# Middletown to Norwalk Project Summary Report on 345 kV Underground Transmission Line

*Performed for*

**Northeast Utilities and the ISO New England**

*Prepared by*

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December 20, 2004

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# Foreword

This document was prepared by EnerNex Corporation and submitted to Northeast Utilities (NU) and ISO New England (ISO-NE). Technical and commercial questions and any correspondence concerning this document should be referred to:


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# Table of Contents



# List of Figures



# List of Tables

## *Introduction*

EnerNex Corporation's engineering study group has performed a transient switching study of an XLPE alternative (referred to as Case 5 Old) for Northeast Utilities and United Illuminating's Middletown to Norwalk 345 kV transmission cable project proposed for Southwest Connecticut. In this study, the two cables between Singer and East Devon are modeled as two parallel 3000 kcmil XLPE cables and there is a single, 2500 kcmil HPFF cable between Plumtree and Norwalk. In addition to this base case, three variants were evaluated for varying lengths of cable (5, 10, and 20 miles) for the 345 kV circuit from East Devon to Beseck. These sections consisted of 3 parallel, 3000 kcmil circuits of the specified length to a transition point where the circuit continues as an overhead line to Beseck.

The study considered 4 system load levels – 30%, 40%, 50%, and 70% - which determined the respective reactor and capacitor bank dispatch scenarios. For these scenarios, almost all local generation was off-line. Further, variants from the base were evaluated including weaker source equivalents (i.e. estimating the impact of line and generator outages in the external network), alternate capacitor scheduling, and variations to the load model to represent medium voltage capacitor banks.

The objectives of this study were to investigate:

- The temporary overvoltages (TOV) resulting from various fault clearing scenarios
- The effects of system load variations and line outages on TOVs over a range of fault conditions and breaker clearing times
- The effects of load model methodology, source equivalent strength, and alternate capacitor dispatch on the resulting TOVs
- The effects of extending the amount of cable on the TOVs

In order to evaluate the TOVs at numerous bus locations around the system for all of the variations described above, nearly three thousand cases were run as shown in Table 1.

**Table 1 - Summary of Scenario Variations**

| | | | |
|---|---|---|---|
| Case 5 | Case 5 with no extra cable | | |
| | Case5 | 148 | Case 5 at 30, 40, 50 and 70% load Base system strength |
| | Case5-EQ1-C2 | 111 | Case 5 at 40, 50 and 70% load Base system strength and Extra Capacitors |
| | Case5-EQ8 | 111 | Case 5 at 40, 50 and 70% load 80 % system strength |
| | Case5-EQ8-C2 | 111 | Case 5 at 40, 50 and 70% load 80 % system strength and Extra Capacitors |
| | Case5-EQ9 | 111 | Case 5 at 40, 50 and 70% load 90 % system strength |
| | Case5-EQ9-C2 | 111 | Case 5 at 40, 50 and 70% load 90 % system strength and Extra Capacitors |
| | Case5-Spec | 37 | Case 5 at 50% load, base system strength, more capacitors at Glenbrook, North Haven, Waterside, |

| | | | |
|---|---|---|---|
| | | | Sacket and Southington Rings 1 & 2 |
| Case 5A | Case 5 with 20 Miles of Additional Cable | | |
| | Case5A | 148 | Case 5A at 30, 40, 50 and 70% load and full system strength |
| | Case5A-EQ8 | 148 | Case 5A at 30, 40, 50 and 70% load, 80% system strength |
| | Case5A-EQ8-C2 | 148 | Case 5A at 30, 40, 50 and 70% load, 80% system strength and extra capacitors |
| | Case5A-F2 | 148 | Case 5A at 30, 40, 50 and 70% load with successive 0 faults 3.5 cycle clear |
| | Case5A-F3 | 148 | Case 5A at 30, 40, 50 and 70% load with successive 0 faults 4 cycle clear |
| Case 5B | Case 5 With 5 Miles of Additional Cable | | |
| | Case5B | 148 | Case 5B at 30, 40, 50 and 70% load and full system strength |
| | Case5B-EQ8 | 148 | Case 5B at 30, 40, 50 and 70% load, 80% system strength |
| | Case5B-EQ8-C2 | 148 | Case 5B at 30, 40, 50 and 70% load, 80% system strength and extra capacitors |
| | Case5B-F2 | 148 | Case 5B at 30, 40, 50 and 70% load with successive 0 faults 3.5 cycle clear |
| | Case5B-F3 | 148 | Case 5B at 30, 40, 50 and 70% load with successive 0 faults 4 cycle clear |
| Case 5C | Case 5 with 10 Miles of Additional Cable | | |
| | Case5C | 148 | Case 5C at 30, 40, 50 and 70% load and full system strength |
| | Case5C-EQ8 | 148 | Case 5C at 30, 40, 50 and 70% load, 80% system strength |
| | Case5C-EQ8-C2 | 148 | Case 5C at 30, 40, 50 and 70% load, 80% system strength and extra capacitors |
| | Case5C-F2 | 148 | Case 5C at 30, 40, 50 and 70% load with successive 0 faults 3.5 cycle clear |
| | Case5C-F3 | 148 | Case 5C at 30, 40, 50 and 70% load with successive 0 faults 4 cycle clear |
| Total | | 2960 | |

## *Frequency Response and Temporary Overvoltage Phenomena*

A general observation that can be made about this system, which is true for most transmission systems, is that seemingly minor changes in system topology (load changes, capacitor and reactor dispatch, line out conditions, etc.) can have a significant impact on the harmonic and transient behavior of the power system. This is because these changes affect the frequency response of the power system.

For any given system topology, the power system has an impedance that varies with frequency. If we only had very short, overhead lines, no loads, and no capacitor banks, then the impedance would increase linearly with frequency. When we have long overhead lines, extra-high-voltage cables, numerous substation capacitor banks, and nonlinear loads, the frequency response becomes much more complex and is usually dominated by one or more resonances – a frequency at which the impedance is much higher than what would be expected without system capacitance. The more capacitance we have or the weaker the system is (less generation and/or less transmission capacity in the area than "normal") then the lower the main resonance will be.

The power system's frequency response comes into play in many ways, but the most significant can most easily be explained as follows. Normally in power systems we only concern ourselves with the fundamental power frequency – 60 cycles per second, or 60 Hz. When a disturbance occurs, however, the impedance at other frequencies becomes important.

Certain kinds of disturbing phenomena generate voltages and currents at magnitudes and frequencies based on their physical characteristics. For this transmission study, the current inrush to multiple transformers following the clearing of a nearby fault is the most significant, because large currents at several frequencies other than the fundamental power frequency are generated. The largest magnitude of these frequencies occurs at low order multiples of the fundamental power frequency (120, 180, and 240 Hertz for example).

By combining the system impedance and the load characteristics, we can get a feel for how the system will behave. We do this by simply considering Ohms Law – the voltage is the product of the current times the system impedance. If the impedance of the system at 180 Hz is 100 Ohms and the transformer inrush current after a fault clears has a 180-Hz component of 100 Amps, then we would have a temporary overvoltage of 10,000 Volts added to the normal system voltage. This is a simplistic explanation, ignoring phase angle differences between voltages, but it describes the key phenomena involved.

From this explanation, one can make an important observation:

> The system can have high impedance at a specific frequency, but without a significant source of excitation current at that frequency, there won't be a voltage high enough to worry about. Similarly, with low impedance at a given frequency, a large current at that frequency might be tolerated, without producing an overvoltage of concern.

In general, the Southwest Connecticut Power System is electrically weak – there are relatively few generation resources in the immediate vicinity of where the load is concentrated, and there are fewer strong transmission paths from outside sources to the area of load concentration (hence the need for this project). When you add devices to the system that increase the capacitance of the system (cables and capacitors), the primary resonant frequency moves lower. The main source of disturbing current comes from transformer saturation after clearing a fault. Because transformers produce their highest currents at low frequency, one would expect the highest transient overvoltages when the system resonance is lowest.

For this reason, power engineers try to keep the primary resonance of the power system from getting too low. A common rule is to avoid resonances at or below the third harmonic, or 180 Hz. With 345-kV cables added to the Southwest Connecticut power system, the first resonance is below 180 Hz, and will closely approach 120 Hz in some configurations. Because of this, there is a concern that fault clearing transients will produce sustained temporary overvoltages (TOVs), which could damage equipment and lead to outages.

Figure 1 shows a sample TOV after clearing a fault, with a large third harmonic component that decays slowly. Under normal conditions, each phase's waveform peak should reach a level between 0.95 and 1.05 per-unit. Transient voltage peaks reaching 2 per-unit, or higher, may typically occur from switching operations and other causes, but these are normally single peaks. While the peak magnitude in Figure 1 is only 1.74 per-unit, there are 9 significantly elevated peaks on phases B and C, which is the nature of a TOV. This waveform slightly exceeds the acceptance criteria established for the study, detailed in a later section.

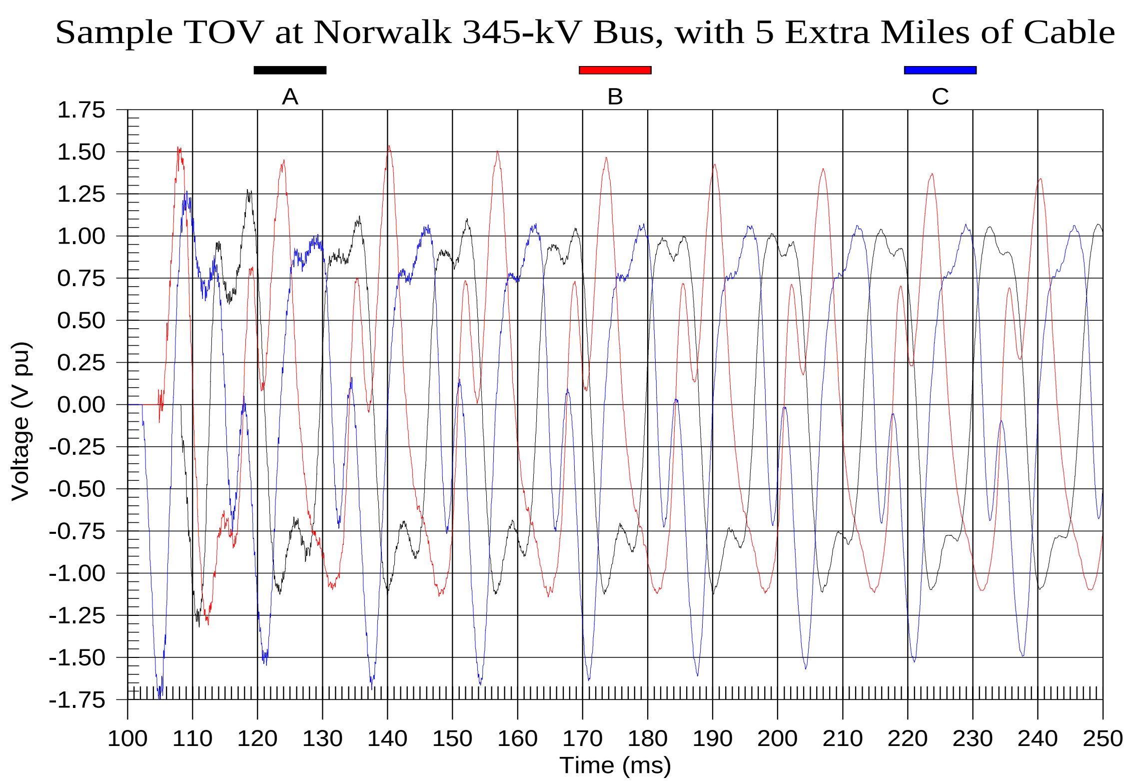


**Figure 1 - Sample temporary overvoltage that fails the acceptance criterion**

As we mentioned earlier, one must have a combination of high impedance and high current at a specific frequency to cause a transient overvoltage of concern. If these two elements don't coincide, there may still be a transient overvoltage, but most likely within the withstand capability of the power system equipment (breakers, transformers, arresters, etc.) There are many parameters that can affect the system frequency response, so it is very difficult to predict the worst-case configuration in advance. Many of the important parameters cannot be easily measured or controlled, either. Therefore, we simulate a large number of permutations, and analyze the results with probability concepts.

Although the first resonance causes the most concern, there are many other capacitive elements already in the system, and also variations in shunt reactive compensation, load, and generation. These produce many other resonances that can potentially interact with the first, and generally most important, resonance produced by the cables. It is not possible to analyze this correctly with a simple model of just the new cables, and their immediate neighborhood, to reproduce only the first resonance. In reality, problematic TOVs may occur elsewhere in the system, and not necessarily under conditions of the most severe first resonance as predicted from a simple model.

## *Consequences of a TOV Failure*

When the consequences of a failure are relatively low, some power system components may be designed with a small risk of failure during transient overvoltages. One example is the lightning protection of an overhead line, because a flashover usually causes no damage to the line, because the flashover usually causes only one outage, and because the line can usually be placed back in service quickly. Another example is high-speed reclosing of an overhead line; because no equipment damage would occur, a small failure probability is acceptable.

Other components are designed with, **in theory**, zero probability of failure due to transient overvoltage. One example is transformer protection, because a failure would require replacement of the transformer, and this process may take weeks or more. The designer would compare the maximum stress, plus a safety margin, to the protected equipment's corresponding ability to withstand the stress. The safety margin allows for several factors:

- Equipment withstand capabilities and protective levels vary with age and with manufacturing tolerances.
- Standard tests define equipment withstand capabilities and surge arrester protective levels, so that all equipment may be evaluated, purchased, and applied on a common basis. However, naturally occurring transient overvoltages will never exactly match the standard test waveforms, so the comparison of stress to strength cannot be exact.
- Even if one studied every foreseen system configuration, and this is usually not practical, the system may grow or change in ways not foreseen at the time of the design study.
- System parameters are not known precisely enough to design right up against the equipment's capability. For example, very precise analytical models exist for the impedance of an overhead line, and the utility knows the conductor and tower configurations precisely. However, the impedance still varies with temperature (including sag effects) and soil conditions (including moisture) along the line. Other parameters, especially those involving customer loads, will show even more variation and uncertainty.

Traditionally, TOVs have been evaluated with zero acceptable risk of failure, for at least three reasons:

- Any TOV-caused damage to a surge arrester, transformer, cable, or other equipment will be "permanent". Replacement or repair must be performed, which takes hours or days to complete.
- To be most effective, surge arresters are installed right on the terminals of the protected equipment. If the arrester fails thermally due to a TOV, the protected equipment must also be taken out of service.
- The TOV-caused outage is always a second contingency, and it occurs very close in time to the previous contingency.

The last point is most important. Suppose the fault occurs on an overhead line, and circuit breakers clear the fault by taking the line out of service. This is the first contingency, the loss of that overhead line. Then suppose a surge arrester fails, less than one second later, due to a TOV. This is the second contingency, because a transformer (for example) will be taken out of service. These are the types of events that can lead to blackouts, which never occur due to a single contingency, because the system is always operated to survive a single contingency, with ample margin. But some second and higher order contingencies may lead to a local or regional loss of service to customers. The TOV-induced failure creates at least a second contingency, close on the heels of a first contingency. The timing is important because dynamic effects of the two contingencies may aggravate each other, and because the system operators will not have had time to reconfigure the system in response to the first contingency.

Not every TOV-induced failure will cause a blackout, but it creates the condition where a blackout becomes possible. This is why the present study pays so much attention to TOVs, and safety margins for TOVs.

## *Evaluation Criteria*

The 2,960 combinations evaluated for this study are only the most likely scenarios out of millions of other plausible system conditions and events. For this reason, engineering judgment must come into play to add sufficient margin based on experience to the TOVs predicted in the study, which determines where to draw the line on allowable topology.

<u>The first evaluation criterion is the likelihood that the TOV will be too high</u>, given a fault event. This represents a general risk of failure, expressed as a percentage. To estimate the annual number of failures, one would multiply this percentage by the total number of faults in the local area, mostly on the 345-kV system. If not zero, this percentage must be a small fraction of 1%.

Surge arresters are installed throughout the system, to protect equipment from transient overvoltages. These surge arresters also have a TOV withstand capability, guaranteed by the vendor, that we use to establish the TOV acceptance criterion for this study. When the TOV exceeds the arrester withstand capability, there is a risk that the arrester will fail thermally. This produces a fault, which most likely leads to removing some protected equipment (e.g., a transformer) from service. The surge arrester must then be replaced before the protected equipment returns to service. The protected equipment should have a higher TOV withstand than a modern surge arrester, although this may not be the case for relatively low TOVs that are sustained over longer time periods. In general, however, the arrester fails before the protected equipment. Therefore, the surge arrester TOV withstand capability is the most appropriate TOV acceptance criterion.

The longer the TOV lasts, the less the surge arrester can withstand it. We used two points on the TOV withstand curve, to evaluate the study results. The most important point is TOV6, which is the maximum voltage allowed, if it lasts for 6 cycles (0.1 seconds) or less. On the system voltage base, this is 1.80 per-unit. A secondary evaluation point is TOV2, which is the maximum voltage allowed lasting for 2 cycles or less. On the system voltage base, this is 1.85 per-unit. The TOV2 criterion is considered less important, because it is more conservative than the TOV6 requirement. That is, a 2-cycle TOV looks more like a repeated switching surge, which arresters are designed for, and it is likely the arrester capability is really more than 1.85 per-unit over 2 cycles.

A consultant specializing in surge arresters supplied the values of TOV2 and TOV6 that are higher than published standard curves. This allows higher simulated TOVs to be accepted. It's also necessary to account for uncertainties and variations in load characteristics, generation dispatch, and shunt capacitor dispatch. These result in a 0.25 per-unit margin, by a root-sum-square aggregation of different margins, detailed in Table 2.

**Table 2 - TOV Margins**

| **Factor** | **Margin** | **Margin Squared** |
|---|---:|---:|
| Load levels and damping characteristics | 0.2 | 0.04 |
| Generation dispatch | 0.1 | 0.01 |
| Capacitor dispatch, and LV capacitors | 0.1 | 0.01 |
| | Sum of Squares: | 0.06 |
| | **Total Margin:** | **0.25** |

The most uncertain factor is the load, for several reasons:

- The utility does not control the load level or the load characteristics, as it can (to some degree) the generation and capacitors.
- The metered characteristics of loads do not include parameters most important to transients and TOVs, namely, the damping characteristics at high frequencies.
- The load is an aggregate of many individual customers, each with different characteristics, some even including their own capacitors.

Note that the final margin is less than the arithmetic sum, assuming the uncertainties in load, generation, and capacitance are somewhat independent. Additional margin factors might be included, for example, to reflect that TOV levels beyond 6 cycles are not evaluated. However, additional factors would not change the total margin very much, because of the root-sum-square aggregation procedure.

In summary, the first evaluation criterion is:

TOV6 <= 1.55 per-unit

TOV2 <= 1.60 per-unit

<u>The second evaluation criterion is simply the maximum level of TOV that occurs</u>. While obviously important, this figure of merit by itself says nothing about the overall number of failures, hence its secondary importance. In addition to the absolute maximum TOV, we also consider the TOV level that is exceeded 2% of the time, i.e., the 98$^{th}$ percentile value. The maximum and 2%-exceed levels are denoted $E_{max}$ and $E_2$, respectively. Comparing these two figures will give an indication of how often values close to the maximum actually occur.

### *Case 5 Configuration*

The studied configuration, referred to as “Case 5”, has two XLPE cables, with lower shunt capacitance, from Norwalk-Singer and from Singer-East Devon 345-kV buses. There is only one HPFF cable in service instead of two, with higher shunt capacitance than the XLPE cable, from Norwalk-Plumtree 345-kV buses. Three variations were simulated on this base configuration, providing for 5, 10, or 20 miles of cable (three in parallel) between the East Devon-Beseck 345-kV buses, the remainder being overhead line. Figure 2 shows the portion of the system with variable cable length.

As mentioned in the introduction, load levels of 30%, 40%, 50%, and 70% peak were included, with appropriate VAR dispatch at each load level. The fault locations and types, all on the 345-kV system, included:

- Plumtree Cable Terminal, 3-phase
- East Devon Cable Terminal, 3-phase
- East Devon Cable Terminal, 1-phase
- Norwalk Junction Cable Terminal, 3-phase
- Singer Cable Terminal, 3-phase
- Norwalk Bus, 3-phase
- Plumtree Bus, 3-phase

The following pre-fault contingencies were considered, to weaken the overall source strength and potentially make the first resonance more severe:

- Plumtree-Long Mountain 345-kV Line
- Beseck-East Devon 345-kV Line
- Long Mountain-Pleasant Valley 345-kV Line
- Northport-Norwalk Harbor 138-kV Line

With these pre-fault contingencies, the simulated fault and clearing represents the second contingency.

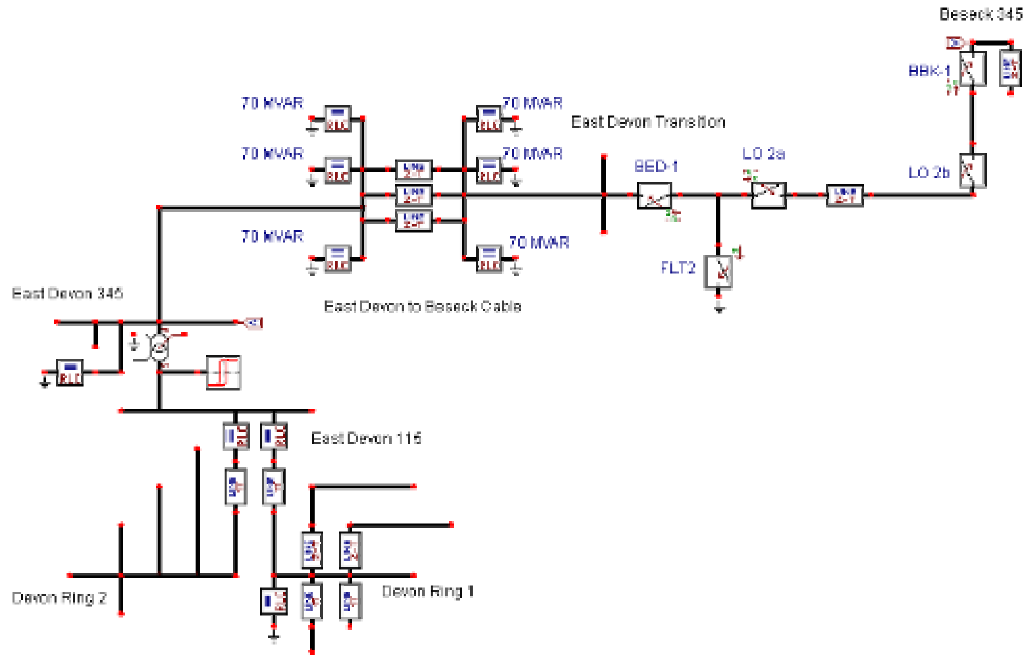


**Figure 2 - Case 5 system configuration, Beseck-East Devon variants**

## *Observations*

For the Southwest Connecticut system, we can observe the following:

- As more cable is added, the first resonant frequency of the system decreases.
- As more cable segments are added with their associated shunt compensating reactors, additional local resonances are created in addition to the main resonance point.
- More complicated dynamic behaviors occur as we add more capacitance.
- At key 345-kV and 115-kV buses throughout Southwest Connecticut, the worst TOVs increase as more cable is added.
- The impact of load, capacitor dispatch, and other topology changes seem to be more pronounced as more cable or capacitance is added (e.g. more variability in results – sometimes large reduction in TOVs, sometimes large increase in TOVs).

Figure 3 shows the aggregated worst-case TOVs for the base case, and for the additional cable variants in Beseck-East Devon. Again, $E_{max}$ refers to the maximum TOV, while $E_2$ refers to the TOV level exceeded 2% of the time. For each data point, over 700 simulations were aggregated. The maximum TOV levels trend upward with increasing cable length, as might be expected. The 2% levels do not trend upward uniformly, particularly at the 5-mile point. This reflects interaction with other system resonances, as described later. The maximum TOV exceeds the acceptance criteria for both TOV2 and TOV6, at all of the lengths shown.

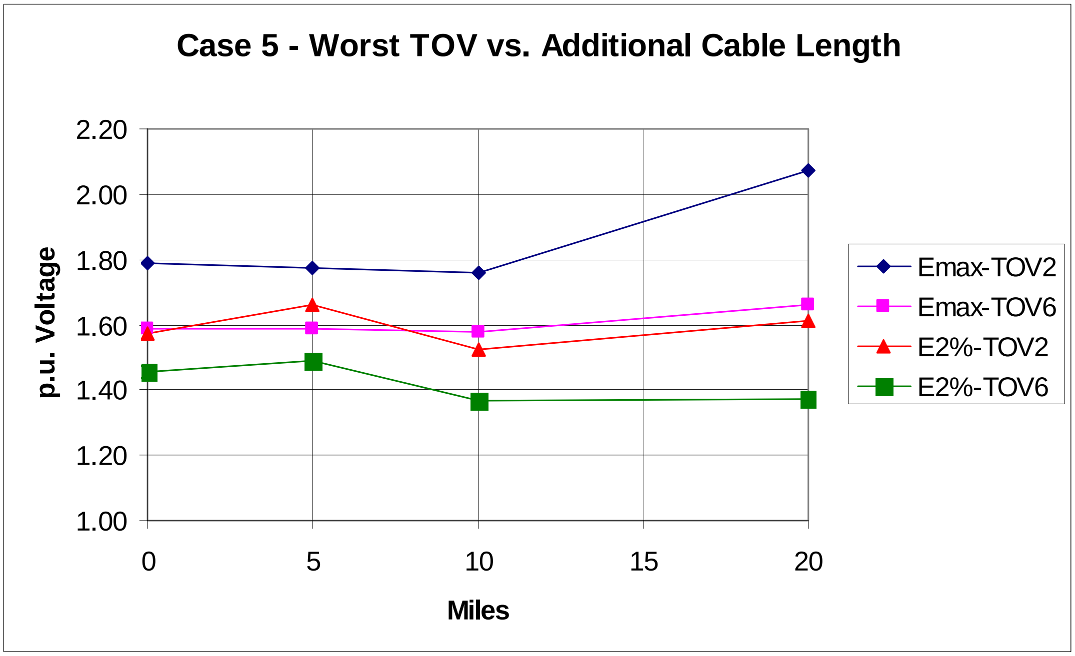


**Figure 3 - Maximum and 2% aggregated TOV levels**

Figure 4 shows the percentage of simulated fault events that exceed the TOV6 acceptance criterion, namely, TOV6 <= 1.55 per-unit. First and foremost, the base case and all of the extra-mile cases exceed this criterion.

Second, the 0.85% percent maximum risk level in Figure 4 is significant, even though it's less than 1.00%. To roughly estimate the number of arrester failures, this 0.85% could be multiplied with the total number of faults near the new cable, in order to estimate (roughly) the actual number of arrester failures. Each such arrester failure would lead to a second (or higher order) contingency. The base configuration has a risk level of 0.35% in Figure 4.

The curve labeled "Sys" represents the probability that TOV6 > 1.55 per unit at **any** monitored bus in the system for a specific fault event; it may be exceeded at one or more locations during the event. The curve labeled "Bus" represents the probability that TOV6 >1.55 at a **specific** monitored bus during the event. In other words, the "Bus" probability is normalized to the number of buses, and it will always be less than or equal to the "Sys" probability. If these two values are equal, the unacceptably high TOV is widespread; it appears at every monitored bus. In Figure 4 (and later, Figure 5), the ratio between the "Sys" and "Bus" probabilities varies from 4 to 7, indicating that the incidence of high TOVs is not especially widespread among the monitored buses.

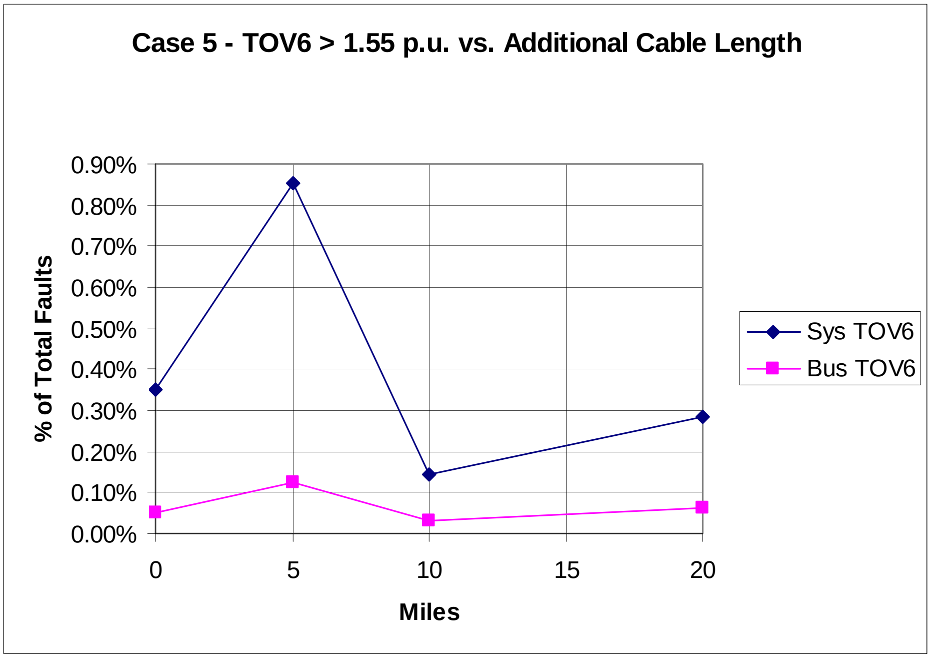


**Figure 4 - Aggregated TOVs exceeding the 6-cycle acceptance criterion**

Figure 5 shows the percentage of fault events exceeding the TOV2 <= 1.60 per-unit acceptance criterion. As explained earlier, this criterion is less important than the one for TOV6. However, there is a more significant level of events, 4.0%, exceeding the criterion at 5 extra miles. The risk levels are decreased from this at 10 and 20 extra miles, but still significantly greater than zero.

The "bump" in results at 5 extra miles reflects a dynamic overvoltage produced with supplemental contributions from another resonance, at a higher frequency, than the primary one. Fortunately, this dynamic overvoltage decays quickly enough that it appears less significant in the TOV6 results.

The base case has a non-zero risk level of 0.94% in Figure 5. Because the TOV2 criterion is more conservative than the TOV6 criterion, this relatively low level of risk could be accepted.

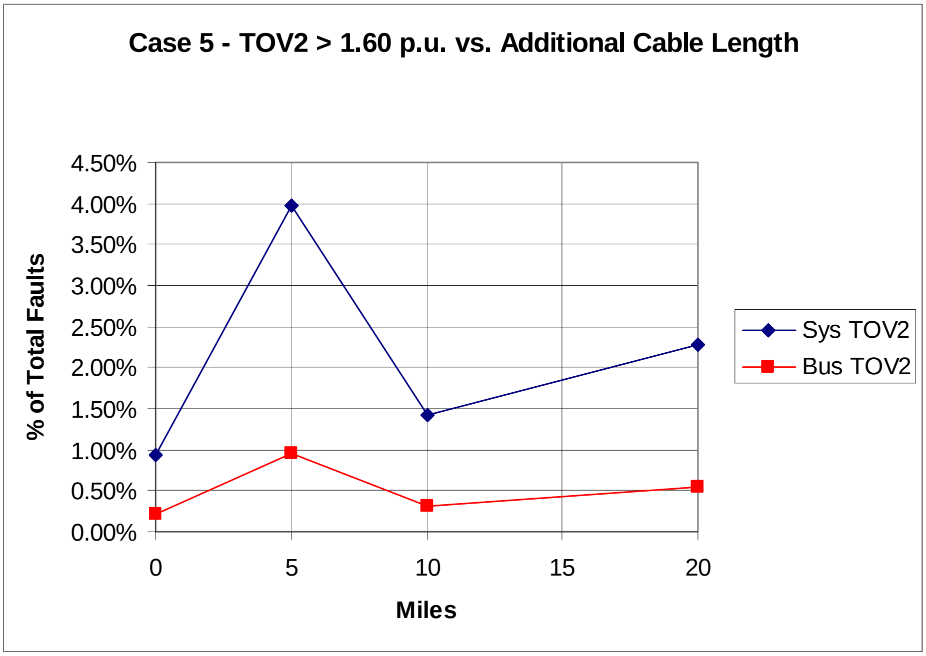


**Figure 5 - Aggregated TOVs exceeding the 2-cycle acceptance criterion**

Figure 6 shows a sample frequency scan from the Norwalk 345-kV bus, under conditions of a double contingency, at 30% load, weakened source, with increasing amounts of cable. Figure 6 represents a line-out condition, with a subsequent fault creating the second contingency.

As the cable length increases, the magnitude of driving point impedance increases slightly at the second harmonic. This by itself would tend to increase the TOV as cable length increases. But the second resonance peak increases sharply in magnitude, and shifts lower in frequency, as the cable length increases. The second resonance is due primarily to the cables alone, not interacting with other parts of the system. At 5 extra miles, this second peak is very close to the fourth harmonic. There is a significant fourth harmonic current component in the transformer saturation currents that produce the TOV. Therefore, this second resonance can increase the TOV levels, as we observed in Figures 3-5 at 5 extra miles.

At 10 and 20 extra miles, the magnitude of the second resonance is higher than at 5 extra miles, but it does not coincide as closely with the fourth harmonic. Therefore, the effect on TOV is not as severe. In fact, the impedance at 10 extra miles has a minima at the third harmonic, which helps to explain the relatively lower TOV levels at 10 extra miles.

However, the second resonance is very sensitive to cable parameters and cable operating contingencies. It is easily shifted. The high magnitudes of this peak for the extra-mile variants in Figure 6 indicate that problems are likely at 10 or 20 extra miles, for a relatively small frequency shift in the peak.

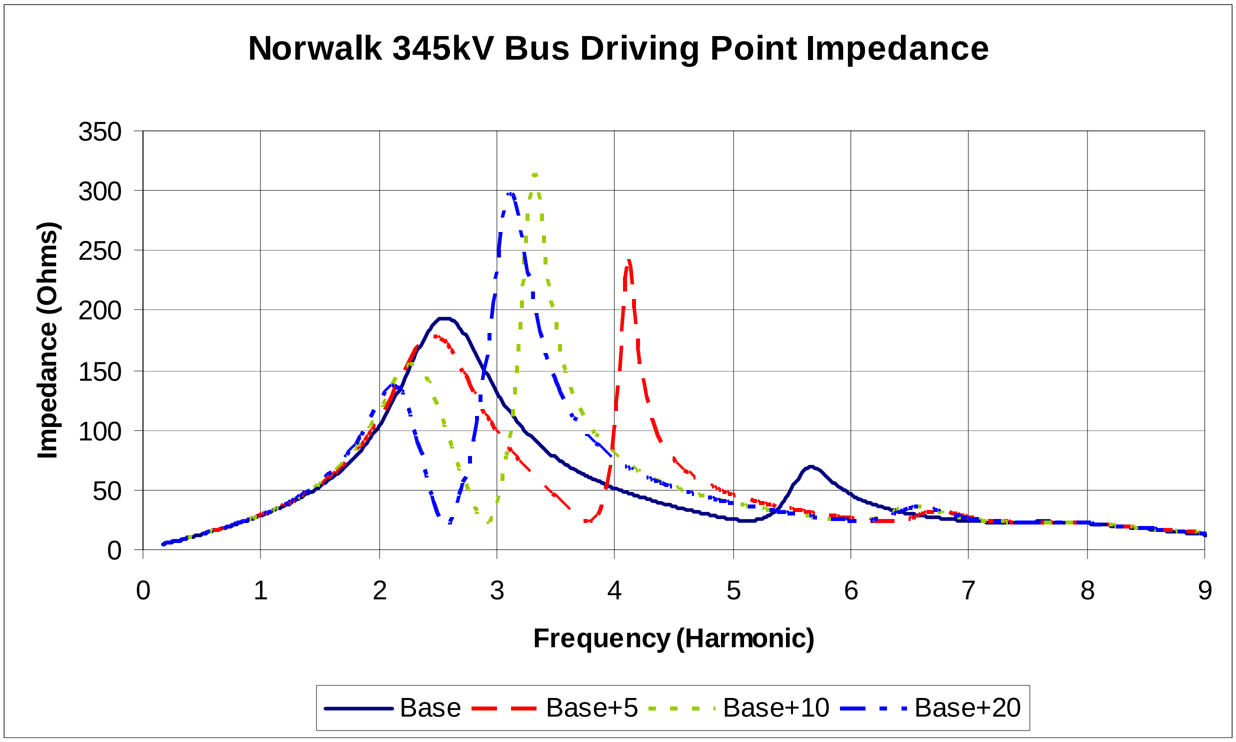


**Figure 6 - Sample frequency scan at different cable lengths.**

## *Recommendations*

Based on this analysis and the acceptance criteria described in this and other consultant reports, EnerNex recommends that the 5, 10, and 20 extra-mile variants on Case 5 be excluded from consideration. There is a sharp increase in risk at 5 extra miles, as evidenced by the increase in both 6-cycle and 2-cycle TOV levels. Even if it were possible to add cable beyond 5 extra miles and avoid this clearly problematic region, the risk levels are still significant at 10 and 20 extra miles. The sample frequency scans show that the parallel resonance from additional cable reaches a higher peak at 10 and 20 extra miles, compared to 5 extra miles. It just happens to miss the most critical frequency at 10 and 20 extra miles. However, a relatively slight shift in system parameters could produce more serious problems at 10 and 20 extra miles.

EnerNex recommends that the Case 5 base case be investigated further as an acceptable configuration for high cable penetration. It will be necessary to upgrade some existing surge arresters, or other equipment, so that they actually have the TOV capabilities assumed in the study. This option stretches power system planning, design, and construction beyond customary practices, as represented in our Case 2 reporting. It is necessary to accept a non-zero risk of TOV-induced failure, even in the Case 5 base configuration. Further study is needed for mitigation of TOVs in the Case 5 base configuration.