INTEGRAL energy

Power Quality and Reliablity Centre

University of Wollongong

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TRANSIENT OVERVOLTAGES ON THE ELECTRICITY SUPPLY NETWORK – CLASSIFICATION, CAUSES AND PROPAGATION

This Technical Note presents an overview of the transient overvoltages that can occur on the electricity distribution network, how they are classified, their causes, and how they propagate through the network. Integral Energy, your local Network Operator or the Integral Energy Power Quality and Reliability Centre can give you additional advice if you have particular concerns with these issues.

Summary

Transient overvoltages in electrical transmission and distribution networks result from the unavoidable effects of lightning strikes and network switching operations. These overvoltages have the potential to result in large financial losses each year due to damaged equipment and lost production.

Transient overvoltages can be classified as being either impulsive e.g. transients resulting from lightning strikes, or oscillatory e.g. transients resulting from network switching.

These transients move through the distribution network in different ways depending on their frequency content. The lower frequency oscillatory transients propagate in essentially the same way as the 50 Hz fundamental voltage. However, impulsive transients tend to move in a very different way which can give unexpected consequences. A full study of their effects requires travelling wave analysis.

Contents

1. Introduction

Transient overvoltages in electrical transmission and distribution networks result from the effects of lightning strikes and switching operations and are hence unavoidable. They are of very short duration (microseconds to milliseconds) and can be of large magnitude. Transient overvoltages and other power quality disturbances cause billions of dollars of losses each year worldwide due to damaged equipment and lost production [1]. They are also known as surges or spikes but will be referred to in this Technical Note by their more correct technical name of transient overvoltages.

This Technical Note will classify transient overvoltages, detail what causes them, and explain how they travel through the distribution network. A subsequent Technical Note (in preparation) will describe the impact of transient overvoltages on network and customer equipment, and suggest ways to either protect distribution networks and customer equipment or prevent the transient overvoltage from occurring.

2. Classification of transient overvoltages

A transient overvoltage can be defined as the response of an electrical network to a sudden change in network conditions, either intended or accidental, (e.g. a switching operation or a fault) or network stimuli (e.g. a lightning strike). A transient is a natural part of the process by which the power system moves from one steady state condition to another. Its duration is in the range of microseconds to milliseconds.

Transient overvoltages can be classified into two broad categories:

- Impulsive
- Oscillatory

2.1 Impulsive Transients

An impulsive transient is a sudden, non-power frequency change in the steady state condition of the voltage and/or current waveforms that is essentially in one direction, either positive or negative, with respect to those waveforms. The most common cause of this type of transient is lightning. Figure 1 shows a typical impulsive transient (at point X) occurring on a normal voltage waveform. The magnitude of such a transient can be many times larger than the peak value of the normal voltage waveform.

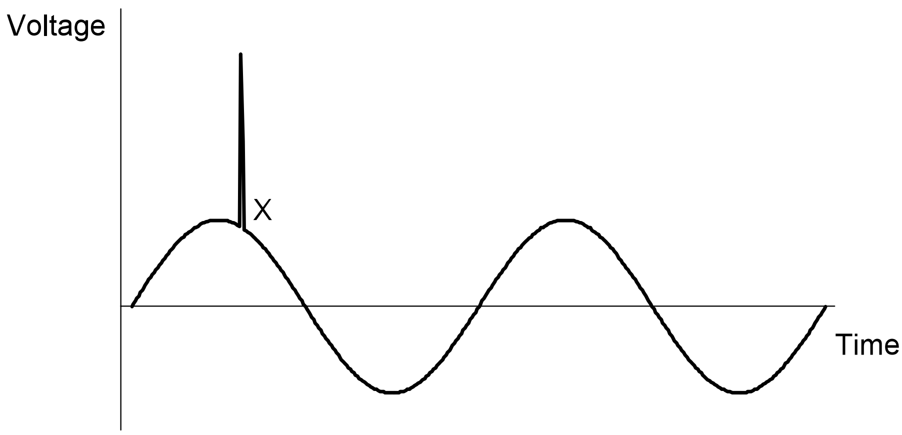


Figure 1: A typical impulsive transient shown at point X.

Impulsive transients are usually characterised by their rise and decay times and peak value. This is illustrated in Figure 2 which is a magnification of point X in Figure 1. The vertical axis scale in Figure 2 is relative to the peak value of the transient with the zero value being at point X on the power frequency waveform in Figure 1. The rise time (front time) T_1 considered is usually calculated as 1.67 times the time T for the transient to rise from 30% to 90% of the peak value, and the decay time (time to half value) T_2 is usually the time from the virtual beginning of the transient to the time that its magnitude has fallen to 50% of the peak value [2]. The waveform shown in Figure 2 would be called a T_1/T_2 waveform where T_1, T_2 are expressed in μs. A 1.2/50 waveform (1.2 μs front time, 50 μs time to half value) with some peak value of V_{pk} (e.g. 95 kV for 11 kV systems) is often specified as a standard lightning impulse test waveform.

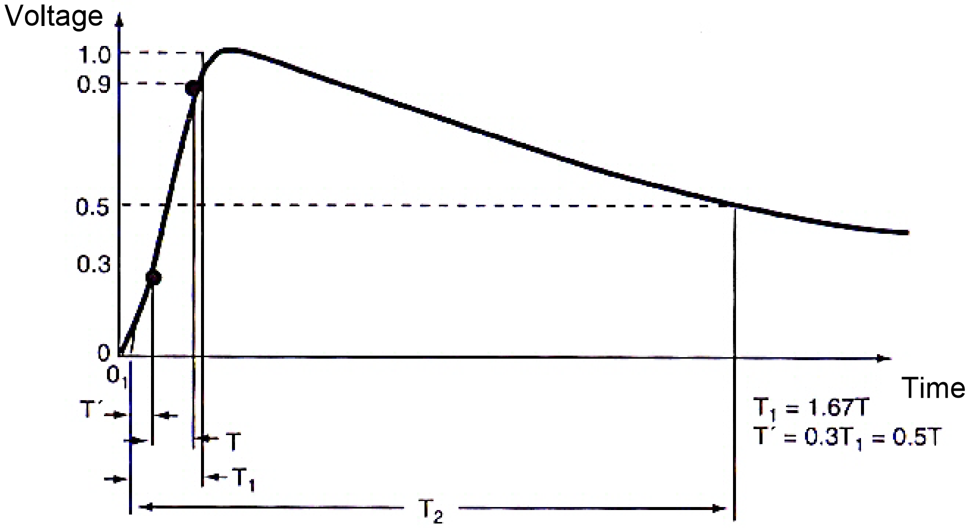


Figure 2: Characterisation of impulsive transient.

2.2 Oscillatory Transients

An oscillatory transient is a sudden, non-power frequency change in the steady state condition of the voltage and/or current waveforms that swings (oscillates) both positively and negatively with respect to the normal voltage waveform. The frequency of this oscillation can be quite high. Figure 3 shows a typical oscillatory transient (at point Y) occurring on a normal voltage waveform.

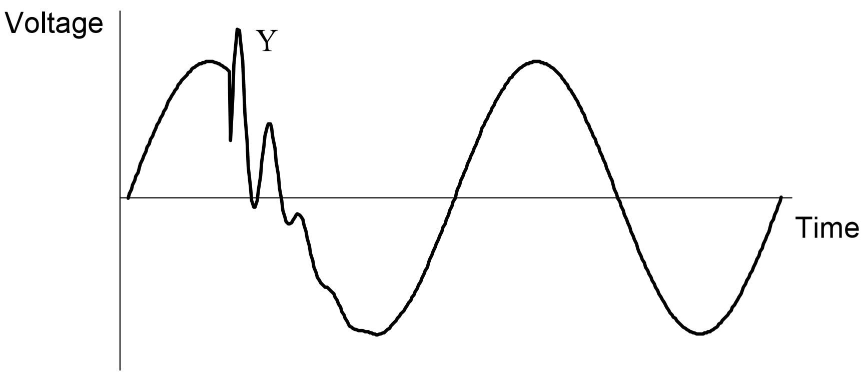


Figure 3: A typical oscillatory transient shown at point Y.

Oscillatory transients are described by their magnitude, predominate frequency and decay time (duration). They can be subdivided into low, medium and high frequency categories.

An oscillatory transient with a primary frequency component less than 5 kHz, and duration from 0.3 ms to 50 ms, is considered a *low frequency transient* according to the classification given in IEEE Standard 1159-1995 [3]. This category of phenomena is frequently encountered on sub-transmission and distribution systems and is caused by several types of switching event. The most frequent event is capacitor bank energisation. Capacitor bank energisation typically results in an oscillatory voltage transient with a predominant frequency between 300 and 900 Hz and a peak magnitude between 1.3 and 1.5 times the crest voltage of the 50 Hz waveform. Oscillatory transients associated with ferroresonance and transformer energisation also fall into this category.

An oscillatory transient with a predominant frequency component between 5 and 500 kHz and a duration measured in tens of microseconds is termed a *medium frequency transient*. A typical example would be the transients generated by back-to-back capacitor energisation and cable switching.

Finally, oscillatory transients with a predominant frequency component greater than 500 kHz and a typical duration in microseconds are considered *high frequency transients*. These transients often occur when an impulsive transient excites the natural frequency of the local power system network.

3. Causes of transient overvoltages

As indicated in Section 2, transient overvoltages that occur in distribution systems have two main causes:

- Lightning strikes
- Network switching operations

3.1 Overvoltages due to lightning

Lightning is an electrical discharge in the air between clouds, between different charge centres within the same cloud, or between cloud and earth (or earthed object). Even though more discharges occur between or within clouds, there are enough strokes that terminate on the earth to cause problems to power systems and sensitive electronic equipment. When lightning strikes occur in or near an electricity distribution system, lightning currents are generated and conducted through the power system into connected equipment. Large impulsive transient overvoltages are produced as a result of this current flow.

Lightning can strike directly to the phase conductors of overhead power lines producing very high magnitude transient overvoltages. Peak current can be up to 200 kA with voltages over 1 MV. This situation usually causes power system faults that eventuate into supply interruptions and voltage sags throughout the distribution network. Lightning can also strike the overhead earth wire (shield wire) that is sometimes installed above the phase conductors to protect them from a direct lightning strike, or the tower or power pole itself. This can lead to what is known as a back-flashover to the phase conductors as the voltage on the earth wire or tower rises to become much greater than the voltage on the phase conductors.

In addition to direct strikes, lightning can induce currents and voltages on power lines without touching them (known as an indirect strike). The large electromagnetic fields produced by lightning discharges can couple into the power network and produce induced transients. Currents produced in this manner are usually less than 2 kA with voltages less than 100 kV.

Another situation where an impulsive type of transient can occur is where overhead conductors at a higher voltage level physically fall on to lower voltage mains, a condition sometimes called high voltage injection or intermix [4]. Initially, a wavefront will travel from the point of contact with a magnitude equal to the instantaneous difference between the voltages on the clashing conductors – this can be quite significant for the lower voltage system. This wavefront will be reflected and refracted at points of discontinuity of surge impedance in the overhead network and will quickly die out due to the losses inherent in the distribution network. See Section 4.1 for details about surge impedance and travelling waves.

3.2 Overvoltages due to network switching

Switching operations within the distribution network are a major cause of oscillatory transient overvoltages. Such operations include switching of utility capacitor banks, switching of circuit breakers to clear network faults, and switching of distribution feeders to rearrange the network for maintenance or construction.

Capacitor banks are installed by utilities at various locations on their transmission and distribution networks to provide reactive power for voltage support. They are switched in and out depending on the level of support needed at any one time. When a discharged capacitor is energised, the voltage of the busbar to which it is attached will momentarily collapse. This occurs because the voltage across a capacitor cannot change instantaneously. This is followed by an oscillatory recovery that usually lasts for ½ a cycle or more. The overshoot associated with this oscillation can result in a voltage that has a theoretical peak value of two times the maximum value of the 50 Hz sine wave but typically is no more than 1.5 times, as mentioned above. An example of a capacitor switching waveform is shown in Figure 4. The same effect can occur when a capacitor is switched off and a re-strike occurs (i.e. the circuit recovery voltage causes the dielectric between the switch contacts to break down and capacitor current is re-established).

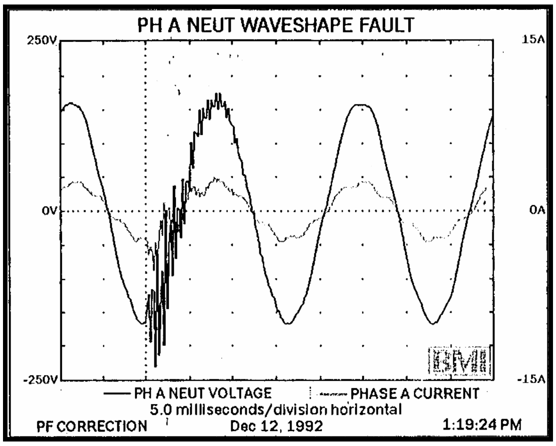


Figure 4: Voltage and current transients resulting from capacitor bank energisation [5].

Capacitor switching transients can be magnified to quite high values as they pass to a lower voltage level if certain network conditions are met. This can occur when transients originating in the medium voltage (MV) distribution network move into the low voltage (LV) network and there are power factor correction (PFC) capacitors present at LV consumers' installations. Such a situation is given in Figure 5 which shows an MV/LV network supplied by an MV feeder with inductance L_1. A switched capacitor C_1 is connected to the MV busbar. The series combination of the outgoing MV feeder and the MV/LV transformer has an inductance of L_2. PFC capacitors C_2 are connected to the LV busbar. Magnification occurs when the predominant frequency of the switching transient is approximately equal to the resonant frequency of the LV system.

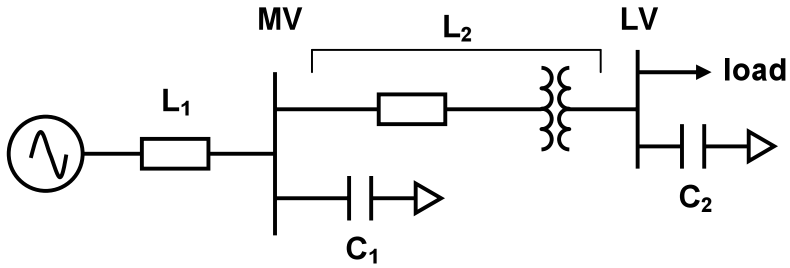


Figure 5: Power system network conducive to magnification of capacitor switching transients

With reference to Figure 5, this situation can be represented mathematically as:

$$L_1C_1 \cong L_2C_2$$

where L_1 = system source inductance seen from MV busbar
C_1 = capacitance of switched capacitor
L_2 = inductance of step-down transformer and associated MV feeder
C_2 = capacitance of LV PFC capacitor

In practice, voltage magnification can occur over a wide range of step-down transformer and PFC capacitor sizes, and can lead to peak voltages on the end-user busbar up to 4 times the normal 50 Hz crest voltage.

Apart from capacitor switching, oscillatory transient overvoltages can occur when circuit breakers clear faults on the distribution network. Waveforms associated with such a situation are shown in Figure 6. During time period 'a', fault current is flowing (arcing) between the circuit breaker contacts as they are opening, the arc voltage increasing in magnitude as they move further apart. Time period 'b' commences when the current reaches zero value and the gap between the contacts is sufficiently large that it will withstand the transient recovery voltage (TRV) imposed on it by the network. The predominant frequency of this TRV is determined by the system inductance and capacitance seen from the circuit breaker terminals looking upstream into the network. This frequency can be tens of kHz and the peak voltage can be up to twice the normal 50 Hz crest voltage. The situation is made worse if the circuit breaker controls an overhead feeder and it is allowed to perform reclose operations to restore supply and/or help clear faults. In this case, the oscillatory transient could be applied to the distribution network up to 4 times in under one minute.

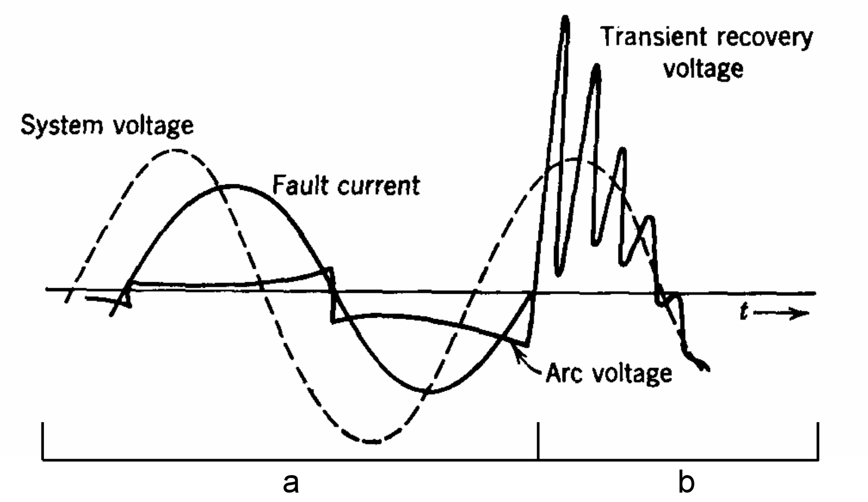


Figure 6: Typical oscillatory transient resulting from clearing of network faults [6].

4. Propagation through the network

The propagation of transient overvoltages through the distribution network will depend on their frequency content. Consequently, the propagation of impulsive and very high frequency oscillatory transients will be far more influenced by the stray and distributed inductance and capacitance of the distribution system than low frequency oscillatory transients.

4.1 Impulsive and very high frequency oscillatory transients

These types of transient move through the distribution network as travelling waves of current and voltage. There can be waves travelling near the speed of light in both directions simultaneously away from the source of the disturbance. This is illustrated in Figure 7 for a lightning strike. For waves travelling in each direction, current and voltage are related to each other by the surge impedance Z_0 of the distribution network. Z_0 is purely resistive so voltage and current waveforms have the same shape.

Z_0 can be calculated from the distributed inductance L and distributed capacitance C of the distribution feeder as follows:

$$Z_0 = \sqrt{\frac{L}{C}}, \Omega$$

Typical values of Z_0 for overhead lines range from 300 to 500 Ω and for cables from 30 to 60 Ω.

Wave velocity is:

$$v = \frac{1}{\sqrt{LC}}, \text{ m/s}$$

For overhead lines, v is near the speed of light (3×10^8 m/s). For underground cables, it is typically between one half to two thirds of this value.

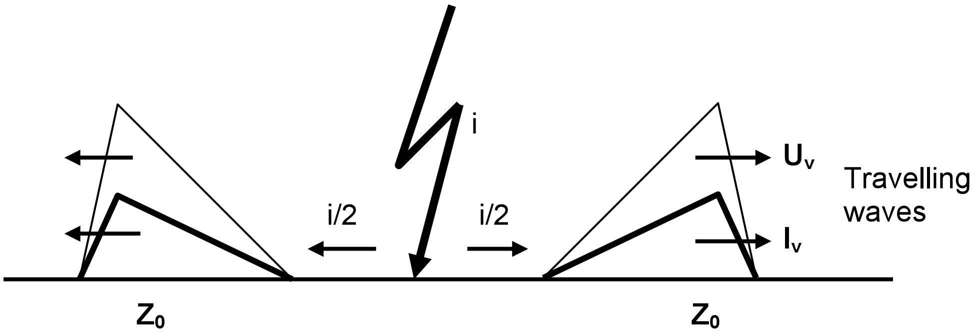
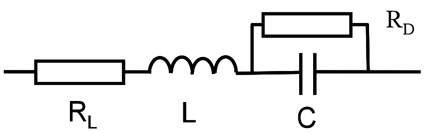


Figure 7: Travelling waves due to a lightning strike.

As travelling current and voltage waves move through the distribution network, they will meet points of discontinuity where the surge impedance changes. Such points include open ends, overhead-underground connections, transformers, etc. At such points, these travelling waves are both *reflected* back towards their origin and *transmitted* onwards with magnitudes that depend on the relative values of the surge impedances involved. For even a relatively small distribution network, this can lead to the establishment of a very complex system of travelling waves which add and subtract possibly producing quite high voltages at some sites. Fortunately these travelling waves rapidly decay as they spread out from their point of origin due to the losses associated with the distribution network and its connected loads.

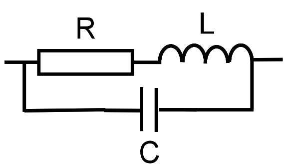
A final point to note is that network components and connected equipment respond differently to impulsive and very high frequency oscillatory transients than to the normal 50 Hz mains voltage. Reactors and transformers will look capacitive and capacitors will look inductive to such transients due to lead inductances and stray capacitances. To a first approximation these effects can be modelled using discrete element circuits. Typical high frequency transient models are illustrated below:

Capacitor:



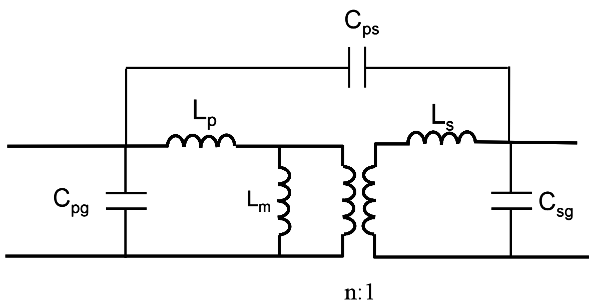
R_L is lead resistance.
L is lead inductance (of the order of μH).
R_D represents dielectric loss (responsible for capacitor heating at higher frequencies).
C is the capacitance of the capacitor.

Reactor:



R is winding resistance.
C is the combined effect of inter-turn capacitance and capacitance to earth (of the order of nF).
L is the inductance of the reactor.

Transformer (single-phase equivalent with losses ignored):



C_{pg} is the effective capacitance of the primary winding to earth.
C_{ps} is the effective inter-winding capacitance.
C_{sg} is the effective capacitance of the secondary winding to earth.
Capacitances are of the order of nF.

L_p and L_s are the primary and secondary winding leakage inductances, respectively.
L_m is the magnetising inductance of the transformer (usually ignored because of its relatively large size).
At high frequencies, the distributed capacitances of the transformer dominate the turns ratio and hence they determine the magnitude of the transient that passes through the transformer.

4.2 Low frequency oscillatory transients

These transients are typically due to utility capacitor switching and have maximum frequency components less than 2 kHz. As such, they propagate through the network in essentially the same way as the 50 Hz fundamental voltage, passing through step-down transformers according to the turns ratio with little attenuation [7]. Discrete element circuit analysis can thus be used to study them.

5. References and additional reading

[1] D. Chapman, "The Cost of Poor Power Quality", Power Quality Application Guide, Section 2.1, Copper Development Association of UK, November 2001.

[2] AS 1931.1-1996, "High-voltage test techniques – Part 1: General definitions and test requirements".

[3] IEEE Standard 1159-1995, "Recommended practice on monitoring electric power".

[4] V. Smith and V. Gosbell, "Theoretical investigation of accidental contact between distribution lines of dissimilar voltage", AUPEC 2004, Brisbane, Sept. 2004.

[5] BMI, "Handbook of Power Signatures", 2nd edition, 1993.

[6] A. Greenwood, "Electrical transients in power systems", 2nd edition, Wiley-Interscience, 1991.

[7] AS/NZS 61000.4.7:1999, "Electromagnetic compatibility (EMC) – Part 4.7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto".

[8] R. Dugan et al, "Electrical power systems quality", 2nd edition, McGraw-Hill, 2002.

6. Integral Energy Power Quality and Reliability Centre

In July 1996, Integral Energy set up Australia's first Power Quality Centre at the University of Wollongong. As of July 2004, the Centre adopted its present name indicating a shift in emphasis to include reliability of supply. The Centre's objective is to work with industry to improve the quality and reliability of the electricity supply to industrial, commercial and domestic users. The Centre specialises in research into the monitoring, assessment and control of network and other disturbances affecting the quality of voltage supply, providing input to national and international standards bodies, training in power quality and reliability issues at all levels, and specialised consultancy services for solution of power quality and reliability problems. You are invited to contact the Centre if you would like further advice on quality of supply.

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