Switching Induced Transients:

Transformer switching is the most commonly performed operation in any power delivery system and most of the times this operation can be performed without any undesirable consequences. However, given the right combination of system parameters, switching can result in a violent interaction between the circuit breaker and the transformer.

This type of failures can best be explained by understanding as to how the switching induced transients are produced and how the transformer windings react to them. Switching transients can be produced by the breaker contact re-ignitions and / or by current chopping.

Breaker Contact Re-Ignition: The generation of transients produced by breaker contact re-ignitions can be understood by considering a simple power system shown in Fig. 1A where a circuit breaker is connected to a generator with a cable on its source side and to a transformer and a load on its load side.

This simple system can be represented as a lumped parameter circuit shown in Fig. 1B simulating the generator and cable capacitance, inductance and resistance on the source side and also the cable connection, transformer and load inductance and capacitance on the load side of the breaker.
The moment circuit breaker (*VCB*) contacts open, a voltage recovery transient (*Trv1*) appears across the breaker contacts as shown in Fig. 1C. The diverging lines *AB* and *AC* shown in Fig.1C, represent the breakdown voltage limits of the gap between the breaker contacts at any time as they continue to separate. As *Trv1* reaches the breakdown voltage limit *AB*, the gap between the contacts breaks down and an arc bridges the contacts. The voltage between the contacts collapses and a current I_1 flows through the circuit show in Fig. 1B. The arc between the contacts goes out only when I_1 reaches its natural zero. Now another recovery transient (*Trv2*) appears across the contacts. This transient causes another breakdown of the gap between breaker contacts which are still in the process of separating. An arc appears across the contacts and a current I_2 flows in the system. This arc extinguishes when I_2 reaches its natural zero and another recovery voltage transient *Trv3* appears across the contacts. This process of contact re-ignition continues until the gap between the breaker contacts is so large that the recovery voltage transient cannot break it down.

The re-ignition of the contacts also stops occurring if the magnitude of the arc current (i.e. I_1 *or* I_2 *or* I_3 etc.) becomes so large that by the time it reaches its current zero, the contacts have gone so far apart that the recovery voltage cannot make them re-ignite. That is why the breaker induced transformer failures have occurred under lightly loaded conditions while carrying predominantly inductive loads.

Current Chopping: Another complication that occurs in the process of contact re-ignition is called *Current Chopping*. As discussed earlier, an arc appears across the circuit breaker contacts during their re-ignition. This arc extinguishes only when the current in the system reaches its natural zero. However, in vacuum type breakers, before the arc current diminishes toward its natural zero, it reaches a threshold level at which the arc becomes unstable and suddenly extinguishes. This threshold is called the current chopping level of the breaker and is a function of the breaker contact materials. The instantaneous chopping of the current to zero results in very high di/dt, producing a high frequency high voltage transient as shown in Fig. 1D. Due to the instantaneous chopping of the current, the resulting voltage excursions can produce flashover of the transformer bushing and / or damage the winding insulation.

It should be noted that breaker contact re-ignitions can occur without current chopping. This phenomenon makes the re-ignition transient more complicated and more injurious.

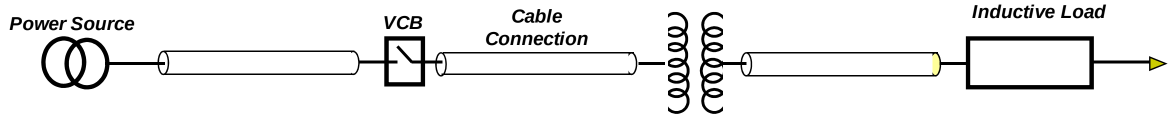


Fig 1A. A typical power system.

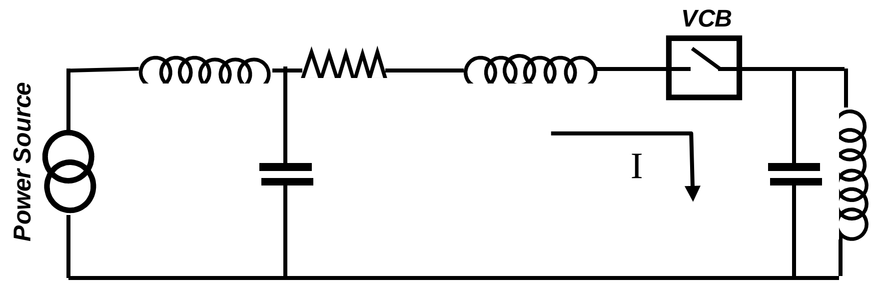


Fig. 1B. Lumped parameter equivalent circuit of the circuit shown in Fig. 4A

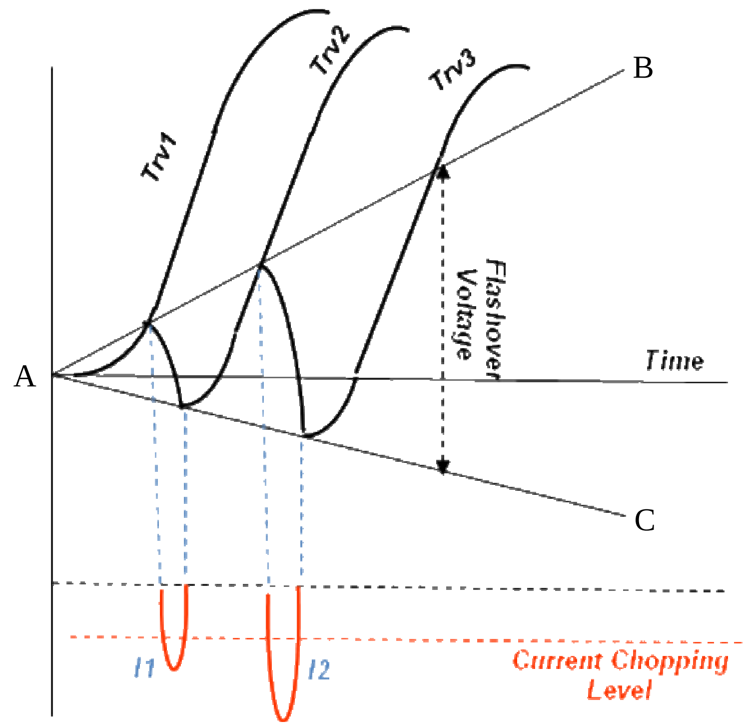


Fig. 1C. Transient produced by breaker re-ignitions.

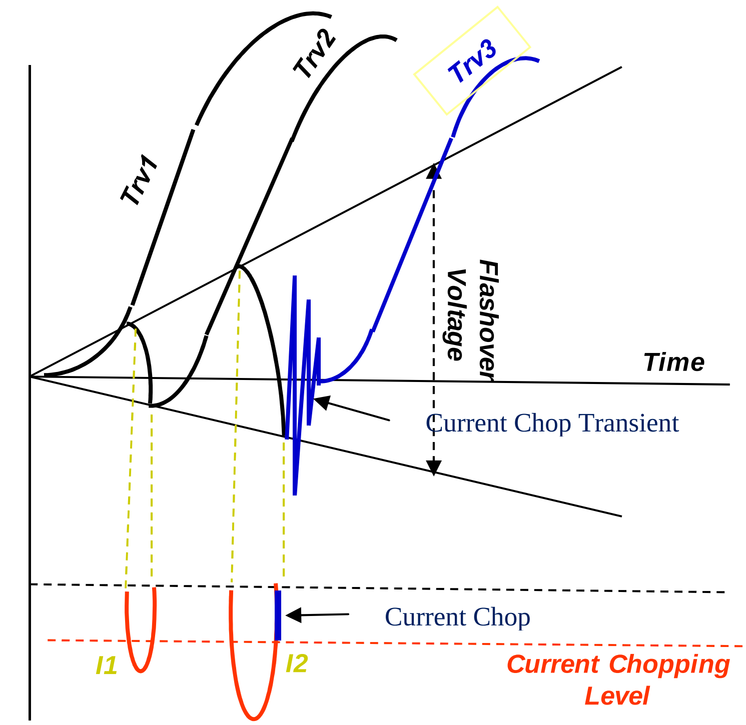


Fig. 1D. Re-ignition transient caused by current chopping.

In systems with very high inductive / capacitive parameters, current chopping can occur without breaker contact re-ignition. In a highly inductive and capacitive circuit, the rate of rise of the TRV can be slow relative to the opening speed of the breaker contacts. This can prevent the repeated contact re-ignitions. However the sudden chopping of the load current can result in a voltage transient that rides the system voltage as shown in Fig. 1E.

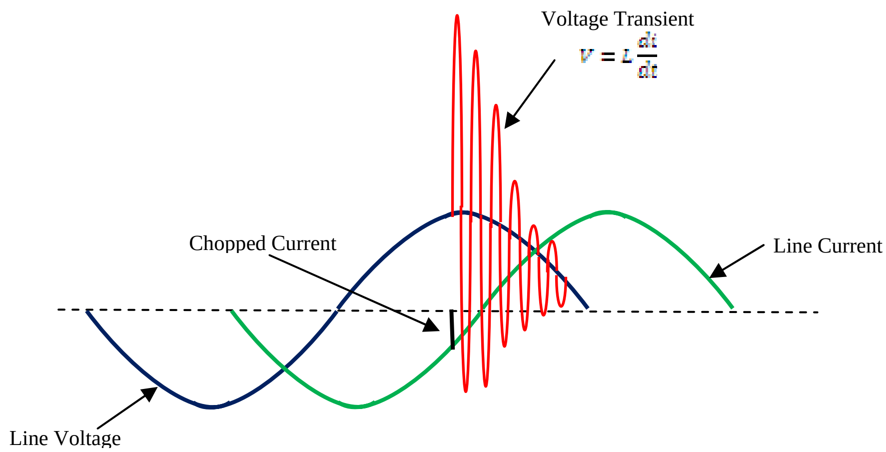


Fig. 1E Current chopping transient without re-ignitions

The complete analytical treatment of this subject is beyond the scope of this standard however, it is well recognized that current chopping voltage transients that can cause flashover on transformer and circuit breaker bushings. This type of rapidly rising voltage produces excessive voltage escalation near the ends of the transformer windings. Excessive voltage can also occur at the neutral end of the winding if it is ungrounded.

Transformer Winding Response to Re-ignition Transients: During a special test, a typical re-ignition transient recorded at one of the New York City Transit system substations is shown in Fig.2. As discussed earlier, such re-ignition transients are very specific to the system parameters at a particular location. They are difficult to simulate and that is why digital studies have not proven effective in predicting the possibility of switching induced transformer failure at a specific location.

This transient resembles a saw-tooth voltage function. The frequency with which the breaker contacts re-ignite is much faster in the beginning and continues to slow down as the breaker contacts get farther apart. The shape and the frequency contents of these transients are a function of the breaker's load side system parameters as shown in Fig. 1B.

It is very commonly believed that this type of transients can induce resonance in transformer windings. Typically the transformer resonant frequencies range from 20 through 100 k Hz.
The resonant frequencies of a transformer winding can be determined by measuring its short-circuit impedance at its terminals with a variable frequency generator (RLC Meter) while all the other windings are short-circuited and grounded as shown in Fig 3A. This type of measurements, yield impedance values, that are a function of applied voltage frequency. Such impedance measurements range between maximum and minimum values at various frequencies, as shown in Fig. 3B.

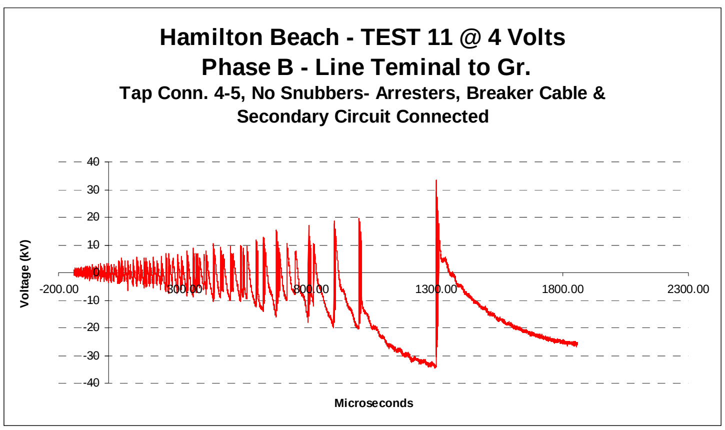
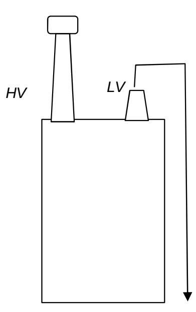


Fig.2 Recorded re-ignition transient at substation.



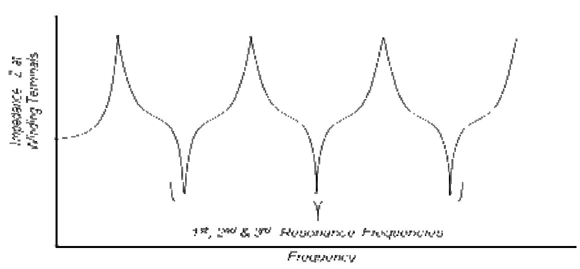


Fig. 3A

Fig. 3B HV to LV short circuit impedance at resonant frequencies.

The frequencies at which the winding impedance values become minimum, represent the resonant frequencies of the winding. Normally, only the first three or four resonance frequencies are consequential in producing dangerous voltage amplifications. At higher resonance frequencies, the dielectric losses and skin effects prevent dangerous voltage escalations from occurring.

The special voltage distribution along a winding when it is excited with first and second resonance frequencies is shown in Fig. 4. Judging from the observed failure locations, as shown in Fig. 3, it is evident that these failures are most likely induced by the first resonance frequencies. It also follows that, re-ignition transient voltages of less than arrester protection levels can go past the lightning arresters and induce resonance in transformer windings resulting in voltage magnification that can cause insulation failures. This appears to be the reason why lightning arresters have been ineffective protecting against re-ignition transients.

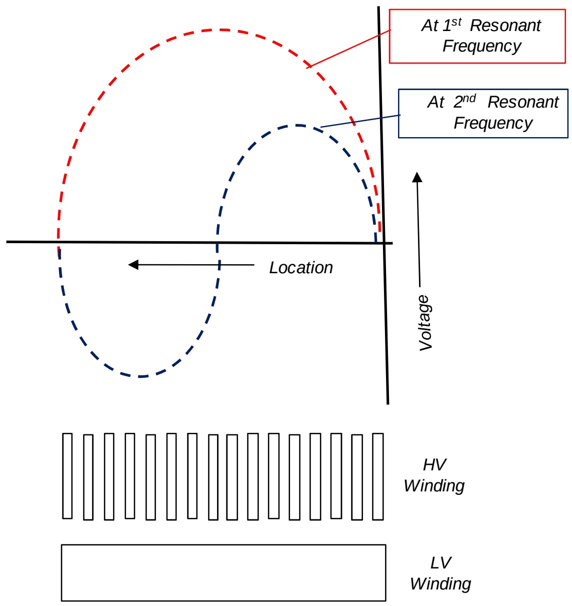


Fig. 4 Spacial voltage distribution at first and second resonant frequencies.