Temporary Overvoltage Equipment Limits – Summary Report

December 17, 2004

Prepared for:
David Forrest
Director – Transmission Engineering
Northeast Utilities

Prepared by:
Kyle G. King
K & R Consulting, LLC

TOV Limit Recommendations

Executive Summary:

The effects of temporary overvoltages (TOVs) on the transmission system have been reviewed and surge arresters were determined to be the limiting element. Existing 115 kV and 345 kV surge arresters limit the allowable TOV to 1.6 per unit at 6 cycles. Replacing these arresters will increase the allowable TOV limit to 1.8 per unit for 6 cycles. A detailed discussion of TOV limit follows.

Introduction:

The ability of electric transmission systems to withstand steady-state overvoltages (long duration) and transient overvoltages (very short duration), are well-defined by standards. The ability of electric transmission systems to withstand overvoltages in the intervening time frames, temporary overvoltages (TOV), is not as well defined. This paper will define the temporary overvoltage limits that are applicable on the Northeast Utilities and United Illuminating electric transmission systems.

Steady State Overvoltages:

Equipment on the transmission system typically can withstand voltages of about 5% over nominal voltages for long periods of time (several minutes or longer). American National Standards Institute (ANSI) Standard C84.1-1995 sets the maximum system voltage at 121 kV for a 115 kV system and 362 kV for a 345 kV system. The standard defines maximum system voltage as “The highest system voltage that occurs under normal operating conditions, and the highest system voltage for which equipment and other components are designed for satisfactory continuous operation without derating of any kind. In defining maximum system voltage, voltage transients and temporary overvoltages caused by abnormal system conditions such as faults, load rejection, and the like are excluded. However, voltage transients and temporary overvoltages may affect equipment operating performance and are considered in equipment application.”

Transient Overvoltages:

The Institute of Electrical and Electronics Engineers (IEEE) Standard 1313.1-1996 defines transient overvoltage as "a short-duration highly damped, oscillatory or nonoscillatory overvoltage, having a duration of a few milliseconds or less. Transient overvoltage is classified as one of the following types: lightning, switching and very fast front, short duration." This standard further defines two transient test wave forms that are used to define equipment overvoltage withstand capabilities. The test waves are not identical to actual lightning and switching events.

The shorter duration transient overvoltage simulates the effect of lightning. This test overvoltage rises to a crest value in 1.2 microseconds (.000072 cycles) and drops to 0.5 of crest value in 50 microseconds (.003 cycles). The voltage withstand level for this test wave form is called the basic lightning impulse insulation level (BIL).

The longer duration transient overvoltage simulates the effects of a switching surge. This test overvoltage rises to crest value in 250 microseconds (.015 cycles) and drops to 0.5 of the crest value in 2,500 microseconds (.15 cycles). The voltage withstand level for this test wave form is called the basic switching impulse insulation level (BSL).

IEEE C.57.12.00-1993 defines the relationship between normal system voltage and BIL levels commonly used on high voltage electric transmission systems.

The US electrical system has a standard frequency of sixty hertz or 60 cycles per second. Thus one cycle is about 16.7 milliseconds. Transient overvoltages last much less than one cycle.

The transient overvoltages from the TNA studies of Southwest Connecticut are within the design capability of existing equipment on the NU and UI electric transmission system.

Temporary Overvoltages:

IEEE Standard 1313.1-1996 defines temporary overvoltages as "an oscillatory phase-to-ground or phase-to-phase overvoltage that is at a given location of relatively long duration (seconds, even minutes) and that is undamped or only weakly damped. Temporary overvoltages usually originate from switching or fault clearing operations (e.g., load rejection, single-phase fault, fault on a high-resistance grounded or ungrounded system) or from nonlinearities (ferroresonance effects, harmonics), or both. They are characterized by the amplitude, the oscillation frequencies, the total duration, and the decrement.

Determining TOV Limits for Transmission Equipment:

Overvoltage conditions can cause problems on a utility's system such as insulation failures, overheating or mis-operation. Since virtually all system equipment is insulated, overvoltages that would cause insulation failure would be problematic for all equipment**.** Overvoltages increase the magnetic flux in the magnetic cores of equipment such as transformers and shunt reactors, which produces heat in the transformer cores, and can cause the equipment to fail. Overvoltage can cause mis-operation of equipment. For instance, it can cause surge arresters to fail, causing short circuits, or it can cause circuit breakers to fail to interrupt power flow.

To determine what problems the overvoltage conditions could cause, it is necessary to identify the equipment that is most vulnerable to such conditions. Using IEEE standards and manufacturers' specifications, each piece of equipment on the system or planned for new construction was reviewed to identify existing TOV capabilities. The equipment reviewed by Dave Forrest (NU) and George Davenport (UI) included:

- Bushings (Most pieces of equipment have bushings)
- Cable
- Capacitors
- Circuit breakers[1]
- Coupling capacitor voltage transformers
- Gas insulated substations
- Insulators
- Transformers
- Shunt reactors
- Surge arresters

[1]Presumes that circuit breaker will not operate during TOV events.

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

Transformer TOV Limits:

Transformers can be impacted by TOVs in two ways, overheating caused by overexcitation or failure of the transformer's insulation system.

Over excitation limits were obtained from transformer manufacturers. These limits vary depending on the load on the transformer and the power factor of the load. The manufacturers' data indicate that overheating would not be a limiting factor as long as the TOV lasted less than two seconds. It takes time to generate significant heat to damage the magnetic core within the transformer during overvoltage conditions. Many of the TOV study waveforms also have second and higher order harmonic components. The higher frequencies have less impact on core saturation and heating than do 60 Hz components and the overvoltages in Southwest Connecticut TOV studies last for cycles rather than seconds, therefore the transformer heating effect is not a concern for these short duration-higher frequency TOVs.

IEEE Standard C57.00 contains transformer overvoltage withstand limits for lightning surges, switching surges and 60 cycle overvoltages. The data in this standard can be used to estimate a transformer overvoltage withstand for short TOVs. The existing transformer TOV limits in per unit nominal system voltage were calculated using the safety margins defined in IEEE Standard C62.22. The transformer TOV limits are shown in Table 1.

Table 1 – Southwest Connecticut Transformer Temporary Overvoltage Limits

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

Surge Arrester TOV Limits:

Surge arresters are designed to prevent insulation flashover and equipment damage by limiting transient voltages between energized conductors and grounded components. Surge arresters are not designed to protect equipment from TOVs. Arresters may be specified within a particular class by the Maximum Continuous Operating Voltage (MCOV). In applying arresters, it is critically important that the arrester MCOV rating be greater than the maximum continuous voltage to which the arrester is exposed at any time. Arresters may also be specified by the "Duty Cycle Rating" which is the maximum voltage an arrester can successfully withstand after a series of discharge tests. The Duty Cycle test procedure is defined in IEEE Standard C62.11. For the purpose of this discussion, the remaining arrester rating parameters will be discussed in terms of MCOV in order to directly compare the arrester rating with the nominal system phase to ground voltage.

At MCOV the arrester current is less than a few milliamperes. As the voltage across the arrester is increased to between 20% and 30% above the MCOV, the arrester resistance decreases and the arrester starts to conduct some current and absorb some thermal energy from the power system. This conduction process occurs quickly and the arrester may "turn on" and "turn off" in a fraction of a microsecond. For lightning and switching overvoltages, arresters may conduct and absorb all the energy from a particular waveshape in much less than one 60 Hz power frequency cycle (16.7 milliseconds).

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

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

Table 2 – Typical (Existing) Southwest Connecticut Surge Arrester Temporary Overvoltage Limits

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

The energy handling capability of an arrester depends on the amount of metal oxide material within the arrester. A higher voltage arrester will have more standard 76 mm disks stacked in series to withstand the applied voltage. A higher voltage arrester is capable of absorbing more energy than a lower voltage arrester of the same type. A higher voltage arrester also withstands a higher voltage before it starts to conduct and absorb energy from the power system. For these two reasons, an acceptable engineering practice when arrester energy limits are a concern, is to increase the specified arrester's MCOV. In certain locations where the existing surge arrester TOV limits are exceeded, the arresters may be replaced. The TOV limits for 84 kV MCOV and 235 kV MCOV arresters are shown in Table 3.

Table 3 – Typical 84 kV MCOV and 235 kV MCOV Surge Arrester Temporary Overvoltage Limits

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

Increasing the MCOV of 115 kV arresters may result in excess energy being transferred to the arresters on the low voltage side of power transformers. On the NU and UI system, the low voltage arresters on power transformers may also have to be replaced if the existing 115 kV arrester size is increased. The arresters at each substation will have to be evaluated independently due to difference in low side voltage (13.8 kV, 23 kV, 27.6 kV), arrester types and manufacturer, arrester rating, etc.

The purpose of surge arresters on the power system is to limit transient overvoltages (not temporary overvoltages) to a magnitude below the insulation strength of a line or particular piece of equipment. Surge arresters are selected to provide a safety margin between arrester discharge voltage and equipment insulation level. Whenever arresters are replaced with higher voltage units, the risk of associated equipment failure is increased.

Older design Silicon Carbide (SiC) surge arresters are still installed in some locations on the transmission system in SWCT. The SiC arrester design includes a small gap which prevents the arrester block material from being exposed to a constant power frequency voltage. When the overvoltage level exceeds the spark-over voltage for the arrester gap, the SiC arresters start to conduct current and absorb energy. The newer Metal Oxide Varistors (MOV) do not require a gap and the MOV material may be continuously exposed to line voltage without degradation.

The gap spark-over characteristics and energy handling capability of the older SiC designs may degrade over time. It is recommended that all Sic arresters that may be exposed to TOVs greater than 1.6 p.u. for 6 cycles be replaced with new MOV arresters of the appropriate rating.

An alternative to increasing the arrester voltage rating is to add multiple parallel columns of matched arresters in the substations where excess TOV may exist. This alternative would limit the amount of TOV energy that propagates through the remainder of the NU and UI transmission and distribution system. EMTP transient modeling would be necessary to determine both the effectiveness of this approach and the amount of energy that would be absorbed by the arresters. The arrester manufacturers would need to be involved with the design, testing, and installation of these custom matched high energy parallel arrester stacks. It is not possible to simply connect various standard arresters in parallel in order to absorb the required amount of energy. The manufacturer must balance the individual discharge voltage of disks columns to ensure the multiple columns will share the energy from the overvoltage. If two standard arresters of the same voltage rating are placed in parallel, it is likely that one of them will have a slightly lower discharge voltage than the other and, consequently, one arrester would absorb a disproportionately larger portion of any electrical surge. This approach would result in a non-standard transmission component with unknown reliability. This option of increasing arrester energy capability is not recommended for control of excess system TOV.

Recommendations:

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