



Temporary Overvoltages Following Transformer Energizing



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A switching transient overvoltage analysis can determine the risk of exposing equipment to high transient overvoltages. The overvoltages can be either short duration switching surges or longer duration temporary overvoltages (TOV). Energizing a large transformer can cause a TOV, and the risk is higher during a black start. A review of the surge arrester and overvoltage relay applications should be included in a switching analysis.

Simulation of switching events with an electromagnetic transient program (EMTP) can provide insight into the expected magnitudes of fast transient overvoltages and currents. The EMTP model should include a detailed three-phase representation of the large power transformers, lines, cables, generators, circuit breakers, and surge arresters. The transformer model must include core saturation in order to simulate inrush currents following energizing. The inductance and capacitance of transmission lines and cables influence the results.

Switching surges are the transient overvoltages that immediately follow the opening or closing of a circuit breaker or other switching device. Switching surges have high frequency (100 Hz to 10 kHz) components that decay quickly, typically within two to three cycles of the power frequency, and are followed by a normal steady state voltage. Switching surges typically contain only one, or just a few, peaks that are of interest, as shown in Figure 1. This sample waveform is from an EMTP simulation of the energizing of a typical overhead line.

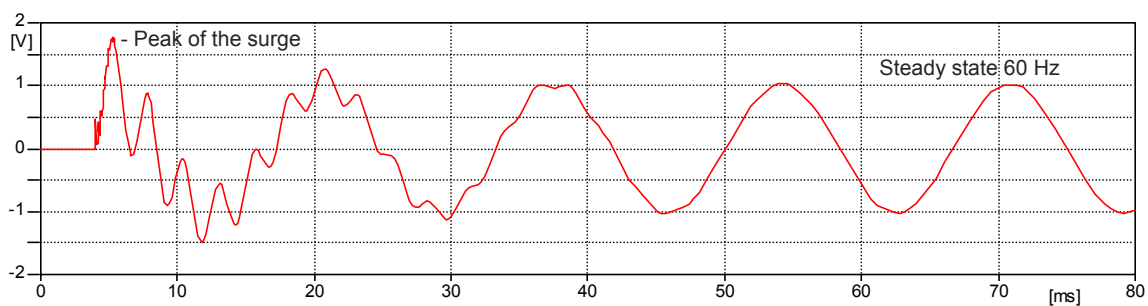


Figure 1 - Switching Surge from an EMTP Simulation of the Energizing of a Typical Overhead Line Where the Voltage is in Per Unit

The magnitude and waveshape of the switching surge depend upon the precise instant when the circuit breaker closes during the power frequency wave of the source. Thus, many simulations must be made with various closing times to obtain the overvoltage results as a statistical distribution. Surge arresters or pre-insertion resistors are usually effective in limiting the peak of the switching surges.

While switching surge overvoltages typically recede to normal steady state levels within a few cycles, a TOV can last seconds. TOV includes many types of events where the voltage exceeds the rated value for three cycles or more. TOV can result from switching circuits that saturate the core of a power transformer, such as when relatively large transformers are energized from a relatively weak transmission system. A TOV can also follow a switching surge such as when a transformer is energized with a line or cable.

Transformer energization creates transient inrush currents when the transformer's core becomes over fluxed, or saturated. Transformer inrush currents can have a high magnitude containing a significant harmonic content. The harmonic rich transformer inrush currents interact with the harmonic resonances of the power system. The resonant frequencies are a function of the series inductance associated with the system's short circuit strength and the shunt capacitances of the cables and lines. Higher inductances (relatively weak systems) and higher capacitances (long lines and cables) yield lower resonant frequencies and a higher chance of TOV. These harmonics can interact with system inductive-capacitive resonances that result in resonant overvoltages lasting several seconds.

A transmission system will generally be weak during the first steps of a system restoration following a black out. Energizing equipment during black start conditions can result in higher overvoltages than during times of normal operation. The equivalent system inductances are relatively high during a restoration process because relatively few generators are on-line and the grid tends to be sparse. Therefore, the first system resonant frequency can be much lower than during normal system operation. Large capacitances also contribute to the low resonant frequencies.

Figure 2 shows an example of a temporary overvoltage from an EMTF simulation of the energizing of a large transformer during black start conditions. In contrast to switching surges with one predominant peak, temporary overvoltages can have hundreds of peaks of about the same magnitude if the TOV duration is several seconds.

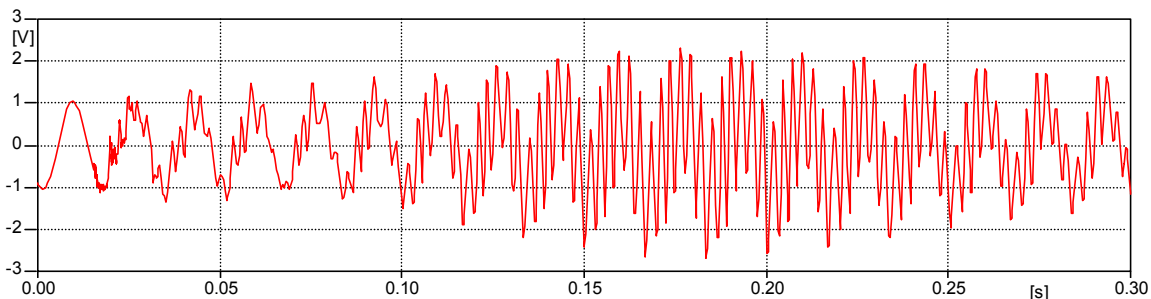


Figure 2 - Example of a Temporary Overvoltage from an EMTF Simulation of the Energizing of a GSU Transformer During Black Start Conditions (V is in per unit of nominal peak phase voltage)

The TOV results are sensitive to several parameters, including the circuit breaker closing times (switching angles), the transformer saturation curve, residual flux in transformer, source impedance and system capacitances.

Generator step up (GSU) transformer energizing is often part of a black start analysis. A GSU can generally be energized in one of two distinct modes. For the case of a unit connected generator (without a generator circuit breaker), the GSU transformer is energized off-line as the turbine-generator set gradually builds up speed and voltage. The GSU will draw a relatively small magnetizing current with the high side open. There should be little or no transient overvoltage or inrush current following the synchronized closure of the transmission side circuit breaker.

Power plant designers may use generator circuit breakers so that the auxiliary transformers can be connected to the medium voltage generator bus. For the case of a system with a generator circuit breaker, the GSU transformer can be energized directly from the transmission system, which may initiate a significant TOV. Energizing other large transformers should also be simulated for a black start analysis.

Overvoltages can lead to equipment failure or damage. Cables and transformers often do not have a switching surge or TOV withstand voltage rating. A long duration TOV can also trip overvoltage relays and therefore hinder the successful implementation of a black start plan.

Both older and newer types of surge arresters are sensitive to high TOV levels. Modern gapless metal oxide varistor (MOV) type surge arresters conduct current at all voltage levels which makes them TOV sensitive. The expected TOV magnitude and duration should be compared with the manufacturer's TOV capability curves for the surge arresters installed. Many substations still contain arresters with the older gapped silicon carbide technology that can fail when the TOV repeatedly exceeds the gap spark over level and the multiple discharges result in excessive energy absorption.

The TOV that can follow a transformer energizing is one of many types of simulations that should be performed during a switching transient analysis of a black start plan. The companion article "Black Start Studies" discusses power flow, short circuit and dynamic analysis.