance $X_d^{"}$, and the generator resistance in series.

3.6.2 CONSIDERATIONS FOR MODELING EQUIVALENT CIRCUITS AND FAULT LEVELS

As indicated above, a relative large network model is included and the short circuit levels on the network borders were modeled with equivalent generators. In these equivalent generators an equivalent sub-transient reactance $X_d^{``}$ and resistance in series R, as well as generating or absorbing MW and MVArs were used.

3.6.3 MODELING CONSIDERATIONS FOR TRANSFORMERS

The equivalent circuit normally used for 60 Hz modeling was used in developing this model, since this was the only model available.

3.6.4 MODELING CONSIDERATIONS FOR LINES AND CABLES

In this study the classical equivalent-π circuit (with R-L series - and C parallel elements) or lumped parameters were used due to the fact that the individual lines and cables considered, are less than 50 miles long [7,6]. The frequency and damping of mainly the higher order resonance points may be affected by this simplification.

3.6.5 MODELING CONSIDERATIONS FOR LOADS

The network model in ASPEN format, provided by Applicant, did not contain load data. Therefore, KEMA used the load data, associated with the 27.7 GW NEPOOL load forecast, as modeled in the PSS/E load flow base cases. These load data were transferred to the ASPEN file. Since the ASPEN model was a reduced system model, the rest of the system was modeled with network equivalents, as discussed earlier. A load in the range of 70 – 100 % of full load with all capacitors in service is expected to be a worst case from the harmonic impedance perspective. System operation with all capacitors in service at lower loading levels seems unlikely.

3.6.6 MODELING CONSIDERATIONS FOR SHUNT CAPACITORS

The different 115 kV capacitor banks for reactive power compensation on the 345 / 115kV network, were included as single capacitors at the different sub-stations. The capacitor sizes and sub-station allocation are shown in Table 3, which indicates the capacitor bank MVAr in service under peak and light capacitor dispatch conditions.

Table 3: Modified Shunt Capacitive Compensation for System Model

Sub-Station	**V_n** [kV]	#	**ALL On** [MVAr]	**ALL Off** [MVAr]
Southington Ring 1	115	3	157.2	0
Southington Ring 2	115	3	157.2	0
Frost Bridge	115	5	262	0
Berlin	115	3	132	0
Plumtree	115	2	92.2	0
* Glenbrook	115	5	190.8	0
Darien	115	1	39.6	0
Waterside	115	1	39.6	0
Norwalk	115	0	0	0
East Shore	115	2	84	0
No. Haven	115	1	42	0
Sackett	115	1	42	0
Rocky River	115	1	25.2	0
Stony Hill	115	1	25.2	0
** Cross Sound Filters	200	3	103	103
Total			**1392**	**103**

* Existing Glenbrook STATCOM is assumed always in service, totaling 2x 75 MVAr
STATCOM & Capacitor – 340.8 MVAr

** Cross Sound HVDC Light filters: 61 MVAr - 25th harmonic; 32 MVAr - 41st; 10 MVAr – 21st

This study considers conditions with all capacitor banks in service and all capacitor banks out of service, except for the Cross Sound HVDC Light filters. These HVDC filters are always on. For Phase I and II the 115 kV capacitor banks at Plumtree and Norwalk were removed from the model. Frost Bridge capacitor dispatch was kept at 262 MVAr and at Glenbrook the dispatch was kept at 190.8 MVAr, excluding the STATCOM rating of 150 MVAr. The STATCOM reactive power allocation was used for the load flow studies, but excluded from the harmonic frequency scans.

3.6.7 MODELING CONSIDERATIONS FOR GLENBROOK STATCOM

In the different study cases, the different capacitor allocations are shown in Table 3. These are indicated in the case definitions. When considering the Glenbrook STATCOM in this study the following approximations were made in the modeling of this STATCOM.

- The existing Glenbrook STATCOM is assumed always in service, totaling 2x 75 MVAr.
- At Glenbrook substation the STATCOM and capacitor rating is a maximum of 341 MVAr, but considered only at the fundamental frequency.
- The capacitive and inductive ratings of the STATCOM were used only in the load-flow analysis.
- In the onic analysis the STATCOM MVAr rating was not included in the model.
- The high frequency filters and injection reactor were ignored in the frequency scans.

3.6.8 SUMMARY OF MODELING CONSIDERATIONS IN POWERFACTORY

A summary of these modeling considerations include the following:

- All cables and overhead lines were modeled using lumped parameters
- The skin effect has not been taken into account, mainly due to a lack of physical line data.
- All the cases are based on solved load-flow scenarios.
- The 60 Hz models of the transformers were used.
- The Glenbrook STATCOM was modeled as a reactive power source at fundamental frequency with no influence on the harmonic impedance at higher frequencies.

4 HARMONIC PERFORMANCE CRITERIA

KEMA used a set of harmonic performance criteria to evaluate the maximum length of undergrounding of the Phase II. The basic harmonic system performance criteria from the Applicant and ISO New England, that the first resonance should be higher than the 3rd harmonic was used as the starting point. The harmonic impedance and system damping, in comparison to the characteristic system impedance was used as a harmonic performance measure of the possible harmonic voltage amplification. The Phase I harmonic performance, with one and two HPFF cables in service, as a starting point, was also used as a criterion. Finally the harmonic impedance at the characteristic harmonics was also used.

4.1 First Significant Resonance Higher Than 3rd Harmonic

The criterion that the first resonance should be higher than the 3rd harmonic was used as a first screening point. It is however important to look at the impedance value at the resonance point and at the characteristic harmonic number, to evaluate different network options against each other. When the resonance is well damped, even resonance below the 3rd harmonic may be acceptable.

4.2 Phase I Harmonic Performance

The harmonic impedance and performance of Phase I is compared under comparable load, capacitor and generator dispatch conditions, to the Phase II network configurations. For Phase I one and two HPFF cables in service were considered.

4.3 Comparison of Harmonic Impedance and Characteristic Impedance

By comparing the harmonic impedance $Z_{h,}$ scans with the characteristic system impedance $Z_{0,}$ possible harmonic voltage amplifications can be identified. If the harmonic impedance falls below the characteristic impedance, then the harmonic voltages will be damped at that frequency. If the harmonic impedance is above the characteristic impedance at the specific frequency, the harmonic voltage may be amplified by the resonance, see Figure 3. As indicated a typical amplification in the harmonic impedance of 3 – 10 is typical in most systems.

4.4 Harmonic Impedance at Key Harmonics

The harmonic impedance is also calculated, tabulated and compared at specific key harmonic frequency levels. This impedance value is a critical element in determining the harmonic voltages that result from harmonic current emissions.

4.5 IEEE-519 Recommended Harmonics Requirements

In the study reports from the different consultants on this project, the IEEE 519-1992: “IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems”, [9] was listed as the only requirement next to the 3rd harmonic requirement. No other tangible harmonic system requirements could be found. Since no detailed background harmonic distortion measurements were available, the IEEE-519 could not be used as a harmonic performance requirement in this study. It is however proposed that a detailed background harmonic voltage measurement program be undertaken to define a compatibility level for this system.

5 MITIGATION OPTIONS CONSIDERED

Different mitigation options were considered for this project to maximize the length of underground cables. For effective mitigation it is important to have a clear indication of the harmonic system performance requirements and the expected harmonic current sources in the region. The mitigation options can be considered on the customer or load side limiting the harmonic sources at the characteristic harmonics, especially around the known system resonances points. Furthermore, mitigation should be considered on the utility side to limit the impact of these harmonic sources.

By considering the harmonic sources in the utility network, the switching of 345 to115 kV step-down transformers were identified as a concern since these switching conditions may generate even (especially 2nd) and triplet (especially 3rd) harmonics in the system. These are, however, short duration distortion events (0.1 – 0.3 seconds) that are naturally damped in the system under normal conditions.

These even harmonics can however excite a system resonance around the 2nd or 3rd harmonic, if it exists in the system. However, the most cost-effective mitigation solution for this phenomenon is to change the system frequency response characteristics to avoid the resonance during the transformer energizing process in the first place. This may be possible by switching one or more shunt capacitors and cables out, prior to energizing the transformer. In a detailed transient calculation, the worst in-rush current events can be simulated and when considered a risk, altered operational procedures, protection and mitigation techniques can be investigated.

From a system reliability point of view, based on the system resonant frequencies, the dominant resonance points should be moved to a number where they will have the lowest impacts on the system operation. Adding or removing capacitance and inductance from the system, as described in the previous chapter and Figure 1, can help to do this. In practical terms for the SWCT system, some of the cable charging and shunt compensating capacitors should electrically be removed from the system at harmonic frequencies. Since the capacitances are required to provide voltage support throughout the system, they have to be included at the fundamental frequency, but maybe “removed” electrically at higher frequencies.

The different options described in this chapter, to influence the system resonance performance, include the replacement of some shunt capacitors with STATCOMs [4,19,20,23,24,25], and changing the characteristics of some of the shunt capacitor banks so that they operate as a filter [5,6,12], which is tuned to system resonances and provide some known damping to the system at specific frequencies in order to minimize the harmonic impedance at key harmonics.

5.1 Replacing Some Capacitors and Shunt Reactors with STATCOMs

As discussed above, in one of the mitigation solutions, some of the 115 kV capacitor banks and shunt compensating reactors at the cable terminations were replaced with STATCOMs. STATCOMs contribute to voltage support at the fundamental frequency, but do not affect the harmonic impedance largely at higher frequencies [4,25,26,27]. If in general the requirement is to increase the resonance harmonic number to higher numbers, the STATCOM mitigation is a good solution, since the large capacitors are removed "electrically" from the system at higher frequencies. However, the operational issues with operating numerous STATCOMs in the SWCT system may be hamper this mitigation method.

The STATCOM mitigation option will move the resonance peak to a higher number and can also be designed to provide active and or passive filtering capabilities at the lower harmonics in the 2nd – 5th harmonic range. In the STATCOM model for this study, no active filtering was incorporated, due to limited modeling time. If the STATCOMs are designed to provide some damping at key low harmonics (2nd and 3rd), improved results are to be expected. A STATCOM provide also increased transient and voltage stability margins. The transient and voltage stability have not been studied here, but in a more detailed study this will provide good added benefits to a STATCOM design [25].

One the other hand one or two STATCOMs on the SWCT system, will not only improve the harmonic performance of the system, but will improve also dynamic voltage support and transient performance after a contingency. These added advantages have not been studied here, but needs to be evaluated in a more detailed dynamic study, specifically involving the STATCOM allocations.

Similarly to the STATCOM study case done by the Applicant, some of the larger capacitor banks are replaced by a STATCOM, as indicated at the different sub-stations in Table 4. This mitigation option will have the effect of increasing the resonance frequency to higher values since the capacitors are replaced by STATCOMs.

Table 4: Modified Shunt Capacitive Compensation for STATCOM Mitigation Option

Sub-Station	V_n [kV]	#	STATCOM Option C [MVAr]	St. [MVAr]
Southington Ring 1	115	3	0	300
Southington Ring 2	115	3	0	0
Frost Bridge	115	5	0	300
Berlin	115	3	132	0
Plumtree	115	2	0	0
Glenbrook	115	5	0	300
Darien	115	1	39.6	0
Waterside	115	1	39.6	0
Norwalk	115	0	0	0
East Shore	115	2	84	0
No. Haven	115	1	42	0
Sackett	115	1	42	0
Rocky River	115	1	0	0
Stony Hill	115	1	0	150
* Cross Sound Filters	200	3	103	0
Total			**482.2**	**1050**

* Cross Sound HVDC Light filters:
61 MVAr - 25th harmonic; 32 MVAr - 41st; 10 MVAr – 21st

The STATCOMs were also sized to replace the shunt charging compensating reactors at the cable terminations. The harmonic analysis was done with both the shunt reactors in service and out of service. When considering STATCOMs in this study, the following approximations were made in the modeling of the STATCOMs.

- The capacitive and inductive ratings of the STATCOMs were used only in the load-flow analysis and the equivalent capacitors were removed from the network when the harmonic analysis was done.
- The high frequency filters and injection reactor were ignored in the frequency scans.
- No active filtering capabilities were modeled for the STATCOM.
- The charging reactors at the 345 kV cable terminations were removed for all the 100% load cases. A separate analysis was done comparing the results with the shunt reactors in and out of service.
- Furthermore the relevant capacitor banks, indicated at the different sub-stations in Table 4, were replaced by the indicated STATCOMs.

5.2 Replacing Some Capacitors with C-Type Filters

The other mitigation option considered, and described in this chapter, includes the replacement of some shunt capacitors with C-Type filters. With limited system impacts some of the larger capacitor bank installations can be changed to C-Type filter banks so that they operate as a filter. These C-Type filter banks contribute in the same way that regular capacitor banks do to provide voltage support at the fundamental frequency, but they do not affect the harmonic impedance at higher frequencies. This assures that the resonance frequencies will not change due to the switching of the C-Type filter capacitors. The damping may be in most cases be better with the capacitors in service than without, due to the design of the filters.

This filter will have low impedance at the tuned harmonic and will provide harmonic filtering and damping characteristics between the 2nd and 3rd harmonic if the filter is tuned at the 3rd harmonic. This will help to filter and damp any harmonic currents generated at these frequencies.

For the SWCT system some of the larger capacitor banks were reconfigured as C-Type filter capacitors in the system model. The C-Type filter still provides fundamental power reactive power, but provide harmonic filtering characteristics at lower frequencies and damping characteristics at higher frequencies. It allows for filtering of low order harmonics (such as 3rd), while keeping low losses at the fundamental frequency. Since the SWCT system has a first resonance between the 2.4 and 3rd harmonic, the C-type capacitor banks were tuned to the 3rd harmonic at the relevant 115 kV sub-stations. The simplified single line diagram of the C-Type, 3rd harmonic tuned capacitor is shown in Figure 6.

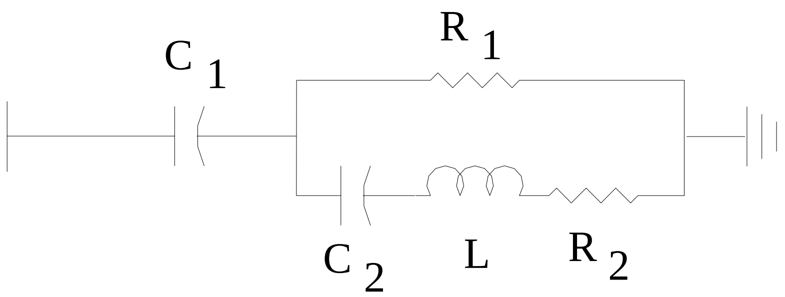


Figure 6: Line Diagram of C-Type Filter Capacitor

For the C-Type capacitor the main reactive power compensation capacitor is C_1, while C_2 and L should be tuned to have zero impedance at 60 Hz. R_1 is selected based on the tolerable losses and required damping and R_2 is a representation of the reactor losses and thus quality factor of the filter. The total filter is thus tuned at 180 Hz or the 3rd harmonic.

This design of the C-Type filter was not optimized for each bank, but assumed to be the same for all the banks. In a follow-up, more detailed study, optimizing the C-Type filter numbers, rating and designs, including designs tuned at the 2nd ; 3rd ; 4th ; 5th ; etc., should be investigated on individual sub-station, and voltage support and harmonic performance as a whole, point of view. Also the added damping resistor design should be optimized from a system damping and loss-appraisal point of view.

In the different study cases the different capacitor and C-Type filter allocations are shown in Table 5. Not all the capacitors have been changed to C-Type filters, only a few of the larger banks.

Table 5: Modified Shunt Capacitive Compensation for C-Type Filter Option

Sub-Station	V_n [kV]	#	C-Type Filter Option C [MVAr]	Filter [MVAr]
Southington Ring 1	115	3	0	157.2
Southington Ring 2	115	3	0	157.2
Frost Bridge	115	5	0	262
Berlin	115	3	0	132
Plumtree	115	2	0	0
* Glenbrook	115	5	0	151.2
Darien	115	1	39.6	0
Waterside	115	1	39.6	0
Norwalk	115	0	0	0
East Shore	115	2	84	0
No. Haven	115	1	42	0
Sackett	115	1	42	0
Rocky River	115	1	25.2	0
Stony Hill	115	1	25.2	0
** Cross Sound Filters	200	3	103	0
Total			**400.6**	**859.6**

* Existing Glenbrook STATCOM is assumed always in service, totaling 2x 75 MVAr.
The STATCOM rating is added to the C-Type Filter at fundamental frequencies
In harmonic analysis the STATCOM MVAr is not included

** Cross Sound HVDC Light filters:
61 MVAr - 25th harmonic; 32 MVAr - 41st; 10 MVAr – 21st

The design values used in this study for the filter design shown in Figure 6 are indicated in Table 6 below. The reactor series resistors R_2 for the reactors were assumed as shown, based on the quality factor of 200.

Table 6: Tuned 3rd harmonic C-Type Filter Values on 115 kV network

Filter Component / Size	Unit	132 MVAr	157.2 MVAr	190.8 MVAr	262 MVAr
Main Capacitor C_1	[μF]	26.48	31.53	38.27	52.55
Filter Capacitor C_2	[μF]	211.8	252.2	306.2	420.4
Filter Inductance L	[mH]	33.22	27.89	22.98	16.73
Damping Resistor R_1	[Ω]	200	200	200	200
Reactor Series Resistor R_2	[Ω]	0.0626	0.0526	0.0433	0.0316
Quality Factor of Circuit	[-]	200	200	200	200

6 DEFINITION OF STUDY CASES

The key study cases investigated by KEMA are defined and described in this chapter.

6.1 Definition of Phase I Case Alternatives

Harmonic studies were conducted for the Phase I alternative in order to compare Phase I and Phase II results. The case definitions are described below and results are provided in the tables and in the frequency scans in the following chapter and plotted in the Appendix.

6.1.1 CASE I-1: ONE PHASE I CABLE IN, LIGHT DISPATCH, ALL CAPACITORS ON

For this case no Phase II changes or upgrades were incorporated. The load on all of the underlying substations was changed between full-load and half-load conditions with all the capacitor banks in service, and light generator dispatch according to Table 2. The minimum dispatch generator scenario could not be run because the load flow would not converge. This may indicate that this is not a realistic operating condition. Results were calculated for the following conditions:

- All capacitors ON with no mitigation according to Table 3.
- Either one or two of the Phase I HPFF cables in service.
- Only light generator dispatch was used due to non-convergence of the minimum dispatch operating conditions.
- System load varied between full-load and half-load.

The results are provided in the tables in the following chapter and frequency scans in the Chapter 7.3.1 and Appendix 10.1.

6.2 Definition of Phase II Case Alternatives

Harmonic studies were conducted for numerous Phase II alternatives. Some of these cases are similar to the Applicant’s study cases. Phase II case definitions are described below, and results are provided in the tables and in the frequency scans in Chapter 7.3.2 and Appendix 10.2.

6.2.1 CASE II-1: NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, ALL CAPACITORS ON

Two parallel XLPE cable sections in the Norwalk – Singer – Devon corridor are included. Overhead line is used on the 40-mile Devon – Beseck corridor. Loads on all of the underlying substations are changed between full-load and half-load conditions with all capacitor banks in service for the minimum generator dispatch scenario, according to Table 2. Results were calculated for the following conditions:

- All capacitors ON with no mitigation according to Table 3.
- One or two of the Phase I HPFF cables in service.

Results are provided in the tables in the following Chapter 7.3.2 and frequency scans in Appendix 10.2.1.

6.2.2 CASE II-2: NORWALK - DEVON XLPE PHASE II, LIGHT DISPATCH, ALL CAPACITORS ON

Two parallel XLPE cable sections in the Norwalk – Singer – Devon corridor are included. Overhead line is used on the 40 mile Devon – Beseck corridor. Loads on all of the underlying substations are changed between full-load and half-load conditions with all capacitor banks in service for the light generator dispatch according to Table 2. The results are calculated for the following conditions:

- All capacitors ON with no mitigation according to Table 3.
- Either one or two Phase I HPFF cables in service.

Results are provided in the tables in the following chapter in Chapter 7.3.2 and frequency scans in Appendix 10.2.2.

6.2.3 CASE II-3: NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, ALL CAPACITORS OFF

Two parallel XLPE cable sections in the Norwalk – Singer – Devon corridor are included. Overhead line is used on the 40-mile Devon – Beseck corridor. All capacitor banks are out of service according to Table 3, with the minimum generator dispatch scenario, according to Table 2.

As discussed earlier, this case did not converge on a load flow basis, and therefore harmonic results could not be obtained. Such a scenario may not represent a realistic operating state for the Phase II system.

6.2.4 CASE II-4: NORWALK - DEVON XLPE PHASE II, LIGHT DISPATCH, ALL CAPACITORS OFF

Two parallel XLPE cable sections in the Norwalk – Singer – Devon corridor are included. Overhead line is used on the 40 mile Devon – Beseck corridor. Loads on all of the underlying substations are changed between full-load and half-load conditions for the light generator dispatch according to Table 2. Results are calculated for the following conditions:

- All capacitors OFF with no mitigation according to Table 3.
- Either one or two Phase I HPFF cables in service.

Results are provided in tables and graphs in the following chapter 7.3.2 and frequency scans in the Appendix 10.2.4.

6.3 Definition of Phase II Case Alternatives, Including Mitigation Options

Harmonic studies were conducted for the Phase II alternatives with two different mitigation options. STATCOMs are added at the same locations proposed by the Applicant, see Table 4 [1]. The other mitigation option included replacing selected capacitor banks with C-Type filters tuned to the 3rd harmonic, as described in Section 5.2, and different capacitor and filter allocations according to Table 5. Case definitions are described below and results are provided in the tables and frequency scans in chapter 7.3.3 and Appendix 10.3.

6.3.1 CASE II-5: NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, STATCOM, ALL REMAINING CAPACITORS ON

Two parallel XLPE cable sections in the Norwalk – Singer – Devon corridor are included. Overhead line is used on the 40-mile Devon – Beseck corridor. Loads on all of the underlying substations are changed between full-load and half-load conditions with all capacitor banks in service for the light generator dispatch according to Table 2. Results are calculated for the following conditions:

- Proposed Mitigation using the STATCOM alternative, see Table 4.
- The remaining capacitors were kept ON.
- Either one or two Phase I HPFF cables in service.
- Case II-5b investigate the effect of the 345 kV shunt reactors on the cable terminations

6.3.2 CASE II-6: NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, C-TYPE FILTER, ALL REMAINING CAPACITORS ON

Two parallel XLPE cable sections in the Norwalk – Singer – Devon corridor are included. Overhead line is used on the 40-mile Devon – Beseck corridor. Loads on all of the underlying substations are changed between full-load and half-load conditions with all capacitor banks in service for the minimum generator dispatch according to Table 2. Results are calculated for the following conditions:

- Proposed mitigation using the C-Type Filter tuned to the 3rd harmonic, see Table 5.
- All remaining capacitors in service.
- Either one or two Phase I HPFF cables in service.

6.4 Definition of Extended Undergrounding Alternatives

Harmonic studies were conducted for the extended Phase II alternatives. The corridor between Devon and Beseck was sectionalized and undergrounded in 10-mile sections. Three XLPE cables, similar to other Phase I XLPE sections, are used in parallel. The case definitions are described below, and results are provided in the tables and frequency scans in Chapter 7.3.4 and Appendix 10.4.

6.4.1 CASE II-7: DEVON - BESECK 10-MILE XLPE PHASE II, MINIMUM DISPATCH

An XLPE cable section of 10 miles, on the Devon side of the Devon-Beseck corridor, is modeled. Three XLPE cables, similar to other sections, are used in parallel. The remainder of the 40-mile corridor uses overhead line. Phase I is modeled with one HPFF cable in service, and full load conditions are assumed. Results are calculated for the following conditions:

a) All capacitors ON with no mitigation.
b) C-Type 3rd harmonic filters according to Table 5 and Table 6.
c) All remaining capacitors ON.
d) STATCOMs included according to Table 4 and all remaining capacitors ON.

6.4.2 CASE II-8: DEVON - BESECK 20-MILE XLPE PHASE II, MINIMUM DISPATCH

An XLPE cable section of 20 miles, on Devon side of the Devon-Beseck corridor, is modeled. Three XLPE cables, similar to other sections, are used in parallel. The rest of the 40-mile corridor uses overhead line. Phase I is modeled with one HPFF cable, and full load conditions are assumed. Results are calculated for the following conditions:

a) All capacitors ON with no mitigation.
b) C-Type 3rd harmonic filters according to Table 5 and Table 6, with all remaining capacitors ON.
c) STATCOMs included according to Table 4 and all remaining capacitors ON.

6.4.3 CASE II-9: DEVON - BESECK 40-MILE XLPE PHASE II, MINIMUM DISPATCH

An XLPE cable section for all 40 miles of the Devon-Beseck corridor is modeled. Three XLPE cables are used in parallel. Phase I is still modeled with one HPFF cable in service, and full load conditions are assumed. Results are calculated for the following conditions:

a) All capacitors ON with no mitigation.
b) C-Type 3rd harmonic filters according to Table 5 and Table 6. All remaining capacitors are ON.
c) STATCOMs included according to Table 4 with all remaining capacitors ON.

6.4.4 CASE II-10:- DEVON - BESECK 15-MILE XLPE PHASE II, MINIMUM DISPATCH

An XLPE cable section of 15 miles, on the Devon side of the Devon-Beseck corridor, is modeled. Three XLPE cables, similar to other sections, are used in parallel. The remainder of the 40-mile corridor uses overhead line. Phase I is modeled with one HPFF cable in service, and full load conditions are assumed. Results are calculated for the following conditions:

a) All capacitors in service with no mitigation.
b) C-Type 3rd harmonic filters according to Table 5 and Table 6 with all remaining capacitors in service.
c) STATCOMs included according to Table 4 with all remaining capacitors in service.

7 RESULTS OF HARMONIC IMPEDANCE STUDIES

The amplitude and phase angle of the impedance as well as the real and imaginary components of the impedance, over a frequency range of 0 to 1000 Hz, for all of the cases defined in Chapter 5 were plotted and are included in the Appendix.

7.1 Harmonic Performance Criteria

KEMA used a set of harmonic performance criteria to evaluate the maximum length of undergrounding of the Phase II as discussed in Section 4.

7.2 Description of Frequency Scan Figures

The harmonic scans plotted in Appendix show the harmonic impedance, Z(h), in ohms as a function of the frequency numbers between 1 and 15, with as fundamental frequency 60 Hz. In one plot different traces are presented, plotting the harmonic impedance for different variations of the specific case, described in Chapter 6. These were plotted for by substations and bus in the following order:

1. Norwalk 345 kV
2. Norwalk 115 kV
3. Plumtree 345 kV
4. Plumtree 115 kV
5. Southington 345 kV
6. Southington Ring–1 115 kV
7. Singer 345 kV
8. Beseck 345 kV
9. Devon 345 kV

For Phase I, no graphs were generated for Singer, Beseck and Devon, because these are substations proposed for Phase II.

In most of the graphs, the limiting conditions in terms of resonance frequency and system operation constraints are presented. The following variations were used in the harmonic scans for relevant cases:

1. Effect of 1 or 2 HPFF cables in Phase I.
2. Effect of underlying reactive and active load variations between 50, 70 and 100% of maximum load.
3. STATCOM as a mitigation option.
4. Passive filter mitigation using C-Type filter.

The data for these harmonic scan results were used to plot different cases against each other on the same axis and populate several tables, included in this chapter. For the plotted graphs comparing the different cases, study conditions were referred to the Norwalk 345 kV substation. All of the harmonic scan results are presented in the Appendix, but selected cases were presented in the figures included in the main section of the report.

7.3 Discussion of Results

7.3.1 DISCUSSION OF PHASE I RESULTS

For these results no Phase II changes or upgrades were used in the model. The load on all the underlying substations was changed between full-load and half-load conditions with all capacitor banks in service, and light generator dispatch according to Table 2.

7.3.1.1 Effects of Phase I HPFF Cable Allocation and Load Variation

The minimum dispatch generator scenario was not possible due to a lack of convergence in the load flow analysis. This may indicate that the minimum generator dispatch is not a realistic operating condition for Phase I alone. The key results are plotted in Table 7 and Figure 7.

Table 7: First Resonance Point Results for Phase I with All Capacitors ON

Phase I Results Light Dispatch, ALL CAPS ON (Case I-1)					
Substation & Bus Voltage		One HPFF Cable In Service		Both HPFF Cables In Service	
		100% Load	50% Load	100% Load	50% Load
Norwalk 345 kV	1st Resonance	3.6	3.1	3.3	2.9
	Impedance Ω	131	130	178	176
Norwalk 115 kV	1st Resonance	3.5	3.1	3.1	2.8
	Impedance Ω	8	10	8	10
Plumtree 345 kV	1st Resonance	3.6	3.1	3.3	2.9
	Impedance Ω	113	114	151	152
Plumtree 115 kV	1st Resonance	3.6	3.1	3.2	2.9
	Impedance Ω	18	20	18	21
Southington 345 kV	1st Resonance	3.4	3	3	2.8
	Impedance Ω	37	45	32	40
Southington Ring 1 115 kV	1st Resonance	3.1	3	2.8	2.8
	Impedance Ω	7	9	8	8

In Figure 7 the harmonic impedance is plotted for the different Phase I configurations (1 and 2 HPFF cables) with the load varied between 50% and 100% for the case with all the capacitors on and light generator dispatch.

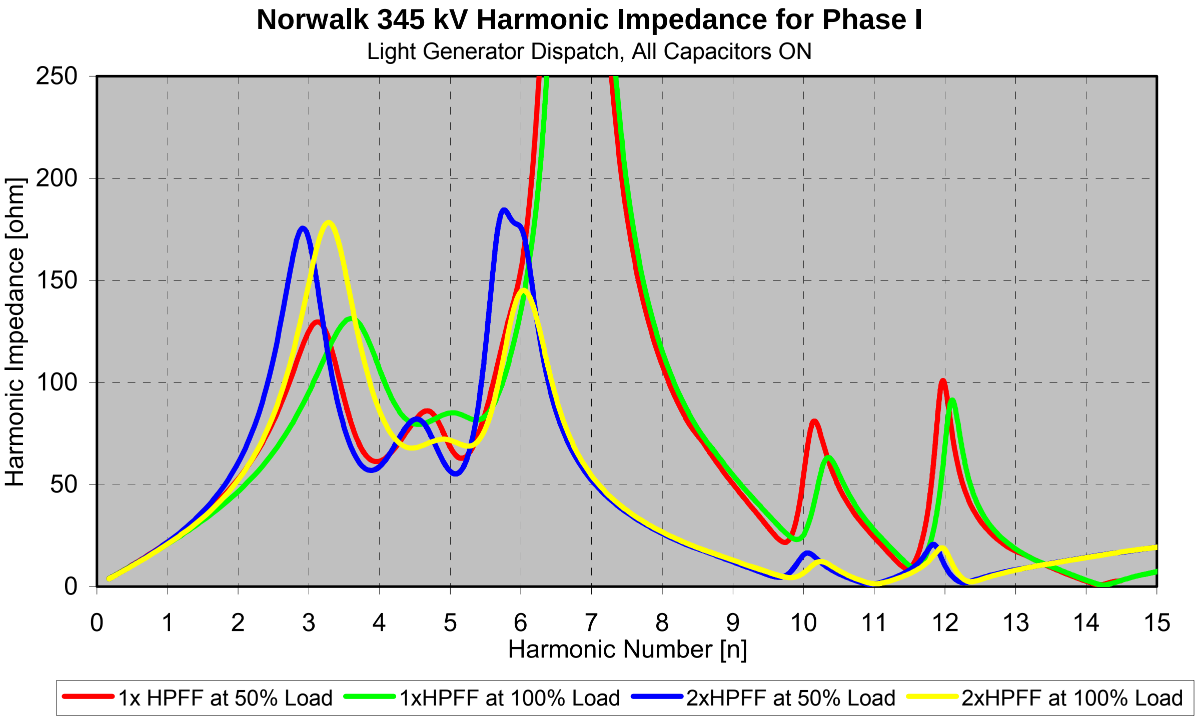


Figure 7: Harmonic Analysis of Phase I Options

It is clear that at light system loading and 2x HPFF cables in service, the first resonance goes below 3.0. Furthermore the resonance is not damped that well. The high 7th harmonic is also clearly visible in the case where only 1 HPFF cable is in service. One HPFF cable in service will result in high levels of 7th harmonic distortion and is not an advisable operating condition.

7.3.1.2 Key Conclusions from Phase I Results

1. Lower resonance point varies in the 2.8 – 3.6 range, with damping on the 345 kV network of better than 180 Ω. Worst condition is with both HPFF cables in service at low load levels, see Table 7. All capacitors on at light load is not a advisable operating condition due to the first resonance point going below 3.0 with little damping. The Southington Ring 1 115 kV substation shows first resonance peaks at 2.8, even at full load. These peaks at Southington are however well damped and should not be a large concern for Phase I as proposed.
2. Mid resonance point varies in the 7th harmonic range, with little damping on the 345 kV network at 1200 Ω. Worst condition is with one HPFF cable in service at light load levels. This condition is a concern for 7th harmonic injection around Norwalk and Plumtree.

3. High resonance point varies in the 10 – 12 range, with damping in the 100 - 250 Ω range. No serious harmonic problems are expected in this range.

7.3.2 DISCUSSION OF PHASE II BASE CASE RESULTS

Harmonic analyses were performed for the Phase II base case alternatives. Results obtained from the Applicant for the Base Case ("Study Case 5") are similar, showing resonance points in the same frequency ranges for the specific substations. In the results presented here the damping is in general better than that indicated in the Applicant's results. A possible explanation is that KEMA modeled the load levels explicitly in its model.

7.3.2.1 Effects of Generator Dispatch and Load Variation

The load on all of the underlying substations was changed between 100% load, 70% load and 50% load conditions with all the capacitor banks in service and light and minimum generator dispatch according to Table 2.

Table 8: First Resonant Point Results for Phase II Base Case Results

Phase II Base Case Results (Cases II-1 and II-2) ALL CAPS ON and 1 HPFF Cable for Phase I						
Substation & Bus Voltage		Light Dispatch (II-2)		Minimum Dispatch (II-1)		
		100% Load	50% Load	100% Load	70% Load	50% Load
Norwalk 345 kV	1st Resonance	3.2	2.9	3.1	2.8	2.6
	Impedance Ω	83	98	71	71	80
Norwalk 115 kV	1st Resonance	3.1	2.8	3	2.7	2.6
	Impedance Ω	7	9	6	7	8
Plumtree 345 kV	1st Resonance	3.2	2.9	3.1	2.8	2.6
	Impedance Ω	73	89	62	63	72
Plumtree 115 kV	1st Resonance	3.1	2.8	3	2.7	2.6
	Impedance Ω	12	15	10	11	12
Southington 345 kV	1st Resonance	3.1	2.8	2.9	2.7	2.6
	Impedance Ω	35	46	31	34	39
Southington Ring 1 115 kV	1st Resonance	3.0	2.8	2.9	2.6	2.5
	Impedance Ω	7	8	6	6	7
Singer 345 kV	1st Resonance	3.2	2.9	3.1	2.8	2.6
	Impedance Ω	81	96	70	70	79
Devon 345 kV	1st Resonance	3.2	2.9	3.1	2.8	2.7
	Impedance Ω	78	92	68	67	76
Beseck 345 kV	1st Resonance	3.1	2.8	3	2.7	2.6
	Impedance Ω	35	44	31	33	37

From this table several substations under light and minimum dispatch scenarios have first resonance points below 3.0. In most cases the first resonance is well damped and minimum dispatch provides better damping conditions compared to light dispatch. The minimum dispatch generator scenario was not possible to run when most of the capacitors were turned off due to convergence problems in the load flow. This may indicate that it is not an acceptable operating condition to turn most of the capacitors off with minimum generator dispatch.

The harmonic impedance of the different loading conditions for 50 – 70 – 100% Load is also plotted for minimum dispatch at Norwalk 345 kV in Figure 8.

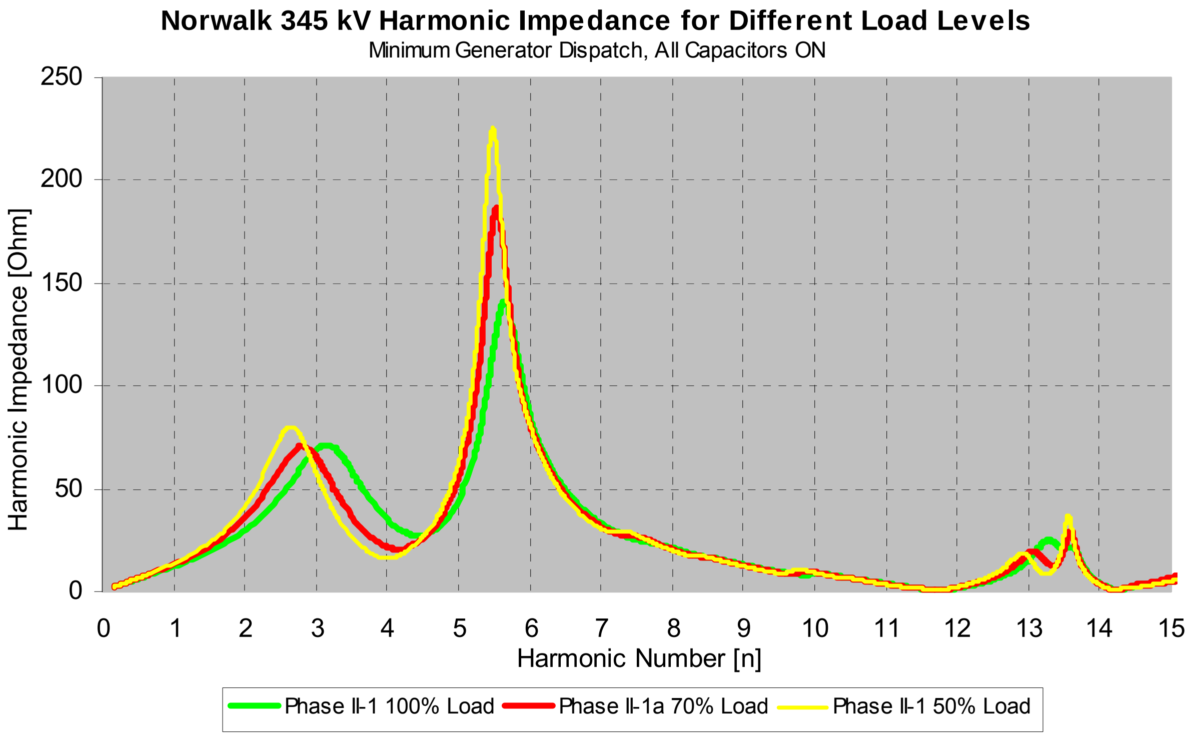


Figure 8: Effect of Load Variation on Harmonic Impedance of Phase II Base Case (II-1)

The effect of load variation is clear from this figure. The maximum load provides the best damping at the higher resonance peaks (5th), while the first resonance peak is also damped with increased load. The first resonance peak around the 3rd harmonic shifts down from 3.1 to 2.6 at light load conditions, with all capacitors in service at minimum generator dispatch. It is also clear from these results to see that the Base Case of Phase II is only marginally acceptable at high system loading.

7.3.2.2 Effects of Capacitor Allocation

A comparison of results with of all capacitors on and most capacitors off is plotted in Figure 9. The comparison was not possible for minimum generator dispatch, because the load flow case did not converge.

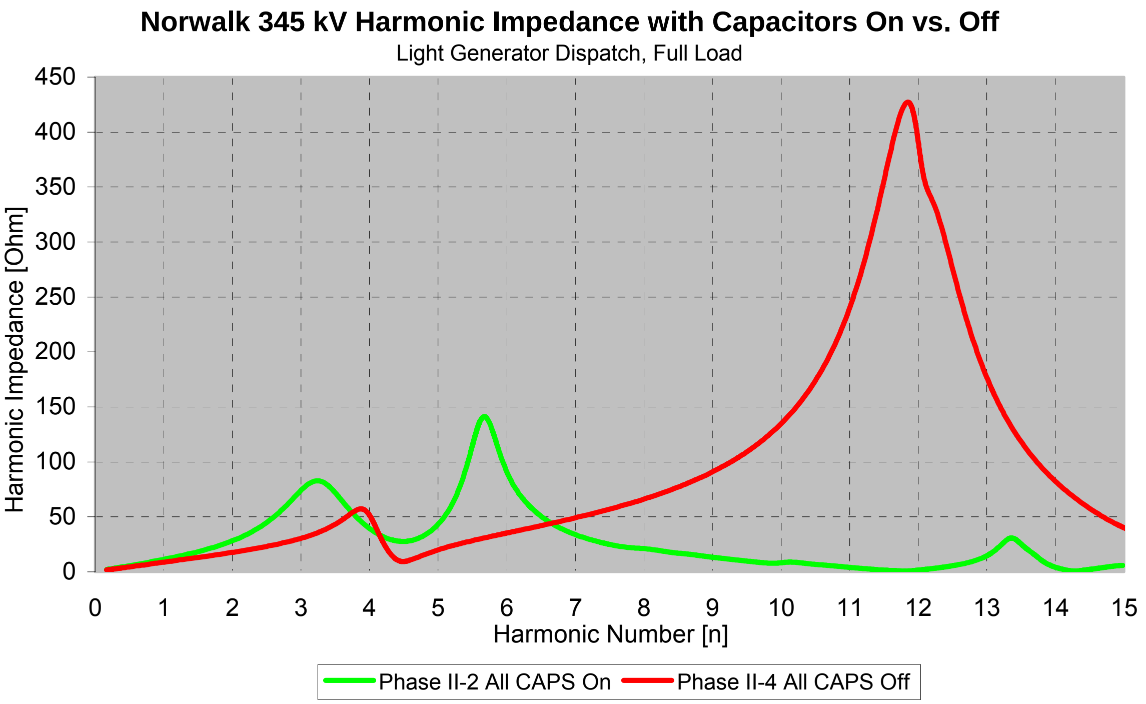


Figure 9: Effect of Capacitor Allocation on Harmonic Impedance of Phase II Base Case

The first resonance peak shifts to around 4 and is well damped with all capacitors off. However a large resonance peak is visible at around the 12th harmonic. It is noted that the capacitor allocations change system resonance over a wide range.

7.3.2.3 Comparison of Harmonic Impedance for Phase II with Phase I

Harmonic impedance and first resonant point results are compared for Phase I and II in Figure 10 and Table 9, for the same capacitor allocation and *light* generator dispatch configuration. Here the results are compared with Phase I alone with 2 HPFF cables in service. For reference purposes the characteristic system impedance Z_0, is also plotted for both Phase I and Phase II.

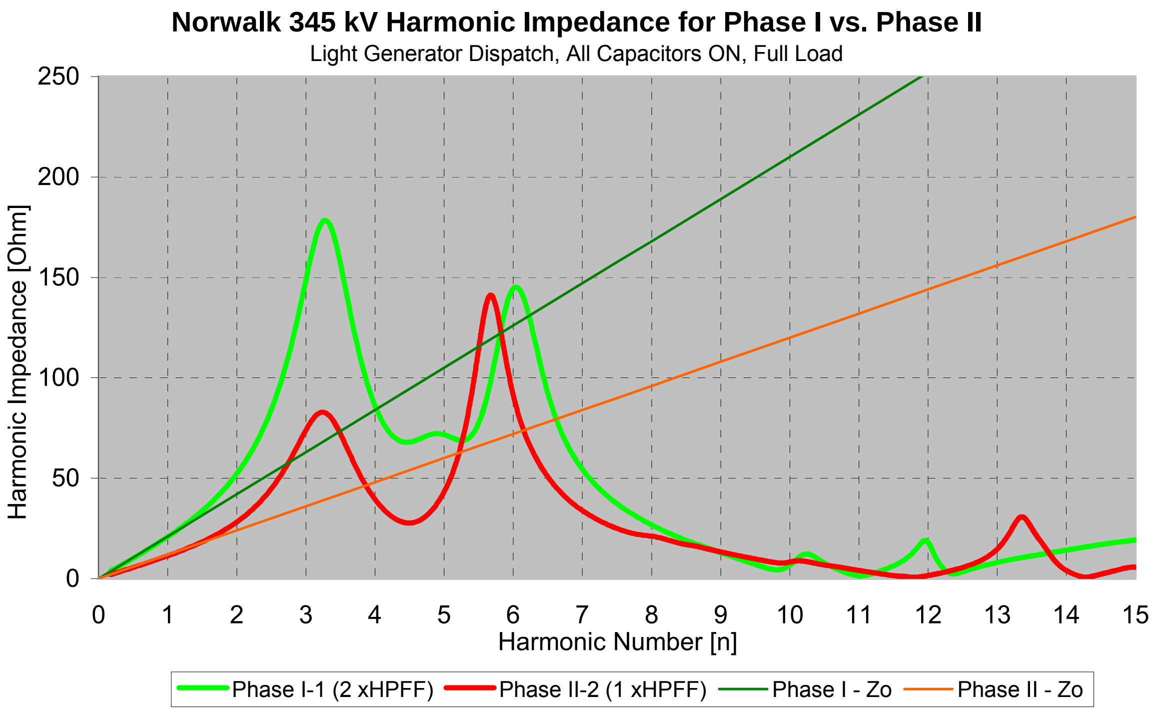


Figure 10: Comparison of Harmonic Impedance between Phase I and Phase II

Table 9: Results Comparison between Phase I and II Cases

<table>
<tr><th colspan="6">Comparison of Phase II and Phase I Results
Light Dispatch, ALL CAPS ON</th></tr>
<tr><th colspan="2" rowspan="2">Substation & Bus Voltage</th><th colspan="2">Phase I (2-HPFF cables in service)</th><th colspan="2">Phase II Base Case (1-HPFF cables in service)</th></tr>
<tr><th>100% Load</th><th>50% Load</th><th>100% Load</th><th>50% Load</th></tr>
<tr><td rowspan="2">Norwalk 345 kV</td><td>1st Resonance</td><td>3.3</td><td>2.9</td><td>3.2</td><td>2.9</td></tr>
<tr><td>Impedance Ω</td><td>178</td><td>176</td><td>83</td><td>98</td></tr>
<tr><td rowspan="2">Norwalk 115 kV</td><td>1st Resonance</td><td>3.1</td><td>2.8</td><td>3.1</td><td>2.8</td></tr>
<tr><td>Impedance Ω</td><td>8</td><td>10</td><td>7</td><td>9</td></tr>
<tr><td rowspan="2">Plumtree 345 kV</td><td>1st Resonance</td><td>3.3</td><td>2.9</td><td>3.2</td><td>2.9</td></tr>
<tr><td>Impedance Ω</td><td>151</td><td>152</td><td>73</td><td>89</td></tr>
<tr><td rowspan="2">Plumtree 115 kV</td><td>1st Resonance</td><td>3.2</td><td>2.9</td><td>3.1</td><td>2.8</td></tr>
<tr><td>Impedance Ω</td><td>18</td><td>21</td><td>12</td><td>15</td></tr>
<tr><td rowspan="2">Southington 345 kV</td><td>1st Resonance</td><td>3</td><td>2.8</td><td>3.1</td><td>2.8</td></tr>
<tr><td>Impedance Ω</td><td>32</td><td>40</td><td>35</td><td>46</td></tr>
<tr><td rowspan="2">Southington Ring 1 115 kV</td><td>1st Resonance</td><td>2.8</td><td>2.8</td><td>3.0</td><td>2.8</td></tr>
<tr><td>Impedance Ω</td><td>8</td><td>8</td><td>7</td><td>8</td></tr>
</table>

From these results it is clear that Phase II improves the harmonic performance in a very positive way for light generator dispatch. All of first resonance points for Phase II are better damped compared to Phase I alone, and the resonance frequency stays about at the same levels for both full and 50% loading. This implies that completing Phase II is very important both from system strength and harmonic performance perspectives. Having a Phase II first resonance point lower than 3.0 is, however, still a matter of concern, especially at lower load conditions with all capacitors in service. However it is noted that for *light* generator dispatch and high system loading, the first resonance point stays marginally above 3.0.

7.3.2.4 Resonance Peaks at Different Harmonic Ranges

Harmonic resonance point and impedance results are categorized in three ranges for the Base Case II-1. The results in low, mid and high frequency ranges, are plotted in Table 10.

Table 10: Frequency Category Results for Base Case (II-1)

Phase II Base Case Results (Case II-1) ALL CAPS ON; 1 HPFF Phase I; Minimum Dispatch Resonance Frequency & Impedance							
Substation & Bus Voltage		$1 < n < 4$		$4 \le n < 10$		$10 \le n < 17$	
		100%	**70%**	**100%**	**70%**	**100%**	**70%**
Norwalk 345 kV	1st Resonance	3.1	2.8	5.6	5.5	13.3	13/13.6
	Impedance Ω	71	71	141	186	25	19/30
Norwalk 115 kV	1st Resonance	3	2.7	4.8	4.6	11.5	11.4
	Impedance Ω	6	7	5	6	11	11
Plumtree 345 kV	1st Resonance	3.1	2.8	5.6	5.5/9.7	13.6	11.5/13.6
	Impedance Ω	62	63	49	63.2/74.3	861	272.5/1291.9
Plumtree 115 kV	1st Resonance	3	2.7	5.7	5.6/10	11.6	11.5
	Impedance Ω	10	11	22	18.8/53	108	119
Southington 345 kV	1st Resonance	2.9	2.7	5.2/8.5	5.1/8.4	13.2	13.0
	Impedance Ω	31	34	38/94	38.4/109.4	164	202
Southington Ring 1 115 kV	1st Resonance	2.9	2.6	9.7	9.6	10.7	10.5
	Impedance Ω	6	6	102	124	32	37
Singer 345 kV	1st Resonance	3.1	2.8	5.6	5.5	11.6/13.6	11.5/13.6
	Impedance Ω	70	70	156	206	70/278	72/407
Devon 345 kV	1st Resonance	3.1	2.8	5.6	5.5	11.6/13.6	11.5/13.6
	Impedance Ω	68	67	143	190	89/351	91/520
Beseck 345 kV	1st Resonance	3	2.7	8.4	8.3	13.2	13
	Impedance Ω	31	33	70	78	407	492

7.3.2.5 Harmonic Impedance at Key Harmonics

The different harmonic impedance values at specific key harmonics are plotted for the Base Case (II-1) in Table 11.

Table 11: Phase II Impedance at Key and Characteristic Harmonics

Phase II Base Case Results (Case II-1)
ALL CAPS ON; 1 HPFF Phase I; Minimum Dispatch, 70% Load
Harmonic Impedance at Characteristic Harmonics

Substation & Bus Voltage		**2nd**	**3rd**	**5th**	**7th**	**11th**	**13th**
Norwalk 345 kV	Impedance Ω	36.8	65.6	55.8	31.6	3.6	18.6
Norwalk 115 kV	Impedance Ω	4.8	5.4	3.4	5.2	10.7	13.3
Plumtree 345 kV	Impedance Ω	35.9	56.8	37.5	15.6	114.5	249.2
Plumtree 115 kV	Impedance Ω	7.0	9.3	17.3	2.4	21.3	9.9
Southington 345 kV	Impedance Ω	23.5	26.1	38	27.3	39.5	200.5
Southington Ring 1 115 kV	Impedance Ω	4.7	5.3	18	5.9	24.3	11.2
Singer 345 kV	Impedance Ω	36.6	64.5	60.5	33.6	13.7	51.9
Devon 345 kV	Impedance Ω	36.3	61.7	58	25.2	29.9	92.7
Beseck 345 kV	Impedance Ω	23.1	25.5	29.1	37.6	91.5	480.7

7.3.2.6 Key Conclusions from Phase II Base Case Results

1. First resonance points vary in the 2.6 – 3.5 range, with damping on the 345 kV network of better than 106 Ω. The damping is much better compared to Phase I alone. The system strengthening provided by Phase II is very beneficial. The worst condition is with both HPFF cables in service at low load levels and minimum generator dispatch. With 1 HPFF cable in service for Phase I, the first resonance frequency was contained around or above 3rd harmonic at good levels of damping of around 70 – 90 Ω.
2. In most of the cases mitigation would be required to get the resonance frequency above the 3rd harmonic for a wide load variation and during system contingencies.
3. The mid resonance point varies in the 5th harmonic range at most of the 345 kV substations with damping in the 250 Ω range, again much more damped than the 7th harmonic in Phase I. The worst condition occurs with one HPFF cable in service at low load levels. This condition is a concern for 5th harmonic injection around Norwalk, Singer and Devon.

4. High resonance points vary in the 11 – 13 range, with little damping at the 13th around the 1300 Ω range. Some attention to possible 13th harmonic injection, especially at Plumtree 345 kV and 115 kV buses may be required.
5. Harmonic mitigation would be required for the 5th, 11th and 13th harmonic injections for several substations.

7.3.3 DISCUSSION OF PHASE II MITIGATION OPTIONS

Harmonic analyses were performed for the Phase II alternatives with two mitigation options included. The STATCOM cases are similar to the Applicant and New England ISO study cases. STATCOMs were added at the same locations as proposed by the Applicant, see Table 4. The other mitigation option considered was replacing some of the capacitor banks with a C-Type filters configuration tuned to the 3rd harmonic, as described in Section 5.2.

The load on all the underlying substations was varied between 50% and 100% load conditions with all the capacitor banks in service and minimum generator dispatch according to Table 2. Results for one and two HPFF cables for Phase I were also considered.

The harmonic impedance is plotted for the Base Case (II-1), for STATCOM mitigation (II-5) and for C-Type filter mitigation (II-6) in Figure 11. The shunt cable compensating reactors were removed for the STATCOM case.

The effects of the two mitigation options are clearly shown. For both the STATCOM and C-Type filter options the first significant resonance peak is shifted from 3.1 to 3.9 for the C-Type Filter and 3.1 to 3.6 for the STATCOM option. The resonant peak between 5 and 6 is also fully mitigated with both options. Excellent high frequency harmonic performance characteristics are achieved.

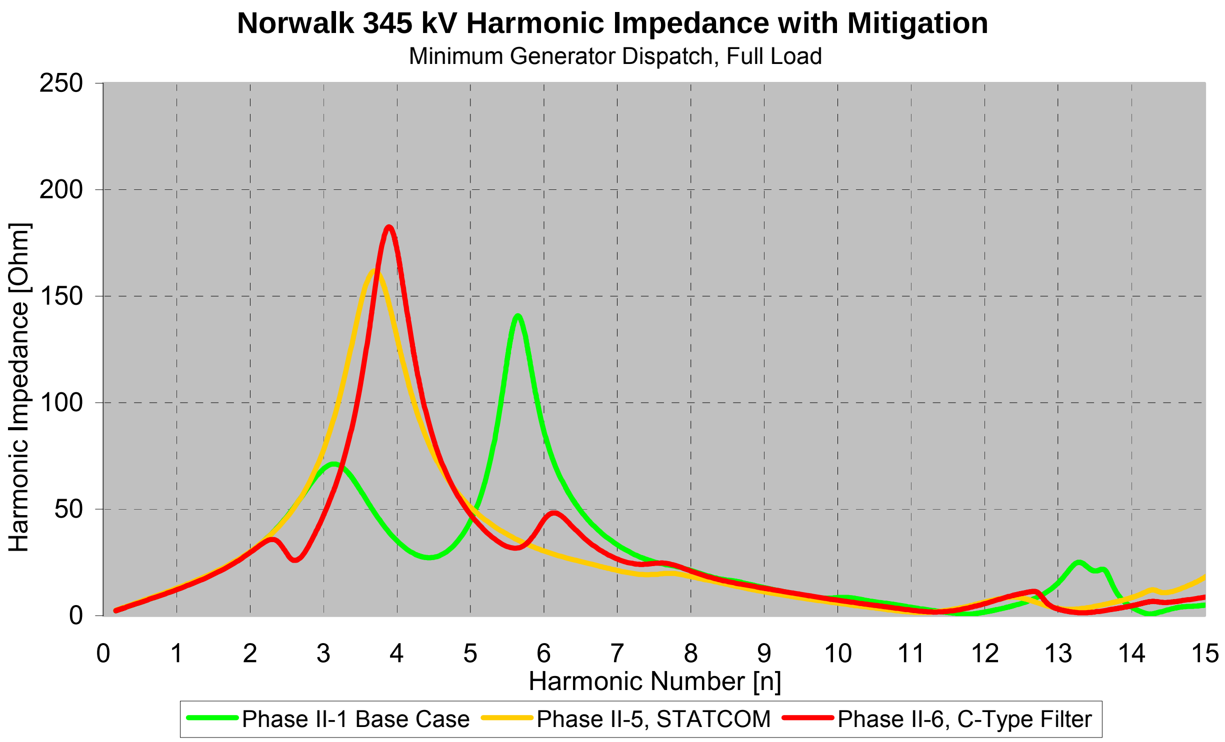


Figure 11: Impact of STATCOM and C-Type Filter Mitigation Options

In the C-Type filter option graph (red), the effect of the harmonic filtering at about 2.6 harmonic is also clearly visible at the Norwalk 345 kV substation. This low impedance provides harmonic filtering and damping characteristics between the 2nd and 3rd harmonic. The harmonic impedance of the C-Type filter is always lower at the key system harmonics between of 3rd, 5th , 7th , 11th and 13th. This option provides excellent mitigation for the key system harmonics. The first resonance peak is shifted towards the 4th harmonic where a low system impact can be expected. As indicated earlier, the C-Type filter design has not been optimized for each individual substation, but the mitigation effect is very good, even with a first pass filter design at the 3rd harmonic.

The STATCOM mitigation option graph (orange) also moves the resonance peak to higher than 3.0, but does not provide any harmonic filtering in the 2nd – 3rd harmonic range. In the modeling of the STATCOM no active filtering was incorporated. The shunt cable compensating reactors were removed for this STATCOM case. If the STATCOMs are designed to provide some damping at these harmonics, better results are to be expected. The increased transient and voltage stability margins associated with a STATCOM design also have not been modeled in this simple STATCOM model.

The effect of the mitigation options were also evaluated at lower loading levels where less damping and a shift of the first resonance point to lower values can be expected. In this case the effect of the shunt charging reactors for the STATCOM option was also evaluated.

The harmonic impedance is plotted for the Base Case (II-1), for STATCOM mitigation without shunt 345 kV compensating reactors (II-5), for STATCOM mitigation with shunt 345 kV compensating reactors (II-5b), and for C-Type filter mitigation (II-6) in Figure 12, all at 50% load with minimum generator dispatch and all remaining capacitors on. This plot is plotted between 0 and the 8th harmonic to show the mitigation results more clearly at the lower frequencies.

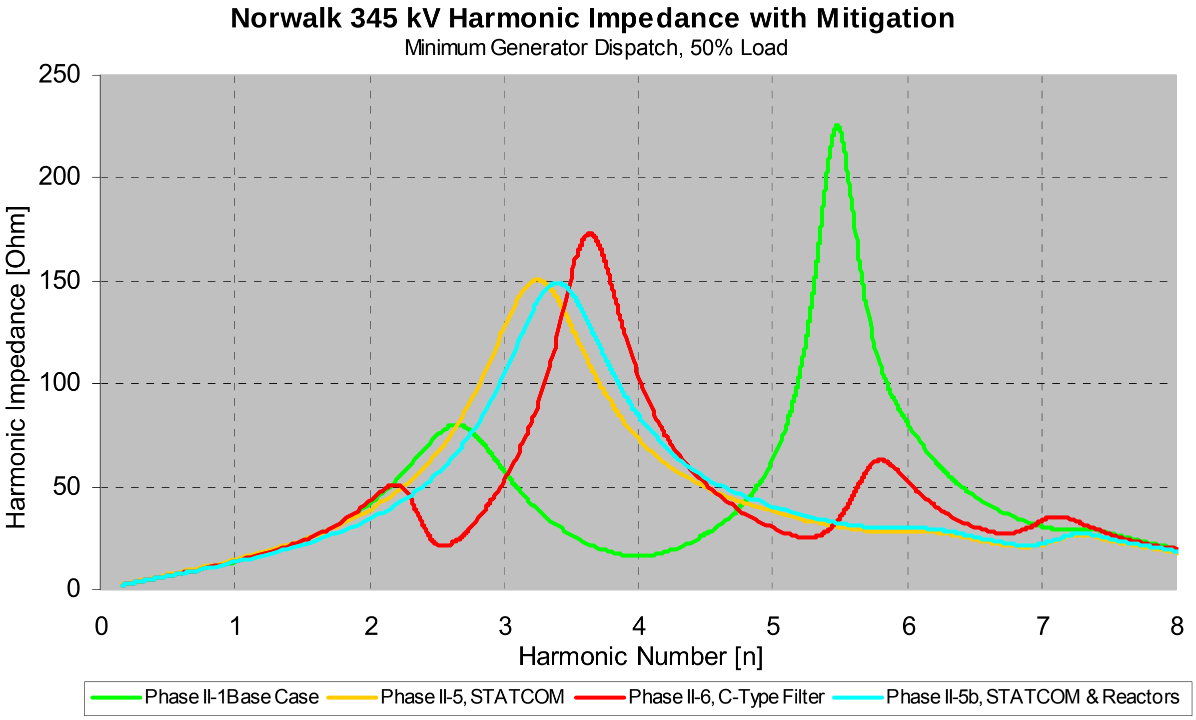


Figure 12: Impact of STATCOM and C-Type Filter Mitigation Options at 50 % Load Levels

The 345 kV shunt-compensating reactors in the STATCOM option (II-5b) improve the first resonance point from 3.3 to 3.4 with the same damping in the STATCOM option (II-5) (From the original 2.7 in the Base Case (II-1)). In the C-Type filter option graph (red), the effect of the harmonic filtering at about 2.5 harmonic is also clearly visible at the Norwalk 345 kV substation. This low impedance provides harmonic filtering and damping characteristics between the 2nd and 3rd harmonic. At the key lower order harmonics (2, 3, 5) the C-Type filter design provides the lowest impedance except for the 2nd. For the second harmonic mitigation the STATCOM option, with shunt reactors in service (II-5b), provides, the best performance.

An optimal mitigation design, also taking advantage of the active filtering capability and increased voltage and transient stability margins, will result in a good balance between the C-Type filter design and one or two STATCOMs, strategically placed on this system. The Glenbrook STATCOM, already on the system, also may play an important role.

The first significant resonance results of the mitigation solutions are summarized in the table below. At all the sub-stations first resonance points higher than the 3rd harmonic were achieved. Damping at the higher resonance points is significantly improved over the base case.

Table 12: Results of Phase II Mitigation Cases

Summary Results of Mitigation Cases at Full Load				
Substation & Bus Voltage		Base Case (Case II-1)	STATCOMs (Case II-5)	C-Filter – 3rd (Case II-6)
Norwalk 345 kV	1st Resonance	3.1	3.7	3.9
	Impedance Ω	71	162	183
Norwalk 115 kV	1st Resonance	3	3.5	3.8
	Impedance Ω	6	9	8
Plumtree 345 kV	1st Resonance	3.1	3.6	3.9
	Impedance Ω	62	116	138
Plumtree 115 kV	1st Resonance	3	3.5	3.8
	Impedance Ω	10	11	16
Southington 345 kV	1st Resonance	2.9	3.4	3.7
	Impedance Ω	31	36	29
Southington Ring 1 115 kV	1st Resonance	2.9	3.4	2.3
	Impedance Ω	6	6	6
Singer 345 kV	1st Resonance	3.1	3.7	3.9
	Impedance Ω	70	163	181
Devon 345 kV	1st Resonance	3.1	3.7	3.9
	Impedance Ω	68	153	170
Beseck 345 kV	1st Resonance	3	3.5	3.8
	Impedance Ω	31	43	40

The harmonic impedance resonance results are categorized in three ranges for the Base Case II-1 and the C-Type Filter mitigation case, II-6. The results are plotted in Table 13. Especially the mitigation results around the 5th harmonic are clearly visible in terms of the frequency and damping.

Table 13: Frequency Category Results for C-Type Filter Mitigation Option

Phase II Base Case (Case II-1) and C-Type Mitigation (Case II-6) ALL CAPS ON; 1 HPFF Phase I; Minimum Dispatch; Full Load Resonance Frequency & Impedance							
Substation & Bus Voltage		**1 < n < 4**		**4 ≤ n < 10**		**10 ≤ n < 17**	
		Filter II-6	**Base II-1**	**Filter II-6**	**Base II-1**	**Filter II-6**	**Base II-1**
Norwalk 345 kV	1st Resonance	3.9	3.1	6.1	5.6	12.7	13.3
	Impedance Ω	183	71	48	141	11	25
Norwalk 115 kV	1st Resonance	3.8	3	8.4	4.8	N/A	11.5
	Impedance Ω	8	6	11	5	N/A	11
Plumtree 345 kV	1st Resonance	3.9	3.1	N/A	5.6	12.7	13.6
	Impedance Ω	138	62		49	1527	861
Plumtree 115 kV	1st Resonance	3.8	3	6	5.7	12.7	11.6
	Impedance Ω	16	10	24	22	48	108
Southington 345 kV	1st Resonance	3.7	2.9	7.3	5.2/8.5	12.3	13.2
	Impedance Ω	29	31	50	38/94	294	164
Southington Ring 1 115 kV	1st Resonance	2.3	2.9	7.2	9.7	12	10.7
	Impedance Ω	6	6	10	102	17	32
Singer 345 kV	1st Resonance	3.9	3.1	6.1	5.6	12.7	11.6/13.6
	Impedance Ω	181	70	56	156	430	70/278
Devon 345 kV	1st Resonance	3.9	3.1	6.1	5.6	12.7	11.6/13.6
	Impedance Ω	170	68	50	143	537	89/351
Beseck 345 kV	1st Resonance	3.8	3	7.4	8.4	12.4	13.2
	Impedance Ω	40	31	51	70	416	407

7.3.3.1 Key Conclusions from Mitigation Results

STATCOM mitigation:-

1. Lower resonance points vary in the 3.2 to 3.6 range, with damping on the 345 kV network of better than 175 Ω. The resonance frequency is higher than 3.2, even with both HPFF Phase I, cables in service. Replacing most of the large capacitor banks with STATCOMs helped significantly. The worst condition occurs with both HPFF cables in service at low load levels and minimum generator dispatch. With 1 HPFF cable in

service for Phase I, the resonance frequency remained above 3.5 at good levels of damping of around 100 Ω.

2. The mid resonance point does not exist, providing excellent mitigation for the 5th harmonic problem in Phase II.
3. The high resonance point varies in the 11 – 13 range, with little damping at the 12th around 1100 Ω range on the 345 kV network. Some attention to possible 11th harmonic injection at Plumtree 345 kV and 115 kV may be required.

3rd Harmonic C-Type Filter Mitigation:-

4. Lower resonance points vary in the 3.4 to 3.9 range, with damping on the 345 kV network of better than 180 Ω. The resonance frequency is higher than 3.4, even with both HPFF Phase I, cables in service. Replacing most of the large capacitor banks with harmonic neutral C-Type filters helps significantly. Also with the filters in and out of service, no large changes in the resonance frequency should be expected. With the C-Type filters in service much better damping performance is obtained. The worst condition is with both HPFF cables in service at low load levels and minimum generator dispatch. With 1 HPFF cable in service for Phase I, the resonance frequency was contained above 3.7 at good levels of damping at around 175 Ω. The low resonance point around Southington is not of a concern due to the high damping.
5. The mid resonance point around the 5th harmonic is also greatly reduced, providing good mitigation for the 5th harmonic problem in Phase II.
6. The high resonance point varies in the 11 – 13 range, with little damping at the 12th around 1100 Ω range on the 345 kV network. Some attention to possible 11th harmonic injection at Plumtree 345 kV and 115 kV may be required.
7. An optimal mitigation design, also taking the active filtering capability and increased voltage and transient stability margins into account, will result in a good balance between the C-Type filter design and one or two STATCOMs, strategically placed on this system. The Glenbrook STATCOM, already on the system, may play an important role.

7.3.4 DISCUSSION OF RESULTS FOR ADDITIONAL UNDERGROUNDING

Harmonic analyses were performed for Phase II alternatives with extended undergrounding. The corridor between Devon and Beseck was sectionalized and undergrounded in 10-mile sections. Harmonic results also were derived for these Phase II extension alternatives with two mitigation options. STATCOMs were added at the same locations as proposed by the Applicant, see Table 3. The other mitigation option considered was replacing some of the capacitor banks with a C-Type filters configuration tuned to the 3rd harmonic, as described in Section 5.2. The load on the underlying substations was varied between 70% and 100%.

7.3.4.1 Case II-7: Devon - Beseck 10-mile XLPE Phase II, Minimum Dispatch

An XLPE cable section of 10 miles, on the Devon side of the Devon-Beseck (D-B) corridor was modeled. Three XLPE cables, similar to those used in Phase I, are used in parallel. The shunt reactors on both sides of the XLPE cable section are included at the 10-mile terminations. The rest of the 40-mile corridor used overhead line. Phase I is still based on only one HPFF cable and the system is loaded between 70 to 100%. Minimum generator dispatch with all capacitors in service, the STATCOM option and C-Type filter option as mitigation solutions were compared for this alternative. For the STATCOM mitigation option the 345 kV shunt compensating reactors were taken out of service.

7.3.4.1.1 First Resonance Point for 10 Mile Underground Results

Table 14 tabulates the first resonance results for the 10 miles underground section between Devon and Beseck, including the effect of the different mitigation solutions.

Table 14: Results of First Resonance for Additional 10 Miles of Undergrounding

Additional 10 Miles of Underground Full Load, Minimum Dispatch (Case II-7)				
Substation & Bus Voltage		No Mitigation All Caps ON	STATCOM Option	3rd C-Type Filter Option
Norwalk 345 kV	1st Resonance	2.9	3.2	3.5
	Impedance Ω	75	138	177
Norwalk 115 kV	1st Resonance	2.7	3	3.4
	Impedance Ω	6	7	7
Plumtree 345 kV	1st Resonance	2.9	3.1	3.5
	Impedance Ω	61	95	122
Plumtree 115 kV	1st Resonance	2.8	3	3.4
	Impedance Ω	9	9	13
Southington 345 kV	1st Resonance	2.7	3	2.3
	Impedance Ω	29	32	25
Southington Ring 1 115 kV	1st Resonance	2.6	2.9	2.3
	Impedance Ω	6	5	5
Singer 345 kV	1st Resonance	2.9	3.2	3.5
	Impedance Ω	77	147	188
Devon 345 kV	1st Resonance	3.0	3.2	3.5
	Impedance Ω	76	145	186
Beseck 345 kV	1st Resonance	2.7	3	3.4
	Impedance Ω	30	39	37

For this extended undergrounding without mitigation the first resonance point goes below 3.0 for most sub-stations, even under full load conditions. It is also important to observe that the resonance points are well damped, even better than the Phase II Base Case at all of the key harmonics. With this level of damping on the system, limited harmonic problems are expected in any case, even resonance points lower than 3.0. Extended undergrounding provides a very strong backbone system.

With added mitigation options in terms of STATCOMs or the C-Type filter configuration, the first resonance point again moves above 3.0, except for the Southington substation, where the 2.3 – 2.9 resonance point is very well damped (at or below the characteristic impedance) and is not considered to be a deciding factor. Damping is a bit worse compared to the situation without mitigation, but still very good compared to the Phase II overhead options.

7.3.4.1.2 Key Conclusions for 10 Mile Underground Results

All Caps On with No Mitigation:-

1. Lower resonance point varies in the 2.6 to 3.0 range, but is well damped on the 345 kV and 115 kV network at better than 75 Ω. Damping is much better compared to Phase I.
2. The mid resonance point around the 5th harmonic is also reduced and provides good mitigation for the 5th harmonic problem.
3. The high resonance point varies in the 11 – 13 range, with reasonable damping around the 500 Ω range on the 345 kV network at Plumtree. Some attention to possible 11th and 13th harmonic injections at Plumtree 345 kV and 115 kV buses may be required.

STATCOM mitigation:-

4. Lower resonance point varies in the 3.0 to 3.3 range (excluding Southington), with damping on the 345 kV network of better than 150 Ω.
5. The mid resonance point does not exist, providing excellent mitigation for the 5th harmonic problem in Phase II.
6. The high resonance point varies in the 11 – 13 range, with little damping at the 11th around 1100 Ω range on the 345 kV network. Some attention to possible 11th harmonic injection at Plumtree 345 kV and 115 kV buses may be required.

3rd Harmonic C-Type Filter Mitigation:-

7. Lower resonance point varies in the 3.4 to 3.7 range (excluding Southington), with damping on the 345 kV network of better than 180 Ω. Also with the filters in and out of service, no large changes in the resonance frequency should be expected. With the C-Type filters in service much better damping performance will be obtained.
8. The mid resonance point around the 5th harmonic is much reduced, providing good mitigation for the 5th harmonic.

9. The high resonance point varies in the 10 – 12 range, with less damping at the 11th around 1100 Ω on the 345 kV network. Some attention to possible 11th harmonic mitigation at Plumtree 345 kV and 115 kV buses should be considered.

7.3.4.2 Case II-8:- Devon - Beseck 20-mile XLPE Phase II, Minimum Dispatch

An XLPE cable section of 20 miles, on the Devon side of the Devon-Beseck (D-B) corridor, is included. Three XLPE cables, similar to the XLPE cables in Phase I, were used in parallel. The shunt reactors on both sides of the XLPE cable sections were included at 10-mile intervals. The remainder of the 40-mile corridor used overhead line. System loading varied between 70 and 100%.

7.3.4.2.1.1 First Resonance Point for 20 Mile Underground Results

Table 15 tabulates the first resonance results for the 20 miles underground section between Devon and Beseck, including the effects of the different mitigation schemes.

Table 15: Results of First Resonance for Additional 20 Miles of Undergrounding

Additional 20 Miles of Underground Full Load, Minimum Dispatch (Case II-8)				
Substation & Bus Voltage		No Mitigation All Caps ON	STATCOM Option	3rd C-Type Filter Option
Norwalk 345 kV	1st Resonance	2.8	2.9	3.3
	Impedance Ω	71	115	155
Norwalk 115 kV	1st Resonance	2.6	2.7	3.2
	Impedance Ω	5	7	6
Plumtree 345 kV	1st Resonance	2.7	2.9	3.3
	Impedance Ω	56	79	103
Plumtree 115 kV	1st Resonance	2.6	2.7	3.2
	Impedance Ω	8	8	11
Southington 345 kV	1st Resonance	2.6	2.7	2.2
	Impedance Ω	29	32	25
Southington Ring 1 115 kV	1st Resonance	2.6	2.6	2.3
	Impedance Ω	5	5	5
Singer 345 kV	1st Resonance	2.8	2.9	3.3
	Impedance Ω	74	124	169
Devon 345 kV	1st Resonance	2.8	2.9	3.3
	Impedance Ω	75	126	171
Beseck 345 kV	1st Resonance	2.6	2.8	3.2
	Impedance Ω	32	41	40

For this extended underground section the first resonance point goes below 3.0 for most substations, even under full load conditions. It is also important to observe that the resonance points are well damped, even better than the Phase II Base Case and with 10 miles underground. With this level of damping on the system, limited harmonic problems are expected even at resonance points lower than 3.0. The extended undergrounding provides a very strong backbone system.

With added mitigation options namely STATCOMs or the C-Type filter configuration, the first resonance point is again far above 3.0, except at Southington. Damping is a bit better than with 10 miles underground. This is especially true for the C-Type filter mitigation scheme.

7.3.4.2.1.2 Key Conclusions for 20 Mile Underground Results

All Caps On with No Mitigation:-

1. Lower resonance point varies in the 2.6 to 2.8 range, but damping on the 345 kV and 115 kV network of better than 71 Ω.
2. The mid resonance point around the 5th harmonic is also much reduced, providing good mitigation for the 5th harmonic.
3. The high resonance point varies in the 10 – 12 range, with reasonable damping around the 400 Ω range on the 345 kV network at Plumtree. Some attention to possible 11th and 13th harmonic injection at Plumtree 345 kV and 115 kV may be required.

STATCOM mitigation:-

4. The lower resonance point varies in the 2.7 to 2.9 range (excluding Southington), with damping on the 345 kV network of better than 120 Ω.
5. The mid resonance point does not exist, providing excellent mitigation for the 5th harmonic problem.
6. The high resonance point varies in the 10th range, with little damping at the 10th around 1100 Ω range on the 345 kV network. Very little harmonic injections exist around 9 and 10th harmonic.

3rd Harmonic C-Type Filter Mitigation:-

7. The lower resonance point varies in the 3.2 to 3.3 range (excluding Southington), with damping on the 345 kV network of better than 155 Ω. Replacing most of the large capacitor banks with harmonic neutral C-Type filters improves the situation.
8. The mid resonance point around the 5th harmonic is also much reduced, providing good mitigation for the 5th harmonic problem in Phase II.
9. The high resonance point varies in the 10th range, with little damping at the 10th around the 800 Ω range on the 345 kV network. Very little harmonic injections exist around 9 and 10th harmonic.

7.3.4.3 Case II-9:- Devon - Beseck 40-mile XLPE Phase II, Minimum Dispatch

An XLPE cable section of 40 miles from Devon side of the Beseck was analyzed. Three XLPE cables, similar to other sections, were used in parallel. The shunt reactors on both sides of the XLPE cable sections were included at 10 mile intervals. No overhead line was included. Only one Phase I HPFF cable is in service.

7.3.4.3.1.1 First Resonance Point for 40 Mile Underground Results

Table 16 tabulates the first resonance results for the 40 miles underground section between Devon and Beseck, including the effect of the different mitigation solutions.

Table 16: Results of First Resonance for Additional 40 Miles of Undergrounding

Additional 40 Miles of Underground Full Load, Minimum Dispatch (Case II-9)				
Substation & Bus Voltage		No Mitigation All Caps ON	STATCOM Option	3rd C-Type Filter Option
Norwalk 345 kV	1st Resonance	2.6	2.7	3.2
	Impedance Ω	53	76	99
Norwalk 115 kV	1st Resonance	2.4	2.5	3.2
	Impedance Ω	5	5	5
Plumtree 345 kV	1st Resonance	2.5	2.6	3.2
	Impedance Ω	45	56	70
Plumtree 115 kV	1st Resonance	2.5	2.5	3.1
	Impedance Ω	7	7	9
Southington 345 kV	1st Resonance	2.5	2.6	3.2
	Impedance Ω	34	40	30
Southington Ring 1 115 kV	1st Resonance	2.4	2.5	2.7
	Impedance Ω	5	5	5
Singer 345 kV	1st Resonance	2.6	2.7	3.2
	Impedance Ω	55	82	108
Devon 345 kV	1st Resonance	2.6	2.7	3.2
	Impedance Ω	56	83	109
Beseck 345 kV	1st Resonance	2.6	2.7	3.2
	Impedance Ω	43	62	73

7.3.4.3.1.2 Key Conclusions for 40 Mile Underground Results

All Caps On with No Mitigation:-

1. The lower resonance point varies in the 2.4 to 2.6 range, but is well damped on the 345 kV and 115 kV network at better than 53 Ω. With this amount of undergrounding the resonances are damped extremely well, with the first resonance frequency shifted below 3rd. Even with this length of undergrounding the increased system strength provides adequate damping at the low resonance points.
2. The mid resonance point around the 5th harmonic is also much reduced, providing good mitigation for the 5th harmonic problem in Phase II.
3. The high resonance point varies in the 9th, with reasonable damping around the 400 Ω range on the 345 kV network at Plumtree. At the Singer and Devon 345 kV stations a well-damped resonance around the 13th was observed.

STATCOM mitigation:-

4. The lower resonance points vary in the 2.5 to 2.7 range, with damping on the 345 kV network of better than 80 Ω. With this amount of undergrounding the STATCOM mitigation option is not that effective in shifting the first resonance point above 3.0. Damping is much improved, but the resonance frequency is shifted below 3rd.
5. The mid resonance point does not exist, providing excellent mitigation for the 5th harmonic.
6. The high resonance point varies around the 9th, with reasonable damping around the 400 Ω range on the 345 kV network at Plumtree. At the Singer and Devon 345 kV stations a well-damped resonance around the 13th was observed.

3rd Harmonic C-Type Filter Mitigation:-

7. The lower resonance points vary in the 3.2 range, with damping on the 345 kV network of better than 110 Ω. Replacing most of the large capacitor banks with harmonic neutral C-Type filters improves the base case situation.
8. The mid resonance point around the 5th harmonic is much reduced, providing good mitigation for the 5th harmonic.
9. High resonance points vary in the 9th range, with good damping around the whole range of around 200 Ω range on the 345 kV network.

7.3.4.4 Case II-10:- Devon - Beseck 15-mile XLPE Phase II, Minimum Dispatch

An XLPE cable section of 15 miles, on Devon side of the Devon-Beseck (D-B) corridor was included. Three XLPE cables, similar to the XLPE cables in Phase I, are used in parallel. Shunt reactors on both sides of the XLPE cable sections are included at 10 and 15 miles. The rest of the 40-mile corridor used overhead line. Only one Phase I HPFF cable is in service.

Harmonic impedance results for the Norwalk 345 kV bus are summarized in Figure 13. Results are shown for no mitigation and for C-Type Filter mitigation, compared to the Base Case results with no undergrounding between Devon and Beseck and no mitigation at a nominal loading of 70%. Minimum generator dispatch with all capacitors on was the network configuration. Only the C-Type mitigation option is shown.

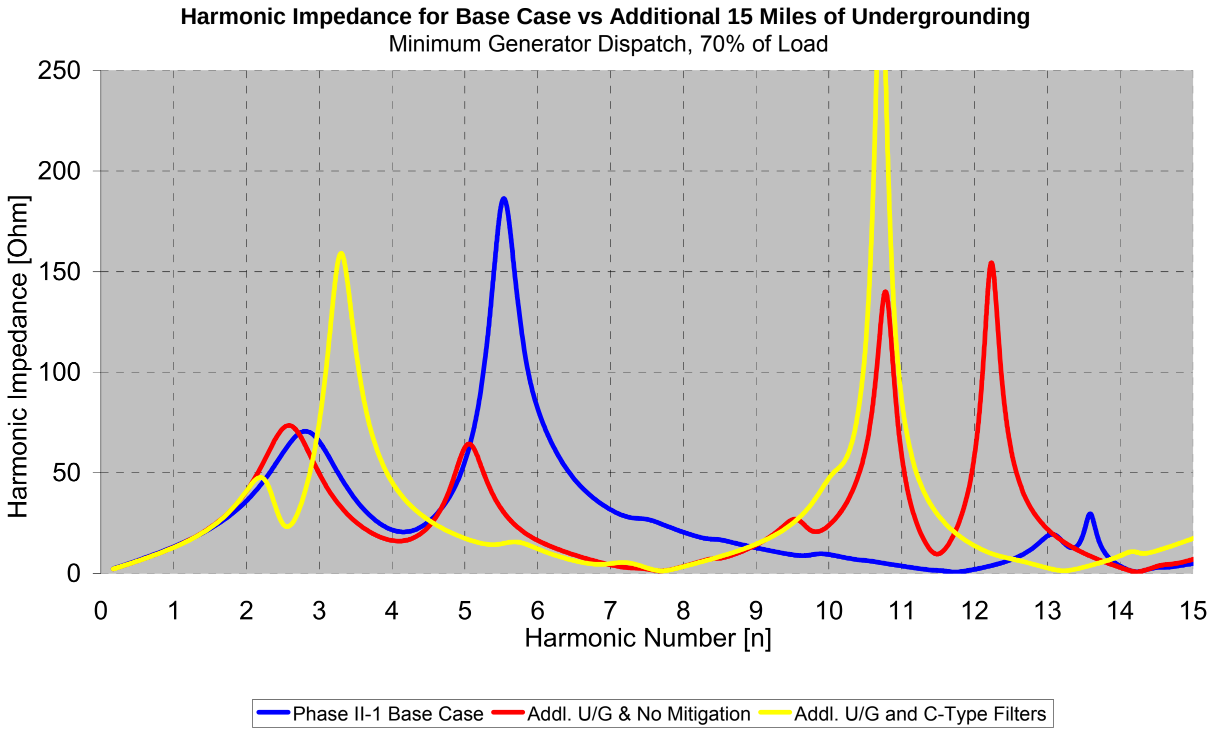


Figure 13: Impedance at Norwalk 345 (15 Miles Underground D – B & Base - Case II-1)

First resonance points moved lower from 2.8 in the base case to 2.6 for the 15-mile underground case at about the same level of damping of around 70 Ω. The large resonance between the 5th and 6th harmonic is reduced to a very low peak, but two peaks in the 10 – 13 range are visible. All of these peaks are however well damped below the characteristic impedance Z_0.

When the C-Type filter mitigation option is added the first resonance peak moves from 2.6 to 3.3, but the damping is reduced from around 70 Ω to around 155 Ω. The harmonic filtering characteristic is also clearly visible at around 2.6. The harmonic impedance at most of the key system harmonics is reduced from the Phase II Base Case, except at the 11th harmonic. With an optimized C-Type filter design the overall spectrum can be optimized.

7.3.4.5 Graphical Results of Undergrounding Cases

A summary of the graphical results for the different undergrounding options (10 miles; 20 miles and 40 miles) is presented in this paragraph. The harmonic impedance results at all these extended undergrounding D-B options are compared with Phase II Base Case (0 miles) at substation Norwalk 345 kV. The harmonic impedance with no mitigation and with C-Type Filter mitigation is presented. The results are already discussed in detail in the previous section.

7.3.4.5.1 Comparison of Extended Undergrounding without Mitigation

The comparison of the harmonic impedance results at Norwalk 345 kV without any mitigation is show in Figure 14. Minimum generator dispatch with all capacitors on and full load were assumed in comparing the different cases.

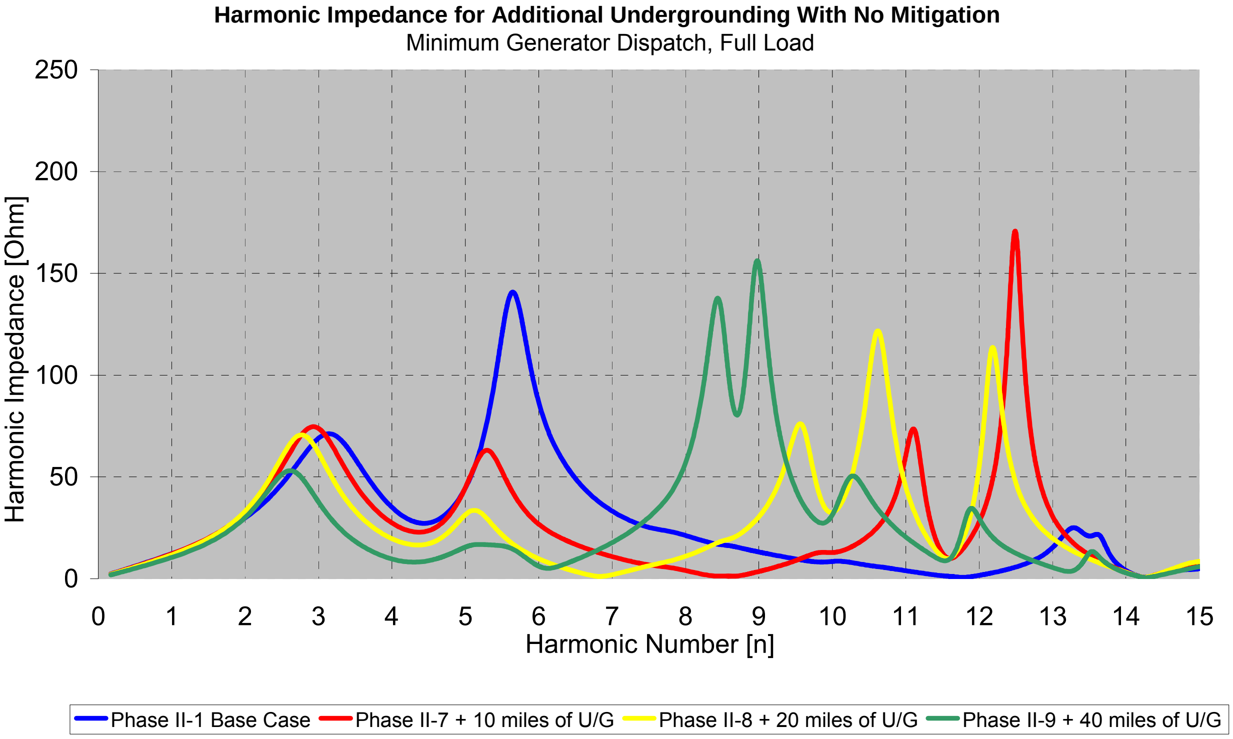


Figure 14: Impedance at Norwalk 345 for Underground D – B & II-1 Cases - Without Mitigation

First resonance peaks move progressively lower with more undergrounding as expected, but damping of the first resonance point increases with increased undergrounding. The large 5th harmonic present in the in the base case, is progressively damped with more under grounding. The higher resonance peaks are less damped with increased undergrounding, but are still very manageable due to the high level of overall system damping.

7.3.4.5.2 Comparison of Extended Undergrounding with C-Type Filter Mitigation

Harmonic impedance results of extended undergrounding with the C-Type filter as mitigation option are shown in Figure 15. Here the Base Case (with C-Type mitigation in blue) is used as basis for comparison.

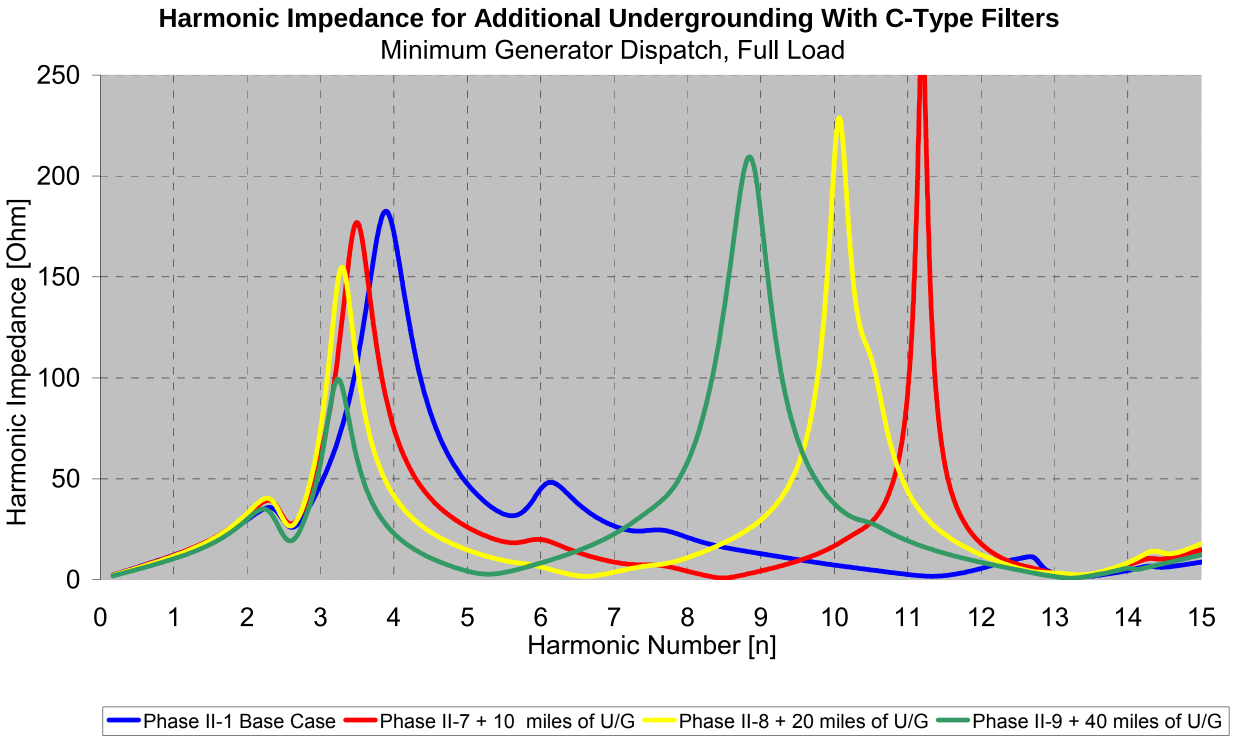


Figure 15: Harmonic Impedance Results of Underground Options with C-Type Filter Mitigation

For all three of the extended undergrounding options the first significant resonance points are well above 3.0, with the harmonic filtering effect of the C-Type filters clearly noticeable at around 2.6. At 40 miles of undergrounding, the resonance peak is closest to 3.0. No contingency analysis has been performed, but it is expected that with some lines out of service the first resonance point will be reduced to lower values. For the 40-mile underground option, the risk is the highest that the first resonance point will move lower than 3.0.

Damping of all the resonance peaks get progressively better with more undergrounding due to the increased charging capacitance and added system strengthening. From these results the lowest harmonic impedance values at most of the key system harmonics are obtained with 40 miles of undergrounding. For 10 miles of undergrounding the high resonance peak is close to the 11th harmonic. If large distortion levels are expected at the 11th harmonic, some of the C-Type filters should be optimized for this condition.

8 CONCLUSIONS AND RECOMMENDATIONS

KEMA performed an independent technical review of the Application to the Connecticut Siting Council for a Certificate for the construction of Phase II facilities in Southwest Connecticut. 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's studies were limited in scope and detail due to time and resource constraints, as follows:

- Only harmonic impedance calculations were performed, and the findings are based only on the results of this harmonic resonance study.

- The desirability of having a first resonance point in excess of the 3rd harmonic was used as one measure of acceptability. The impedance and damping at the different resonance peaks and the impedances at the key system harmonics also were used as a measure. The harmonic performance of the different Phase II options was also compared to the harmonic performance of Phase I.

- No detailed modeling of the STATCOM mitigation option was done. At the substations where the STATCOMs were included, the capacitor banks were taken out of service. No active filtering capabilities were included for the STATCOM model.

- No optimization of the C-Type filter design was performed.

- System transient calculations have to be made for the proposed mitigation solutions with a more detailed system model.

Conclusions:

1. KEMA's Results for the Phase II Base Case are comparable and consistent with harmonic scan results performed by the Applicant and their consultants. The damping of the system resonance peaks are, however, somewhat better in the KEMA results, due to the fact that active and reactive power loading was added at all the different substations.

2. Phase I alone shows high risks in terms of the harmonic performance for the 7th harmonic when only 1 HPFF cable is in operation.

3. The evolution from the Phase I system to Phase II is very positive from a harmonic performance point of view. This is mainly due to the added system strength and increased system damping associated with the 345 kV network.

4. Both the Phase II (Base Case) and Phase II with extended XLPE cable between Devon and Beseck, provide much better harmonic performance than is the case for Phase I alone.

5. STATCOMs provide adequate mitigation from a harmonic performance point of view for the base-case and extended undergrounding cases. However, the multiple STATCOM solution may be difficult to operate from a system operations perspective.

6. When C-Type filters and/or STATCOM mitigation schemes are employed, Phase II with a 20-mile underground extension is a workable solution from a system resonance point of view. Under these conditions a well-damped system with resonance frequencies above 3rd harmonic can be maintained with limited risks to over-voltages from a system resonance point of view.

7. Undergrounding of the entire Devon to Beseck corridor appears to be a risky choice from a reliability perspective, because system resonance points below the third harmonic may occur.

8. A combined mitigation solution, using one or two STATCOMs, together with a number of C-Type filters in place of most large capacitor banks should add excellent harmonic and dynamic voltage performance to the system.

Recommendations:

1. Phase II (Norwalk to Devon) should be designed in detail and commissioned as soon as possible, preferably together with Phase I, to provide the important added system strength and increased system damping.

2. An optimal design of C-Type filters alone, or in the combination with one or two STATCOMs, should be done as soon as possible. Here the tuned C-Type filters should be optimized for each specific substation and for the system as a whole.

3. Transient analyses should be performed with a detailed system model of the selected options with the mitigation solutions in place.

4. If background harmonic measurements are made available for the different substations, the IEEE-519 [9] harmonic design practice can be used as a harmonic performance

criterion to determine whether steady state harmonic performance will be within the IEEE 519 limits. Such an analysis should be performed.

9 REFERENCES

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APPENDIX:

GRAPHICAL FREQUENCY SCAN RESULTS

10 APPENDIX: GRAPHICAL FREQUENCY SCAN RESULTS

10.1 Graphs of Phase I Case alternatives

10.1.1 CASE I-1: PHASE I, ALL CAPACITORS ON, LIGHT DISPATCH

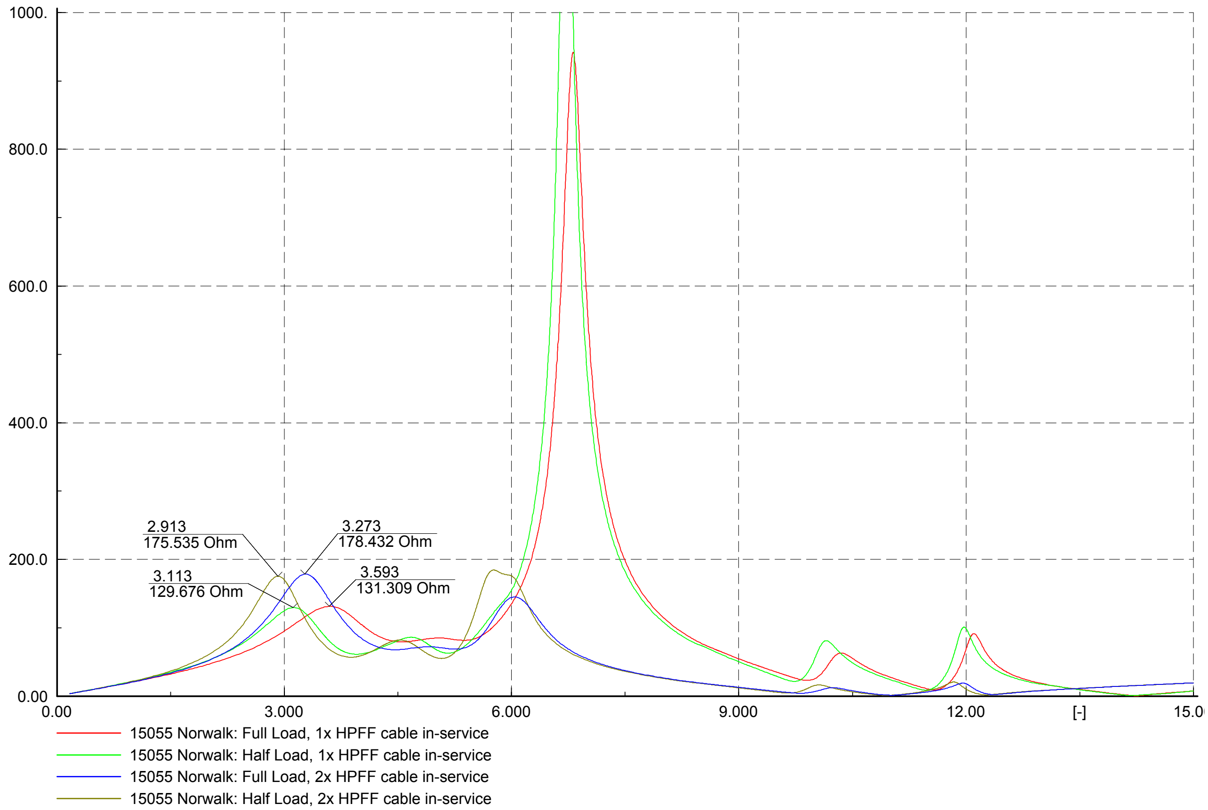

Figure 16: Case I-1:- Phase I, All Capacitors ON, Light Dispatch - Norwalk 345 kV

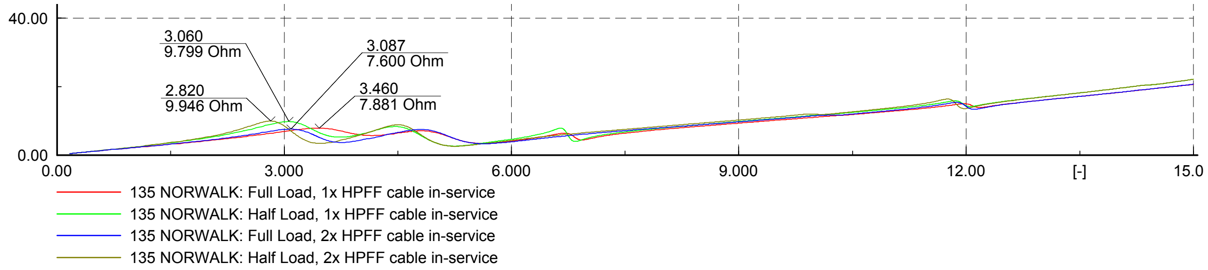

Figure 17: Case I-1:- Phase I, All Capacitors ON, Light Dispatch - Norwalk 115 kV

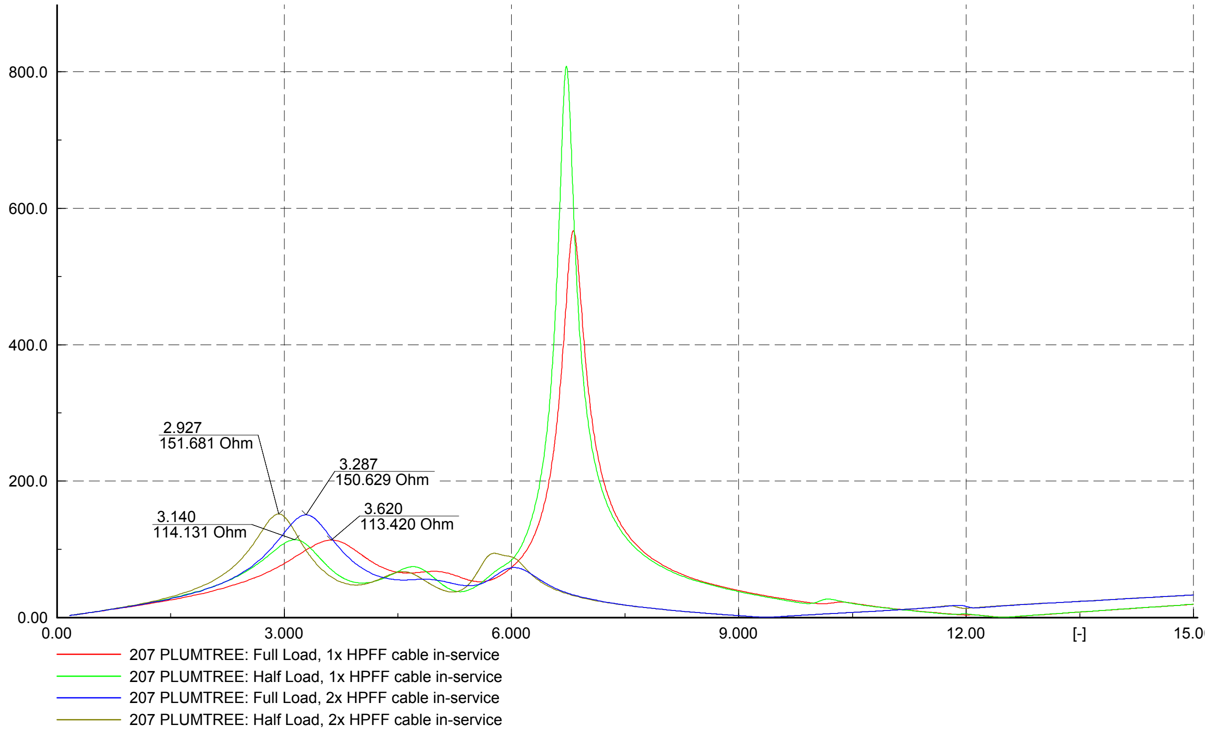

Figure 18: Case I-1:- Phase I, All Capacitors ON, Light Dispatch - Plumtree 345 kV

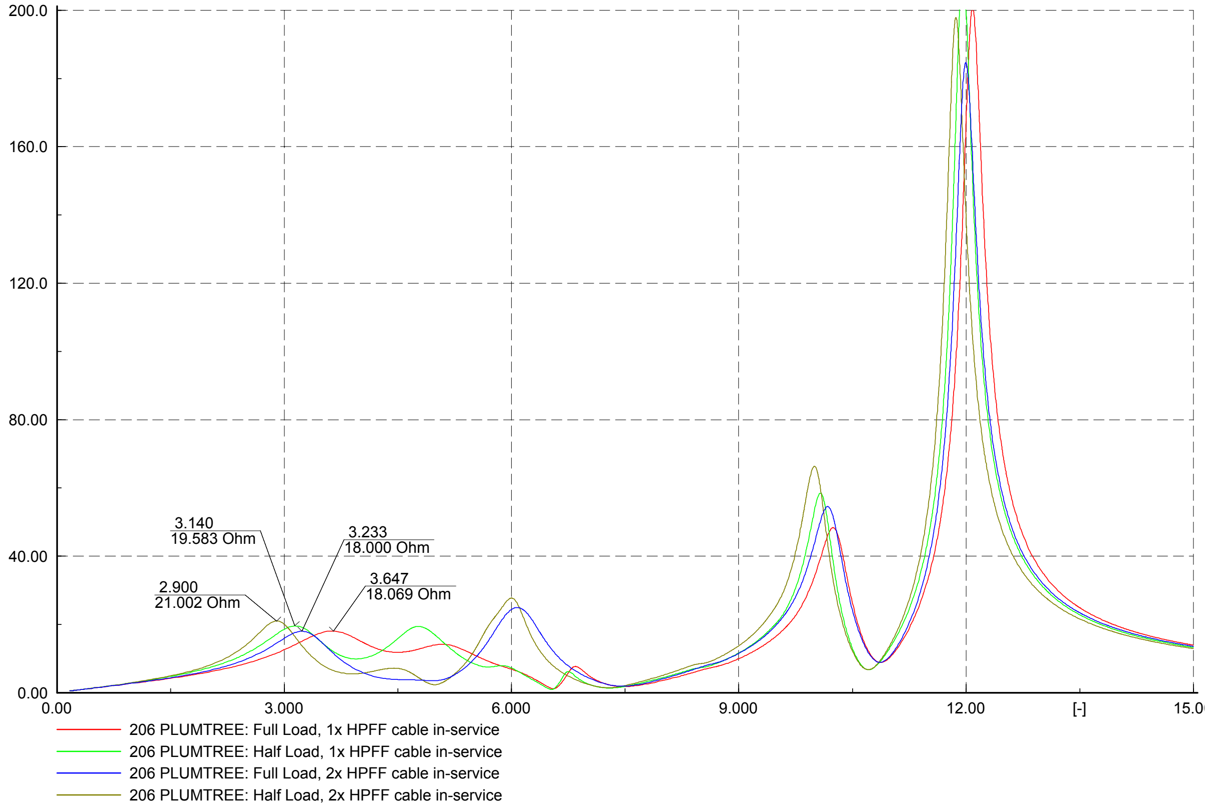

Figure 19: Case I-1:- Phase I, All Capacitors ON, Light Dispatch - Plumtree 115 kV

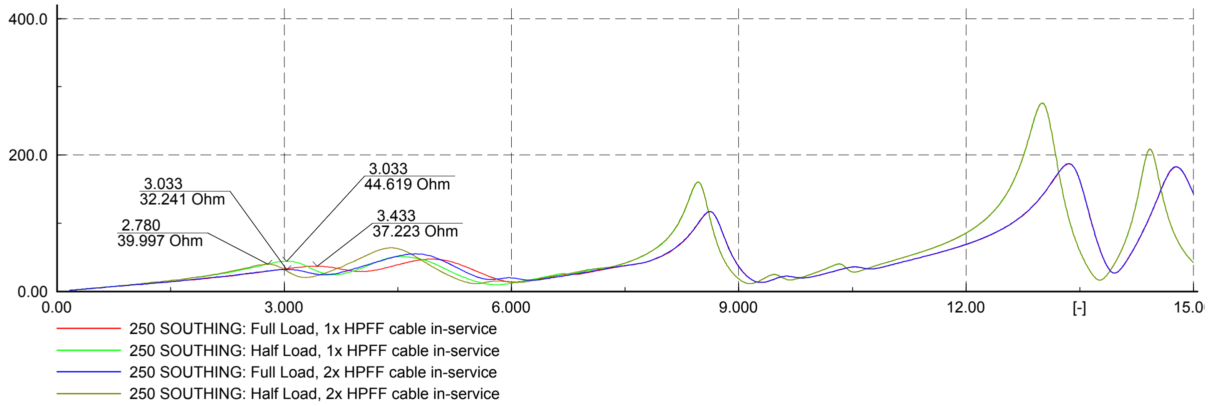

Figure 20: Case I-1:- Phase I, All Capacitors ON, Light Dispatch - Southing 345 kV

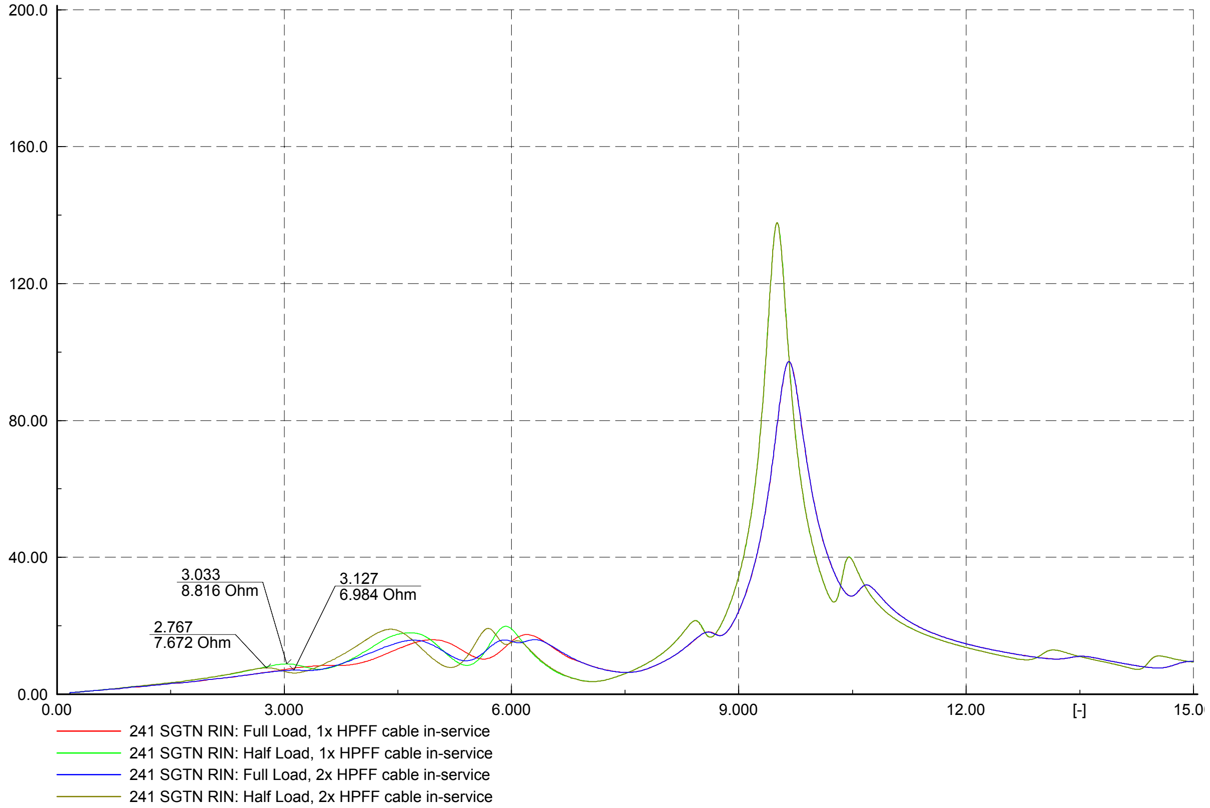

Figure 21: Case I-1:- Phase I, All Capacitors ON, Light Dispatch - Southing 115 kV

10.2 Graphs of Phase II Alternatives

10.2.1 CASE II-1:- NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, ALL CAPS ON

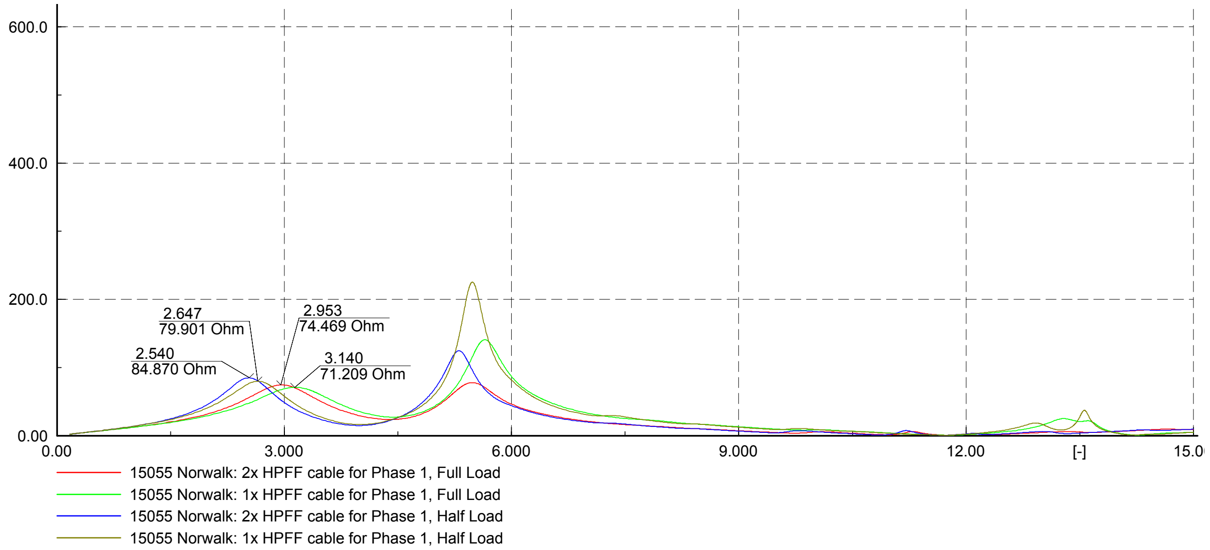

Figure 22: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON - Norwalk 345 kV

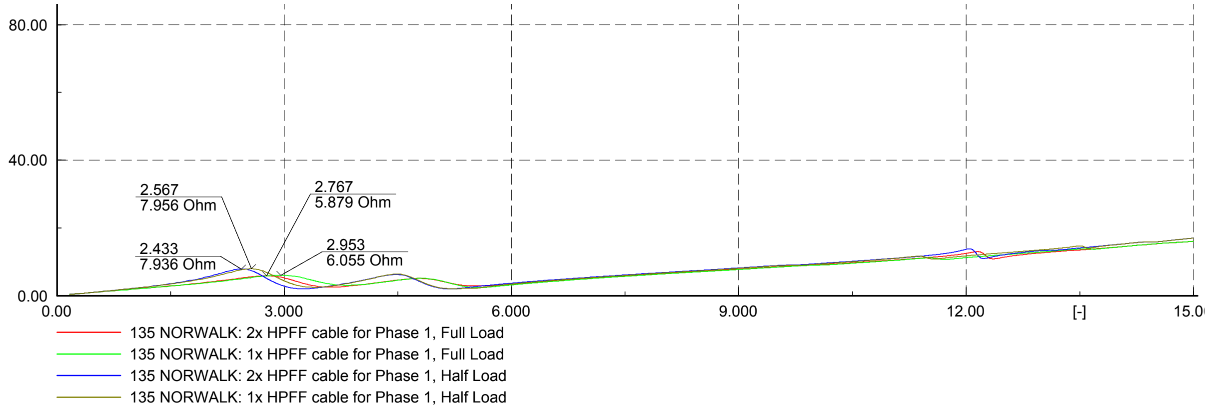

Figure 23: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON - Norwalk 115 kV

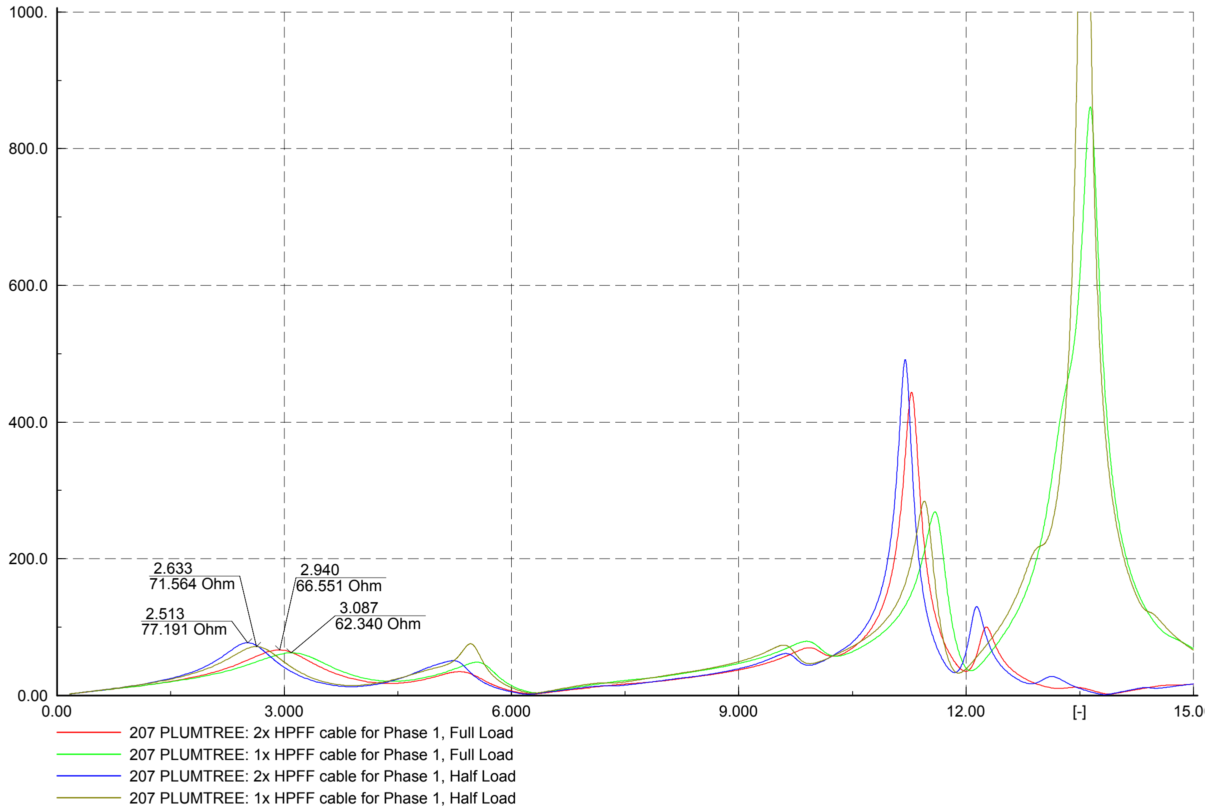

Figure 24: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON - Plumtree 345 kV

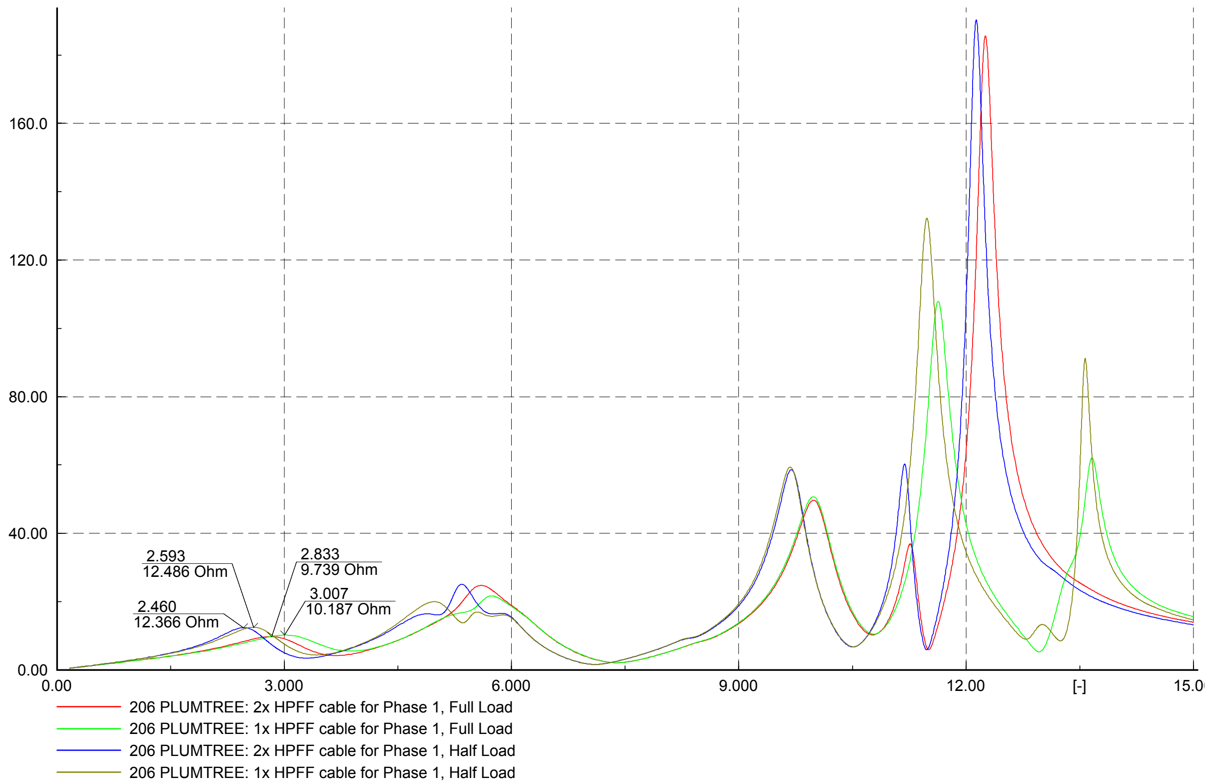

Figure 25: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON - Plumtree 115 kV

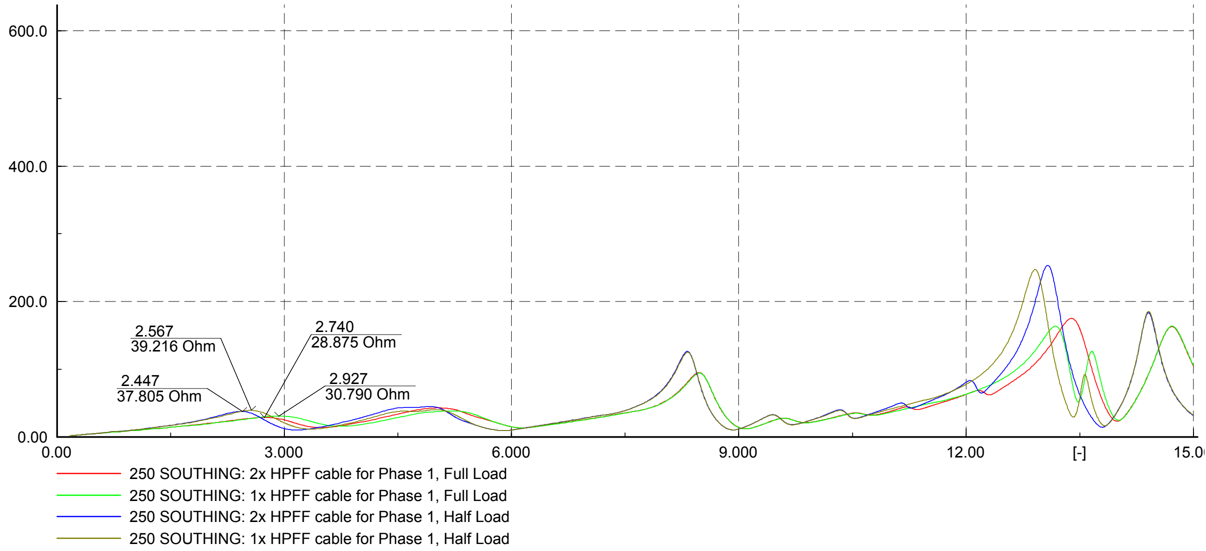

Figure 26: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON - Southing 345 kV

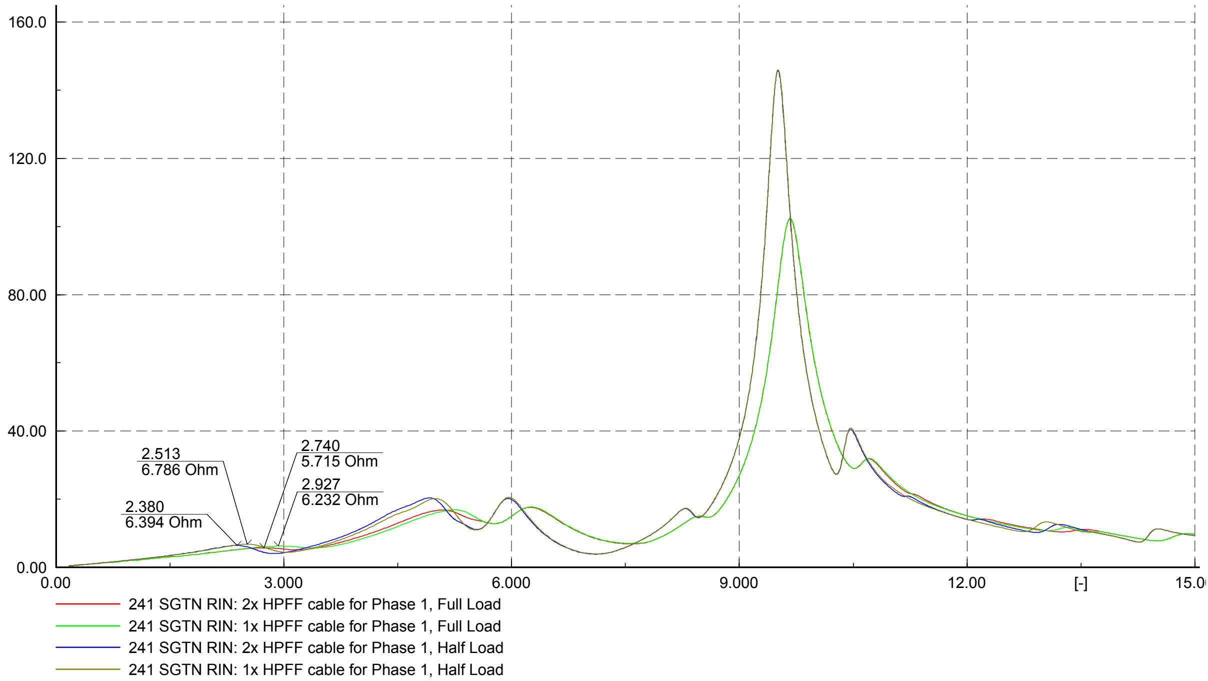

Figure 27: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON - Southing 115 kV

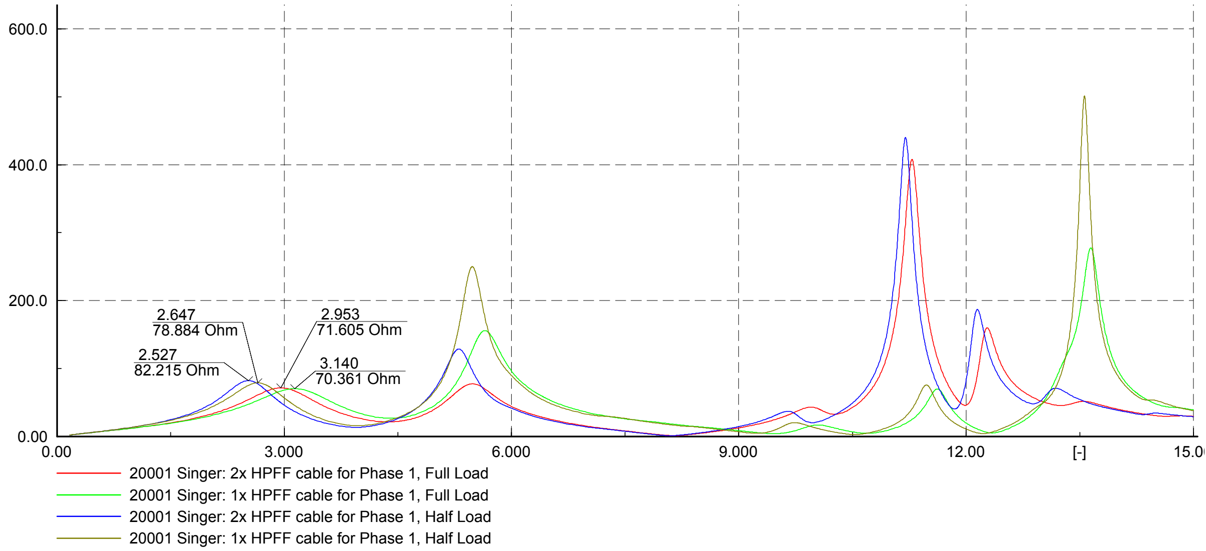

Figure 28: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON - Singer 345 kV

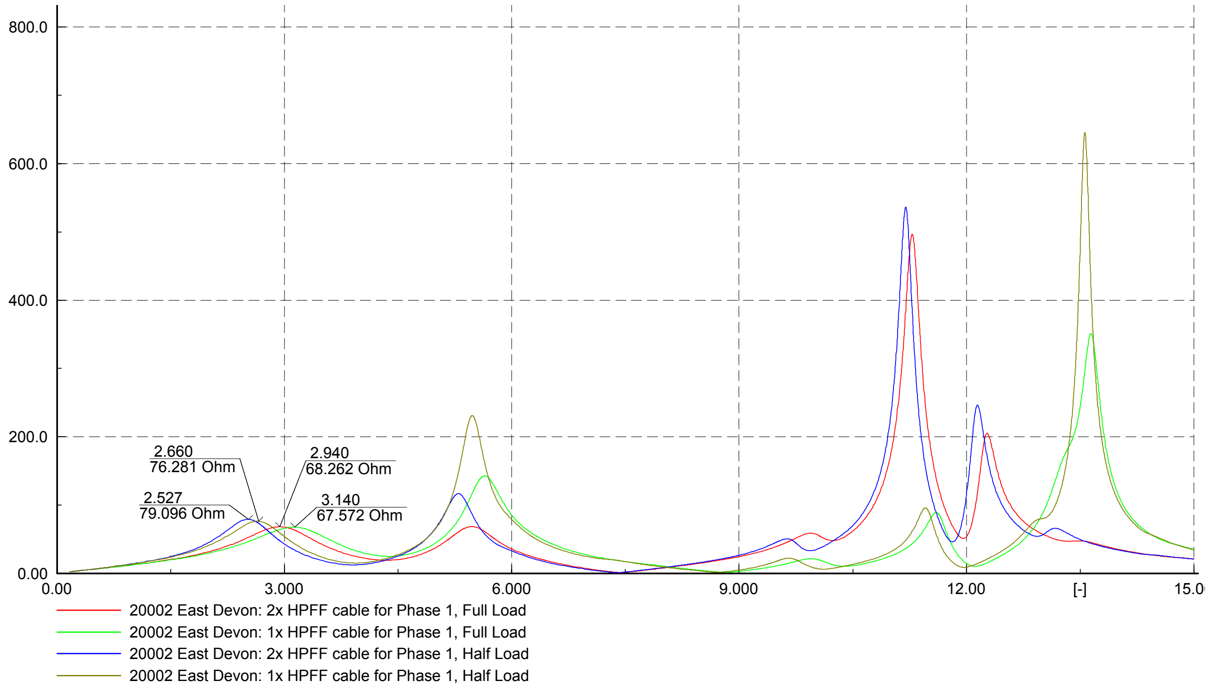

Figure 29: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON – Devon 345 kV

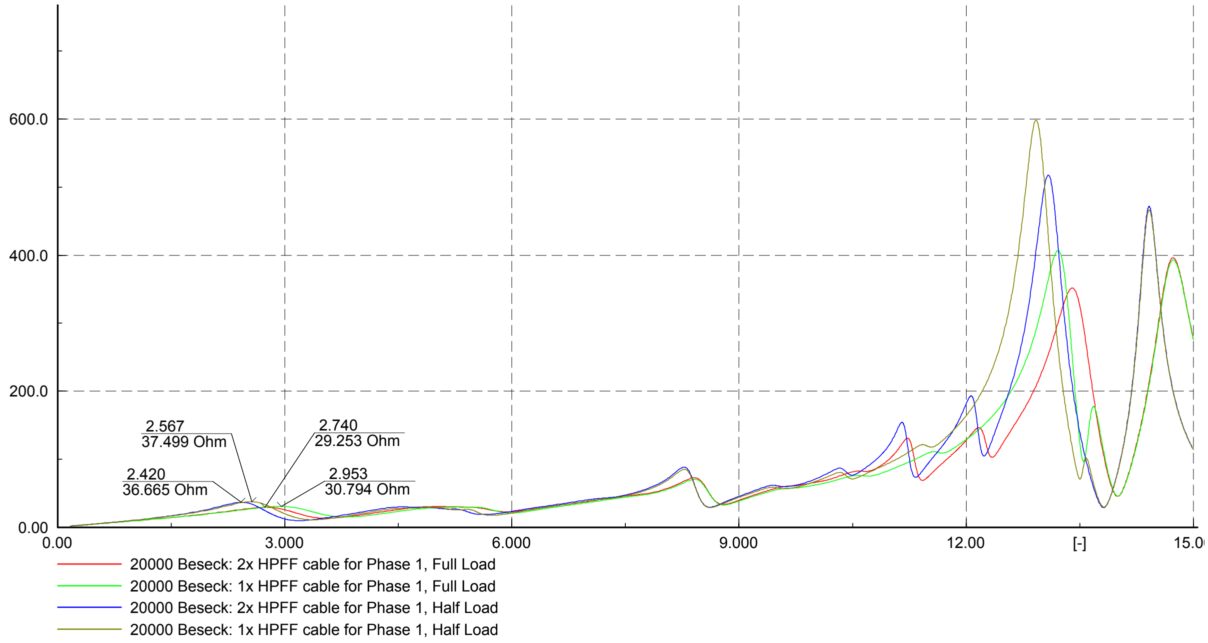

Figure 30: Case II-1:- Norwalk - Devon XLPE, Minimum Dispatch, All Caps ON – Beseck 345 kV

10.2.2 CASE II-2:- NORWALK - DEVON XLPE PHASE II, LIGHT DISPATCH, ALL CAPACITORS ON

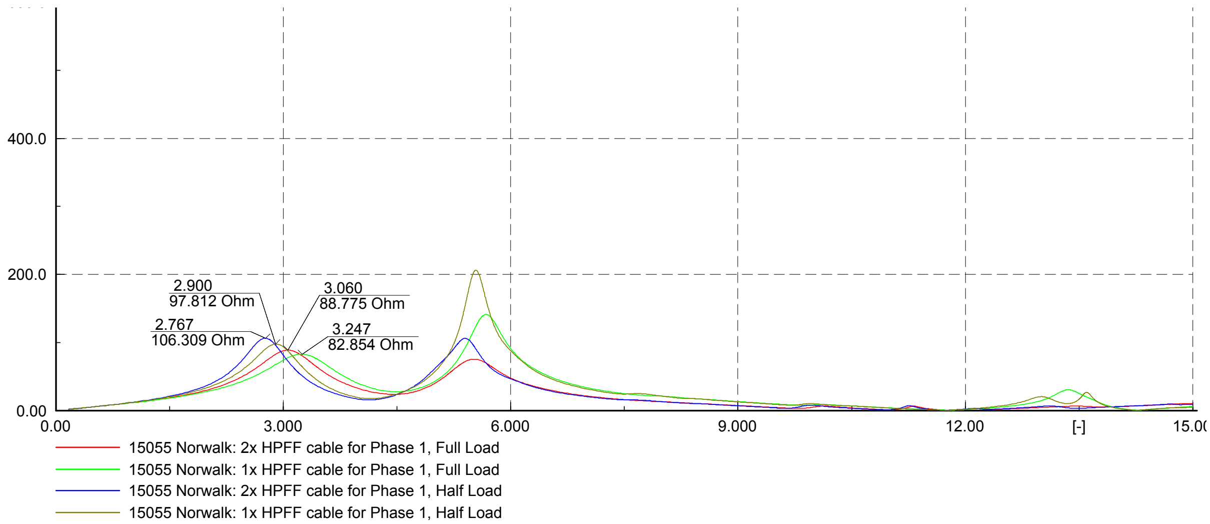

Figure 31: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON - Norwalk 345 kV

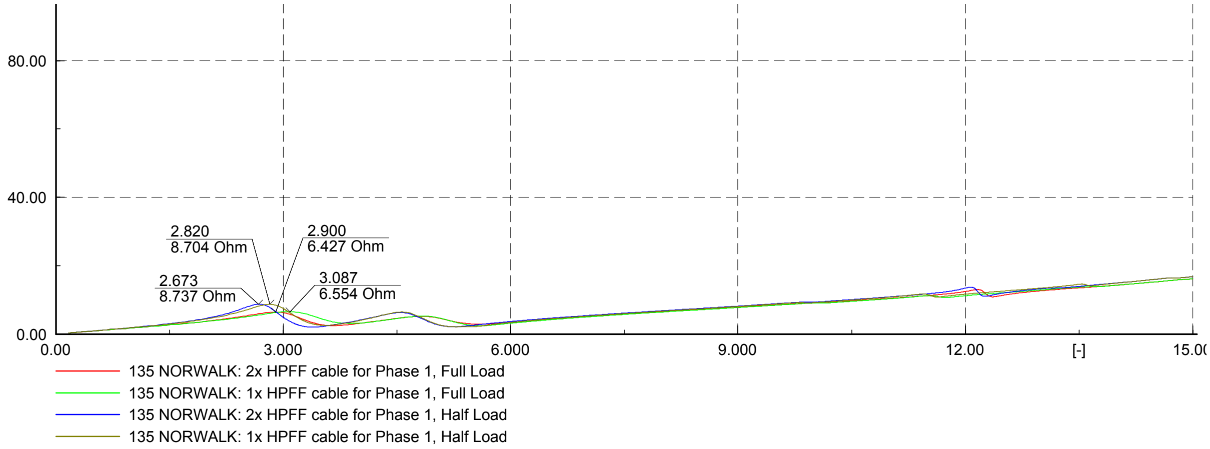

Figure 32: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON - Norwalk 115 kV

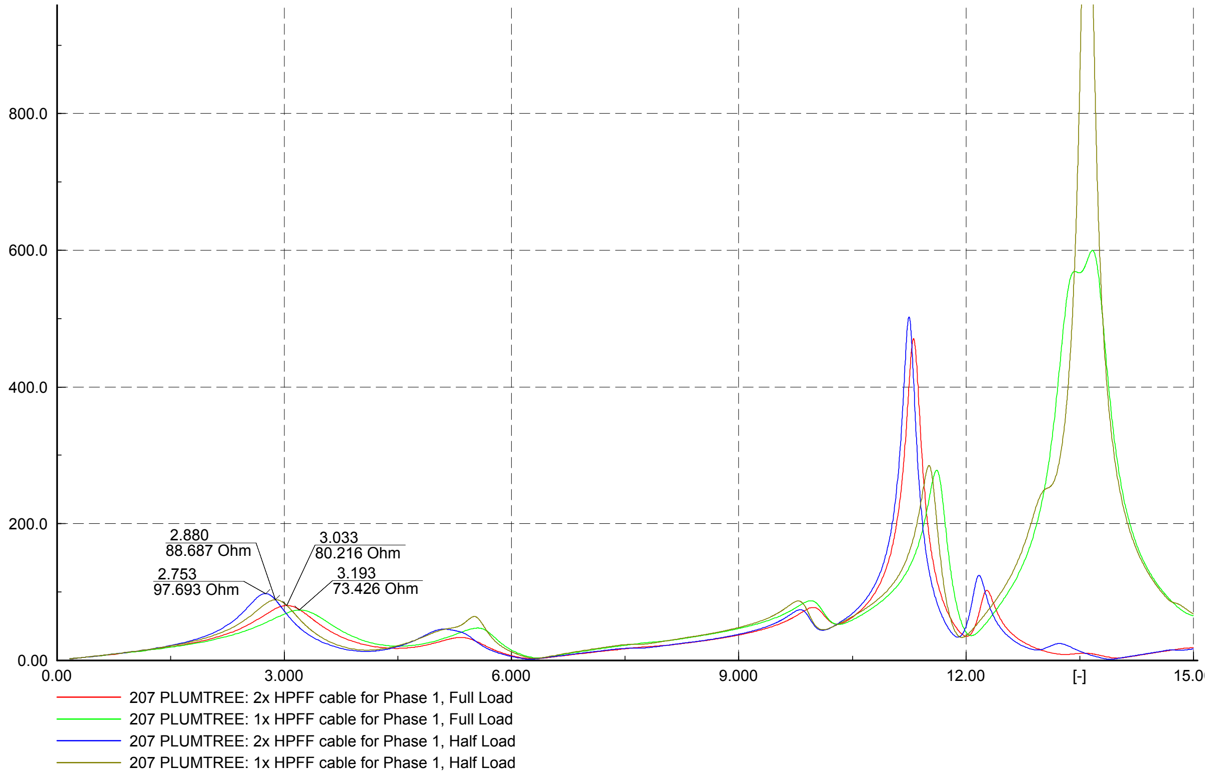

Figure 33: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON - Plumtree 345 kV

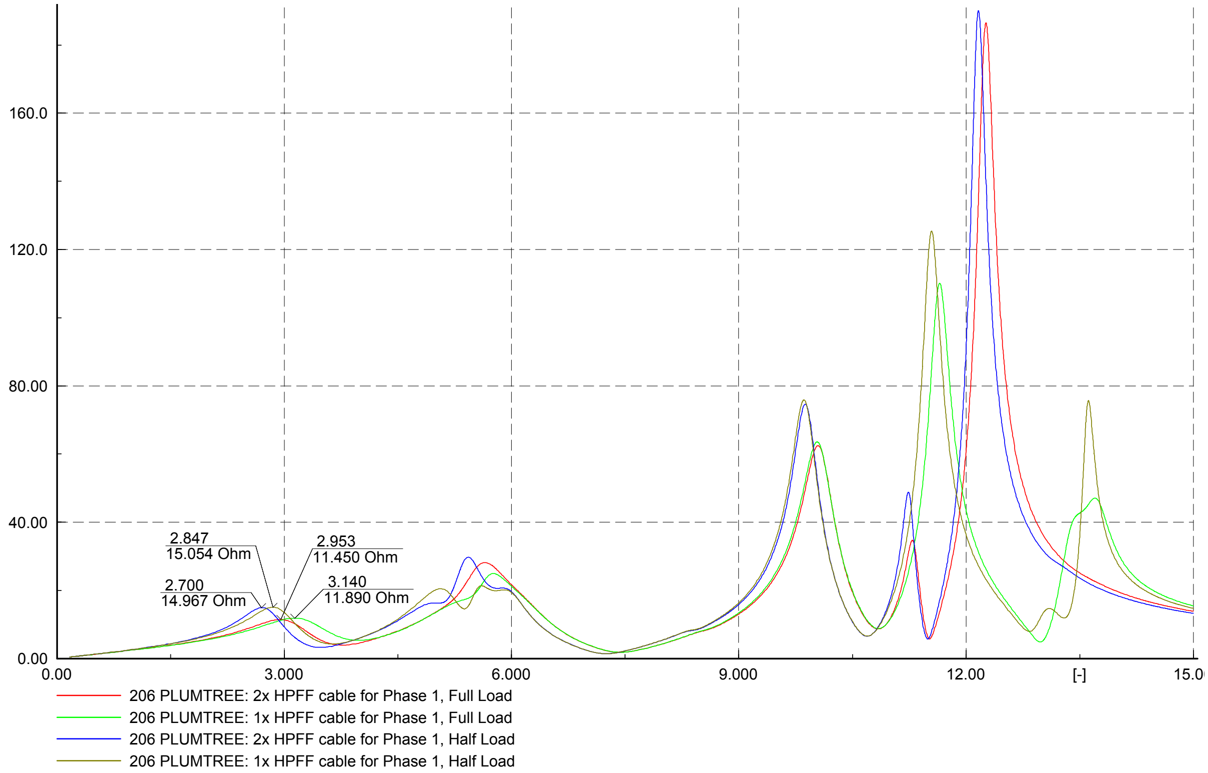

Figure 34: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON - Plumtree 115 kV

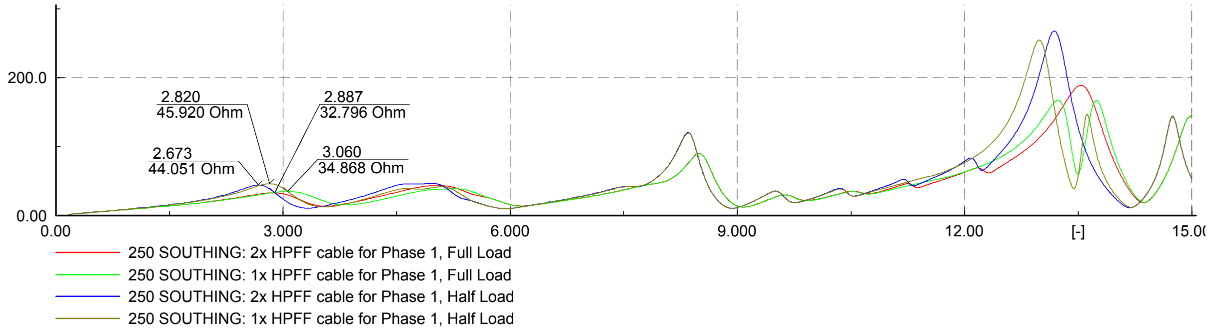

Figure 35: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON - Southing 345 kV

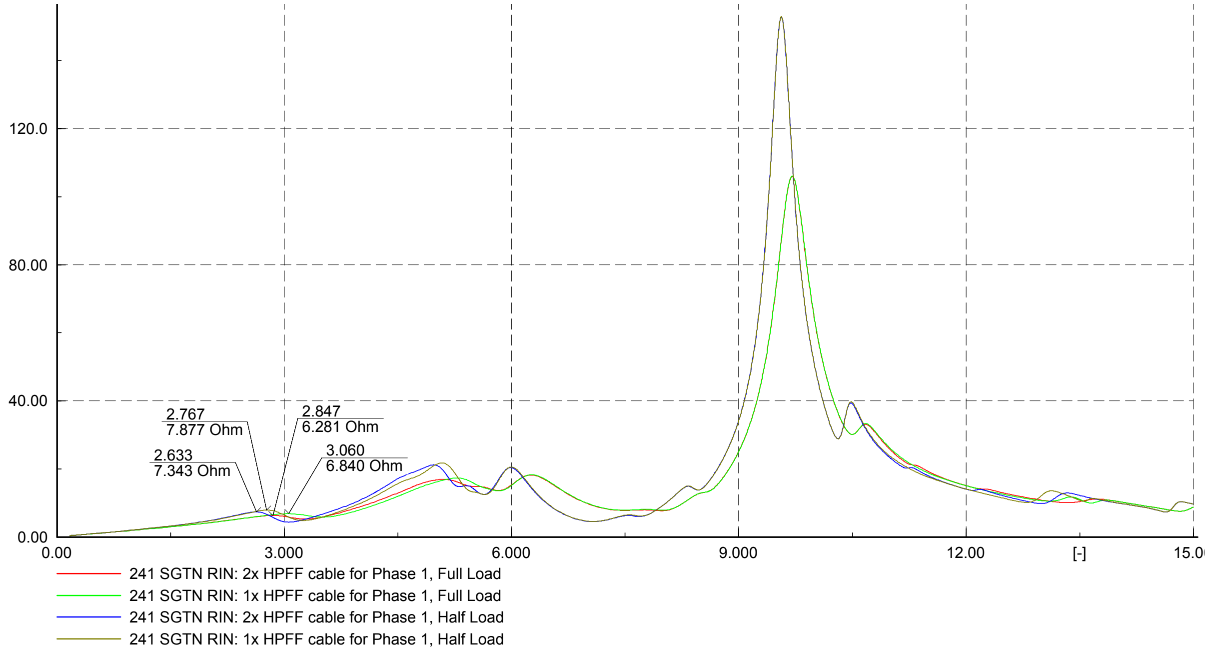

Figure 36: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON - Southing 115 kV

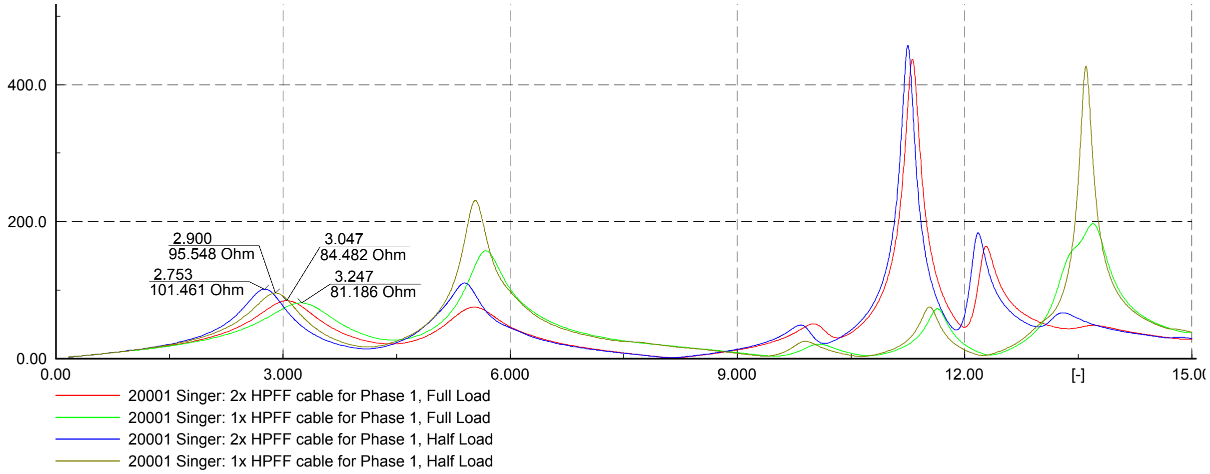

Figure 37: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON - Singer 345 kV

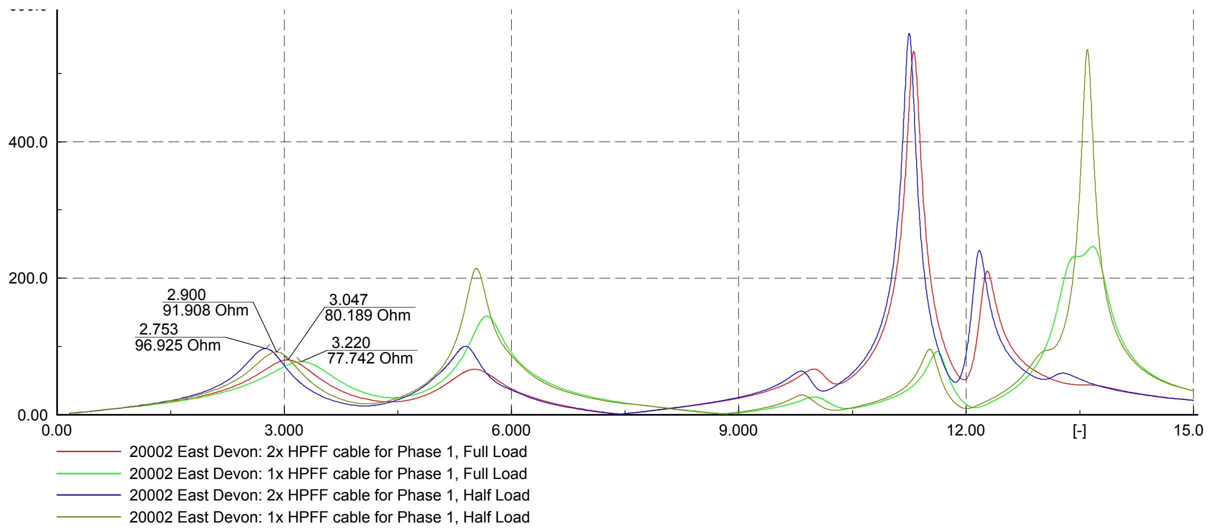

Figure 38: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON – Devon 345 kV

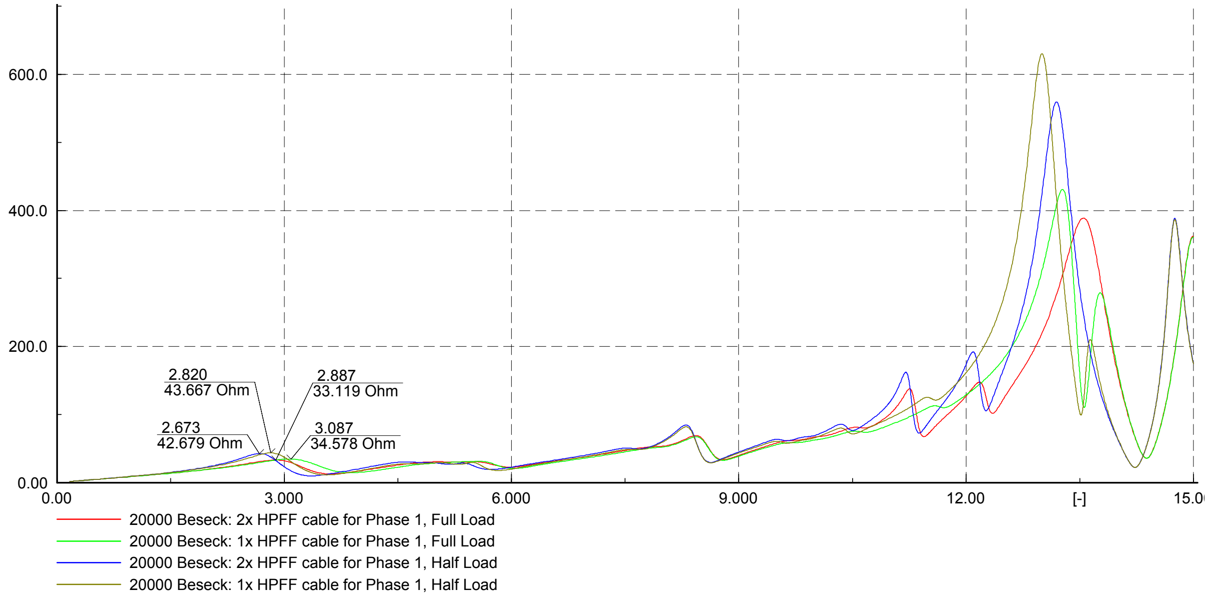

Figure 39: Case II-2:- Norwalk - Devon XLPE, Light Dispatch, All Caps ON – Beseck 345 kV

10.2.3 CASE II-3: NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, ALL CAPACITORS OFF

The load flow for this case did not converge. This is mainly due to the minimum generation dispatch scenario with all the capacitors off. No results are generated.

10.2.4 CASE II-4:- NORWALK - DEVON XLPE PHASE II, LIGHT DISPATCH, ALL CAPACITORS OFF

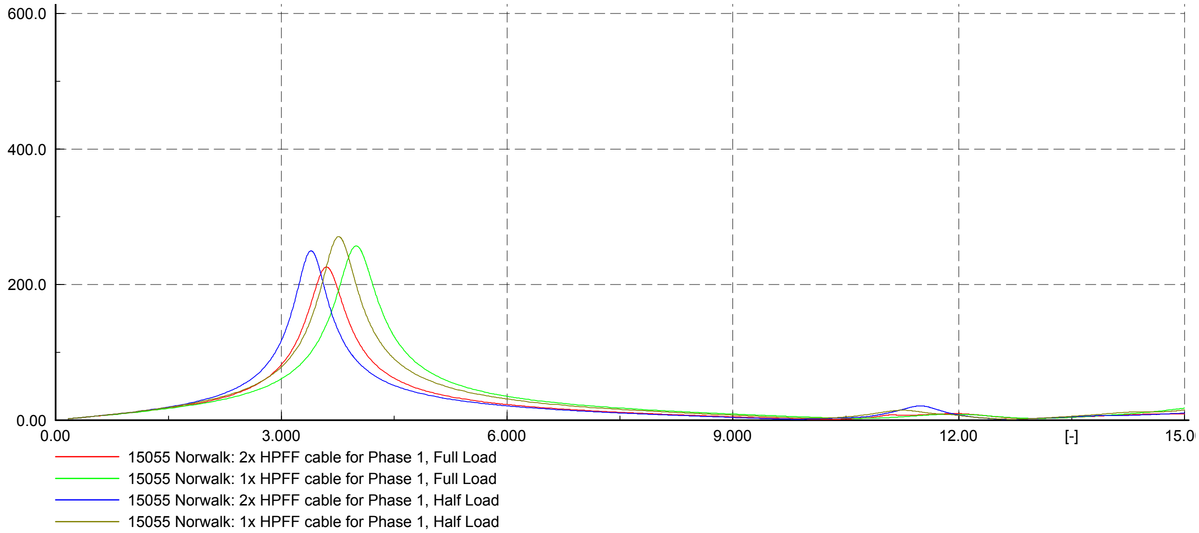

Figure 40: Case II-4: - Norwalk - Devon XLPE, Light Dispatch, All Caps OFF - Norwalk 345 kV

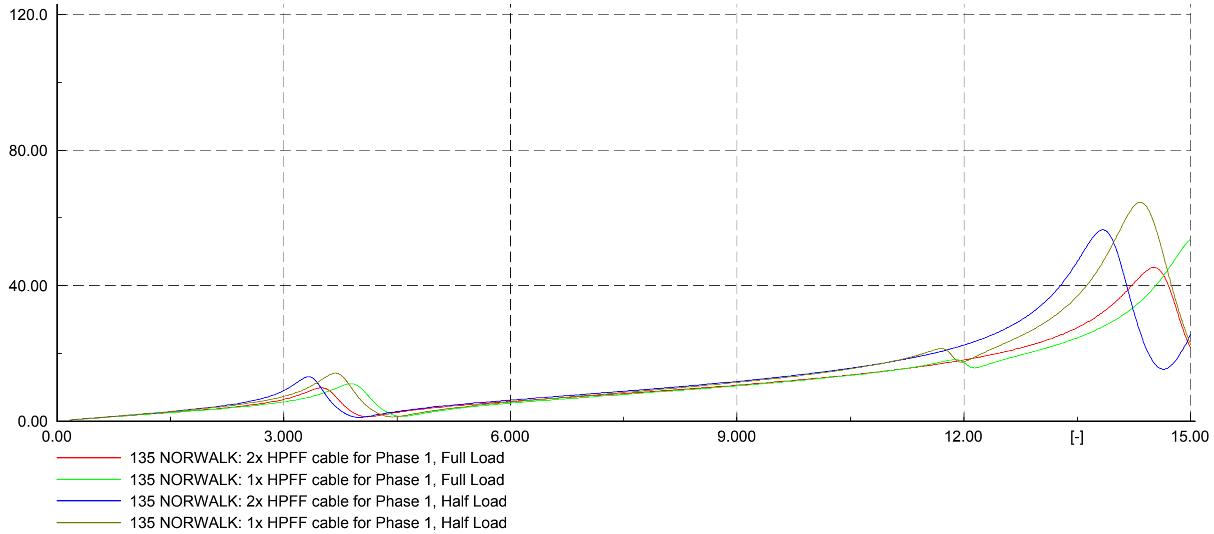

Figure 41: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF - Norwalk 115 kV

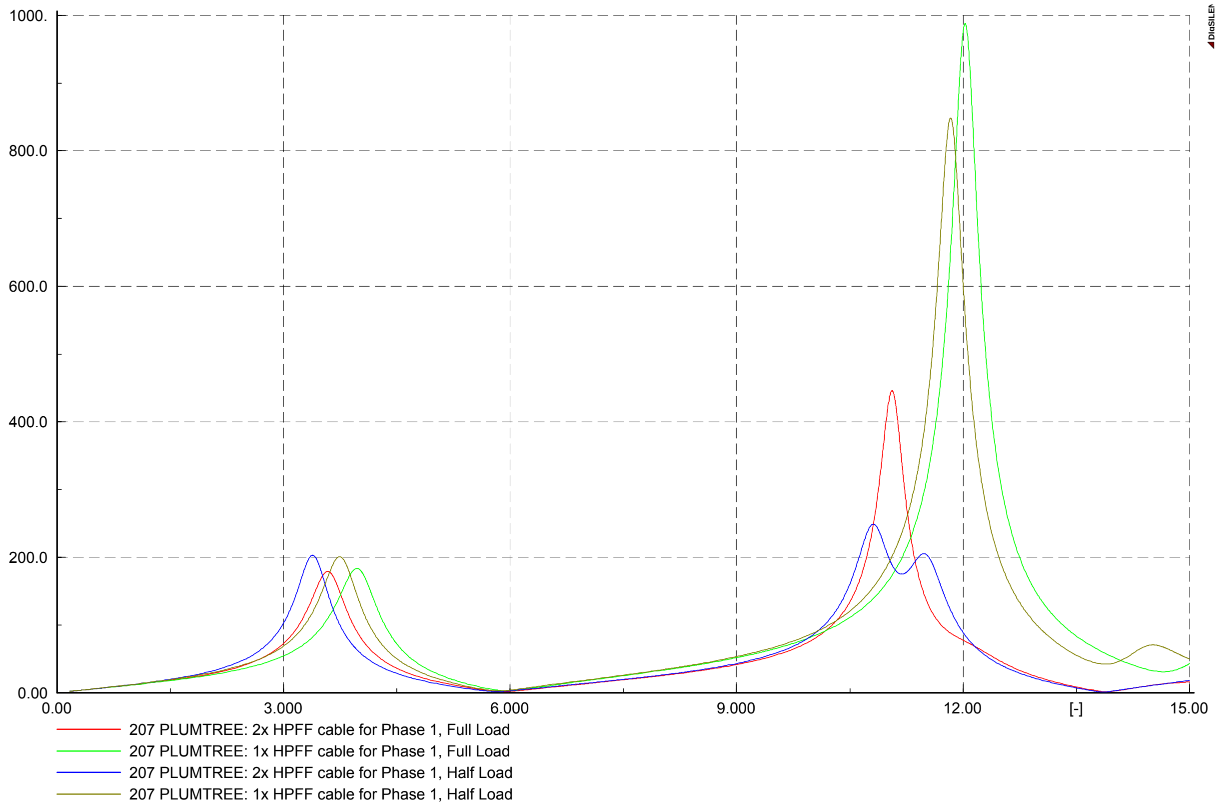

Figure 42: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF - Plumtree 345 kV

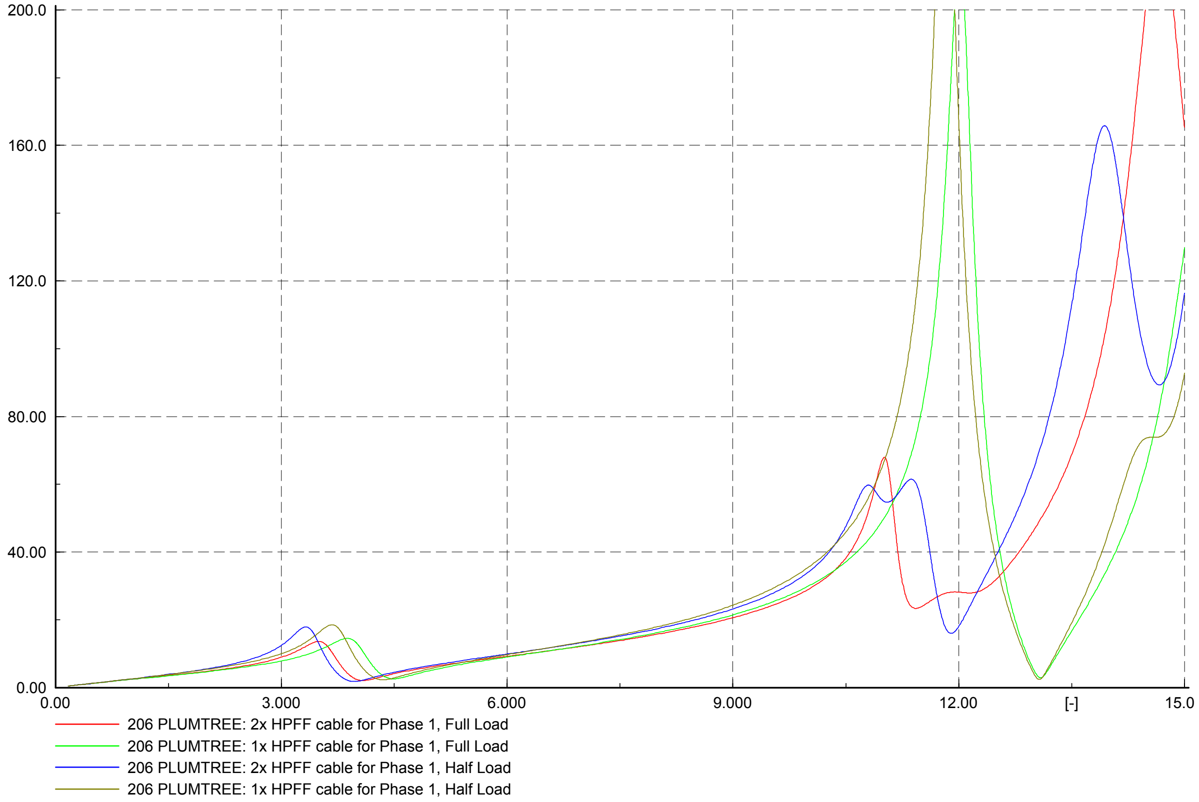

Figure 43: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF - Plumtree 115 kV

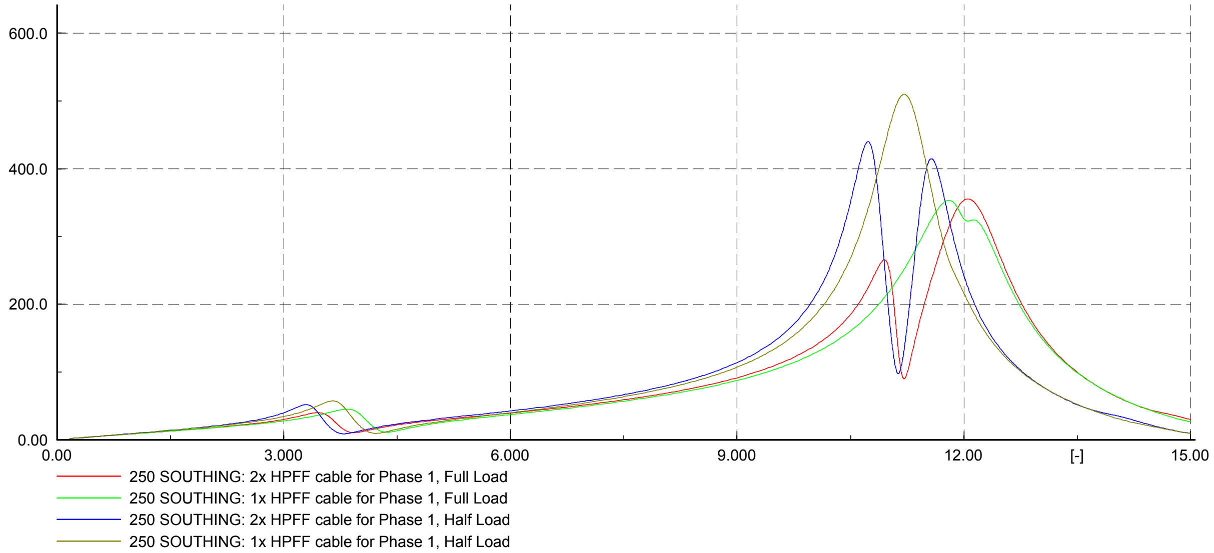

Figure 44: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF - Southing 345 kV

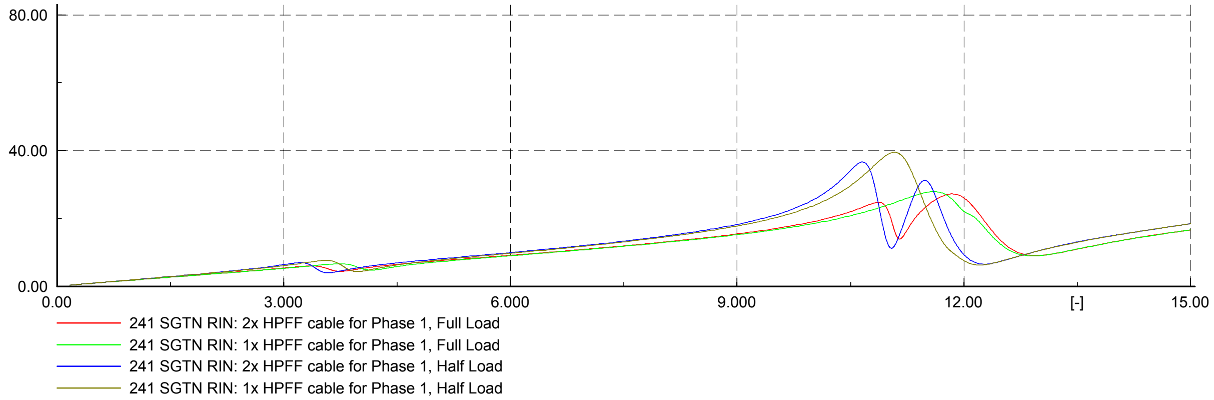

Figure 45: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF - Southing 115 kV

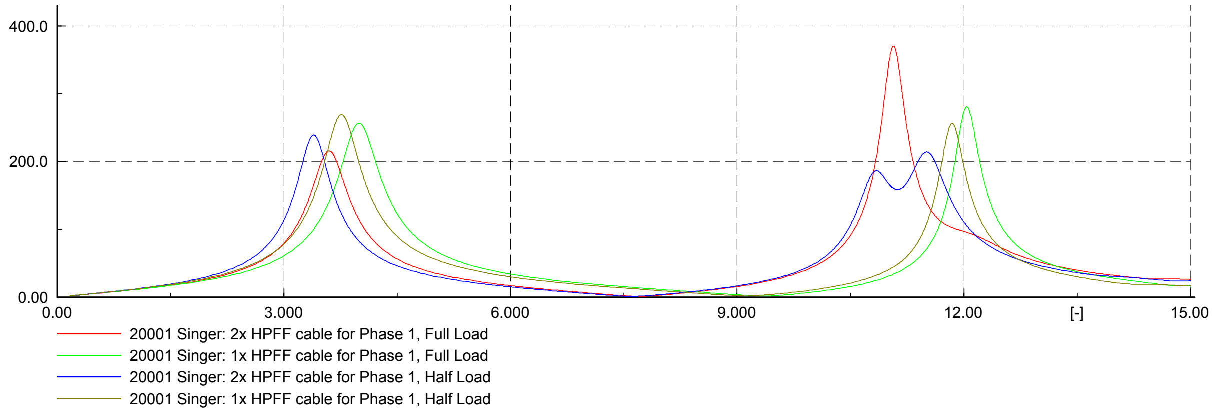

Figure 46: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF - Singer 345 kV

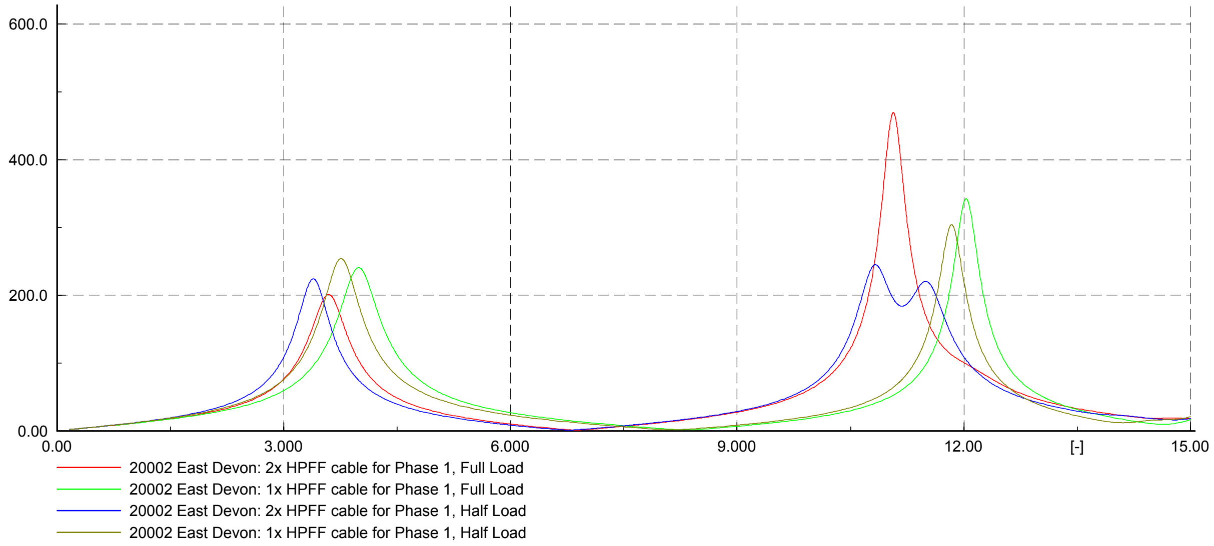

Figure 47: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF – Devon 345 kV

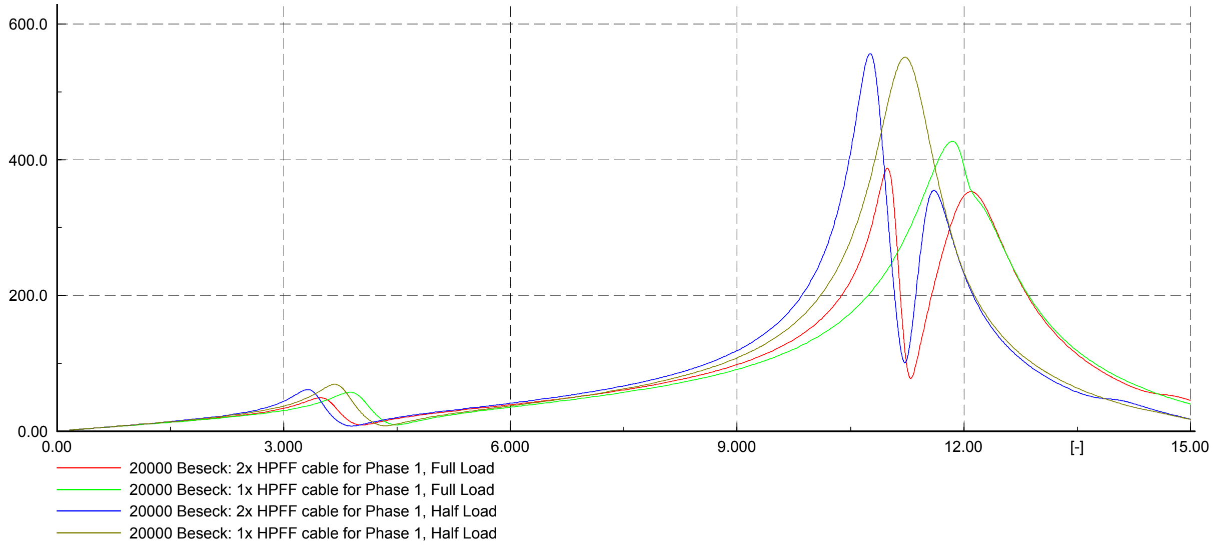

Figure 48: Case II-4:- Norwalk - Devon XLPE, Light Dispatch, All Caps OFF – Beseck 345 kV

10.3 Graphs of Phase II Alternatives, Including Mitigation Options

10.3.1 CASE II-5:- NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, STATCOM, ALL REMAINING CAPACITORS ON

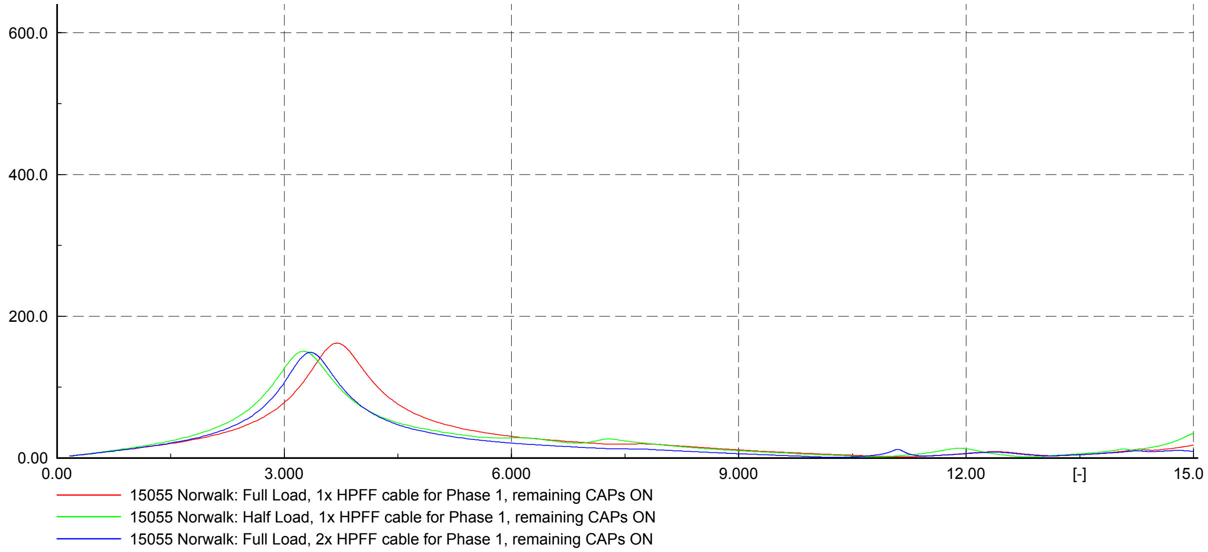

Figure 49: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON - Norwalk 345 kV

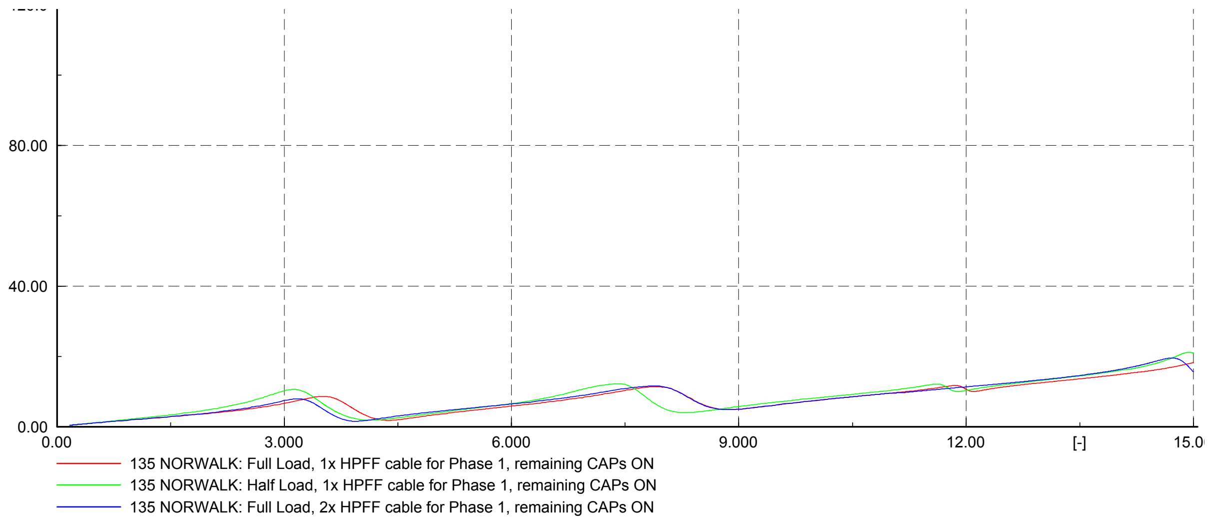

Figure 50: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON - Norwalk 115 kV

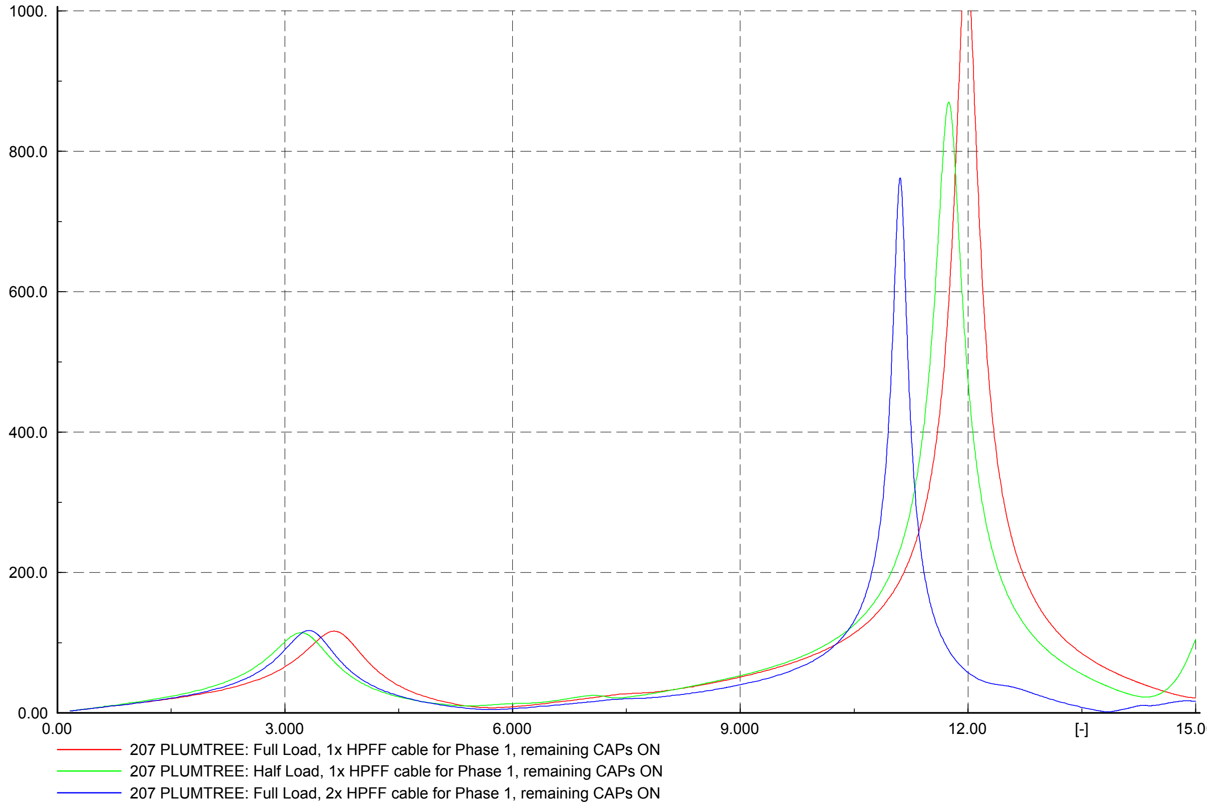

Figure 51: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON - Plumtree 345 kV

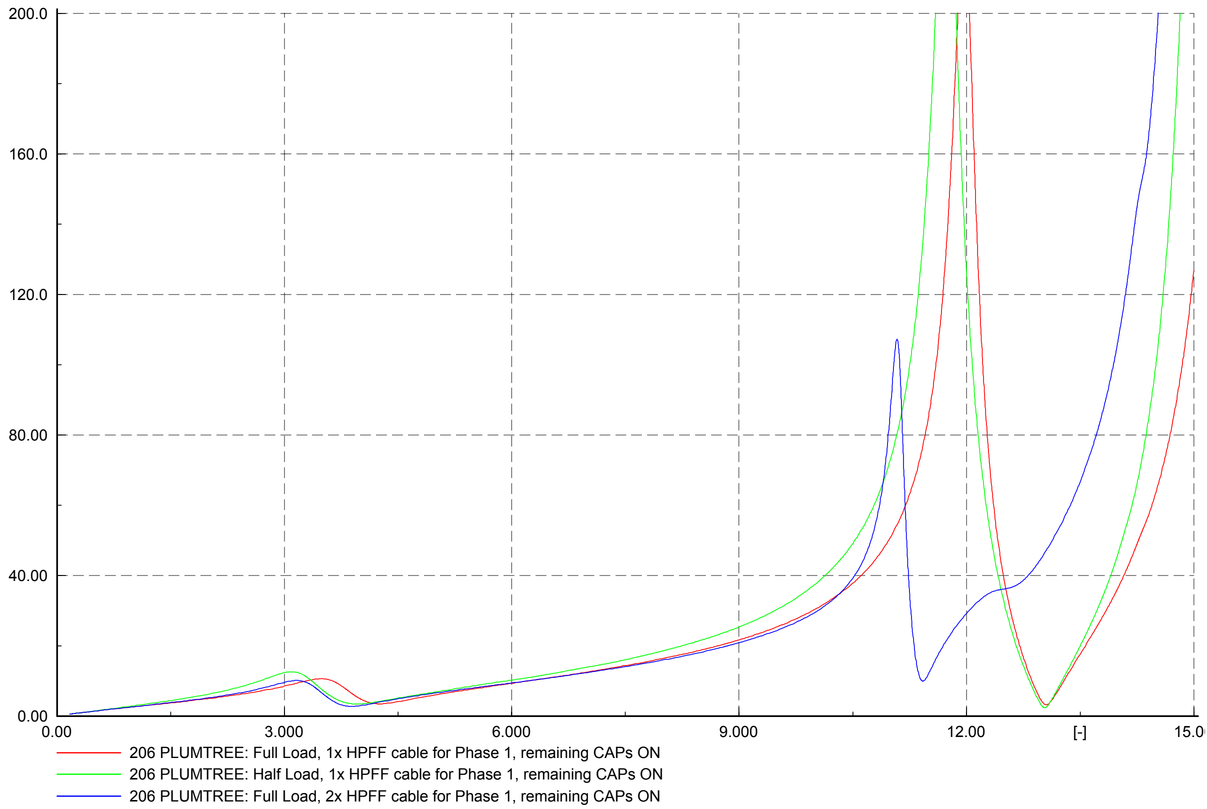

Figure 52: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON - Plumtree 115 kV

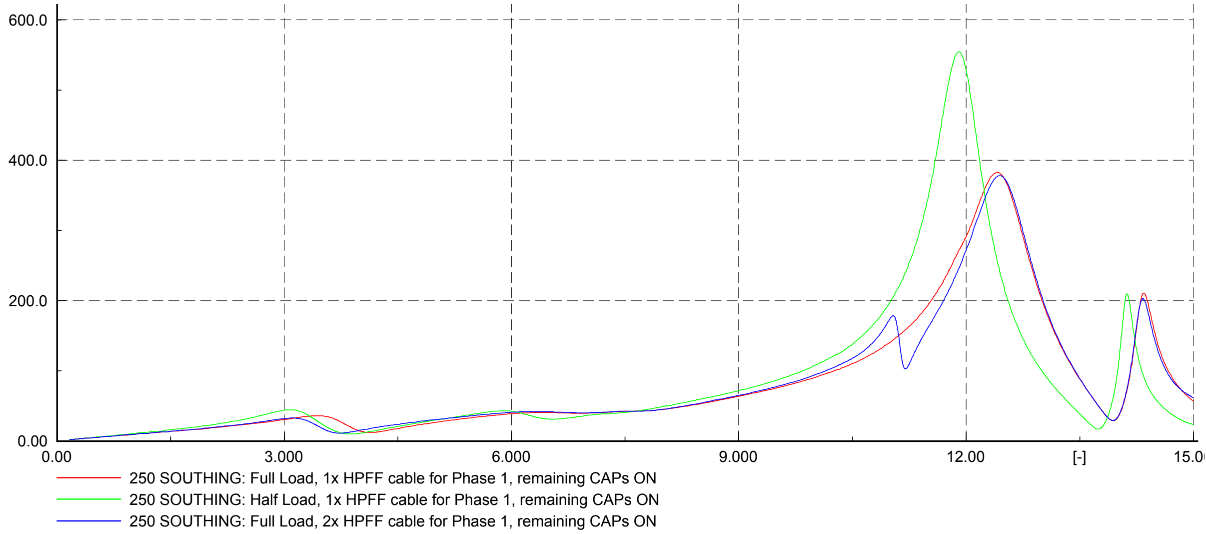

Figure 53: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON - Southing 345 kV

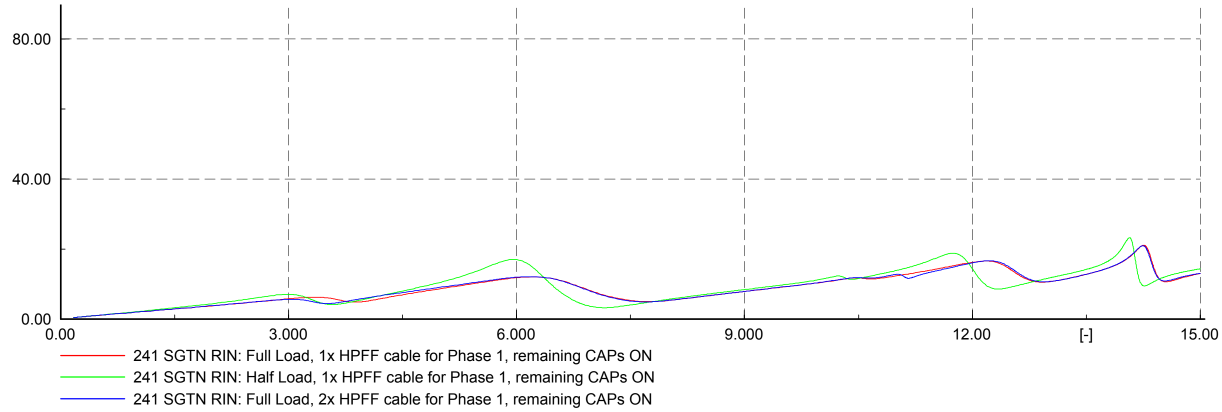

Figure 54: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON - Southing 115 kV

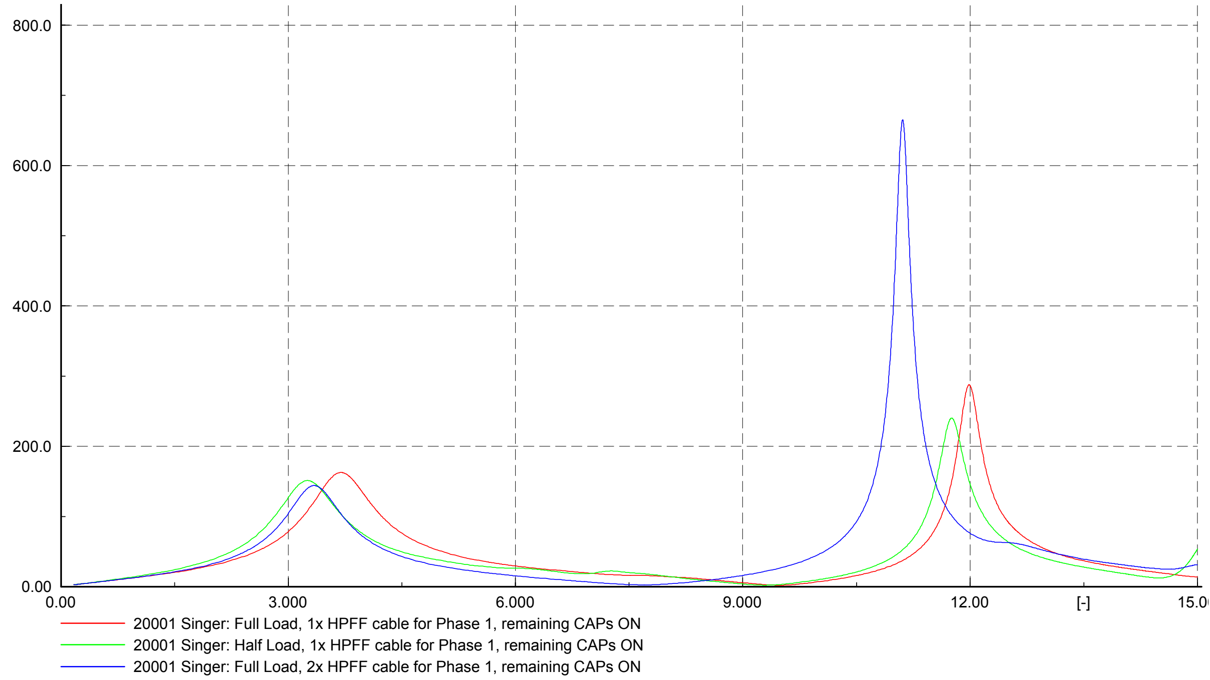

Figure 55: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON - Singer 345 kV

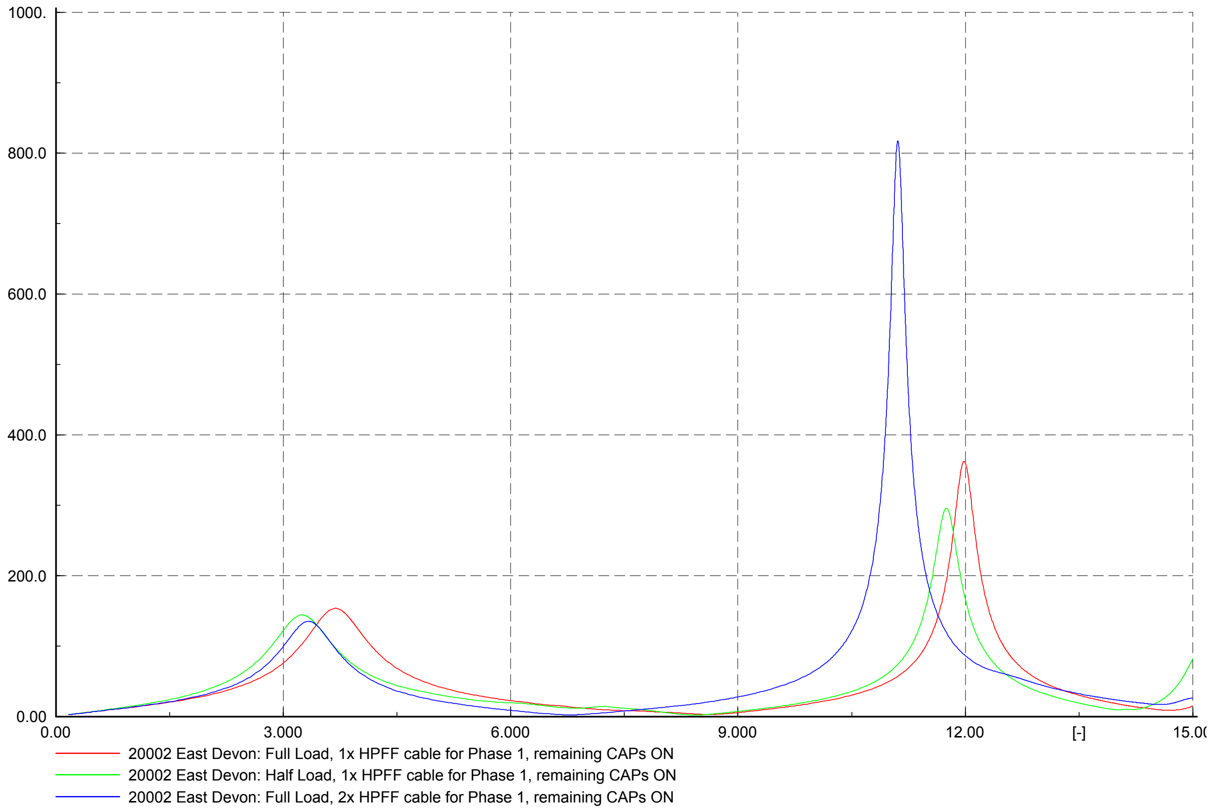

Figure 56: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON – Devon 345 kV

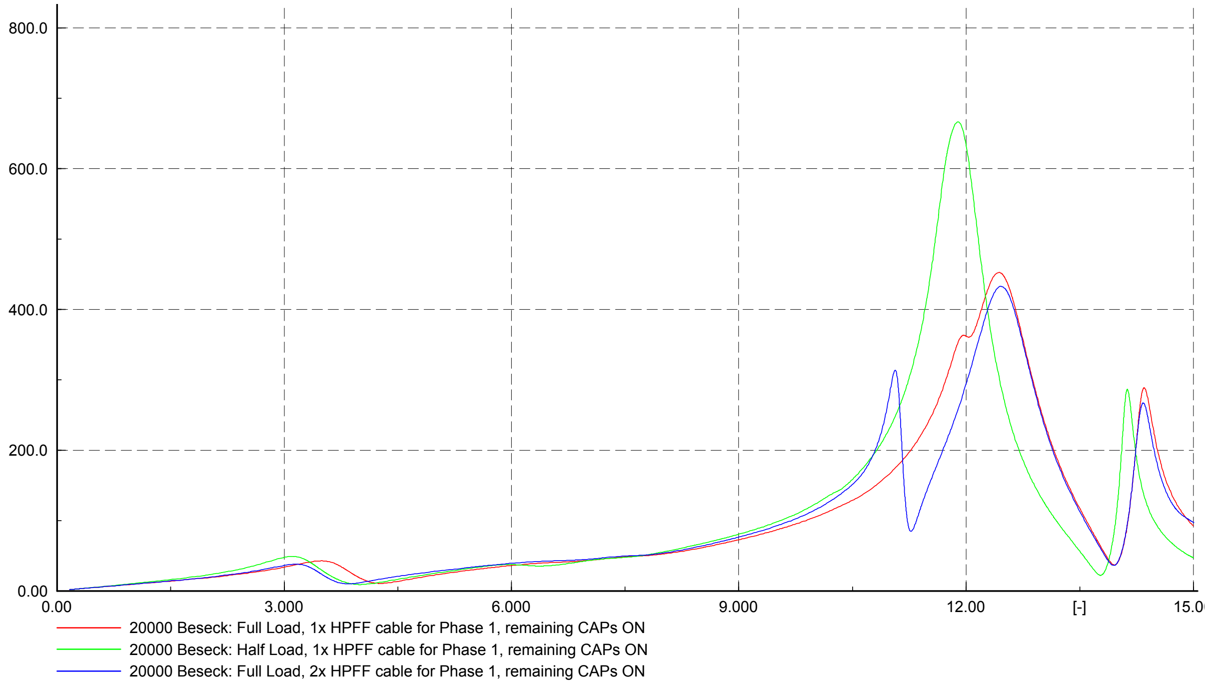

Figure 57: Case II-5:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON – Beseck 345 kV

10.3.2 CASE II-5B:- NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, STATCOM, ALL REMAINING CAPACITORS ON (SHUNT REACTORS ON)

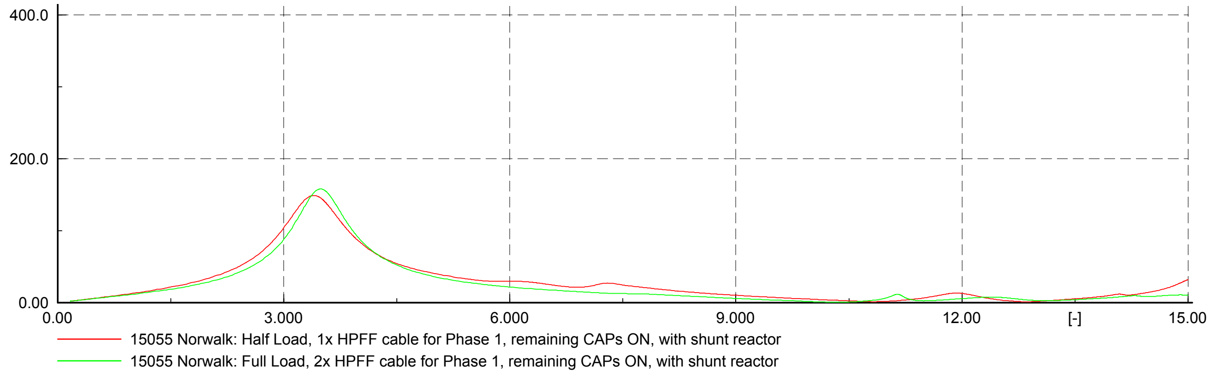

Figure 58: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) - Norwalk 345 kV

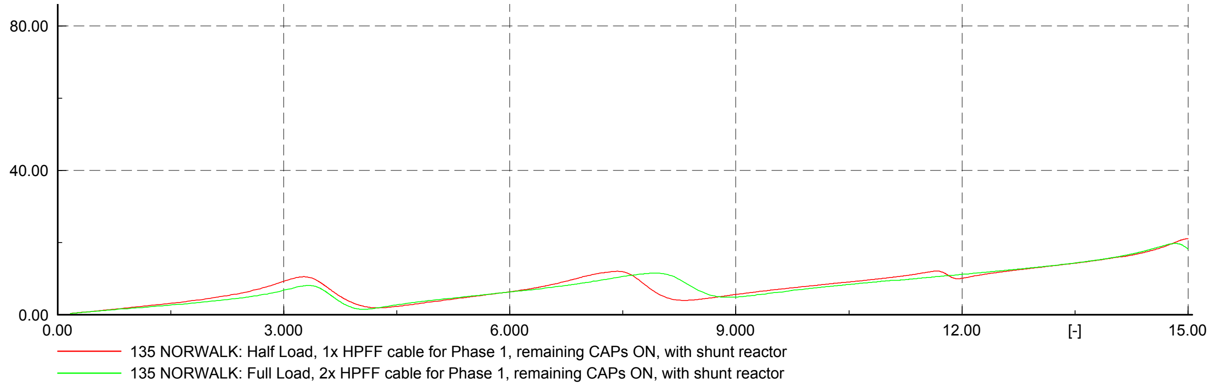

Figure 59: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) - Norwalk 115 kV

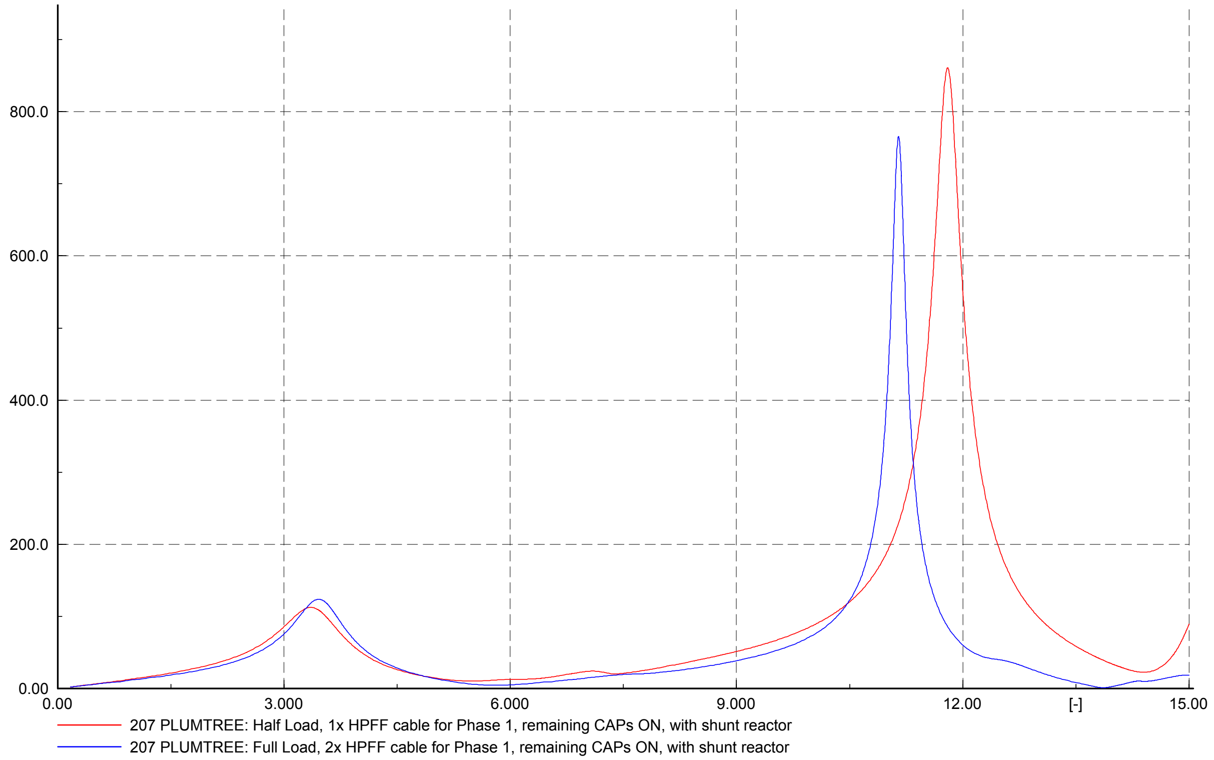

Figure 60: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) - Plumtree 345 kV

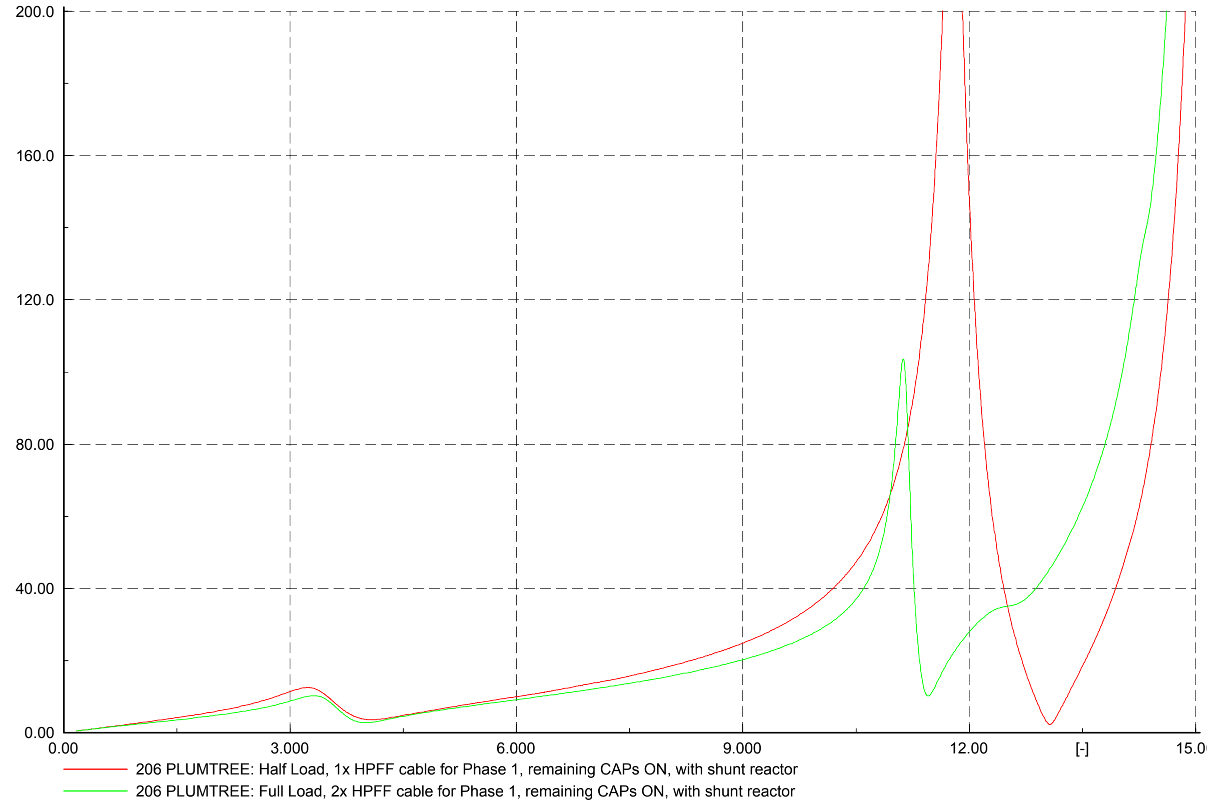

Figure 61: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) - Plumtree 115 kV

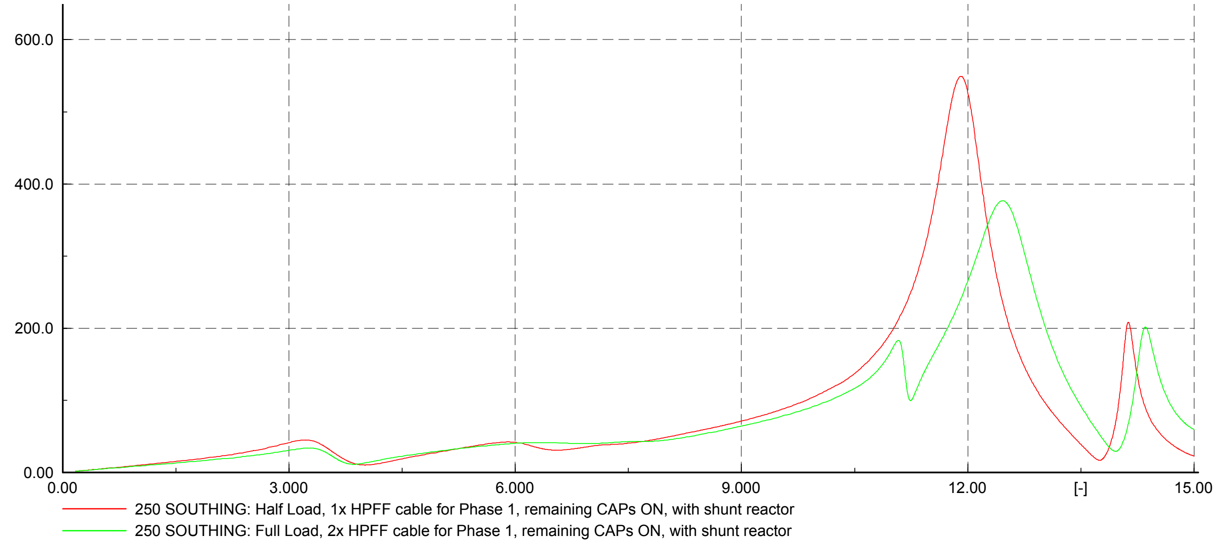

Figure 62: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) - Southington 345 kV

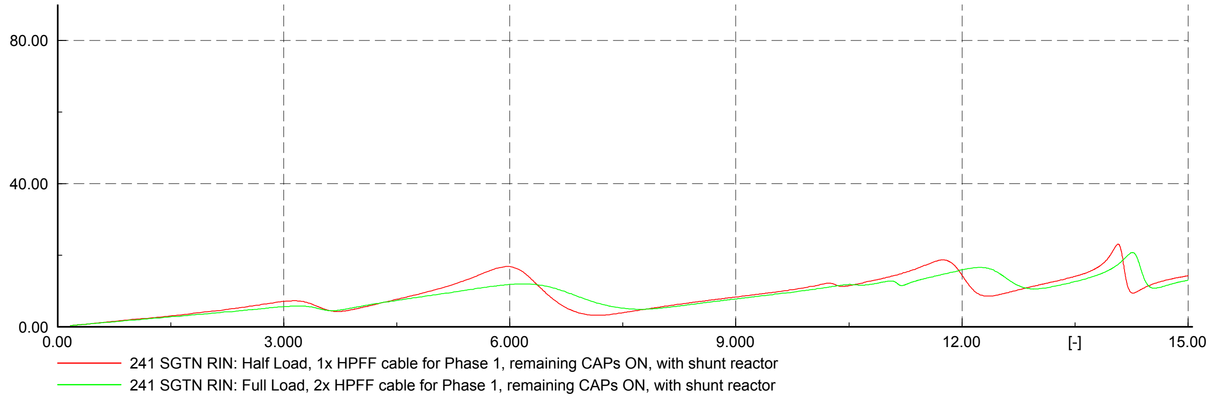

Figure 63: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) – Southington Ring 1 115 kV

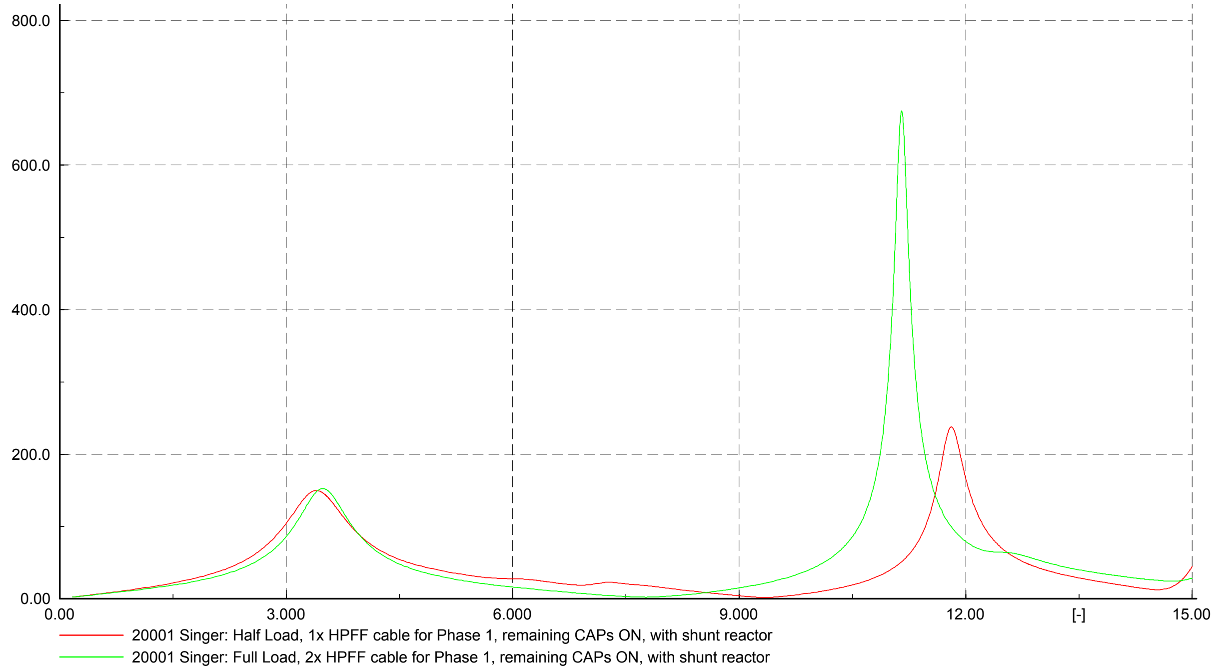

Figure 64: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) - Singer 345 kV

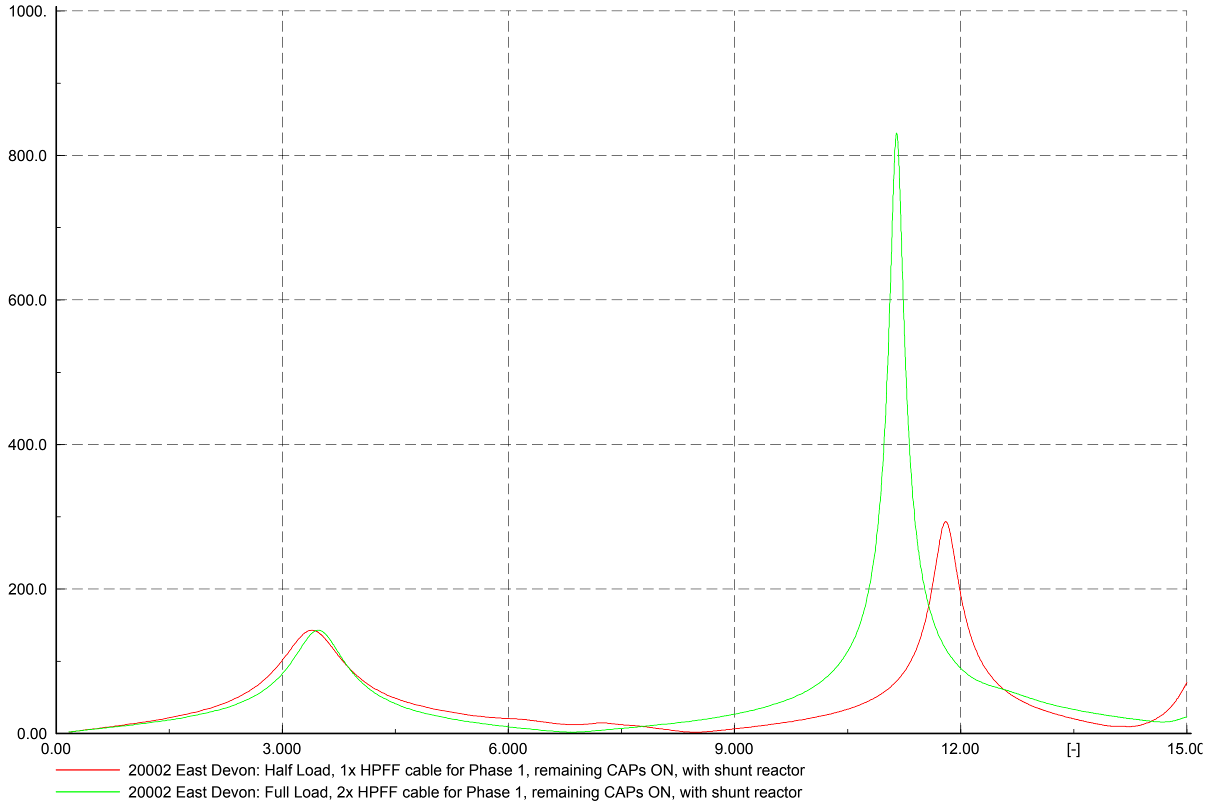

Figure 65: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) – Devon 345 kV

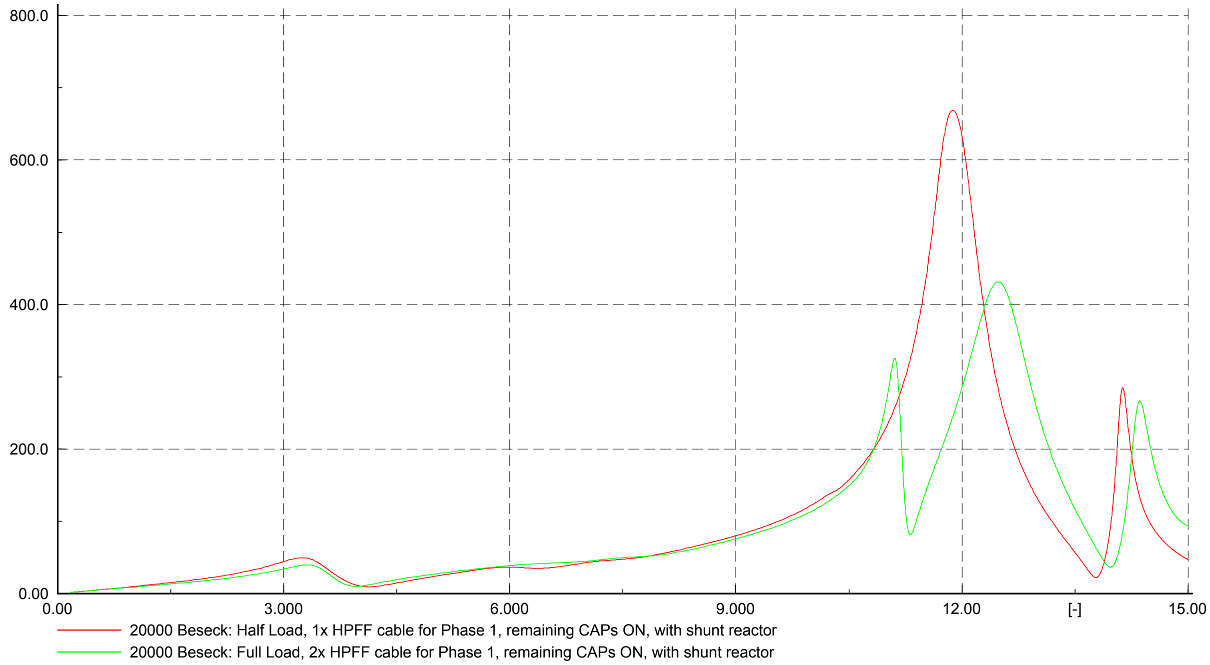

Figure 66: Case II-5b:- Norwalk - Devon XLPE, Minimum Dispatch, STATCOM, All remaining Capacitors ON (Shunt Reactors in Service) – Beseck 345 kV

10.3.3 CASE II-6:- NORWALK - DEVON XLPE PHASE II, MINIMUM DISPATCH, C-TYPE FILTER, ALL REMAINING CAPACITORS ON

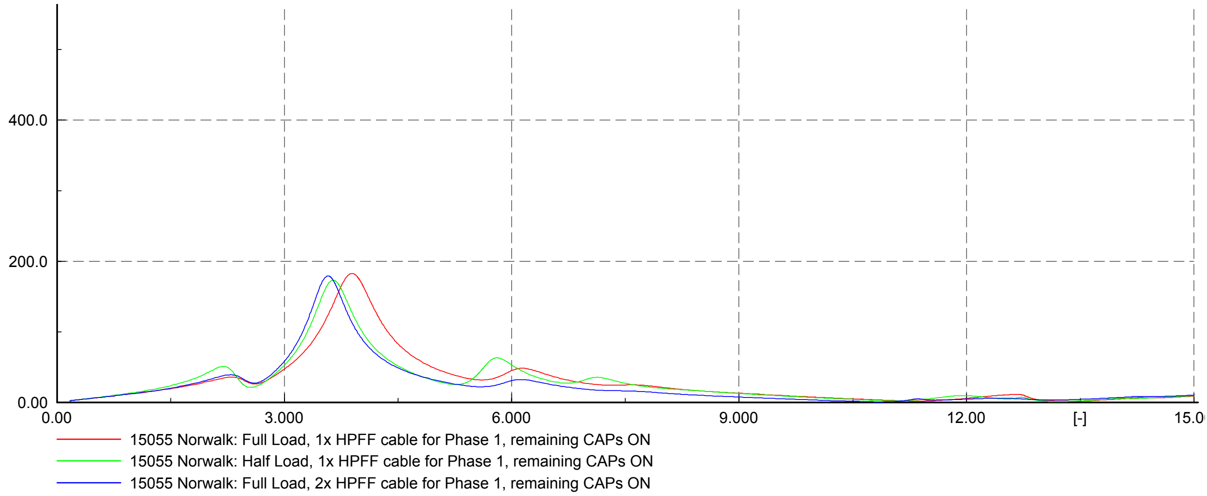

Figure 67: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON - Norwalk 345 kV

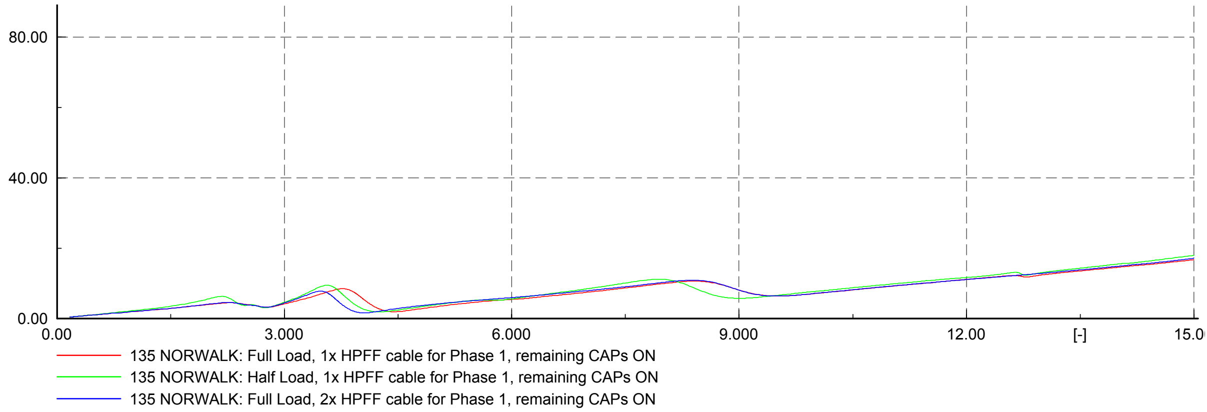

Figure 68: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON - Norwalk 115 kV

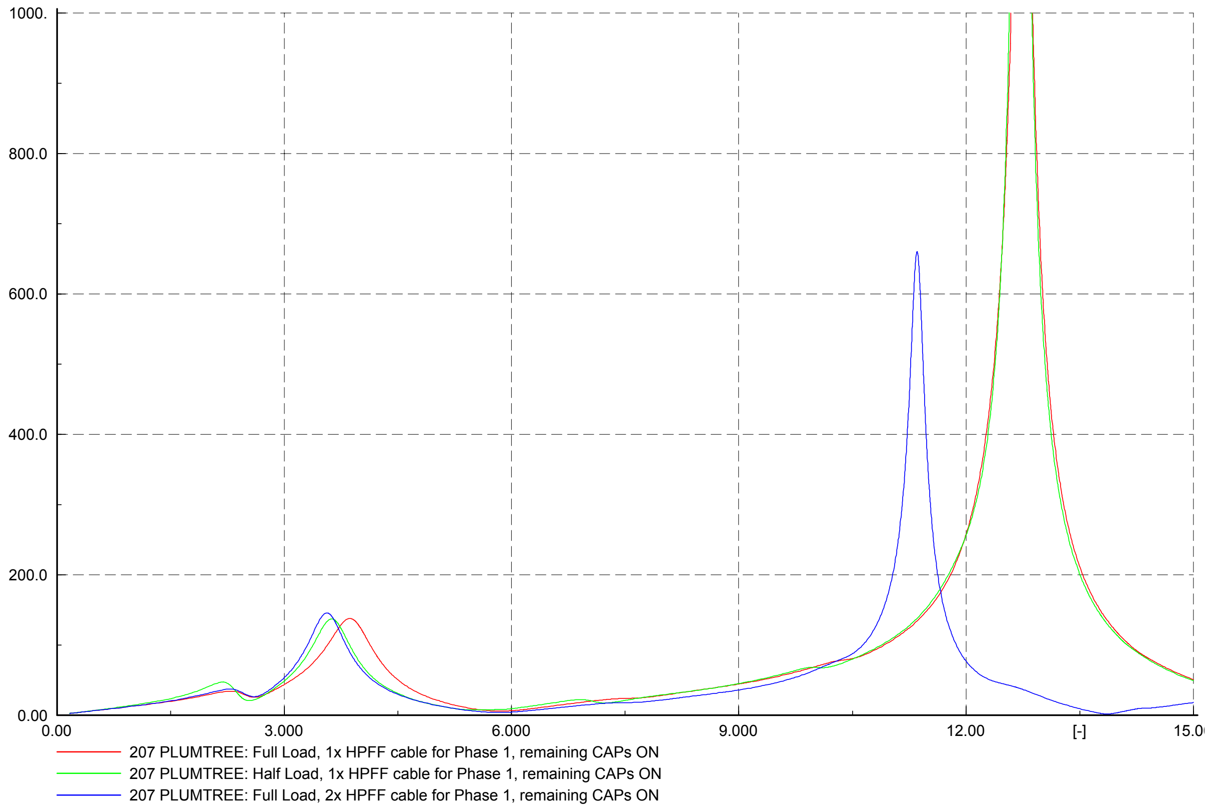

Figure 69: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON - Plumtree 345 kV

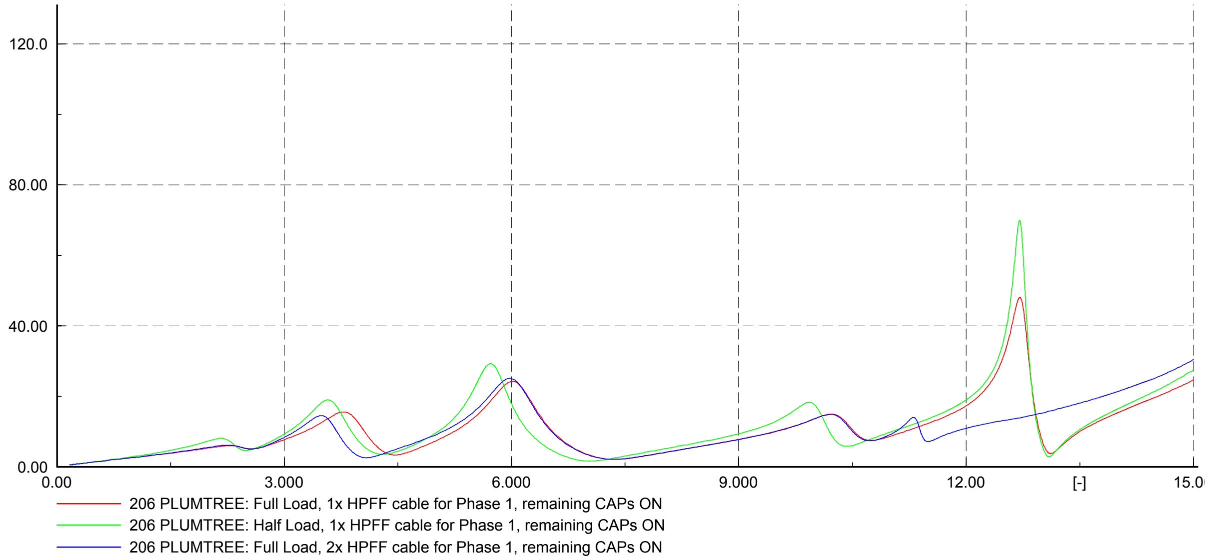

Figure 70: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON - Plumtree 115 kV

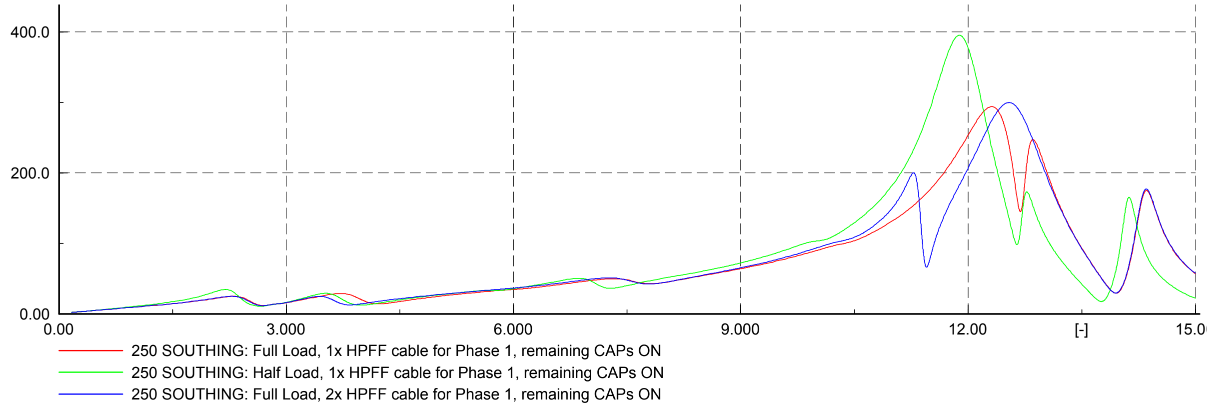

Figure 71: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON - Southing 345 kV

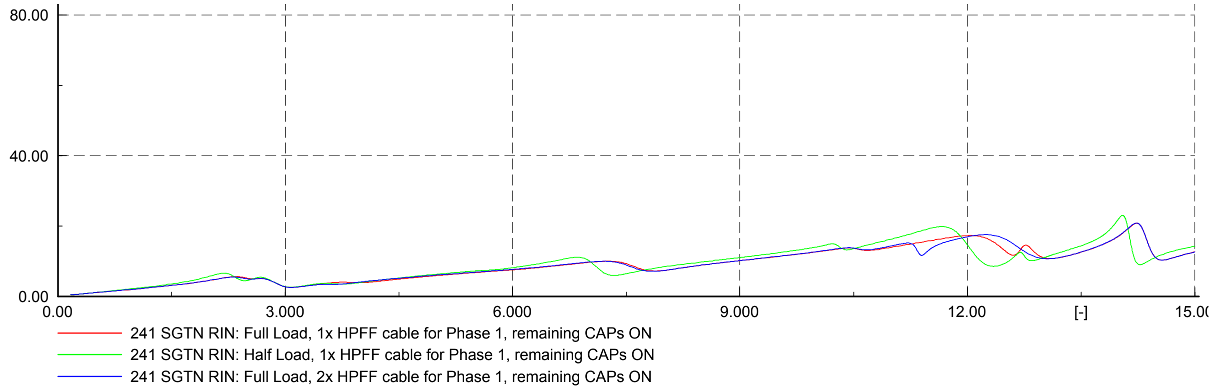

Figure 72: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON - Southing 115 kV

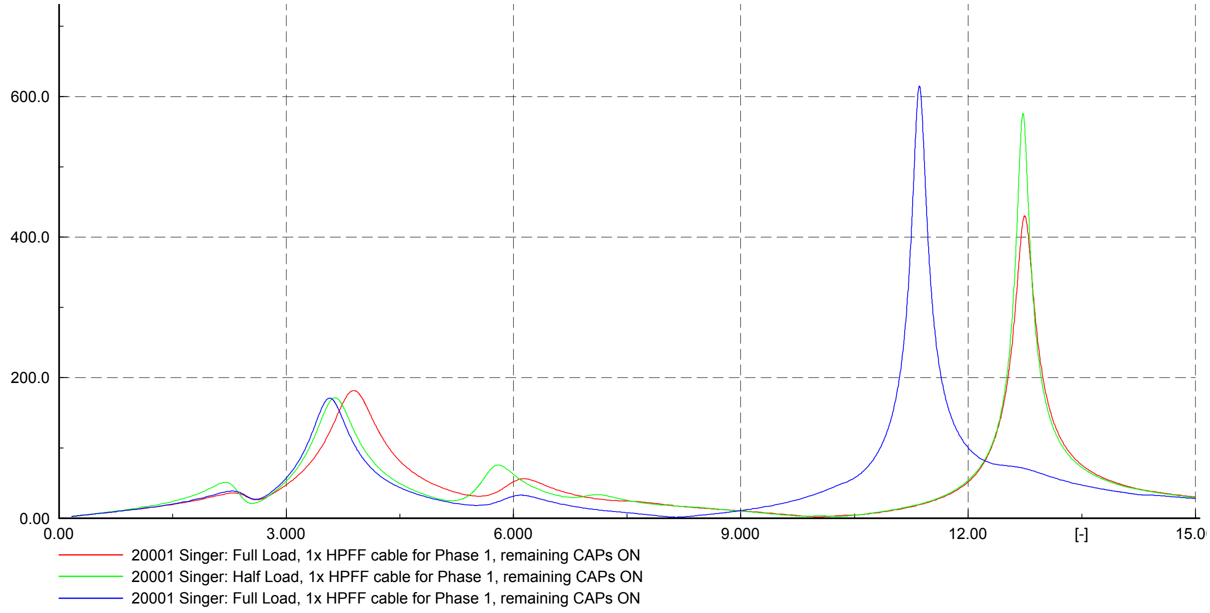

Figure 73: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON - Singer 345 kV

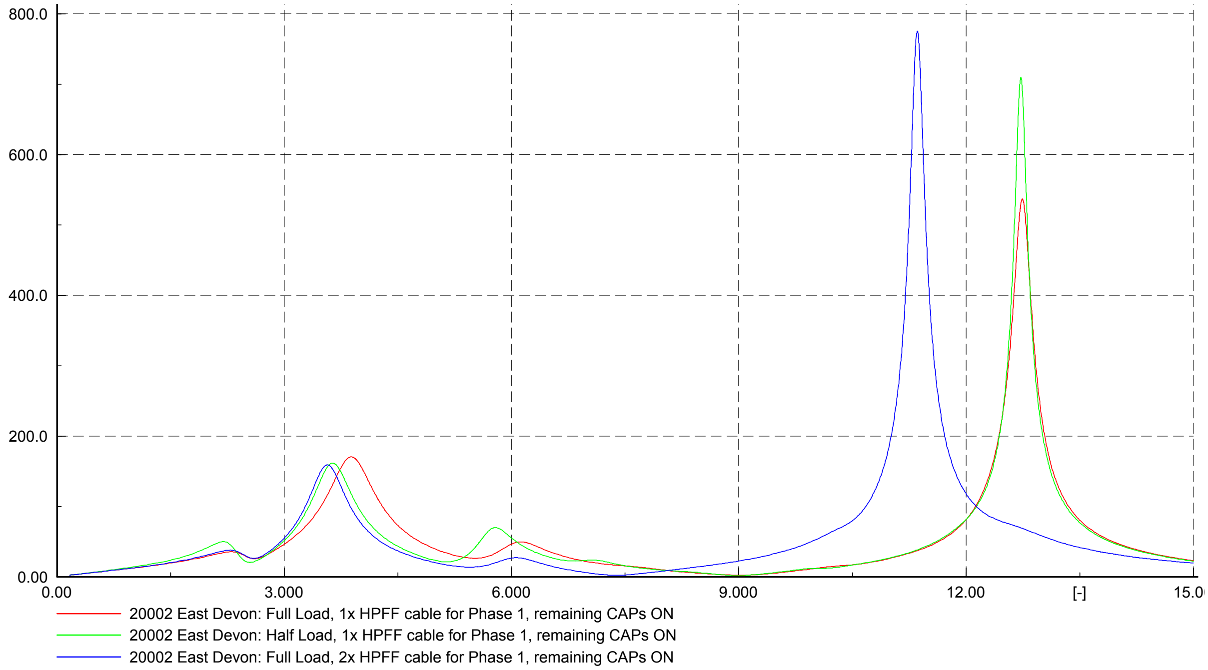

Figure 74: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON – Devon 345 kV

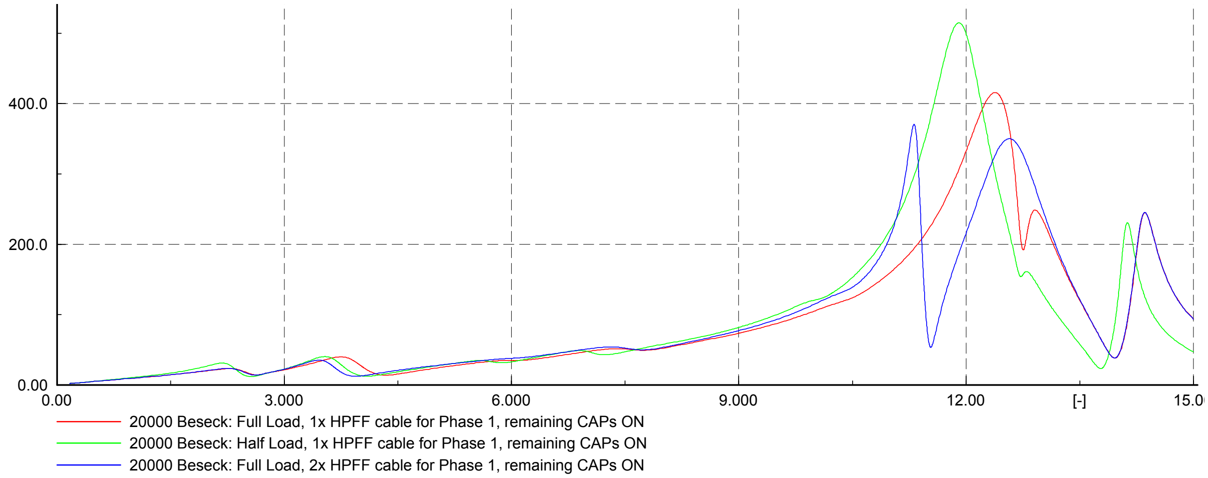

Figure 75: Case II-6:- Norwalk - Devon XLPE Phase II, Minimum Dispatch, C-Type Filter, All remaining Caps ON – Beseck 345 kV

10.4 Graphs of Extended Undergrounding Alternatives

10.4.1 CASE II-7:- DEVON - BESECK 10-MILE XLPE PHASE II, MINIMUM DISPATCH

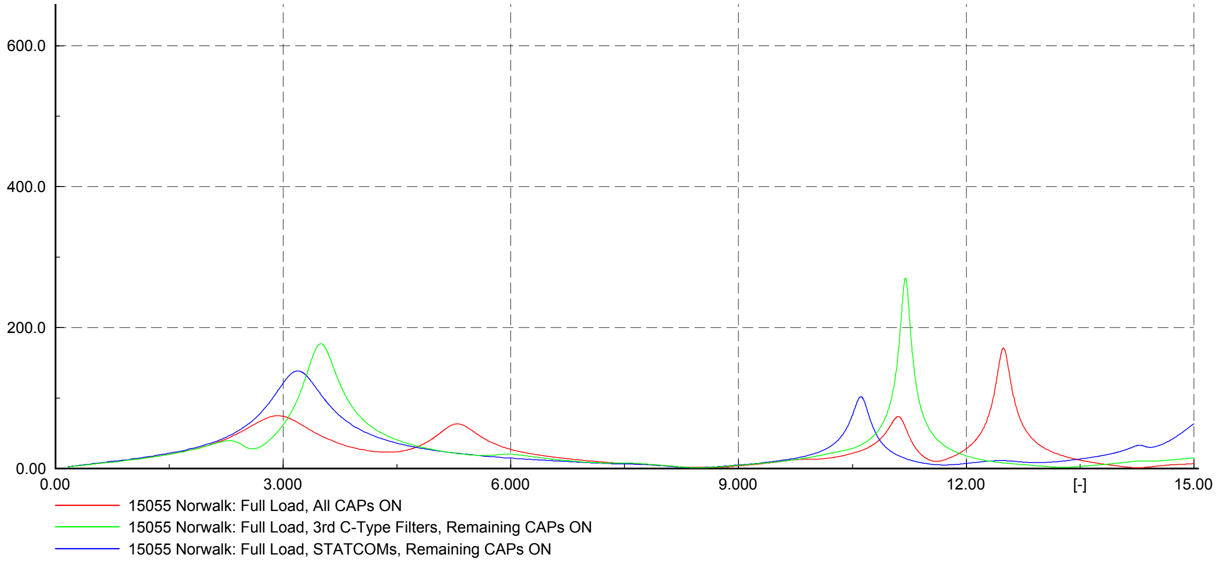

Figure 76: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch - Norwalk 345 kV

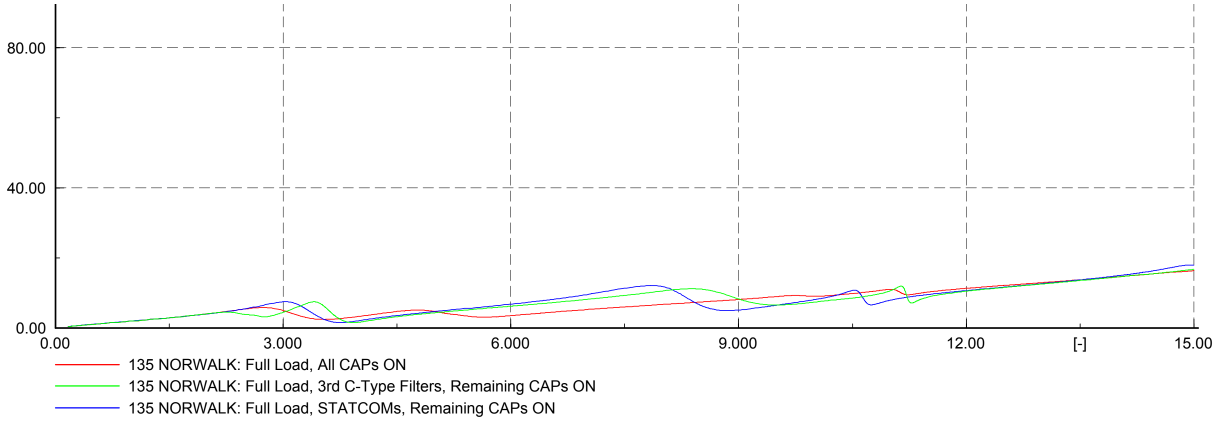

Figure 77: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch - Norwalk 115 kV

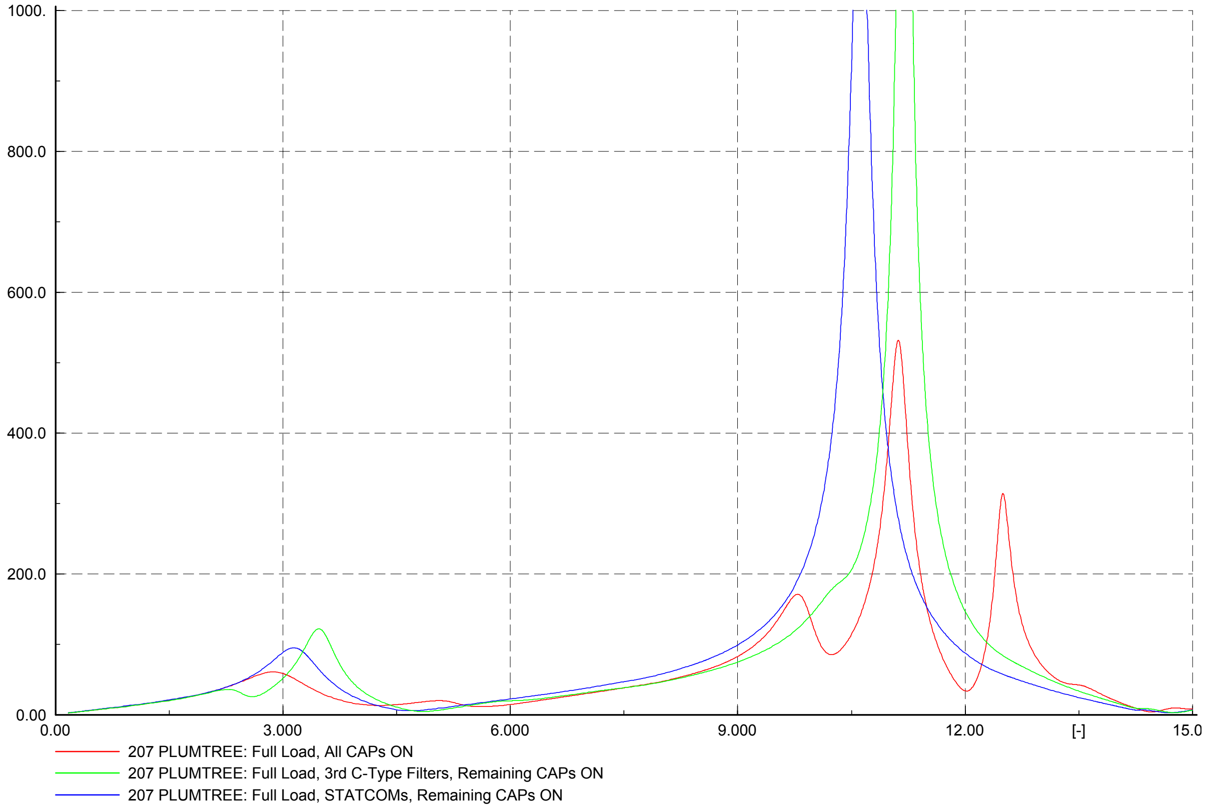

Figure 78: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch - Plumtree 345 kV

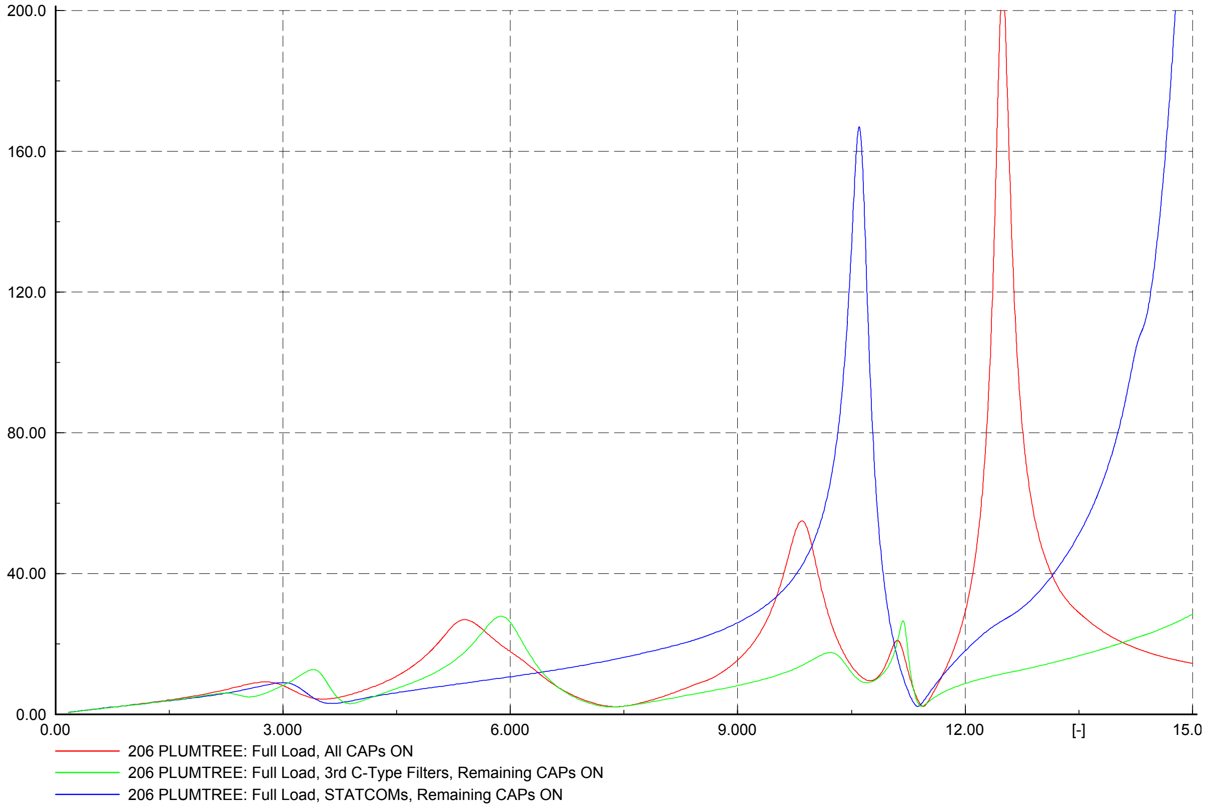

Figure 79: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch - Plumtree 115 kV

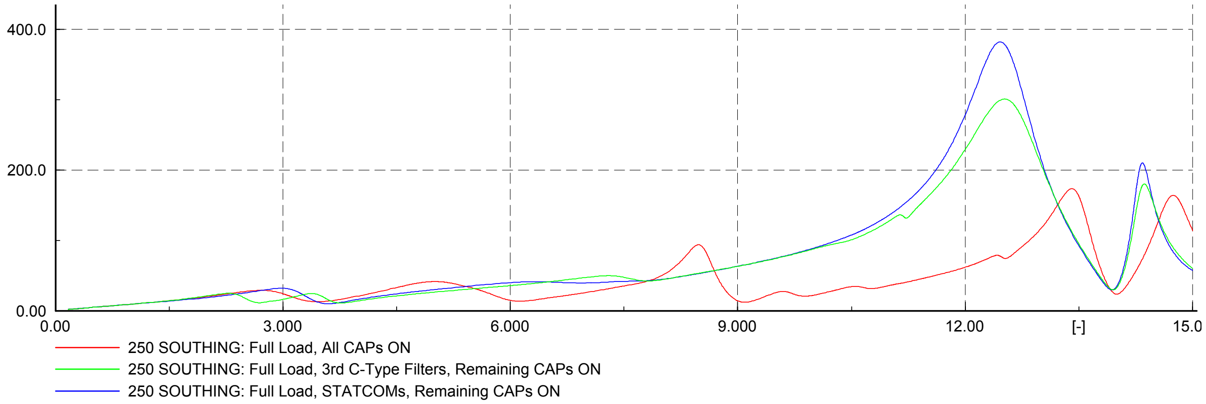

Figure 80: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch – Southington 345 kV

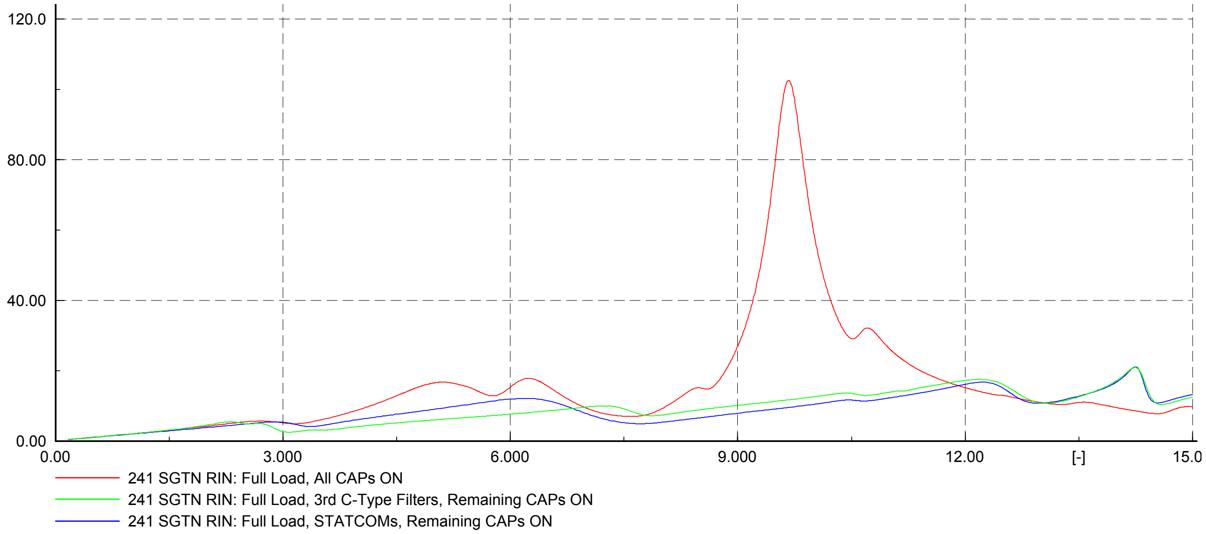

Figure 81: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch – Southington Ring 1 115 kV

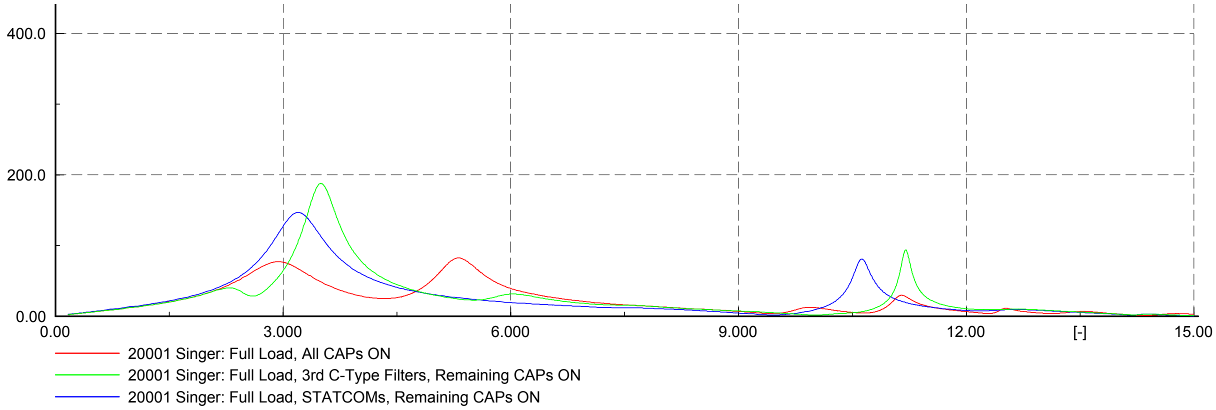

Figure 82: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch - Singer 345 kV

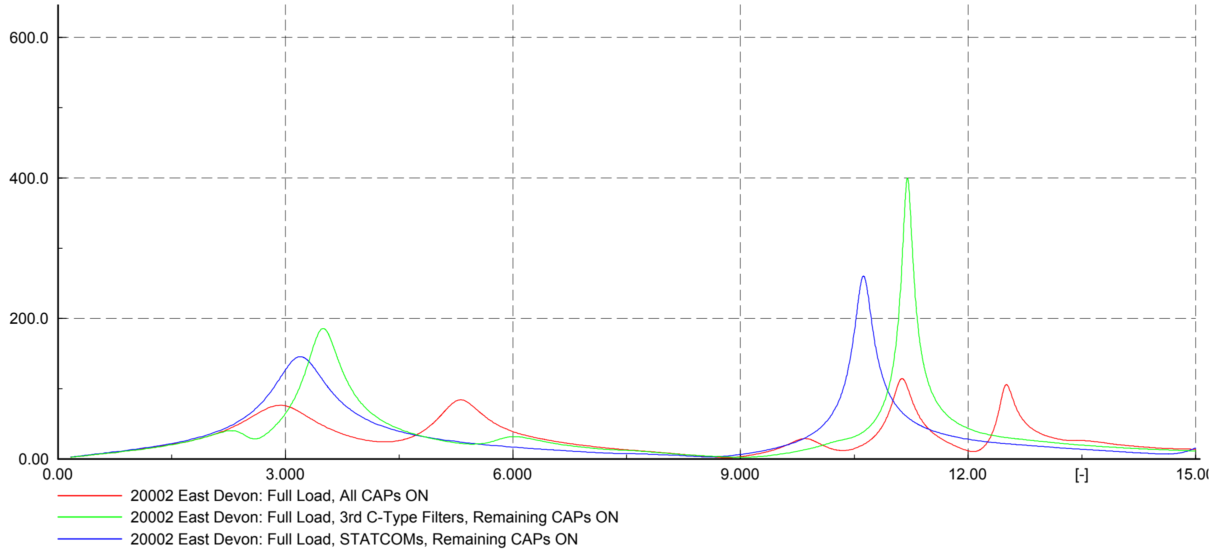

Figure 83: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch – Devon 345 kV

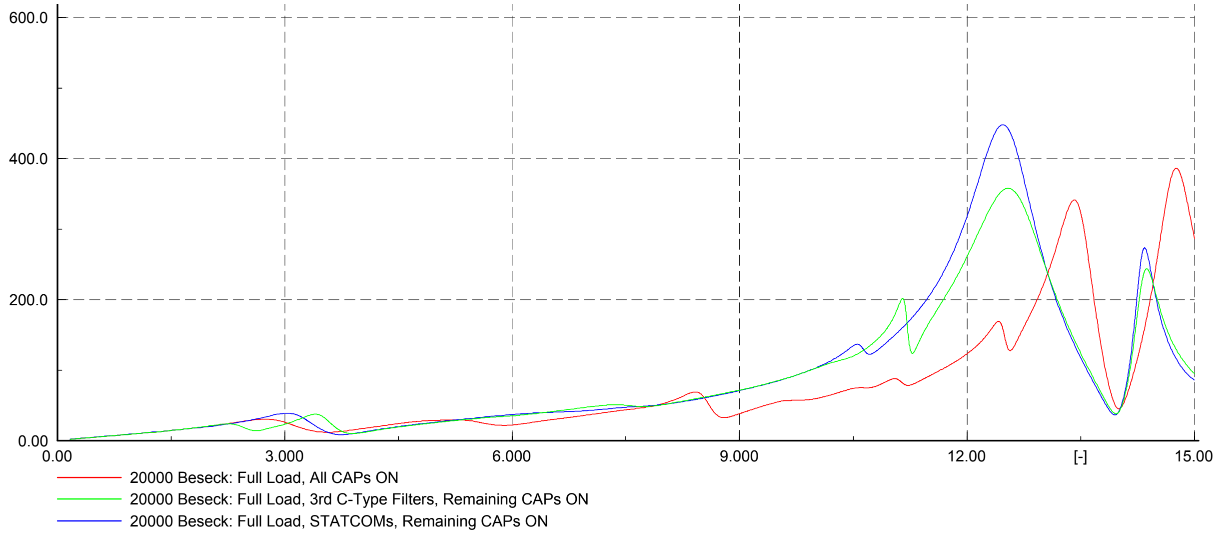

Figure 84: Case II-7:- Devon - Beseck 10-mile XLPE, Minimum Dispatch – Beseck 345 kV

10.4.2 CASE II-8:- DEVON - BESECK 20-MILE XLPE PHASE II, MINIMUM DISPATCH

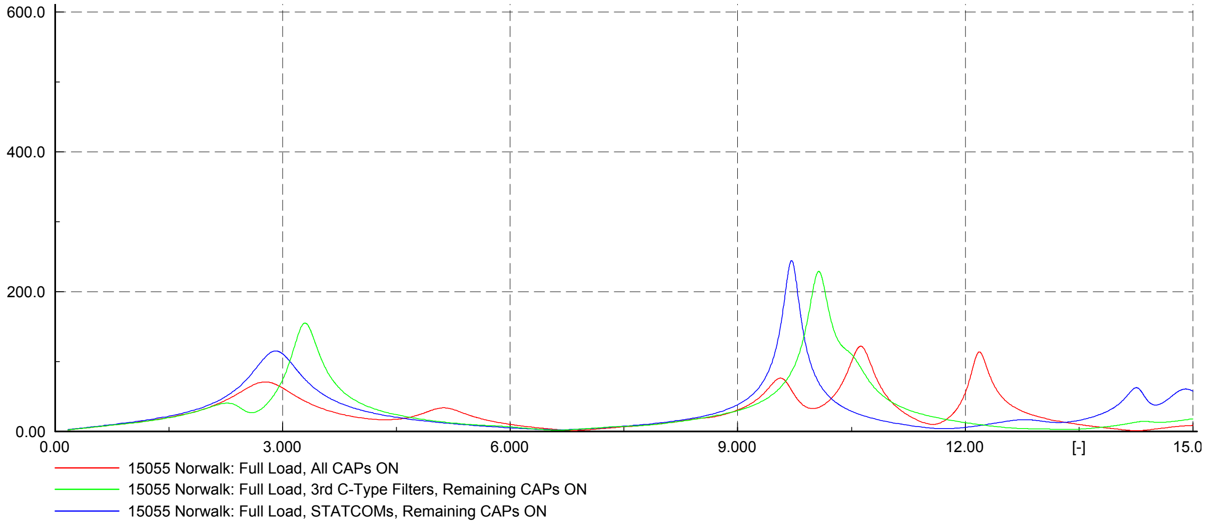

Figure 85: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch - Norwalk 345 kV

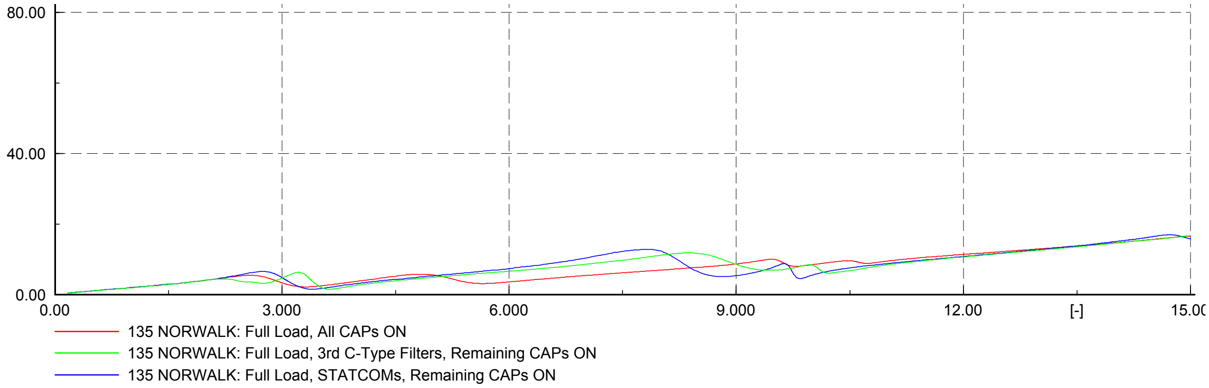

Figure 86: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch - Norwalk 115 kV

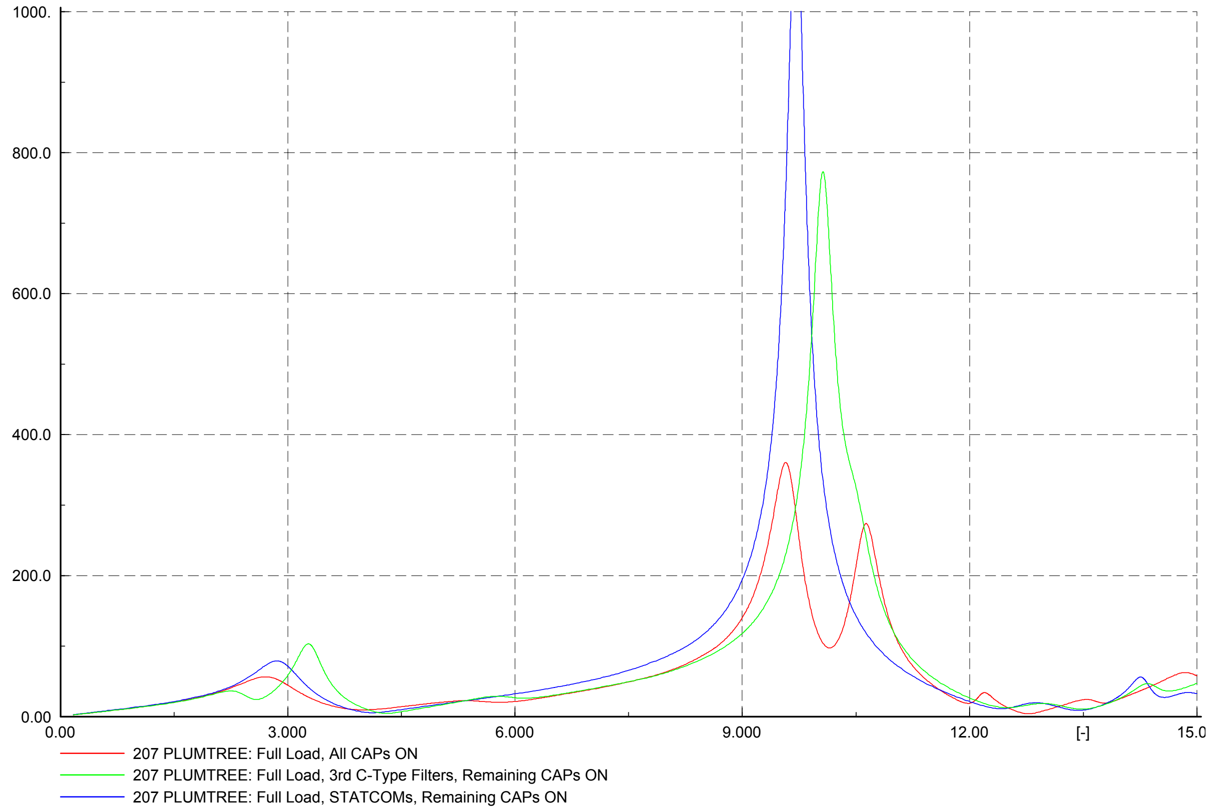

Figure 87: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch - Plumtree 345 kV

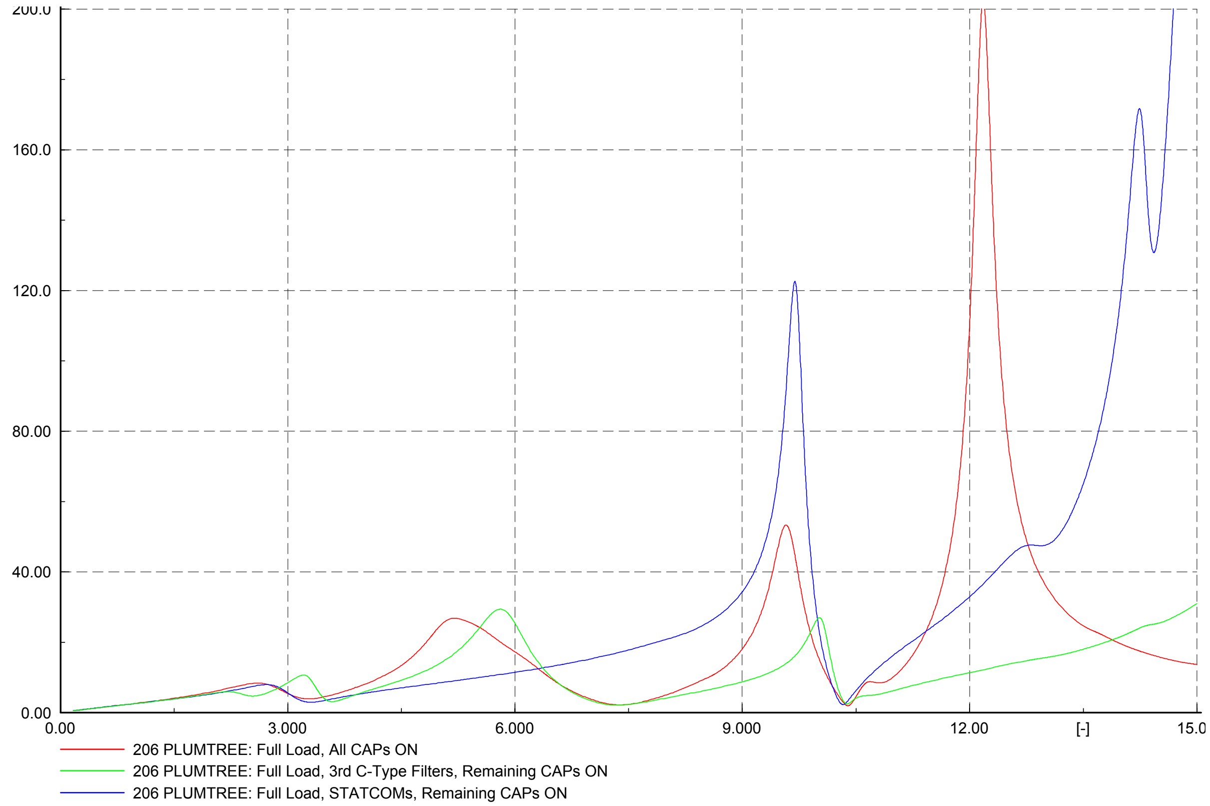

Figure 88: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch - Plumtree 115 kV

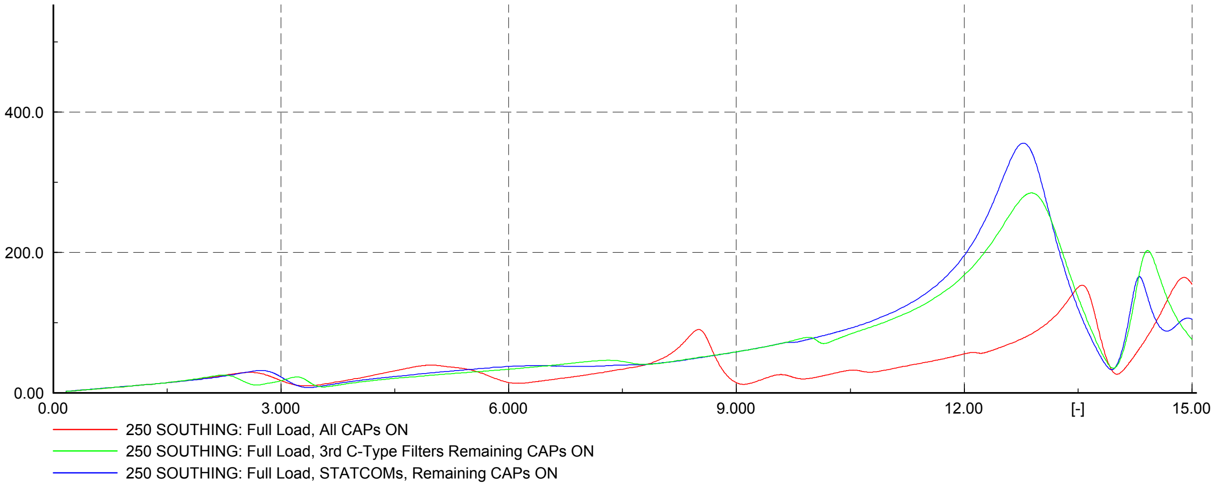

Figure 89: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch – Southington 345 kV

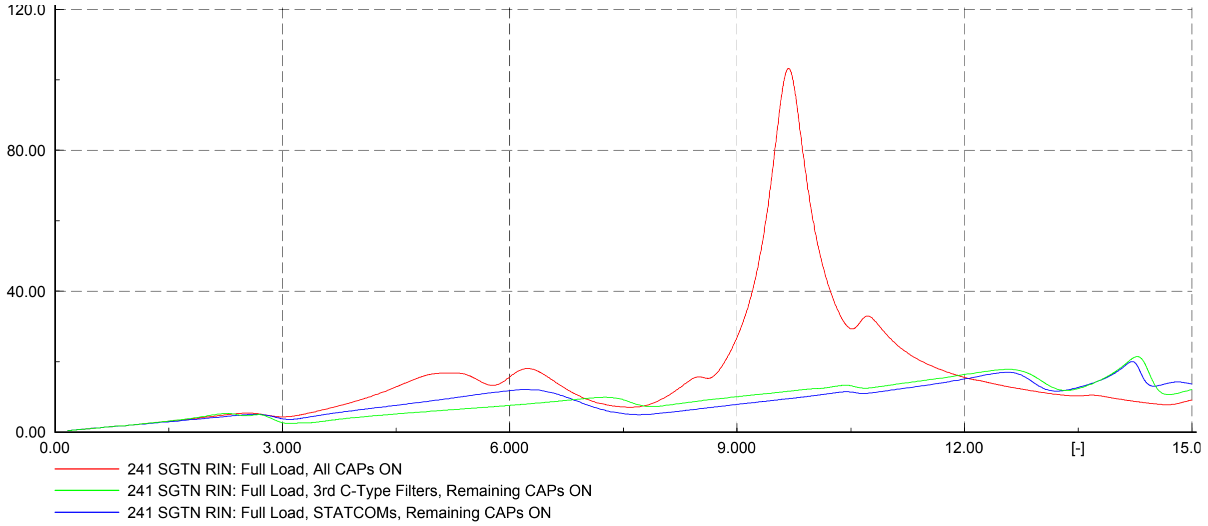

Figure 90: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch – Southington Ring 1 115 kV

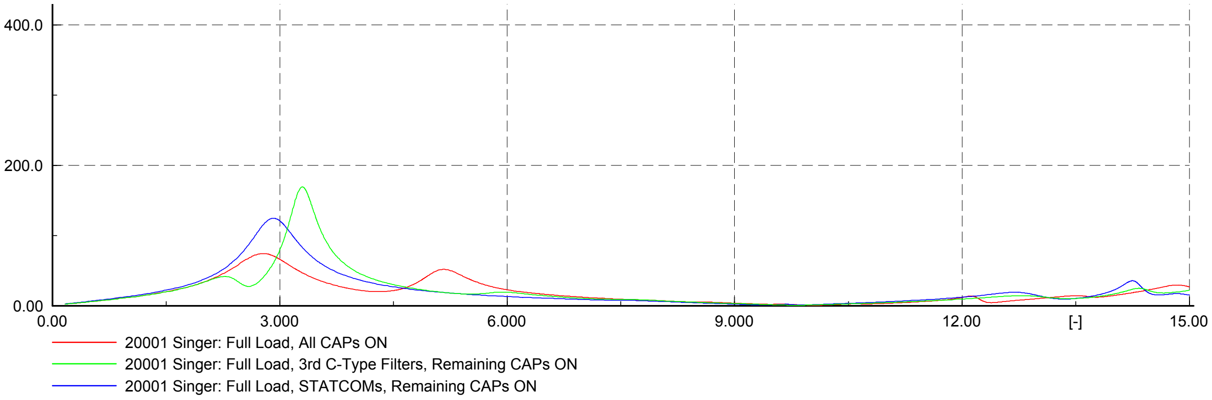

Figure 91: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch - Singer 345 kV

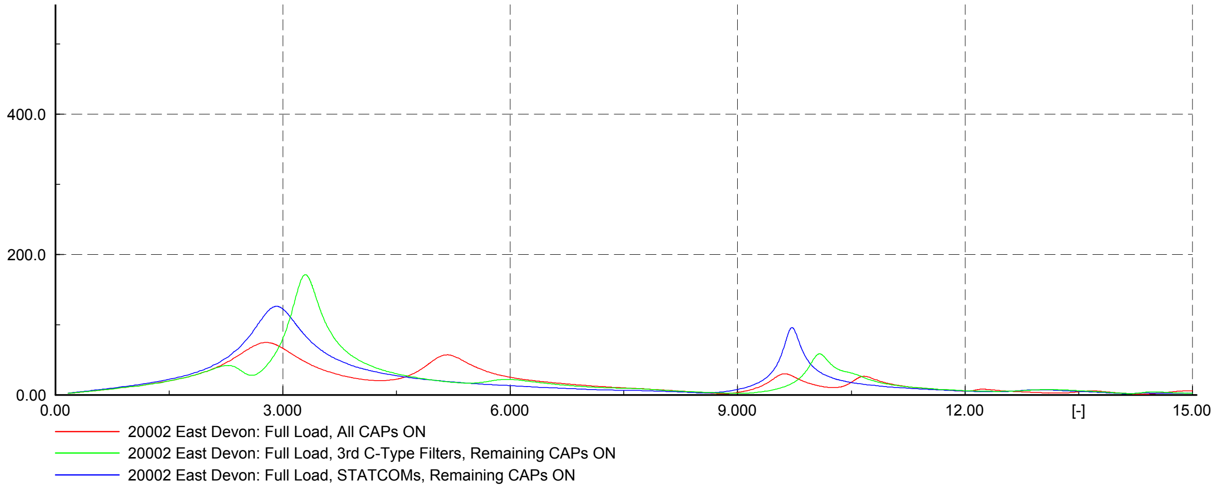

Figure 92: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch – Devon 345 kV

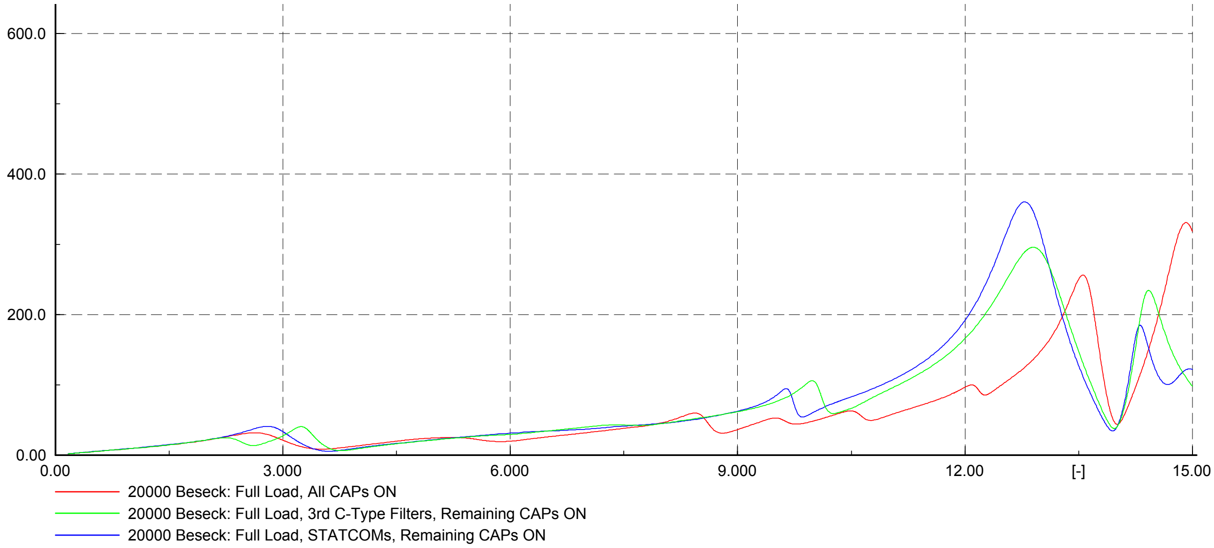

Figure 93: Case II-8:- Devon - Beseck 20-mile XLPE, Minimum Dispatch – Beseck 345 kV

10.4.3 CASE II-9:- DEVON - BESECK 40-MILE XLPE PHASE II, MINIMUM DISPATCH

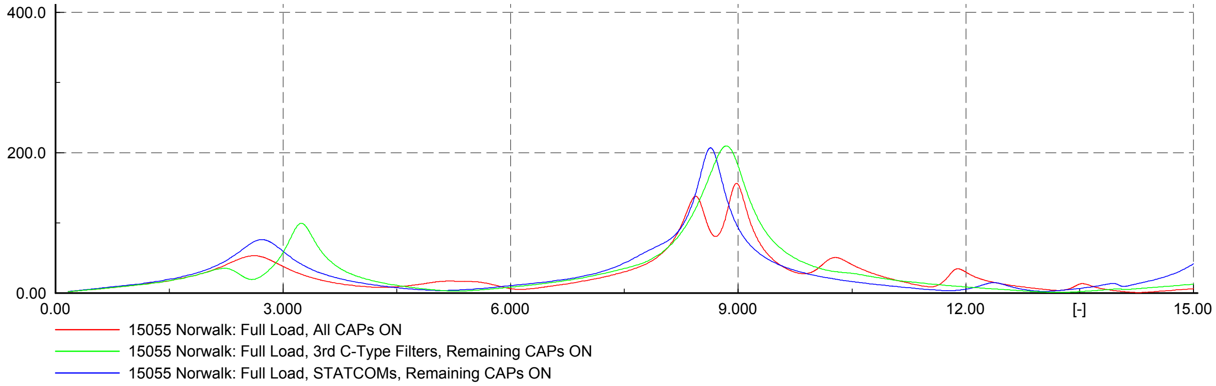

Figure 94: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch - Norwalk 345 kV

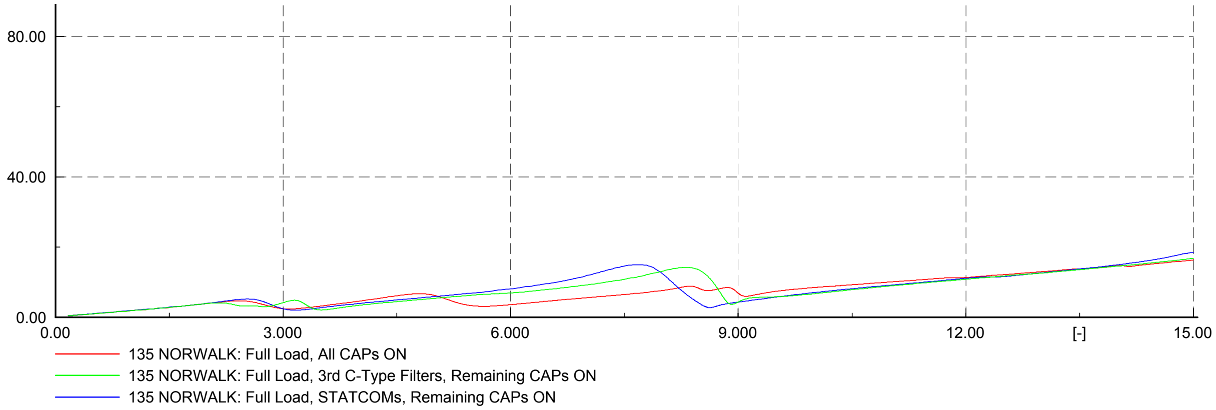

Figure 95: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch - Norwalk 115 kV

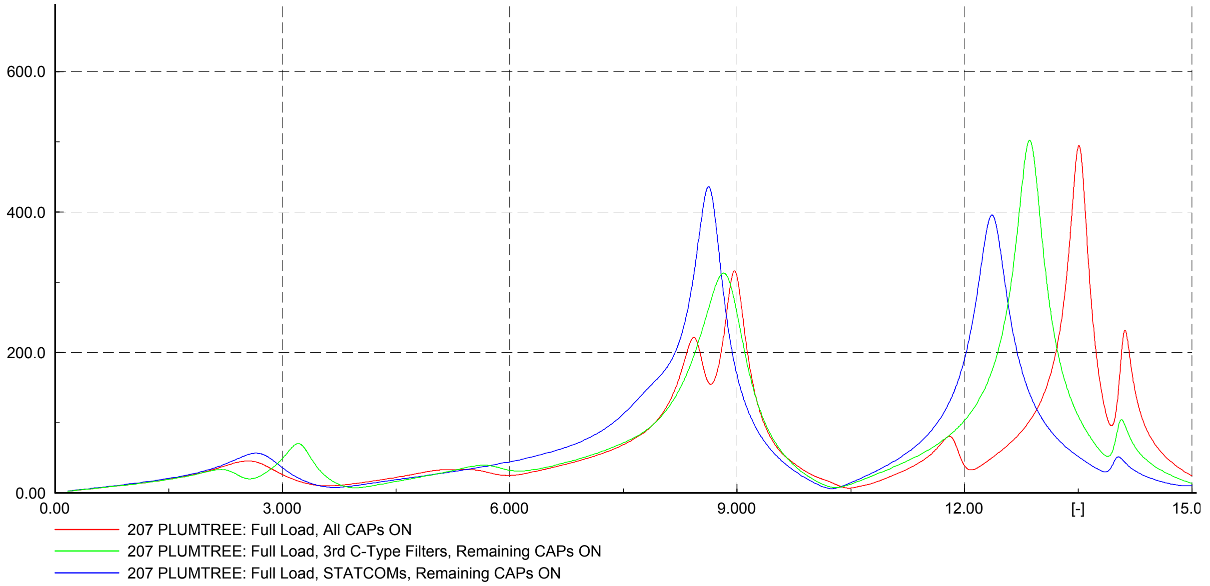

Figure 96: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch - Plumtree 345 kV

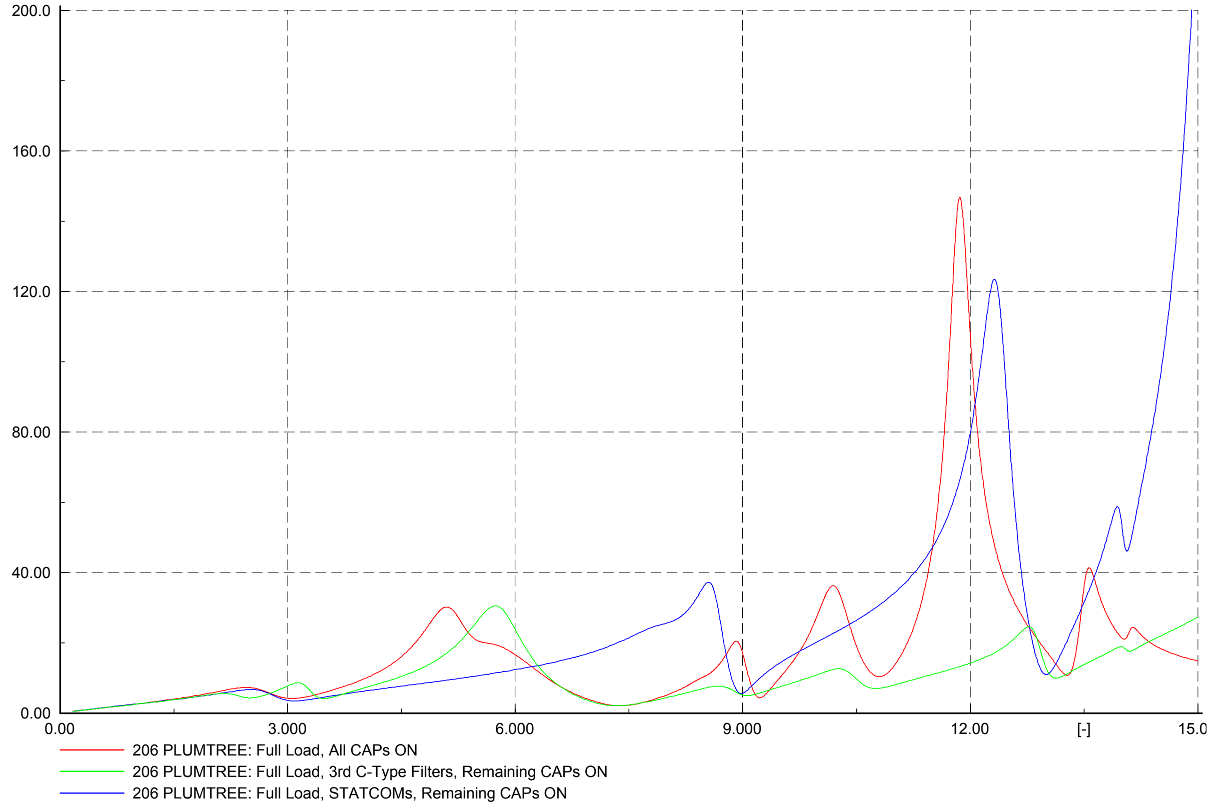

Figure 97: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch - Plumtree 115 kV

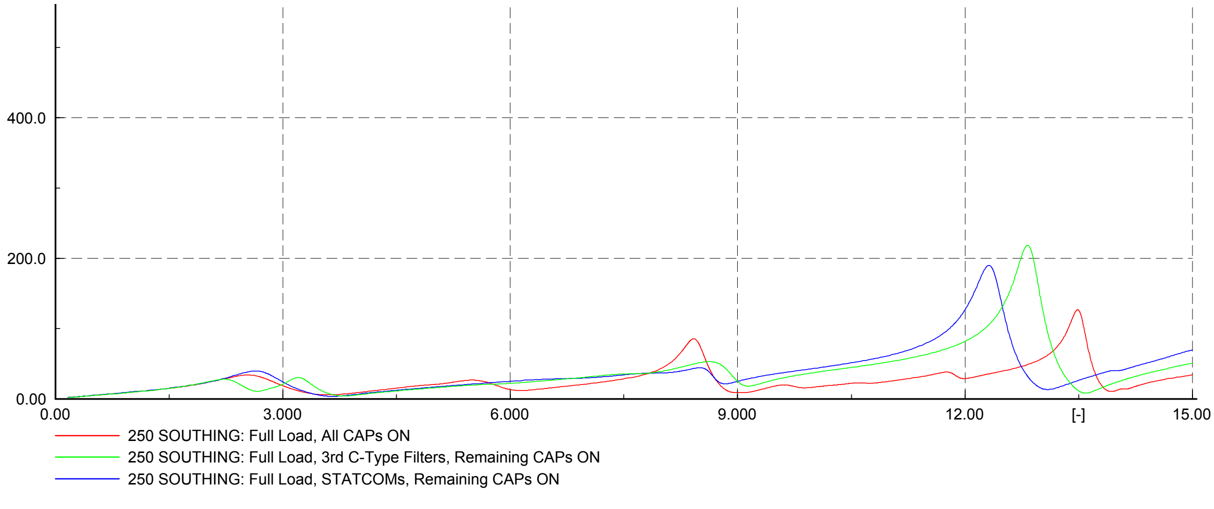

Figure 98: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch – Southington 345 kV

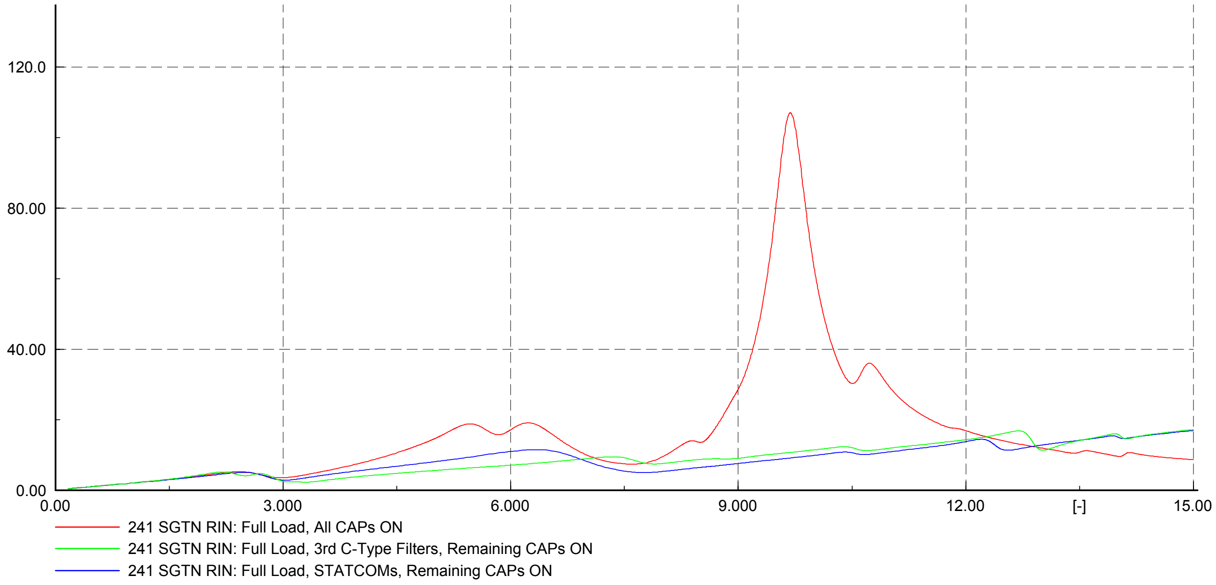

Figure 99: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch – Southington Ring 1 115 kV

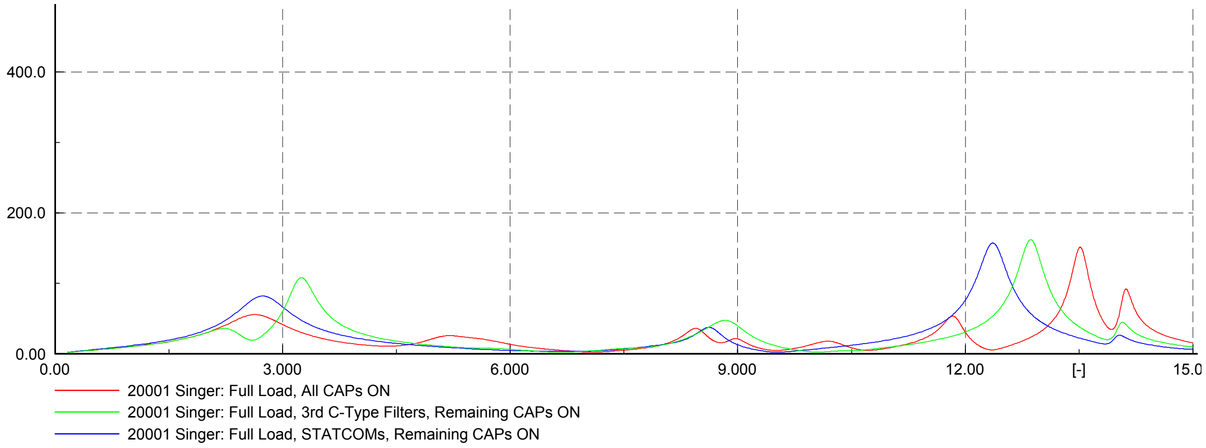

Figure 100: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch - Singer 345 kV

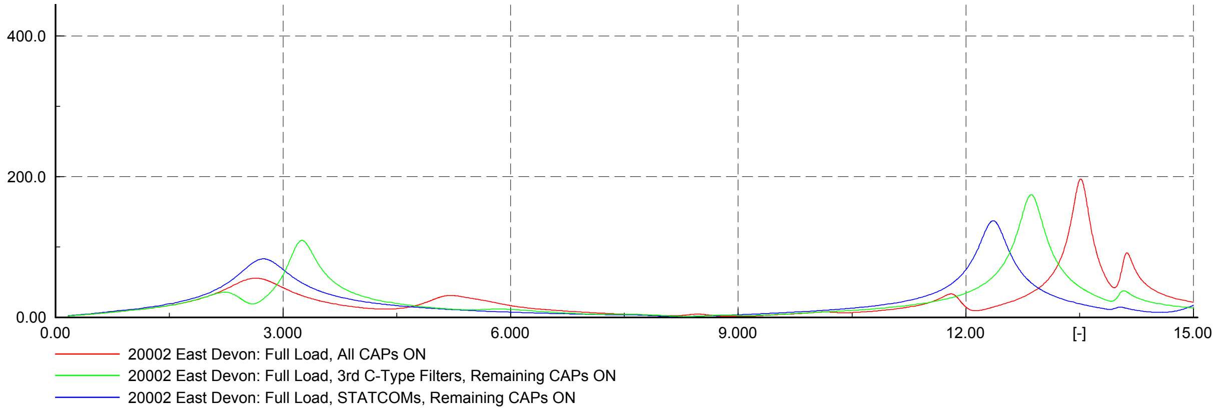

Figure 101: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch – Devon 345 kV

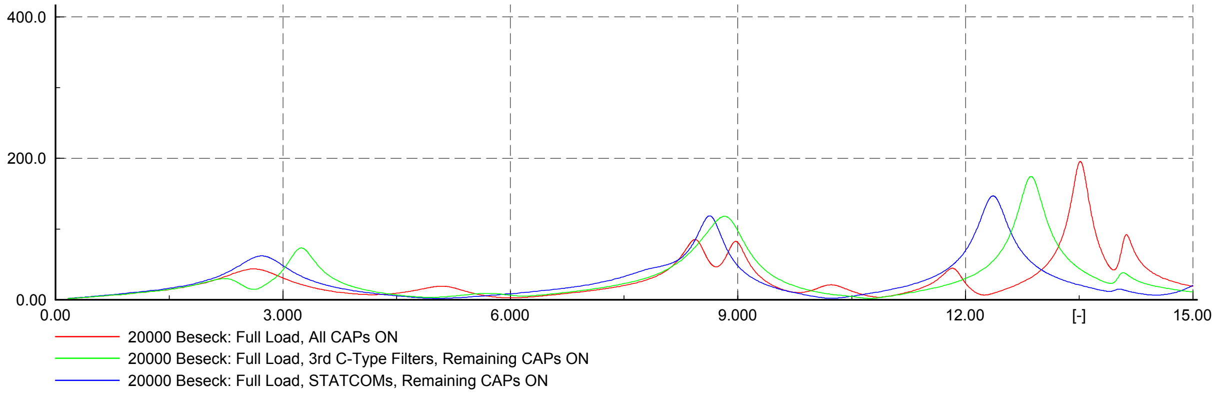

Figure 102: Case II-9:- Devon - Beseck 40-mile XLPE, Minimum Dispatch – Beseck 345 kV

10.5 Graphs of Phase II Alternatives At 70% Load

10.5.1 CASE II-1 AT 70% LOAD: - PHASE II BASE CASE WITH MINIMUM DISPATCH

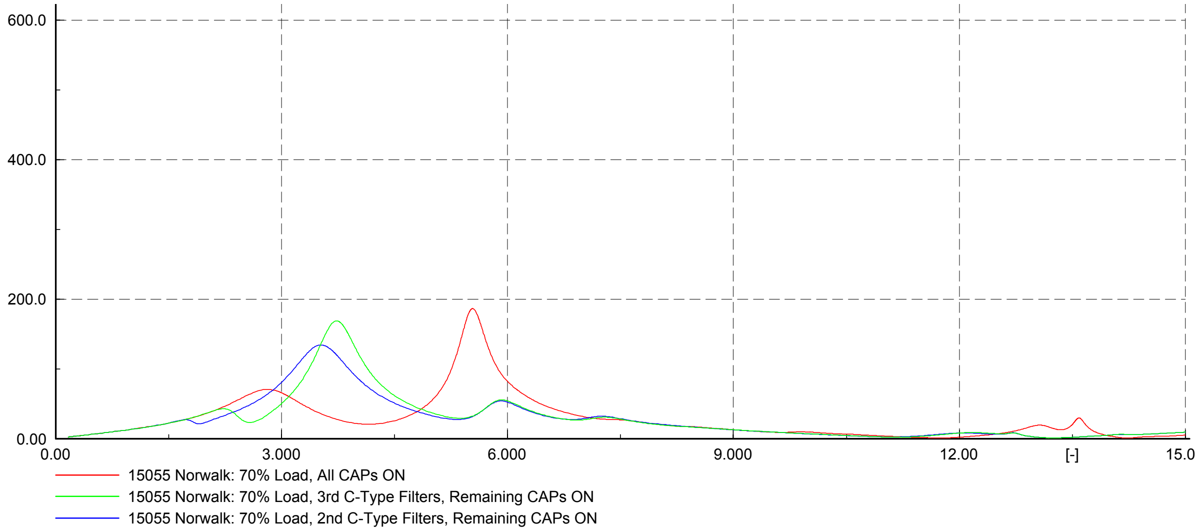

Figure 103: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch - Norwalk 345 kV

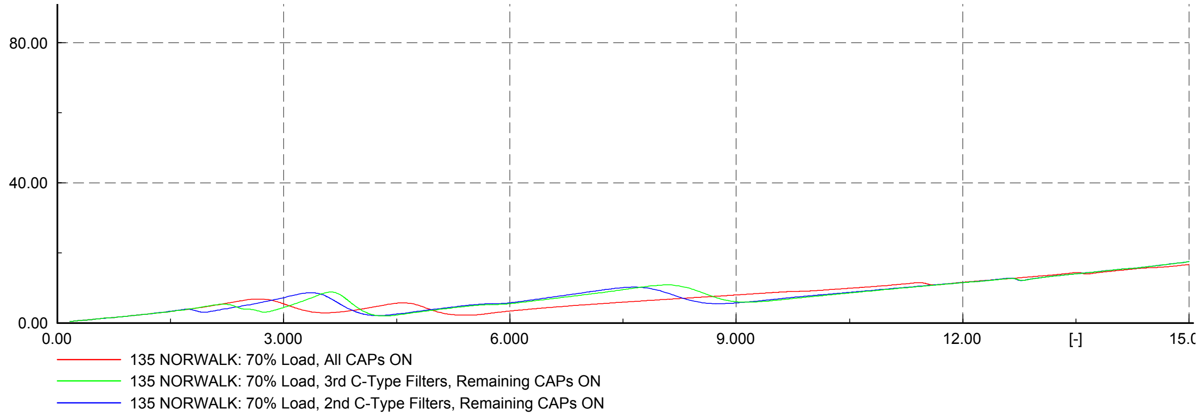

Figure 104: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch - Norwalk 115 kV

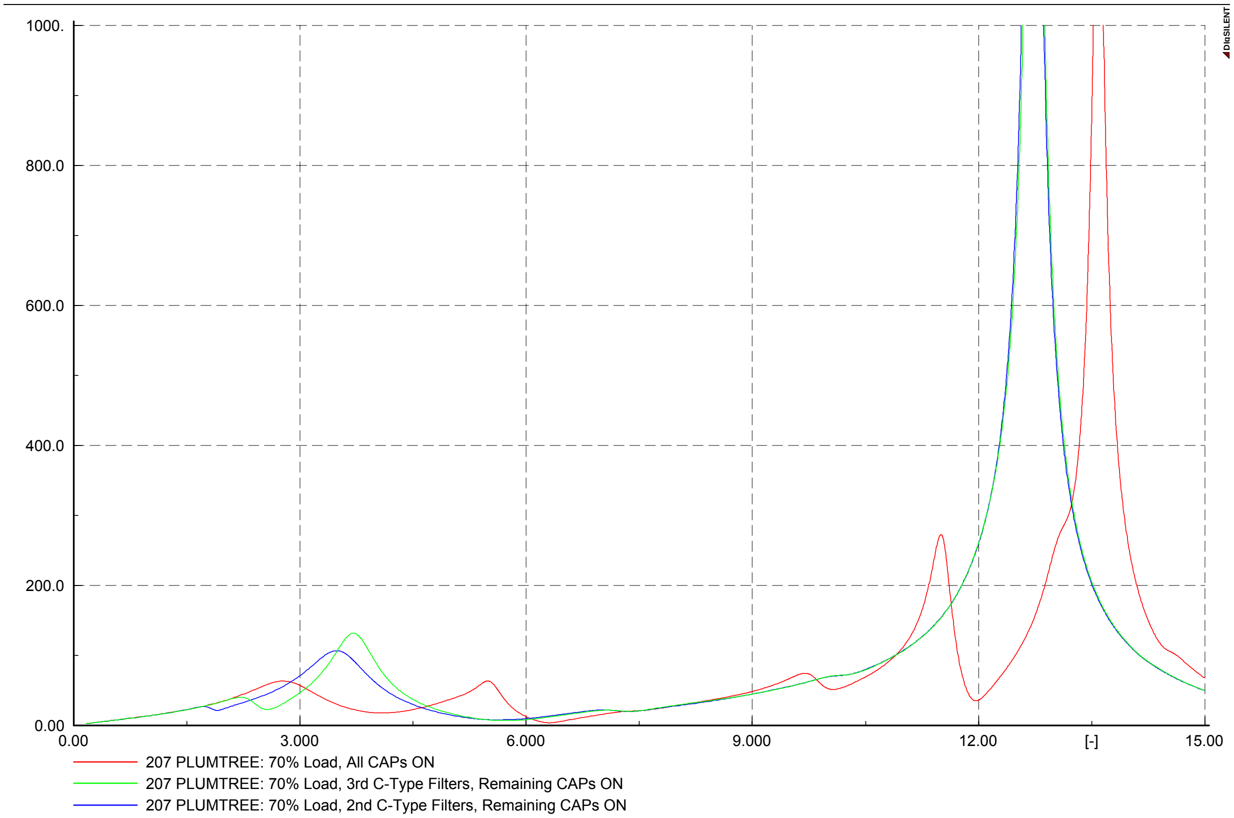

Figure 105: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch - Plumtree 345 kV

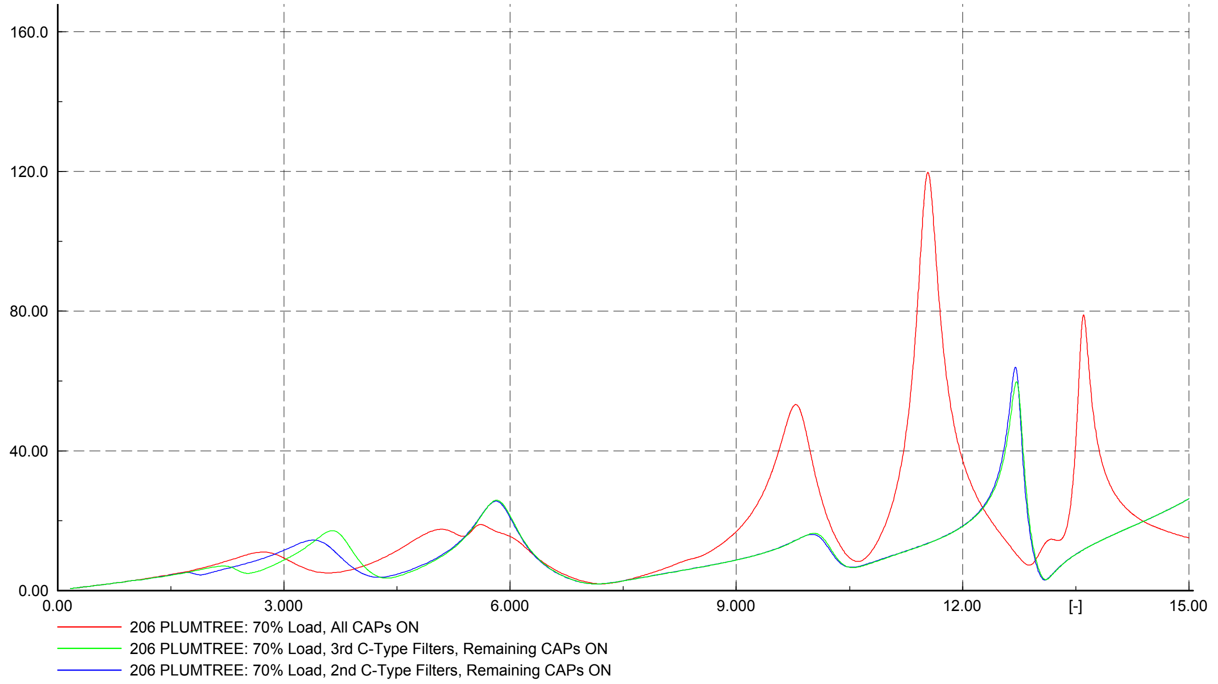

Figure 106: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch - Plumtree 115 kV

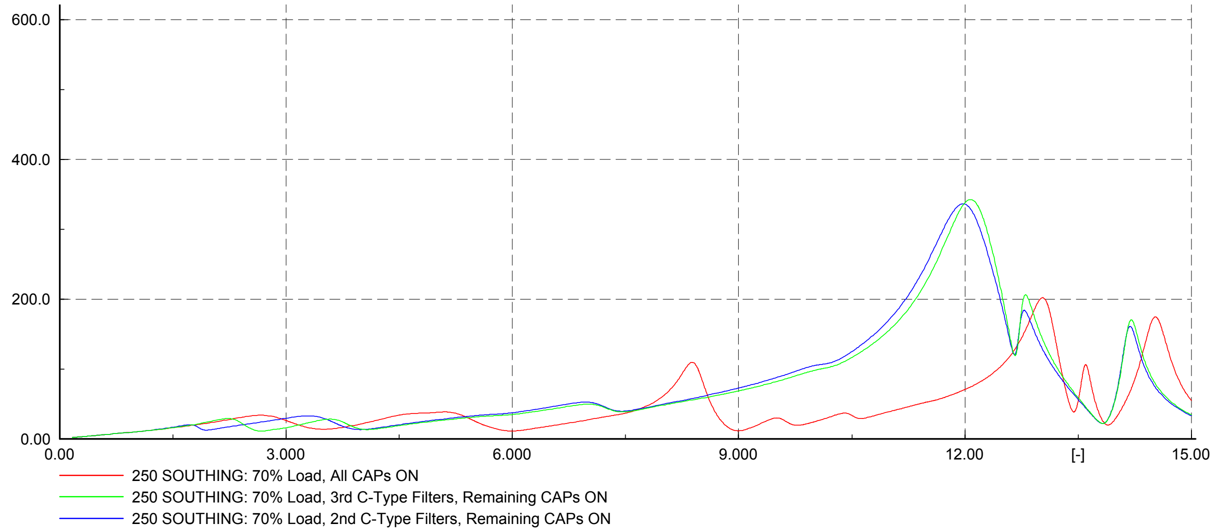

Figure 107: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch – Southington 345 kV

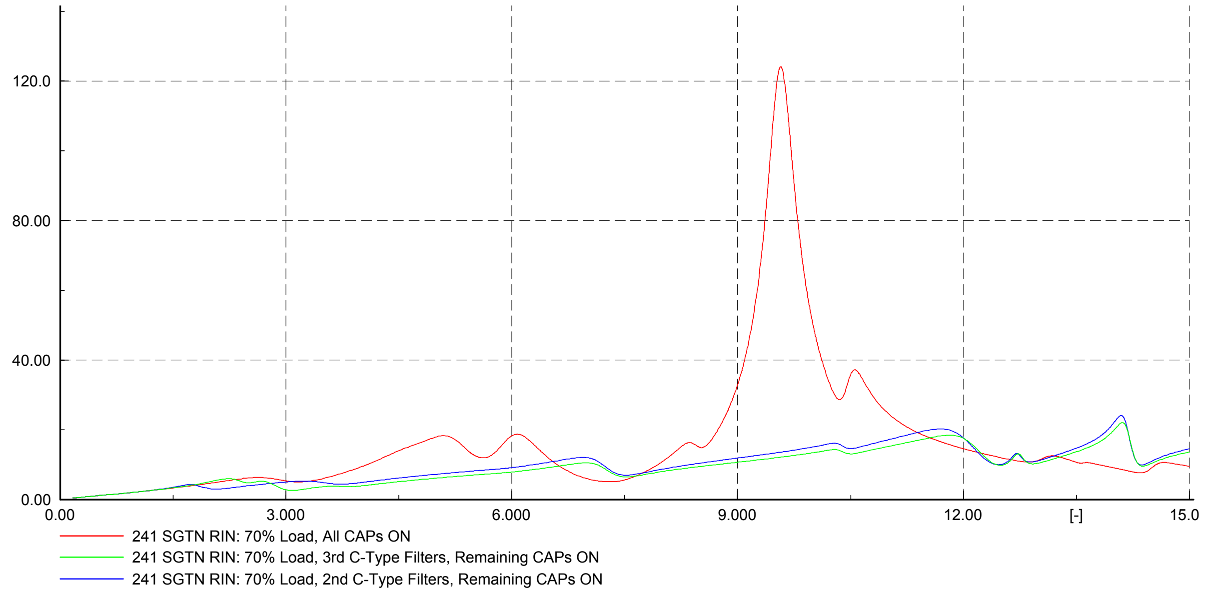

Figure 108: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch – Southington Ring 1 115 kV

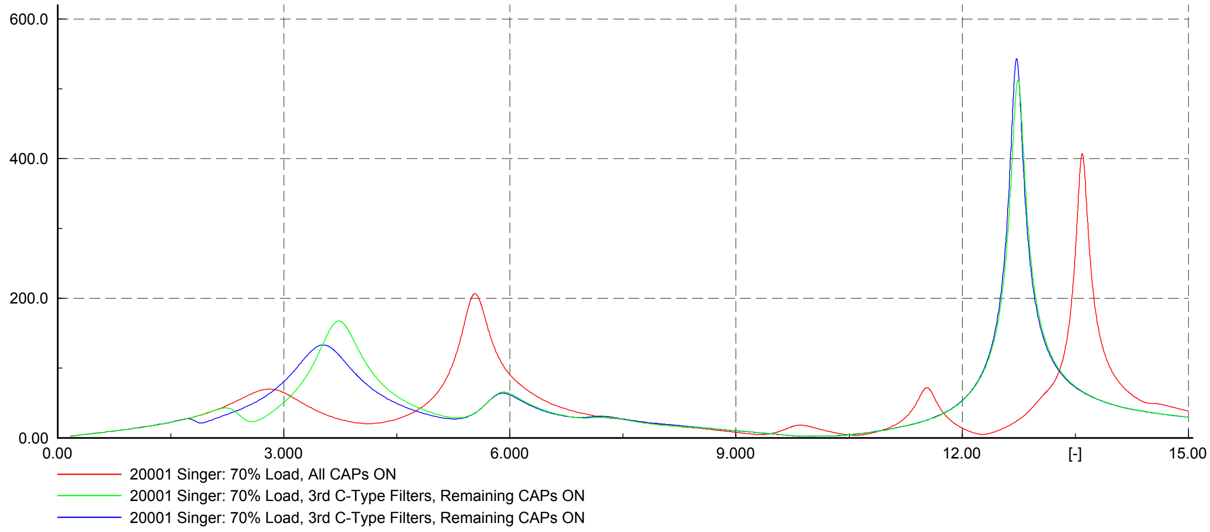

Figure 109: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch - Singer 345 kV

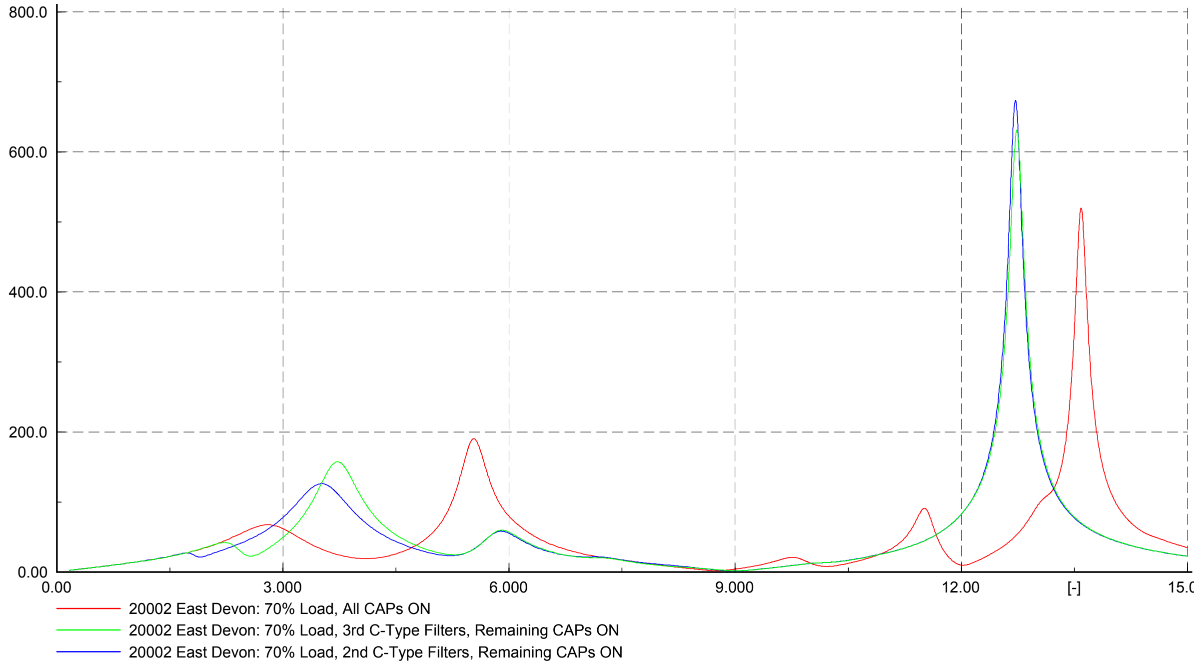

Figure 110: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch – Devon 345 kV

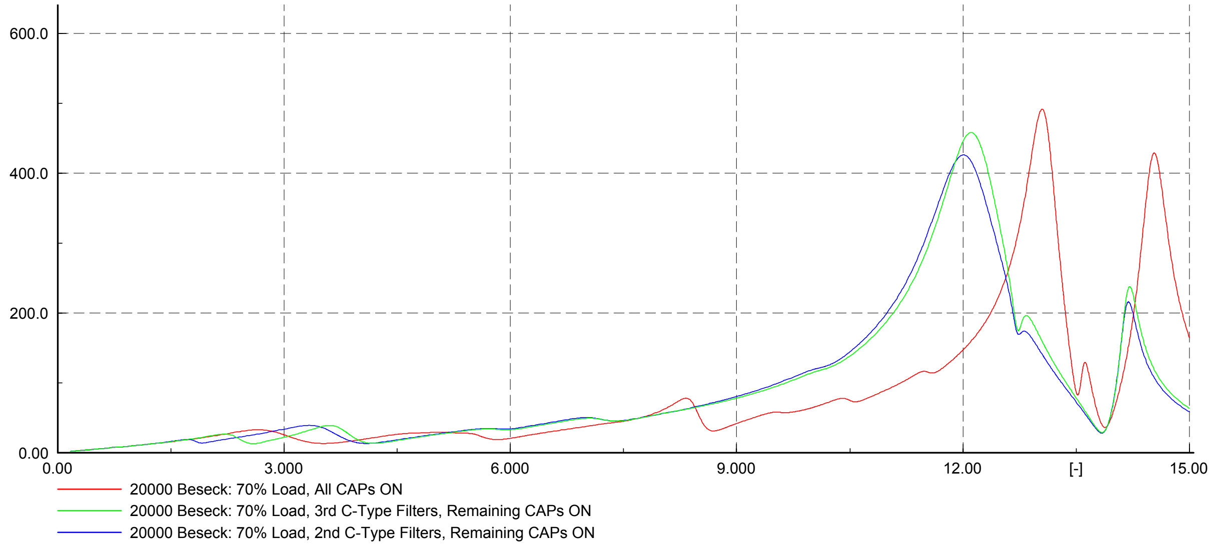

Figure 111: Case II-1 (70% Load): - Phase II Base Case, Minimum Dispatch – Beseck 345 kV

10.5.2 CASE II-7 AT 70% LOAD: - DEVON - BESECK 10-MILE XLPE PHASE II, MINIMUM DISPATCH

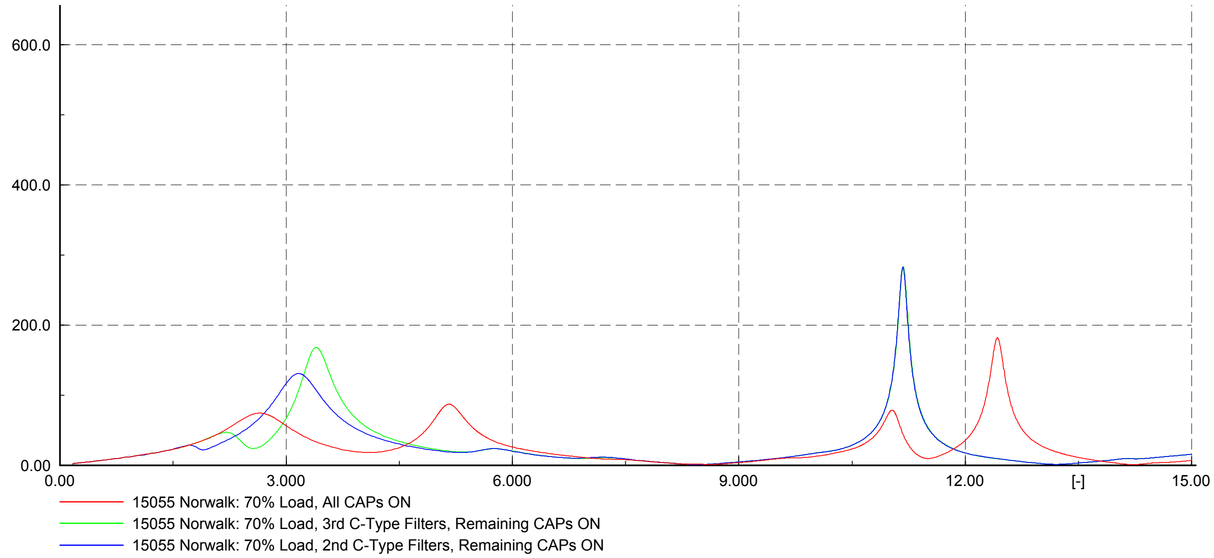

Figure 112: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch - Norwalk 345 kV

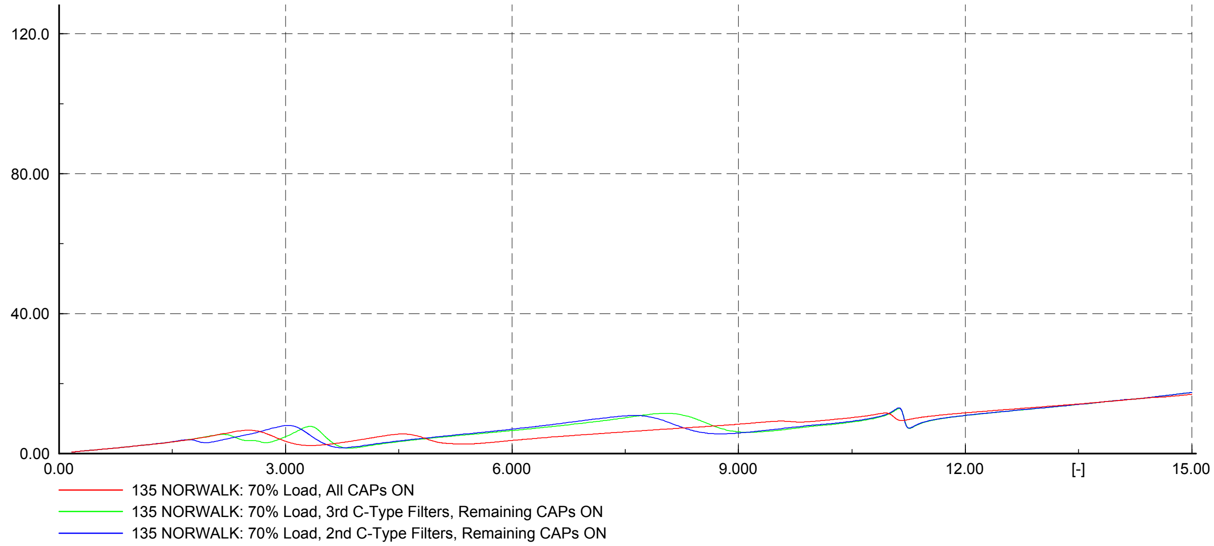

Figure 113: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch - Norwalk 115 kV

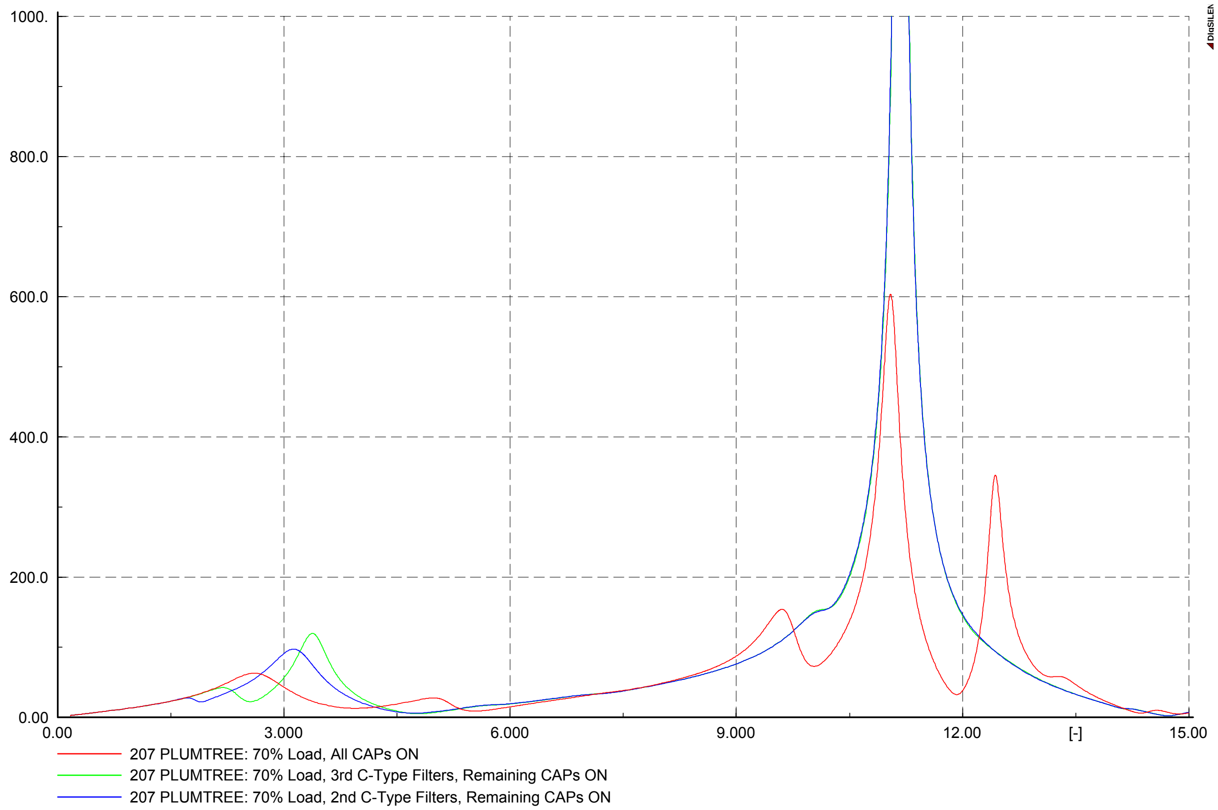

Figure 114: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch - Plumtree 345 kV

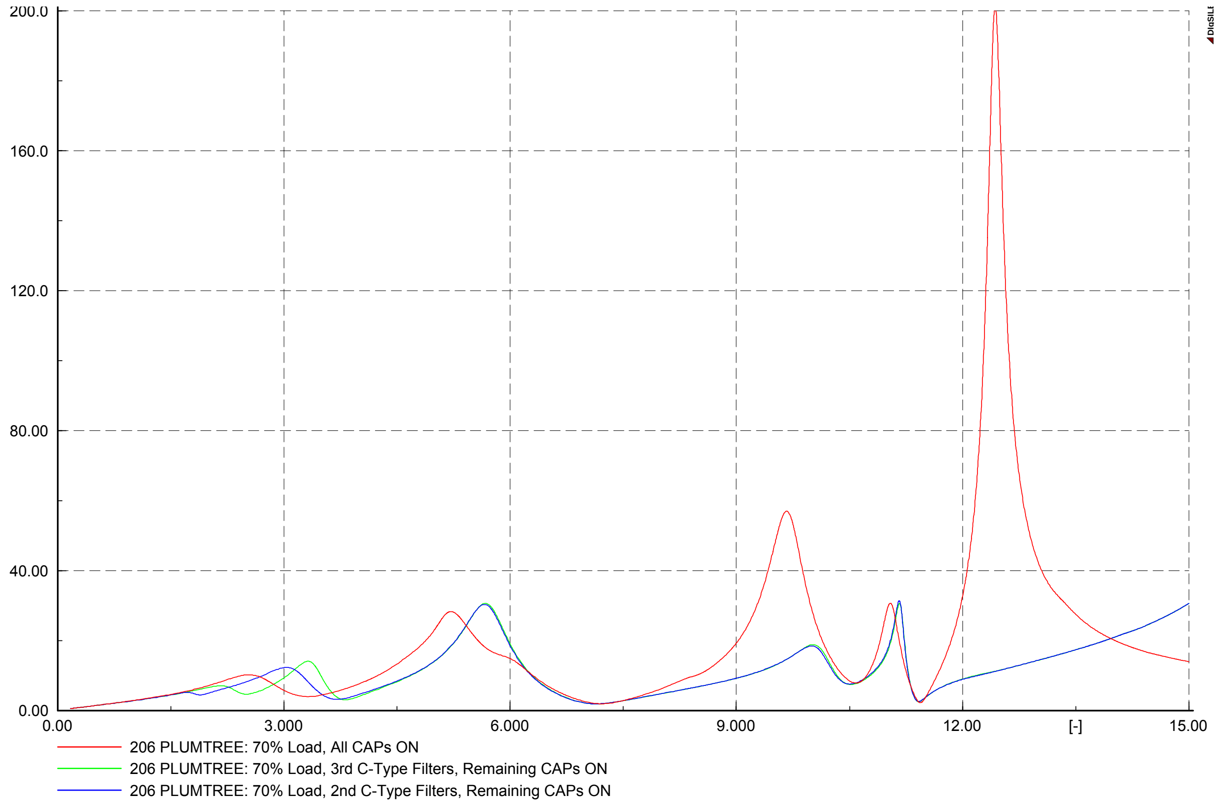

Figure 115: Case II-7 (70% Load) Devon - Beseck 10-mile,Minimum Dispatch - Plumtree 115 kV

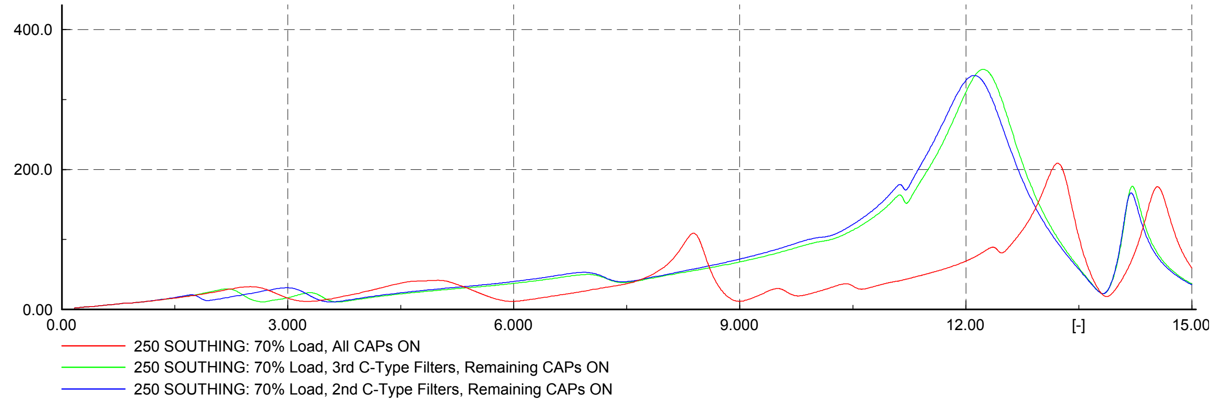

Figure 116: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch – Southing. 345 kV

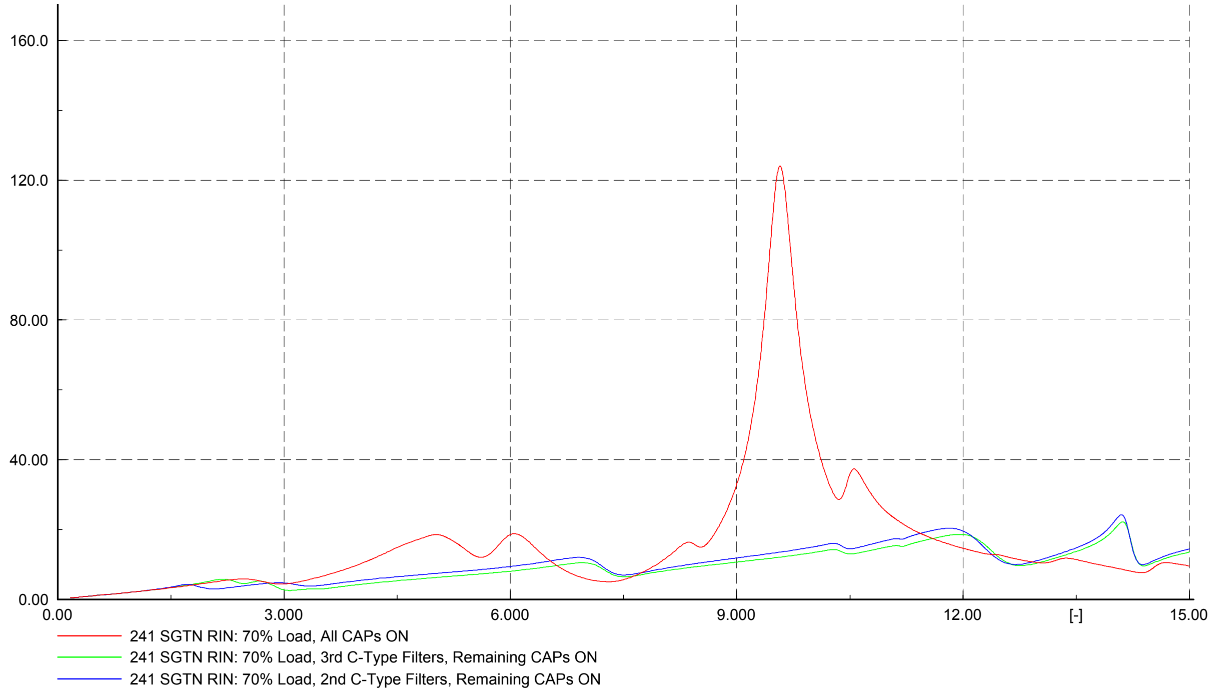

Figure 117: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch – Southing. 115 kV

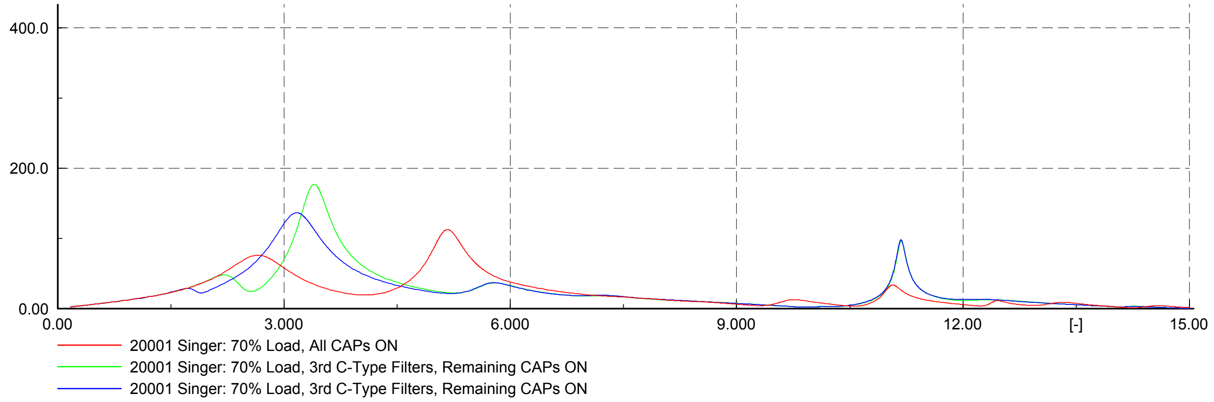

Figure 118: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch – Singer 345 kV

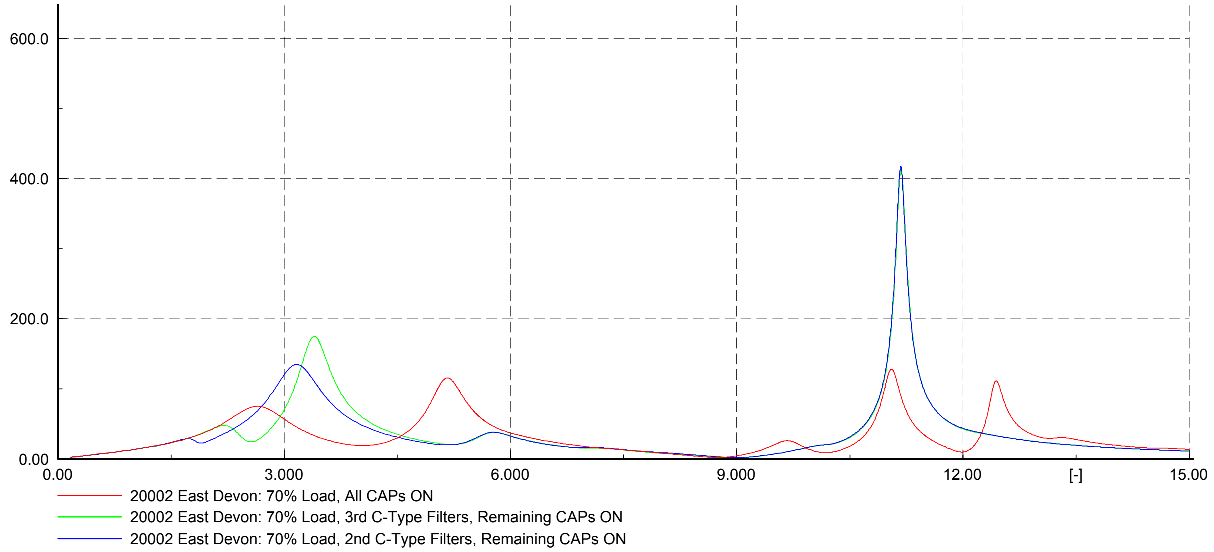

Figure 119: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch – Devon 345 kV

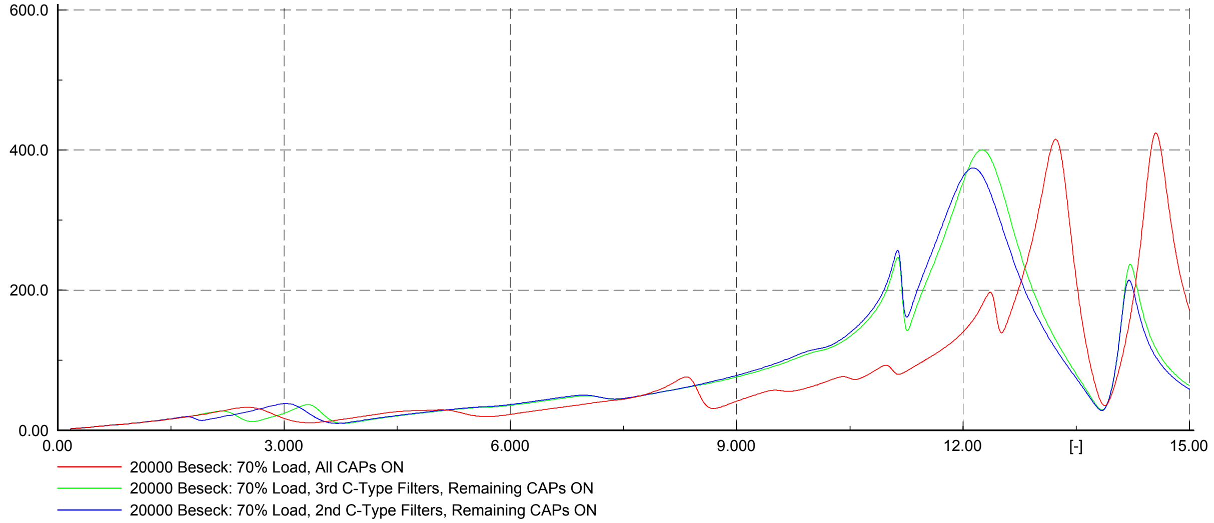

Figure 120: Case II-7 (70% Load) Devon - Beseck 10-mile, Minimum Dispatch – Beseck 345 kV

10.5.3 CASE II-10 AT 70% LOAD: - DEVON - BESECK 15-MILE XLPE PHASE II, MINIMUM DISPATCH

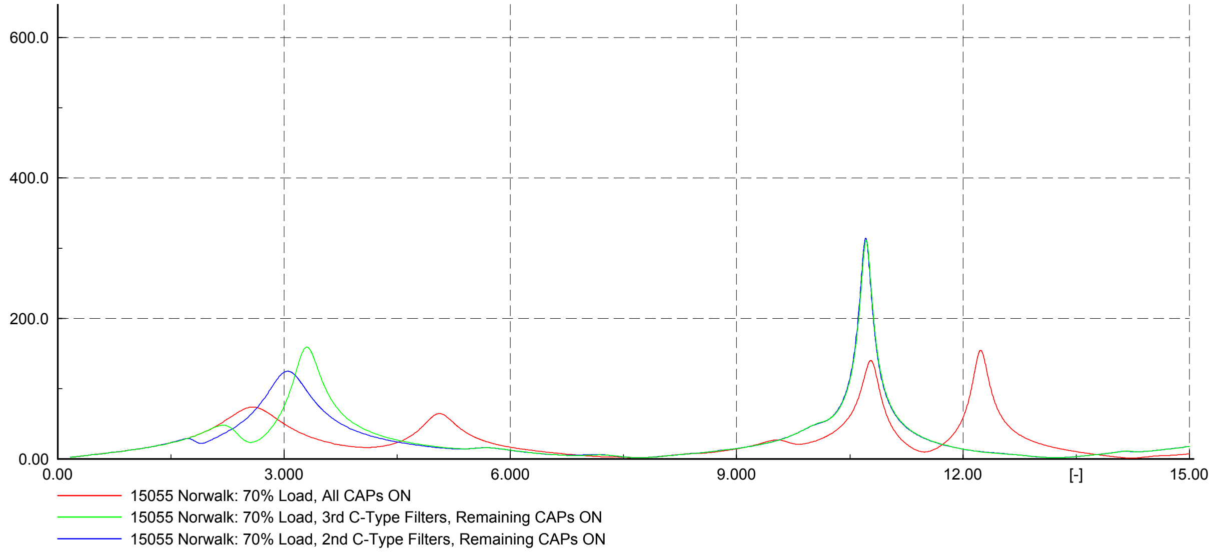

Figure 121: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch - Norwalk 345 kV

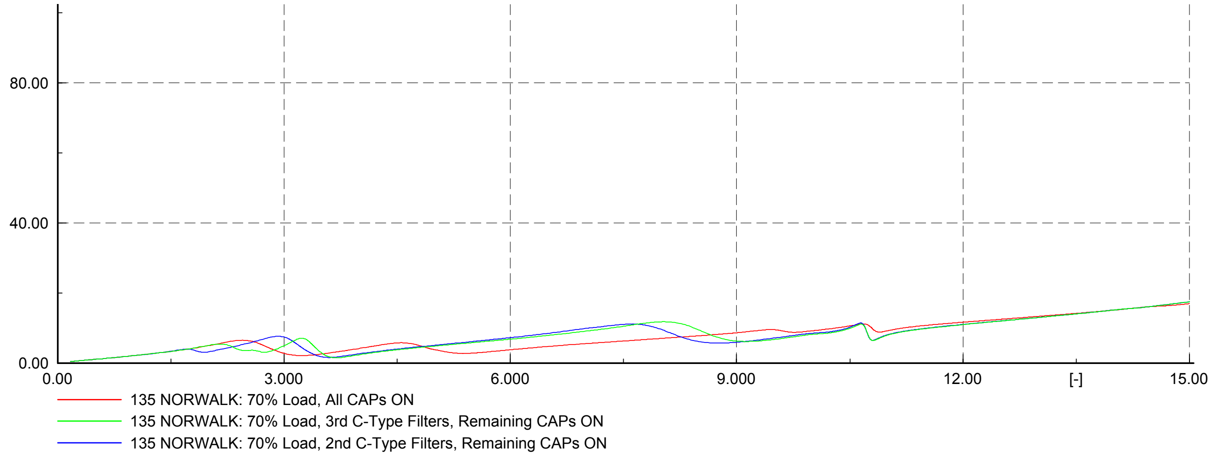

Figure 122: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch - Norwalk 115 kV

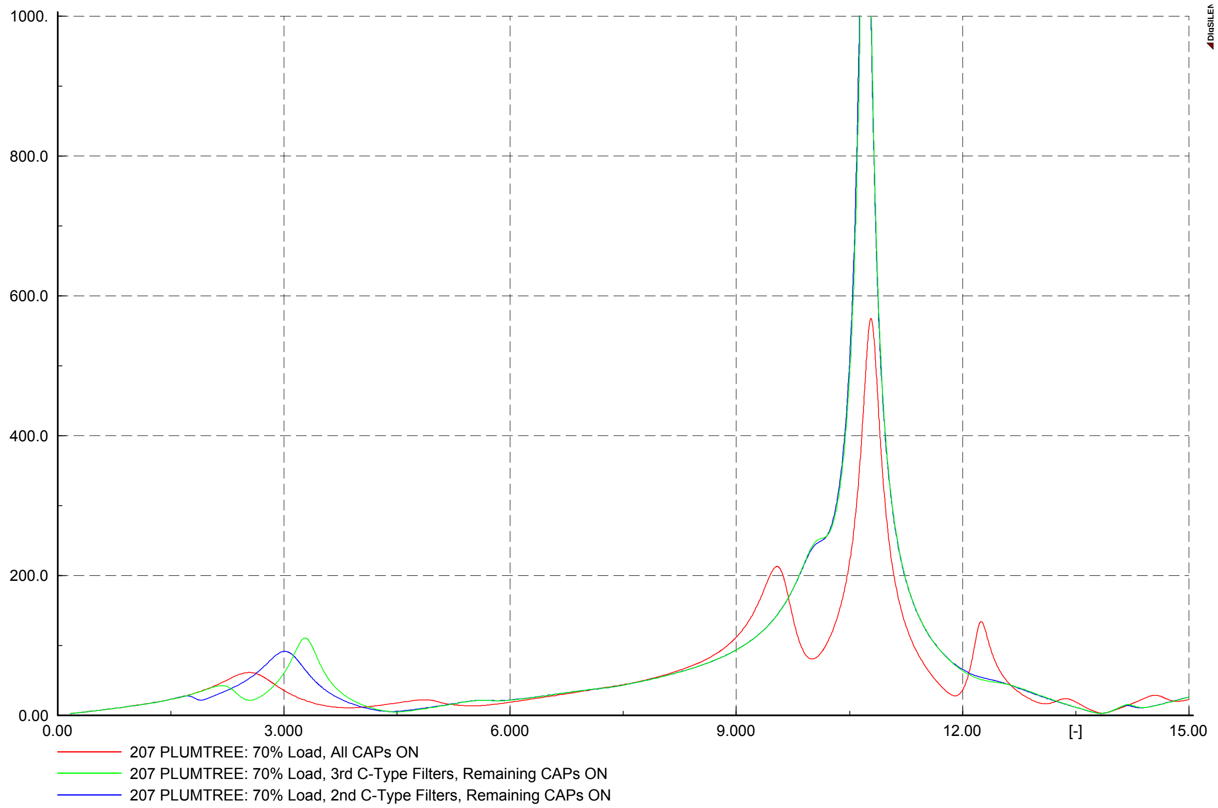

Figure 123: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch - Plumtree 345 kV

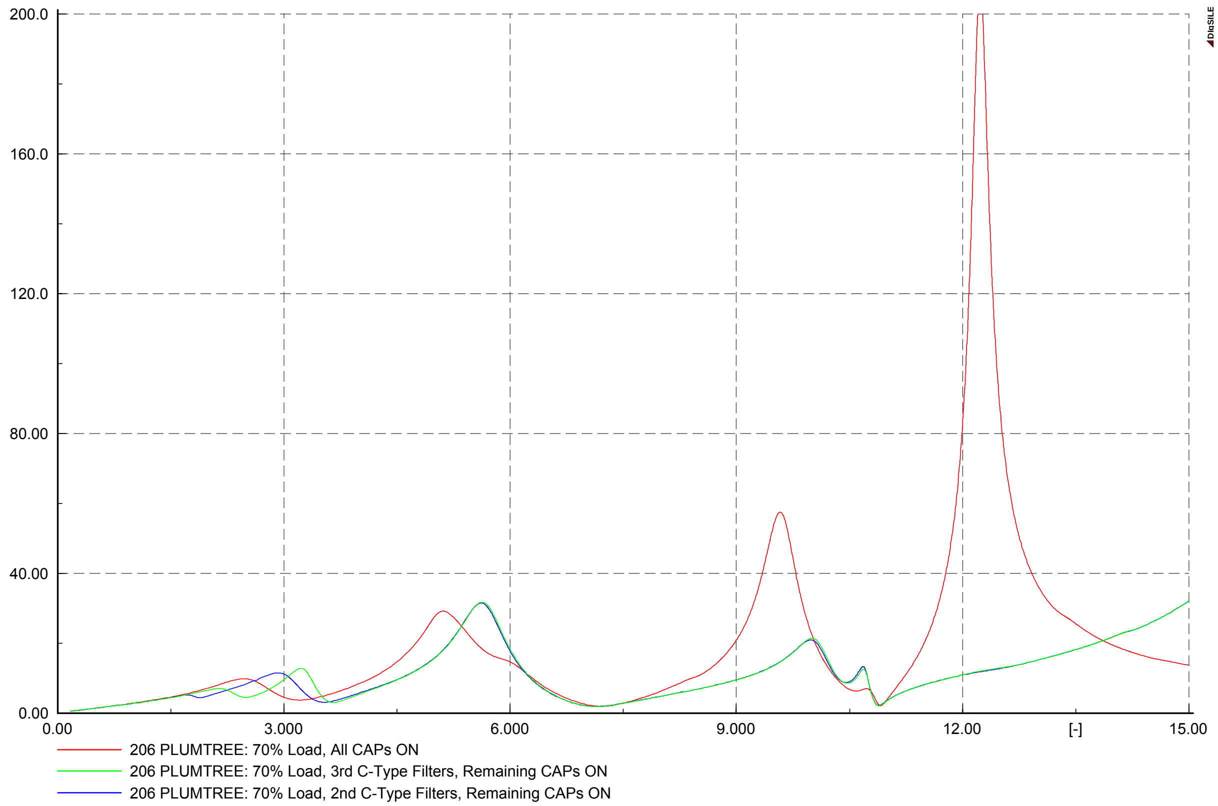

Figure 124: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch - Plumtree 115 kV

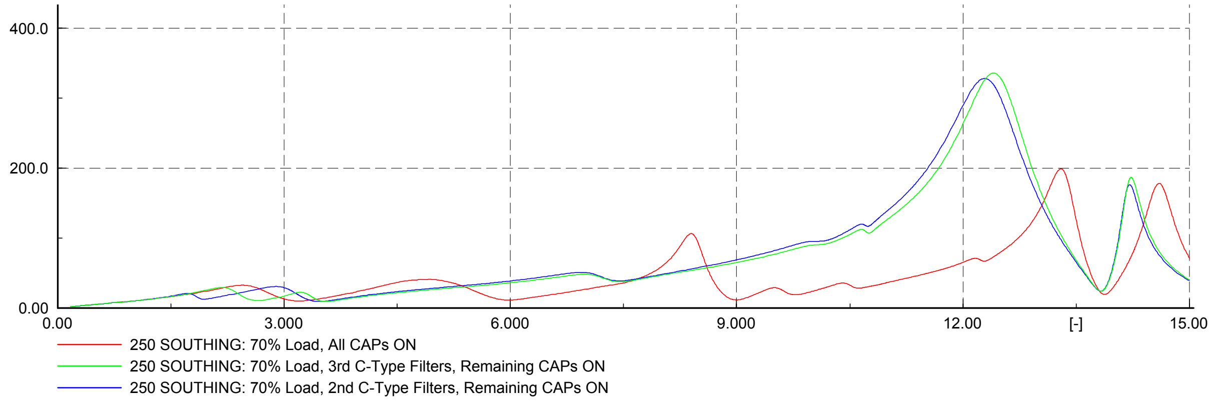

Figure 125: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch – Southing 345 kV

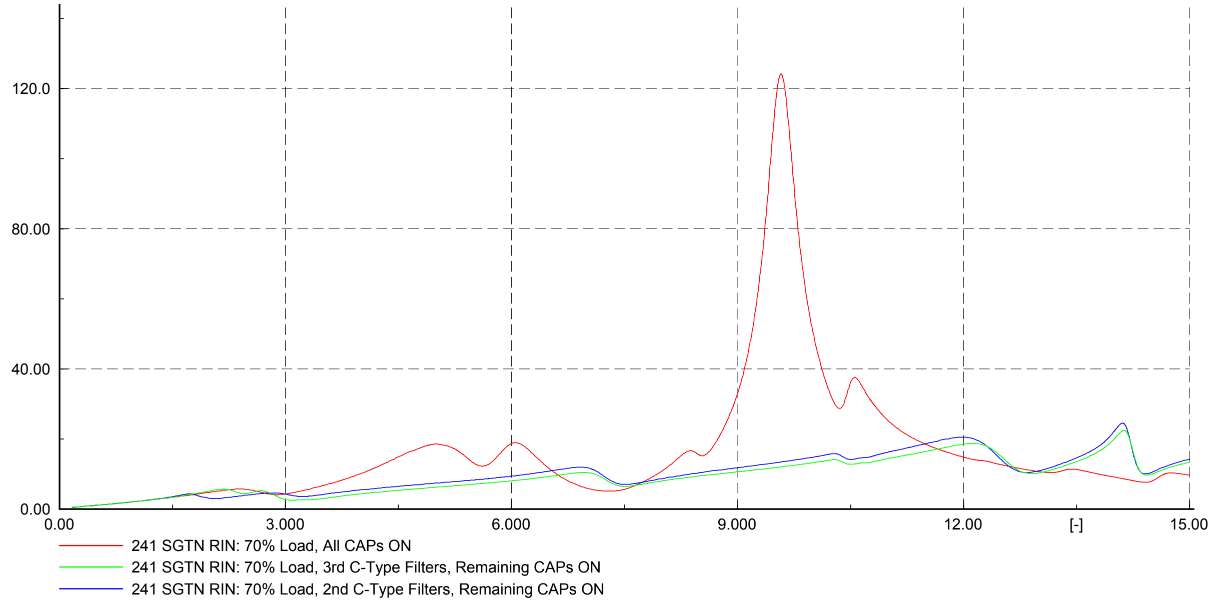

Figure 126: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch – Southing 115 kV

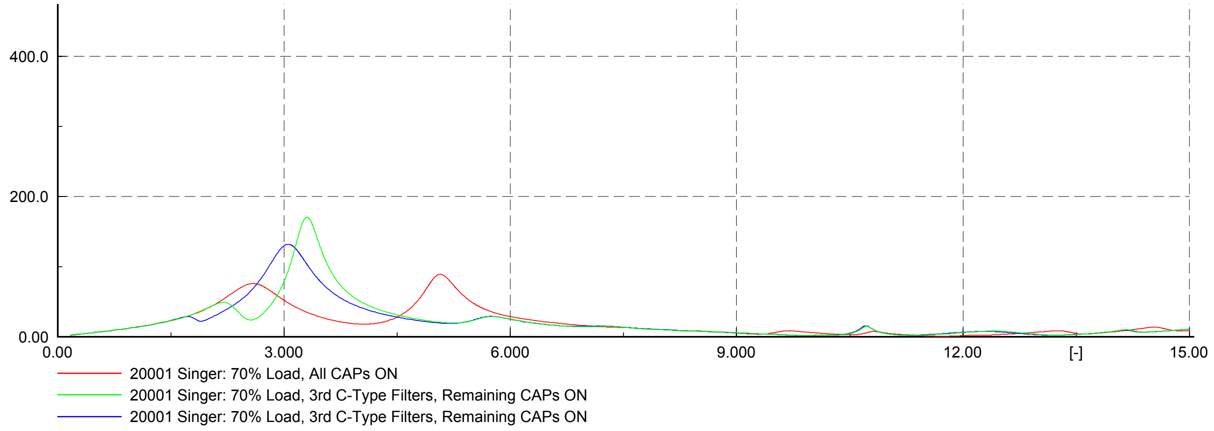

Figure 127: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch - Singer 345 kV

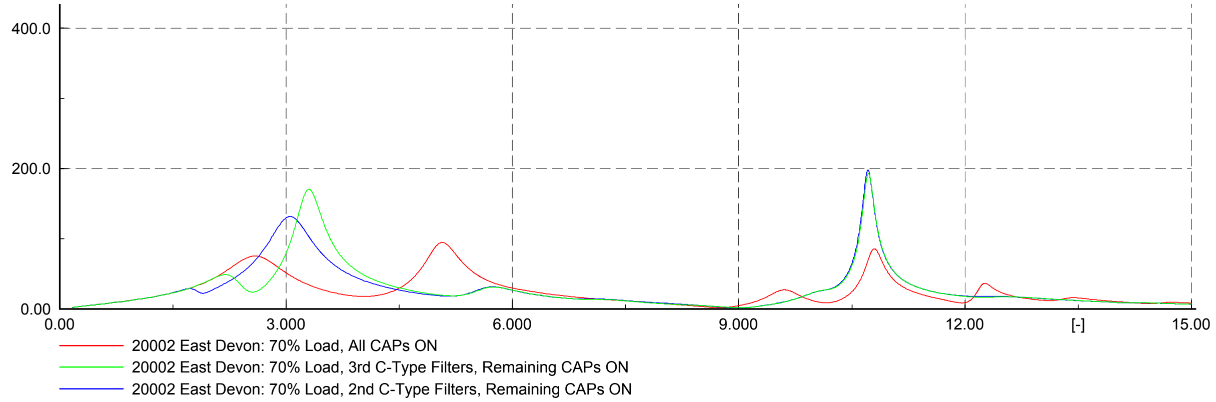

Figure 128: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch – Devon 345 kV

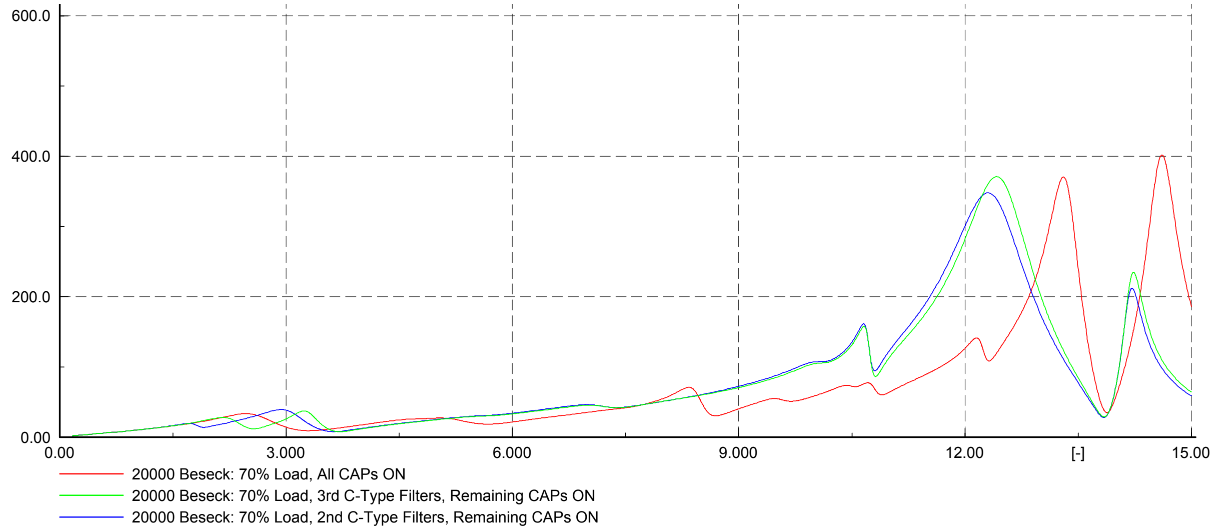

Figure 129: Case II-10 (70% Load) Devon - Beseck 15-mile, Minimum Dispatch – Beseck 345 kV

10.5.4 CASE II-9 AT 70% LOAD: - DEVON - BESECK 40-MILE XLPE PHASE II, MINIMUM DISPATCH

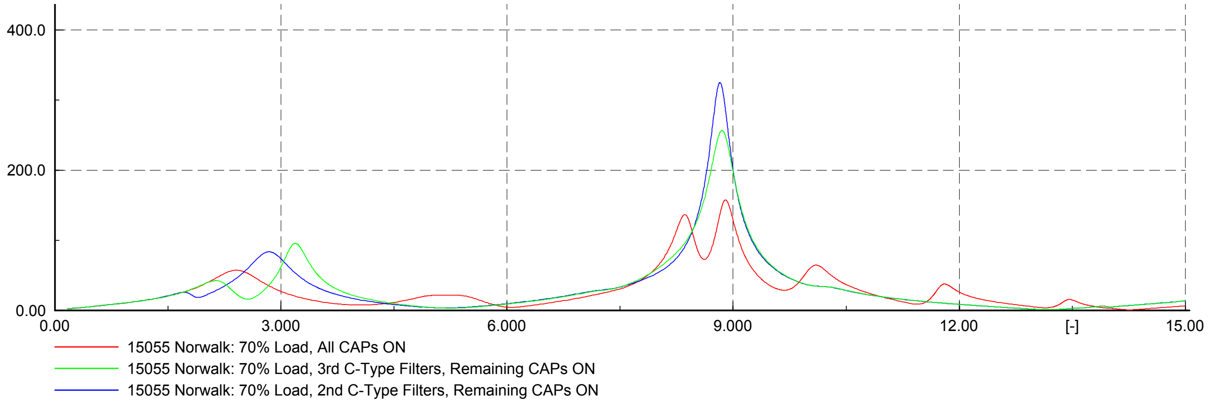

Figure 130: Case II- 9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch - Norwalk 345 kV

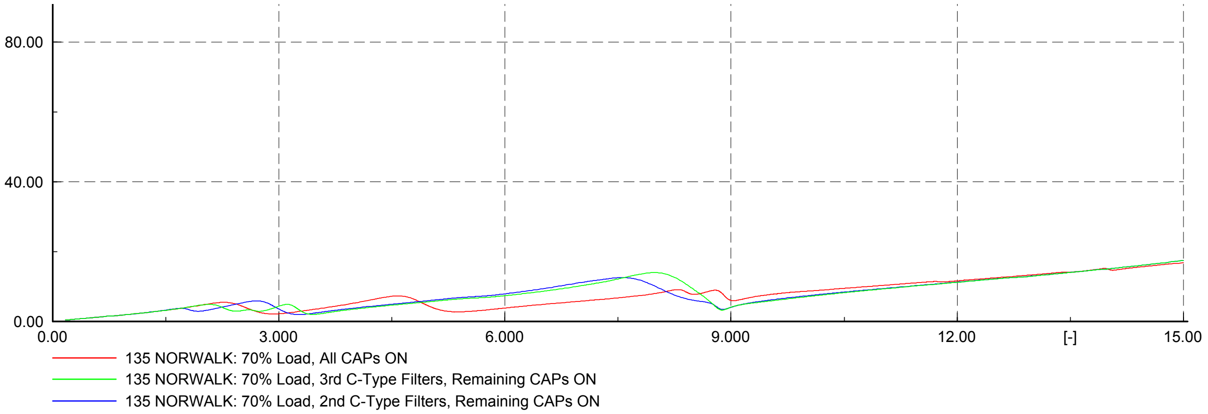

Figure 131: Case II-9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch - Norwalk 115 kV

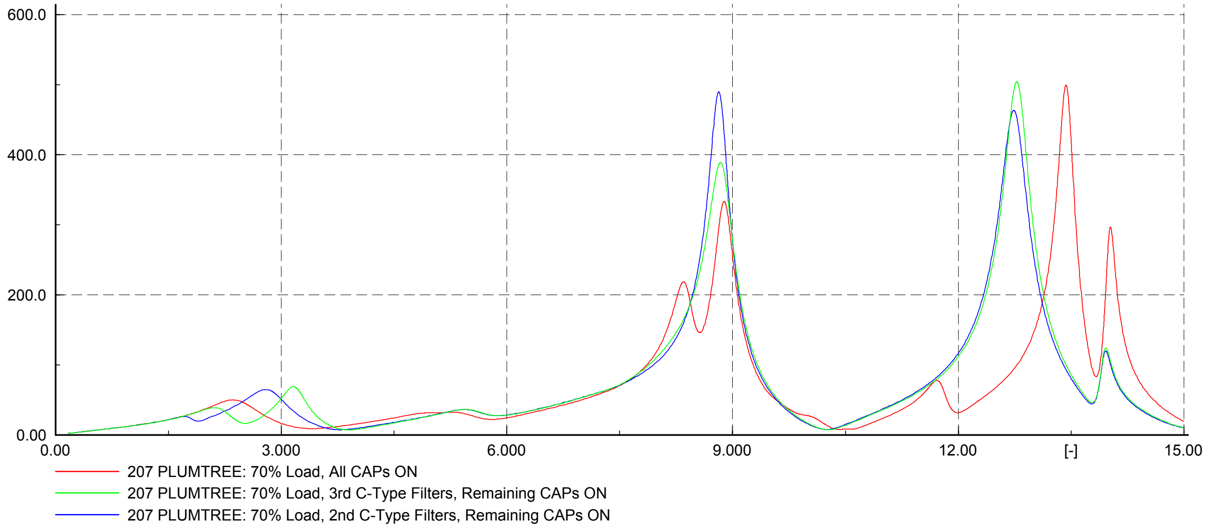

Figure 132: Case II-9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch - Plumtree 345 kV

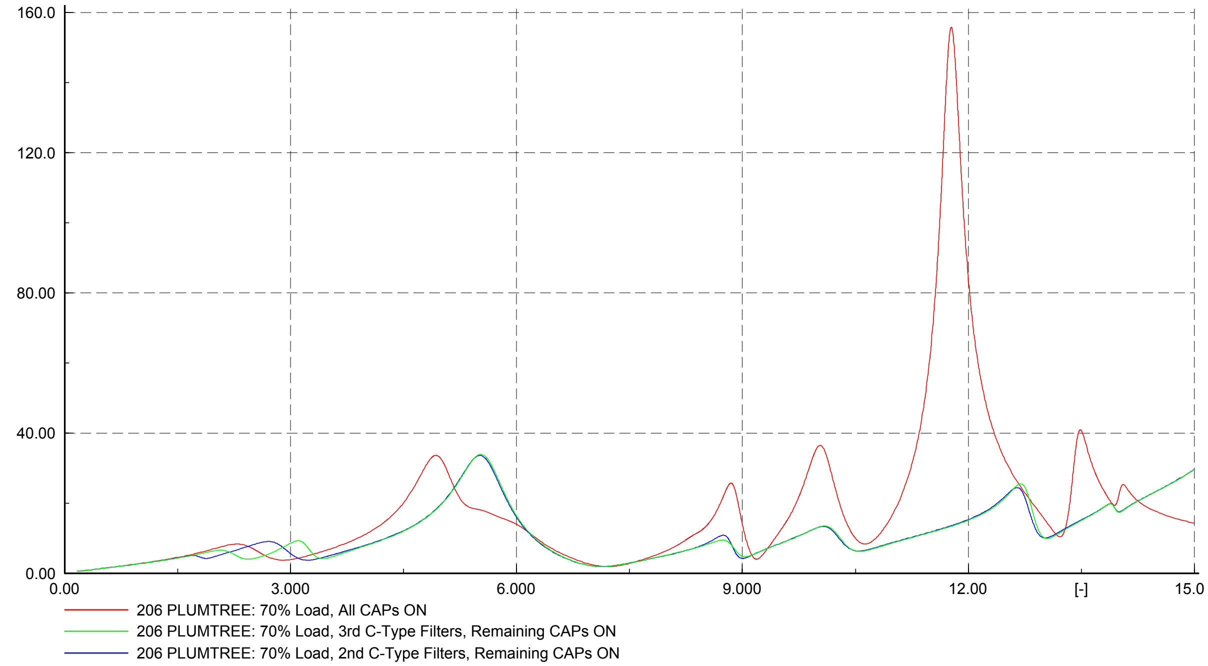

Figure 133: Case II-9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch - Plumtree 115 kV

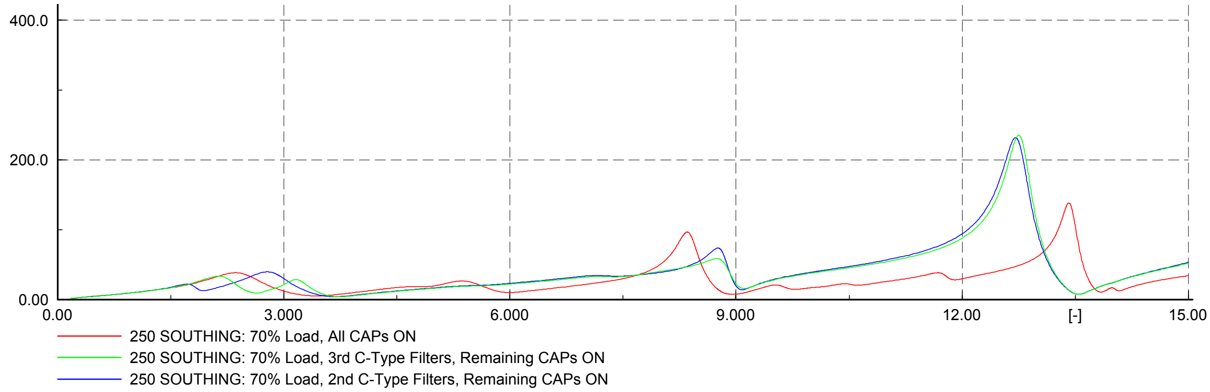

Figure 134: Case II-9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch – Southing 345 kV

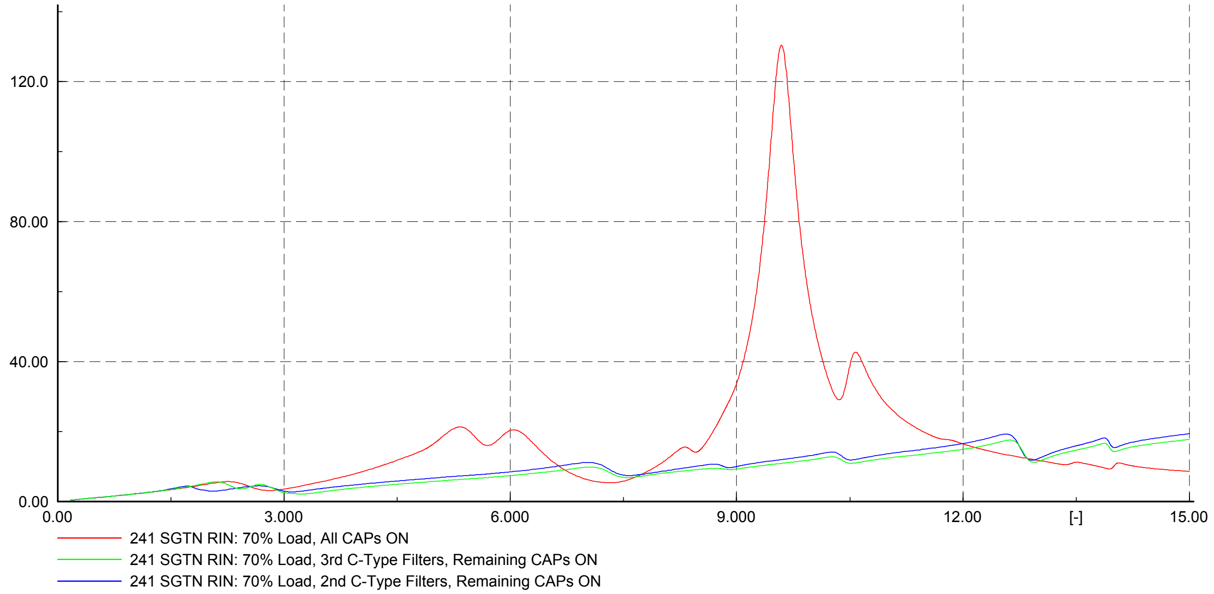

Figure 135: Case II-9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch – Southing. 115 kV

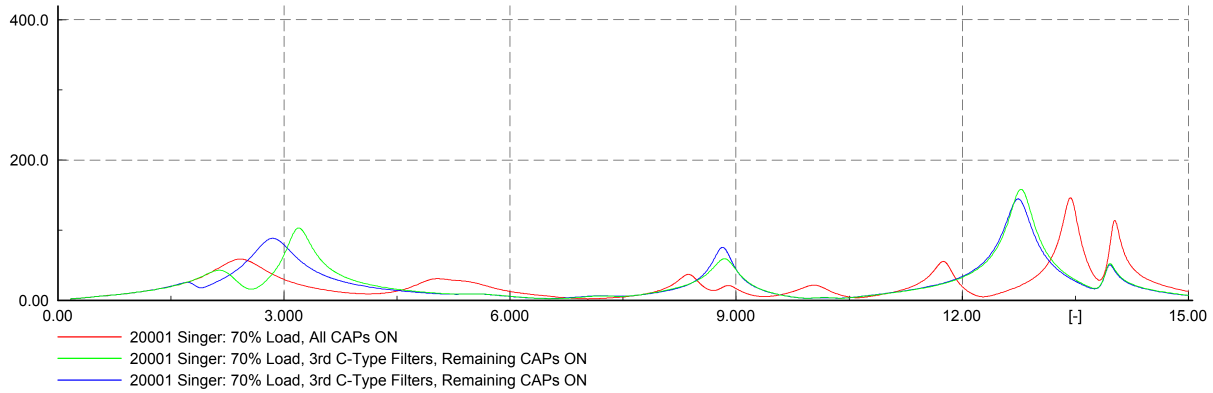

Figure 136: Case II-9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch - Singer 345 kV

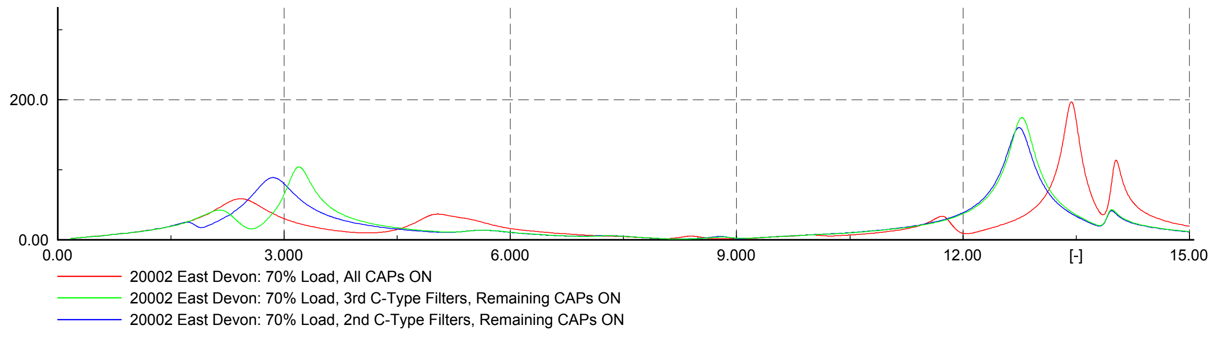

Figure 137: Case II-9 (70% Load) Devon - Beseck 40-mile, Minimum Dispatch – Devon 345 kV

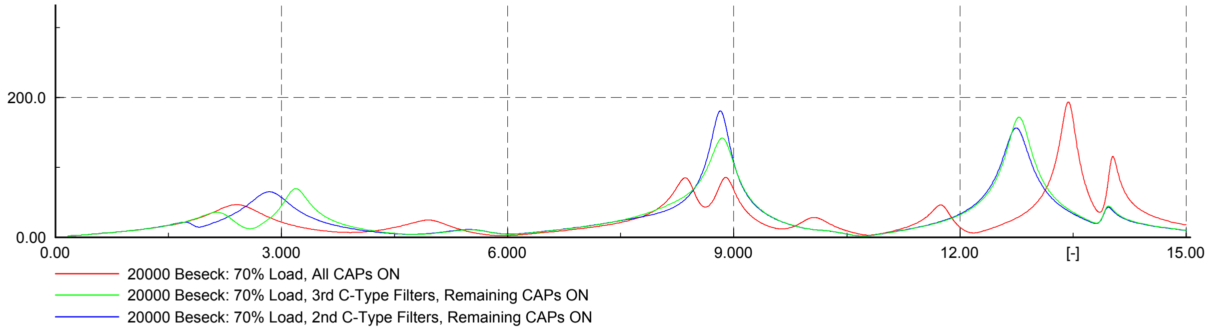

Figure 138: Case II-9 (70% Load): - Devon - Beseck 40-mile XLPE, Minimum Dispatch – Beseck 345 kV