Introduction to Switching Transients Analysis Fundamentals

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Switching Transients Analysis Fundamentals

1. Power System Switching Transients

Introduction

An electrical transient occurs on a power system each time an abrupt circuit change occurs. This circuit change is usually the result of a normal switching operation, such as breaker opening or closing or simply turning a light switch on or off. Bus transfer switching operations along with abnormal conditions, such as inception and clearing of system faults, also cause transients.

The phenomena involved in power system transients can be classified into two major categories:

- Interaction between magnetic and electrostatic energy stored in the inductance and capacitance of the circuit, respectively;

- Interaction between the mechanical energy stored in rotating machines; and

- Electrical energy stored in the inductance and capacitance of the circuit.

Most power system transients are oscillatory in nature and are characterized by their transient period of oscillation. Despite the fact that these transient periods are usually very short when compared with the power frequency of 50 Hz or 60 Hz, they are extremely important because at such times, the circuit components and electrical equipment are subjected to the greatest stresses resulting from abnormal transient voltages and currents. While over-voltages may result in flashovers or insulation breakdown, overcurrent may damage power equipment due to electromagnetic forces and excessive heat generation. Flashovers usually cause temporary power outages due to tripping of the protective devices, but insulation breakdown usually leads to permanent equipment damage.

For this reason, a clear understanding of the circuit during transient periods is essential in the formulation of steps required to minimize and prevent the damaging effects of switching transients.

Circuit Elements

All circuit elements, whether in utility systems, industrial plants, or commercial buildings, possess resistance, R, inductance, L, and capacitance, C. Ohm's law defines the voltage across a time-invariant linear resistor as the product of the current flowing through the resistor and its ohmic value. That is,

$$v(t) = Ri(t) \qquad (1)$$

The other two elements, L and C, are characterized by their ability to store energy. The term "inductance" refers to the property of an element to store electromagnetic energy in the magnetic field. This energy storage is accomplished by establishing a magnetic flux within the ferromagnetic material. For a linear time-invariant inductor, the magnetic flux is defined as the product of the inductance and the terminal current. Thus,

$$\varphi(t) = Li(t) \qquad (2)$$

where $\varphi(t)$ is the magnetic flux in webers (Wb), L is the inductance in henries (H), and $i(t)$ is the time-varying current in amperes (A). By Faraday's law, the voltage at the terminals of the inductor is the time derivative of the flux, namely,

$$v(t) = \frac{d\varphi}{dt} \qquad (3)$$

Combining this relationship with Equation 2 gives the voltage-current relation of a time-invariant linear inductor as:

$$v(t) = L\frac{di}{dt} \qquad (4)$$

Finally, the term "capacitance" means the property of an element that stores electrostatic energy. In a typical capacitance element, energy storage takes place by accumulating charges between two surfaces that are separated by an insulating material. The stored charge in a linear capacitor is related to the terminal voltage by:

$$q(t) = Cv(t) \qquad (5)$$

where C is the capacitance in farads (F) when the units of q and v are in coulombs

(C) and volts (V), respectively. Since the electrical current flowing through a particular point in a circuit is the time derivative of the electrical charge, Equation 5 can be differentiated with respect to time to yield a relationship between the terminal current and the terminal voltage. Thus,

$$i(t) = \frac{dq}{dt} \ or \ i(t) = C\frac{dv}{dt} \tag{6}$$

Under steady-state conditions, the energy stored in the elements swings between the inductance and capacitance in the circuit at the power frequency. When there is a sudden change in the circuit, such as a switching event, a redistribution of energy takes place to accommodate the new condition. This redistribution of energy cannot occur instantaneously for the following reasons:

- The electromagnetic energy stored in an inductor is $E = \frac{LI^2}{2}$. For a constant inductance, a change in the magnetic energy requires a change in current. But the change in current in an inductor is opposed by an emf of magnitude $v(t) = L\frac{di}{dt}$. For the current to change instantaneously $(dt = 0)$, an infinite voltage is required. Since this is unrealizable in practice, the change in energy in an inductor requires a finite time period.

- The electrostatic energy stored in a capacitor is given by $E = \frac{CV^2}{2}$ and the current-voltage relationship is given by $i(t) = c\frac{dv}{dt}$. For a capacitor, an instantaneous change in voltage $dt = 0$ requires an infinite current, which cannot be achieved in practice. Therefore, the change in voltage in a capacitor also requires finite time.

These two basic concepts, plus the recognition that the rate of energy produced must be equal to the sum of the rate of energy dissipated and the rate of energy stored at all times (principle of energy conservation), are basic to the understanding and analysis of transients in power systems.

Analytical Techniques

The classical method of treating transients consists of setting up and solving the differential equation or equations, which must satisfy the system conditions at every

instant of time. The equations describing the response of such systems can be formulated as linear time-invariant differential equations with constant coefficients. The solution of these equations consists of two parts:

- The homogeneous solution, which describes the transient response of the system, and

- The particular solution, which describes the steady-state response of the system to the forcing function or stimulus.

Analytical solutions of linear differential equations can also be obtained by the Laplace transform method. This technique does not require the evaluation of the constants of integration and is a powerful tool for complex circuits; whereas the traditional method can be quite difficult.

Transient Analysis Based on the Laplace Transform Method

Although they do not represent the types of problems regularly encountered in power systems, the transient analysis of the simple *RL* and *RC* circuits are useful illustrative examples of how the Laplace transform method can be used for solving circuit transient problems. Real-life circuits, however, are far more complicated and often retain many circuit elements in series-parallel combination even after simplification. These circuits will require several differential or integro-differential equations to describe transient behaviour and must be solved simultaneously to evaluate the response. To do this efficiently, the Laplace transform method is often used.

LC Transients

General types of circuits that are described by higher-order differential equations are discussed. The double-energy transient, or *LC* circuit, is the first type of circuit to be considered. In double-energy electric circuits, energy storage takes place in the magnetic field of inductors and in the electric field of the capacitors. In real circuits, the interchange of these two forms of energy may, under certain conditions, produce electric oscillations. The theory of these oscillations is of great importance in electric power systems.

In the circuit shown in Figure 1 the circuit elements are represented with Laplace transform impedances. The response of the circuit to a step input of voltage due to the closing of the switch at $t = 0$ will be examined, assuming the capacitor is initially charged to the potential of $V_c(0^-)$ as shown.
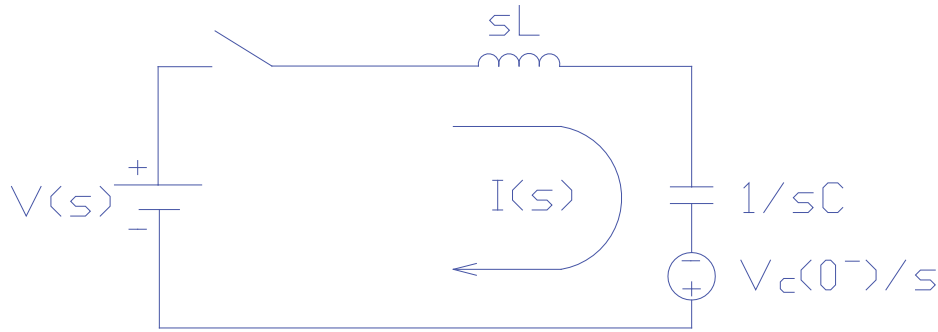

Figure 1. Double energy network

According to Kirchoff's voltage law, the sum of the voltages across all the circuit elements must equal the source voltage at all times. In equation form this is stated as:

$$v(s) = I(s)s^2L - sLI(0) + \frac{I(s)}{C} - V_c(0) \qquad (7)$$

Since there could be no current flowing in the circuit before the switch closes, the term $LI(0) = 0$. Solving for the current $I(s)$ in Equation 7:

$$I(s) = \frac{V(s)+V_c(0)}{L}\left[\frac{1}{(s^2+\omega_0^2)}\right] \qquad (8)$$

where ω_0^2 is the natural frequency of the circuit, namely $\frac{1}{\sqrt{LC}}$. From the table of inverse Laplace transforms, the transient response in the time domain is:

$$i(t) = \frac{V(s)+V_c(0)}{Z_0}[\sin(\omega_0 t)] \qquad (9)$$

where Z_0 is the surge impedance of the circuit defined by:

$$Z_0 = \sqrt{\frac{L}{C}} \qquad (10)$$

Clearly, the transient response indicates a sinusoidal current with a frequency governed by the circuit parameters *L* and *C* only.

Another interesting feature about the time response of the current in the circuit is that the magnitude of the current is inversely proportional to the surge impedance of the circuit Z_0, which is a function of the circuit parameters of *L* and *C*.

In power system analysis, we are often interested in the voltage across the capacitor. Referring to Figure 1, the capacitor voltage is:

$$V_c(s) = \frac{I(s)}{sC} - \frac{V_c(0)}{s} \tag{11}$$

where $V_c(0)$ is the initial voltage of the capacitor. Solving for $I(s)$ in the above equation results in:

$$I(s) = sCV_c(s) + CV_c(0) \tag{12}$$

But because the current *I*(s) is common to both elements *L* and *C*, we can substitute Equation 12 into Equation 8 to obtain the voltage across the capacitor. After rearranging the terms:

$$V_c(s) = \frac{V(s)\omega_0^2}{s(s^2+\omega_0^2)} + \frac{sV_c(0)}{s^2+\omega_0^2} \tag{13}$$

From the table of inverse Laplace transforms, the transient response is:

$$v_c(t) = V(s)[1 - \cos(\omega_0 t)] + V_c(0)\cos(\omega_0 t) \tag{14}$$

The above equation is plotted in Figure 2 for various values of initial capacitor voltage $V_c(0)$.
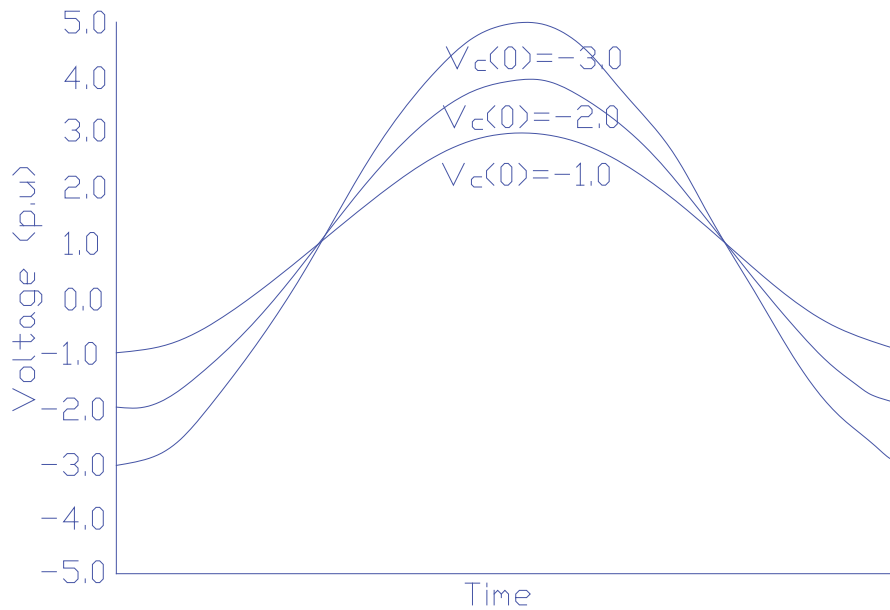
Figure 2—Capacitor voltage for various initial voltages

Examination of these curves indicates that, without damping, the capacitor voltage swings as far above the source voltage V as it starts below. In a real circuit, however, this will not be the case, since circuit resistance will introduce losses and will damp the oscillations. Treatment of the effects of resistance in the analysis of circuits is presented next.

Damping

Nearly every practical electrical component has resistive losses (I^2R losses). To simplify the calculations and to ensure more conservative results, resistive losses are usually neglected as a first attempt to a switching transient problem. Once the behaviour of the circuit is understood, then system losses can be considered if deemed necessary.

A parallel *RLC* circuit is depicted in Figure 3, in which the circuit elements are represented by their Laplace transform admittances. Many practical transient problems found in power systems can be reduced to this simple form and still yield acceptable results. With a constant current source, *I*(s) and zero initial conditions, the equation describing the current in the parallel branches is:

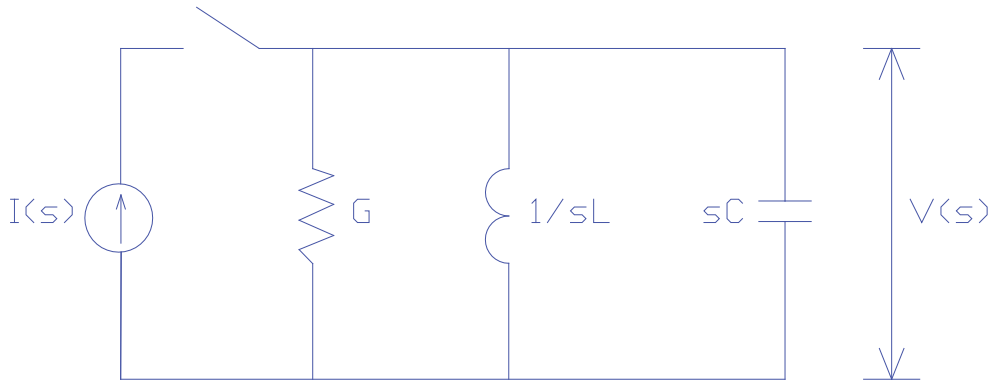$$I(s) = sV(s)G + s^2CV(s) + \frac{V(s)}{L} \qquad (15)$$

Figure 3—Parallel RLC circuit

Solving for the voltage results in:

$$V(s) = \frac{I(s)}{C}\left(\frac{1}{s^2 + \frac{s}{RC} + \frac{1}{LC}}\right) \qquad (16)$$

Equation 16 can be written as:

$$V(s) = \frac{I(s)}{C}\left(\frac{1}{(s+r_1)(s+r_2)}\right) \qquad (17)$$

where r_1 and r_2 are the roots of the characteristic equation defined as follows:

$$r_1 = \frac{1}{2RC} + \frac{1}{2}\sqrt{\left(\frac{1}{RC}\right)^2 - \left(\frac{4}{LC}\right)} \qquad r_2 = \frac{1}{2RC} - \frac{1}{2}\sqrt{\left(\frac{1}{RC}\right)^2 - \left(\frac{4}{LC}\right)} \qquad (18)$$

At the natural resonant frequency ω_0, the reactive power in the inductor is equal to the power in the capacitor but opposite in sign. The source has to supply only the true power P_T required by the resistance in the circuit. The ratio between the magnitude of the reactive power, P_R, of either the inductance or the capacitance at the resonant frequency, and the magnitude of true power, P_T of the circuit, is known as the quality factor of the circuit, or Q. Therefore, for the parallel circuit:

$$Q_P = \frac{P_R}{P_T} \qquad \text{or} \qquad Q_P = \frac{V^2 B}{V^2 G} \qquad \text{or} \qquad Q_P = \frac{R}{X} \qquad (19)$$

where B is the susceptance of either the inductor or capacitor, G is the conductance, and V is the voltage across the element. But, since in a parallel circuit the voltage is common to all elements, substituting $\omega_0 L$ for $\frac{1}{B}$ and R for $\frac{1}{G}$ in Equation 19, results in:

$$Q_P = \frac{R}{\omega_0 L} \tag{20}$$

Furthermore, since the natural frequency of the circuit is:

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{21}$$

Then, substituting Equation 21 into Equation 20 yields:

$$Q_P = \frac{R}{\sqrt{\frac{L}{C}}} \tag{22}$$

Rearranging Equation 18, we have:

$$r_1 = \frac{1}{2RC} + \frac{1}{2RC}\sqrt{1 - 4R^2\frac{C}{L}} \quad \text{and} \quad r_2 = \frac{1}{2RC} - \frac{1}{2RC}\sqrt{1 - 4R^2\frac{C}{L}} \tag{23}$$

Substituting Equation 22 into Equation 23, the result is:

$$r_1 = \frac{1}{2RC} + \frac{1}{2RC}\sqrt{1 - 4Q_P^2} \quad \text{and} \quad r_2 = \frac{1}{2RC} - \frac{1}{2RC}\sqrt{1 - 4Q_P^2} \tag{24}$$

Depending on the values of the circuit parameters, the quantity under the radical in Equation 24 may be positive, zero, or negative.

For positive values, that is $4Q_P{}^2 < 1$, the roots are real, negative, and unequal. In this case, the inverse Laplace transform of Equation 17 is:

$$v_t = \frac{IRe^{-\left(\frac{t}{2RC}\right)}}{\sqrt{1-4Q_P^2}}[e^{\omega_D t} - e^{-\omega_D t}] \tag{25}$$

where,

$$\omega_D = \frac{\sqrt{1-4Q_P^2}}{2RC} \tag{26}$$

is the damped natural angular frequency. Substituting $2\sinh(\omega_D t)$ for the exponential function, the result is:

$$v_t = \frac{2IRe^{-\left(\frac{t}{2RC}\right)}}{\sqrt{1-4Q_P^2}}\left[\sinh\left(\frac{\sqrt{1-4Q_P^2}}{2RC}t\right)\right] \tag{27}$$

For the case where the quantity $4Q_P^2 = 1$, the roots are equal, negative, and real. Therefore, the solution of Equation 25 is:

$$v(t) = \frac{I}{C} e^{-\left(\frac{t}{2RC}\right)}$$ (28)

Finally, when the quantity under the radical sign in Equation 4 is less than zero, that is, $4Q_P^2 > 1$, the roots are unequal and complex. The solution in this case is:

$$v_t = \frac{2IRe^{-\left(\frac{t}{2RC}\right)}}{\sqrt{4Q_P^2-1}} \left[sin\left(\frac{\sqrt{4Q_P^2-1}}{2RC} t \right) \right]$$ (29)
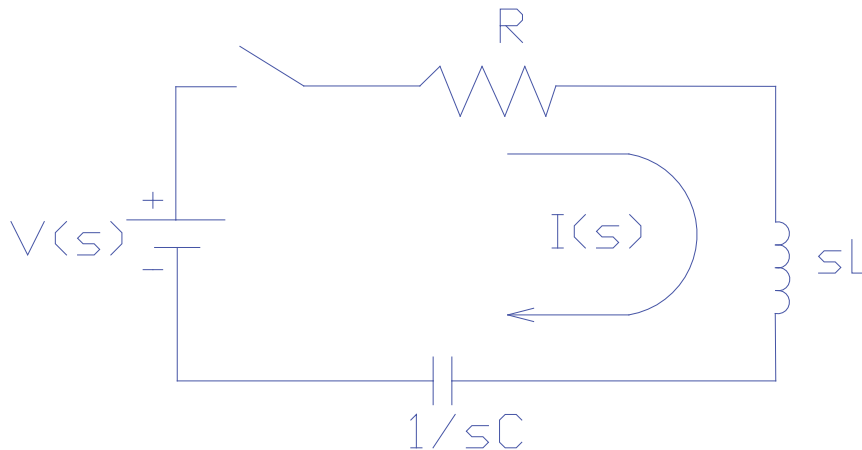
Consider the series RLC circuit shown in Figure 4.

Figure 4—Series RLC circuit

With *V*(s) as a constant source, the equation describing the current in the circuit is:

$$I(s) = \frac{V(s)}{s} \left(\frac{1}{R+sL+\frac{1}{sC}} \right)$$ (30)

Rearranging the terms results in:

$$I(s) = \frac{V(s)}{L} \left(\frac{1}{s^2+s\frac{R}{L}+\frac{1}{LC}} \right)$$ (31)

The expression inside the brackets is similar to the expression for the parallel *RLC* circuit shown in Equation 16. The only difference is the coefficient of *s*. Rewriting, as in Equation 17 gives:

$$I(s) = \frac{V(s)}{L} \left(\frac{1}{(s+r_1)(s+r_2)} \right) \tag{32}$$

where r_1 and r_2 are the roots of the characteristic equation defined as:

$$r_1 = \frac{R}{2L} + \frac{R}{2L}\sqrt{1 - \frac{4L}{R^2C}} \quad \text{and} \quad r_2 = \frac{R}{2L} - \frac{R}{2L}\sqrt{1 - \frac{4L}{R^2C}} \tag{33}$$

Again, we define the quality factor of the series *RLC* circuit, Q_s, as the ratio of the magnitude of the reactive power of either the inductor or the capacitor at the resonant frequency to the magnitude of the true power in the circuit. Stated in equation form, results in:

$$Q_s = \frac{P_R}{P_T} \tag{34}$$

With the reactive power $P_R = I^2 X$ and the true power as $P_T = I^2 R$, then:

$$Q_s = \frac{I^2 X}{I^2 R} \tag{35}$$

But since, in a series circuit, the current is common to all elements, then:

$$Q_s = \frac{\omega_0 L}{R} \tag{36}$$

where $\omega_0 L$ = X. Also, since $\omega_0 = \frac{1}{\sqrt{LC}}$ then Equation 36 can be written as:

$$Q_s = \frac{\sqrt{\frac{L}{C}}}{R} \quad \text{or} \quad Q_s = \frac{Z_0}{R} \tag{37}$$

Note that the above expression is the ratio of the surge impedance to the resistance in the circuit. This is the reciprocal of the expression developed for the parallel *RLC* circuit and described by Equation 22. That is:

$$Q_s = \frac{1}{Q_P} \tag{38}$$

Substituting Equation 37 into Equation 33 results in:

$$r_1 = \frac{R}{2L} + \frac{R}{2L}\sqrt{1 - 4Q_s^2} \quad \text{and} \quad r_2 = \frac{R}{2L} - \frac{R}{2L}\sqrt{1 - 4Q_s^2} \tag{39}$$

Above expressions have already been solved for the parallel *RLC* circuit. To obtain the expression as a function of time, simply substitute Q_s for Q_P and *V/R* for *IR* and *R/L* for 1/*RC* in Equation 26 and Equation 28 and *V/L* for *I/C* and *R/L* for 1/*RC* in

Equation 29. Thus, when the quantity under the radical sign is less than 1, namely, $4Q_s{}^2 < 1$, the result is:

$$i_t = \frac{2Ve^{-\left(\frac{Rt}{2L}\right)}}{R\sqrt{1-4Q_s^2}}\left[\sinh\left(\frac{R}{2L}\sqrt{1-4Q_s^2}\right)\right] \tag{40}$$

For the case where the quantity $4Q_s{}^2 = 1$, then the roots are equal, negative, and real and the solution of Equation 39 is:

$$i(t) = \frac{V}{L}e^{-\left(\frac{R}{2L}t\right)} \tag{41}$$

Finally, when the quantity $4Q_s{}^2 > 1$, the roots are complex and unequal. Therefore, the solution is:

$$i_t = \frac{2Ve^{-\left(\frac{Rt}{2L}\right)}}{R\sqrt{4Q_s^2-1}}\left[\sin\left(\frac{R}{2L}\sqrt{4Q_s^2-1}\right)\right] \tag{42}$$

Normalized Damping Curves

The response of the parallel and series *RLC* circuits to a step input of current or voltage, respectively, can be expressed as a family of normalized damping curves, which can be used to estimate the response of simple switching transient circuits to a step input of either voltage or current. To develop a family of normalized damping curves, proceed as follows:

- To per-unitize the solutions, we use the undamped response of a parallel *LC* circuit as the starting point. Thus, for the voltage:

$$V(t) = \frac{1}{\omega_0 C}\sin(\omega_0 t) \tag{43}$$

  and, for the current:

$$i(t) = \frac{1}{\omega_0 L}\sin(\omega_0 t) \tag{44}$$

  The maximum voltage or current occurs when the angular displacement $\omega_0 t = \pi/2$. Thus:

$$V(t) = \frac{1}{\omega_0 C} \quad \text{and} \quad i(t) = \frac{1}{\omega_0 L} \tag{45}$$

- Setting the angular displacement $\omega_0 t = \theta$, the quantity $\frac{t}{2RC}$ in Equations 26 through 28 can be substituted with the expression: $\frac{Q}{2Q_P}$.

- Finally, dividing Equations 26 through 28 by the right side of the expression for v(t) in Equation 45 produces a set of normalized curves for the voltage on the parallel *RLC* circuit as a function of the dimensionless quantities Q_P and the displacement θ.

Thus, for $4Q_P^2 < 1$:

$$f(Q_P, \theta) = \frac{2Q_P e^{-\left(\frac{\theta}{2Q_P}\right)}}{\sqrt{1-4Q_P^2}}\left[\sinh\left(\frac{\theta\sqrt{1-4Q_P^2}}{2Q_P}\right)\right] \tag{46}$$

And for $4Q_P^2 = 1$:

$$f(Q_P, \theta) = \theta e^{-\left(\frac{\theta}{2Q_P}\right)} \tag{47}$$

And for $4Q_P^2 > 1$ the result is:

$$f(Q_P, \theta) = \frac{2Q_P e^{-\left(\frac{\theta}{2Q_P}\right)}}{\sqrt{4Q_P^2-1}}\left[\sin\left(\frac{\theta\sqrt{4Q_P^2-1}}{2Q_P}\right)\right] \tag{48}$$

Equations 46 through 48 are plotted in Figure 5 and Figure 6 for various values of Q_P. For series *RLC* circuits, divide the same equations in step (c) by the right side of the expression for i(t), and substitute Q_s for Q_P.
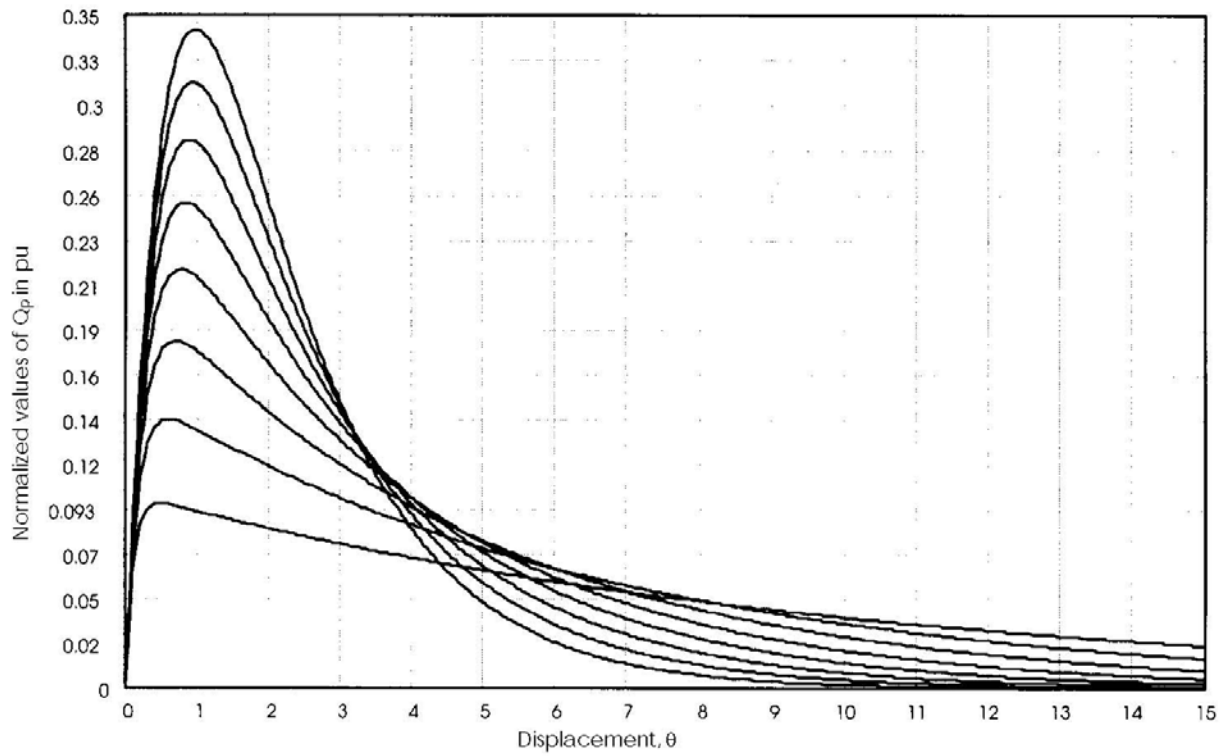
Figure 5—Normalized damping curves, 0.10 ≤ QP ≤ 0.45 in steps of 0.05, with QP
(0.45) = 0.34 pu

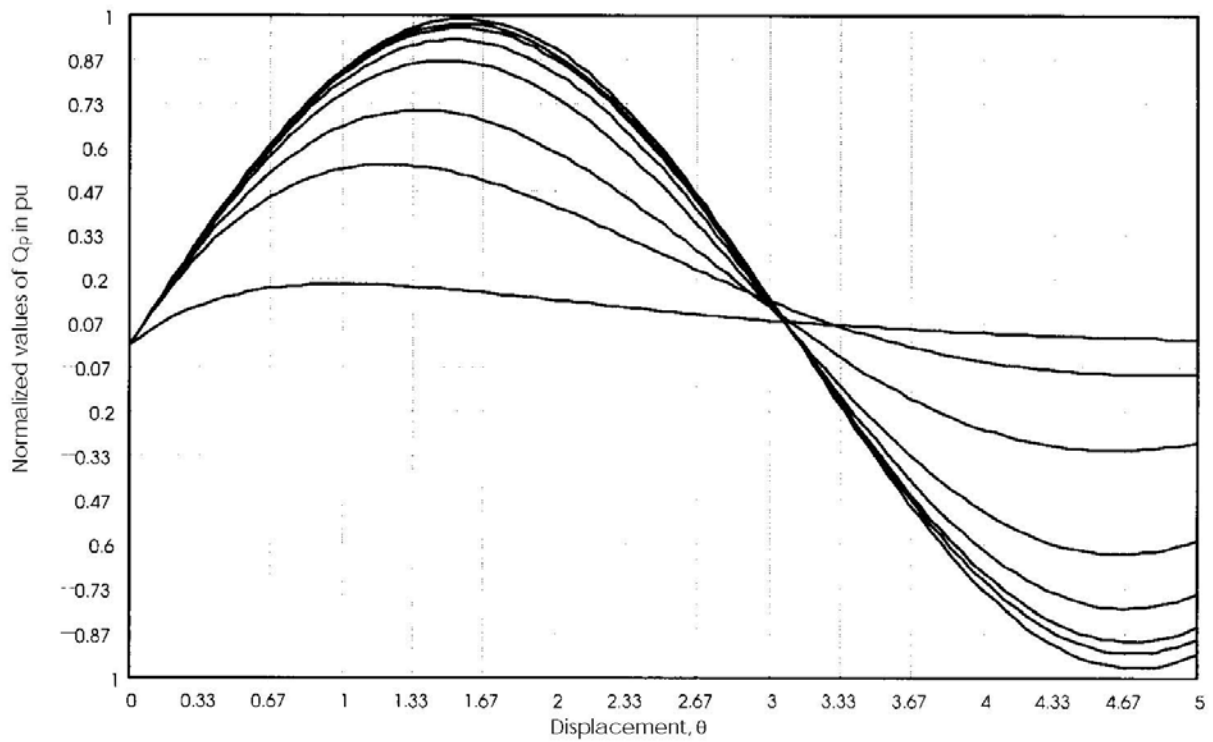Figure 6—Normalized damping curves, 0.50 ≤QP ≤75.0 0.50, 1.0, 2.0, 5.0, 10.0,
15.0, 30.0, and 75.0, with QP (75) = 1.00 p.u.

Transient Example: Capacitor Voltage

Very often, in power systems analysis, the form and magnitude of the transient voltage developed across the capacitor during switching is significant. To develop generalized expressions for capacitor voltage, start with Equation 31, which describes the transient current in the series *RLC* circuit. The voltage across the capacitor is simply the product of the current and the capacitor impedance, that is:

$$V_c(s) = I(s)Z_c(s) \tag{49}$$

or,

$$V_C(s) = \frac{I(s)}{sC} \tag{50}$$

Substituting Equation 30 into Equation 50, yields the expression for the voltage across the capacitor in a series *RLC* circuit. Thus:

$$V_C(s) = \frac{V(s)}{LC}\left[\frac{1}{s\left(s^2+s\frac{R}{L}+\frac{1}{LC}\right)}\right] \tag{51}$$

Equation 51 is similar to the Equation 30, developed for the current, except that it has an extra *s* term in the denominator. The expression can be rewritten as follows:

$$V_C(s) = \frac{V(s)}{LC}\left[\frac{1}{s(s+r_1)(s+r_2)}\right] \tag{52}$$

where the roots of the equation are the same as those defined by Equation 39. Again, the solution of Equation 52 will depend on the values of Q_s.

Equation 14 shows the voltage across a capacitor due to a step input of voltage when the resistance in the circuit is zero. For zero initial conditions, that is, no charge in the capacitor, the last term in Equation 14 can be neglected. Then, the maximum voltage occurs when $\omega_0 t = \pi$. Therefore, the voltage is simply:

$$V_c(t) = 2 \tag{53}$$

Equation 51 has three possible solutions.

For the case in which $4(Q_S^2 < 1)$:

$$f(Q_s, \theta) = 1 - e^{-\left(\frac{\theta}{2Q_s}\right)} \left[\frac{sinh\left(\frac{\theta\sqrt{1-4Q_s^2}}{2Q_s}\right)}{\sqrt{1-4Q_s^2}} + cosh\left(\frac{\theta\sqrt{1-4Q_s^2}}{2Q_s}\right) \right] \tag{54}$$

When $4Q^2 = 1$, the solution is:

$$f(Q_s, \theta) = 2Q_s \left[1 - e^{-\left(\frac{\theta}{2Q_s}\right)} \left(1 + \frac{\theta}{2Q_s}\right) \right] \tag{55}$$

Finally, when $4Q^2 > 1$, the solution takes the form of:

$$f(Q_s, \theta) = 1 - e^{-\left(\frac{\theta}{2Q_s}\right)} \left[\frac{sinh\left(\frac{\theta\sqrt{4Q_s^2-1}}{2Q_s}\right)}{\sqrt{4Q_s^2-1}} + cos\left(\frac{\theta\sqrt{4Q_s^2-1}}{2Q_s}\right) \right] \tag{56}$$

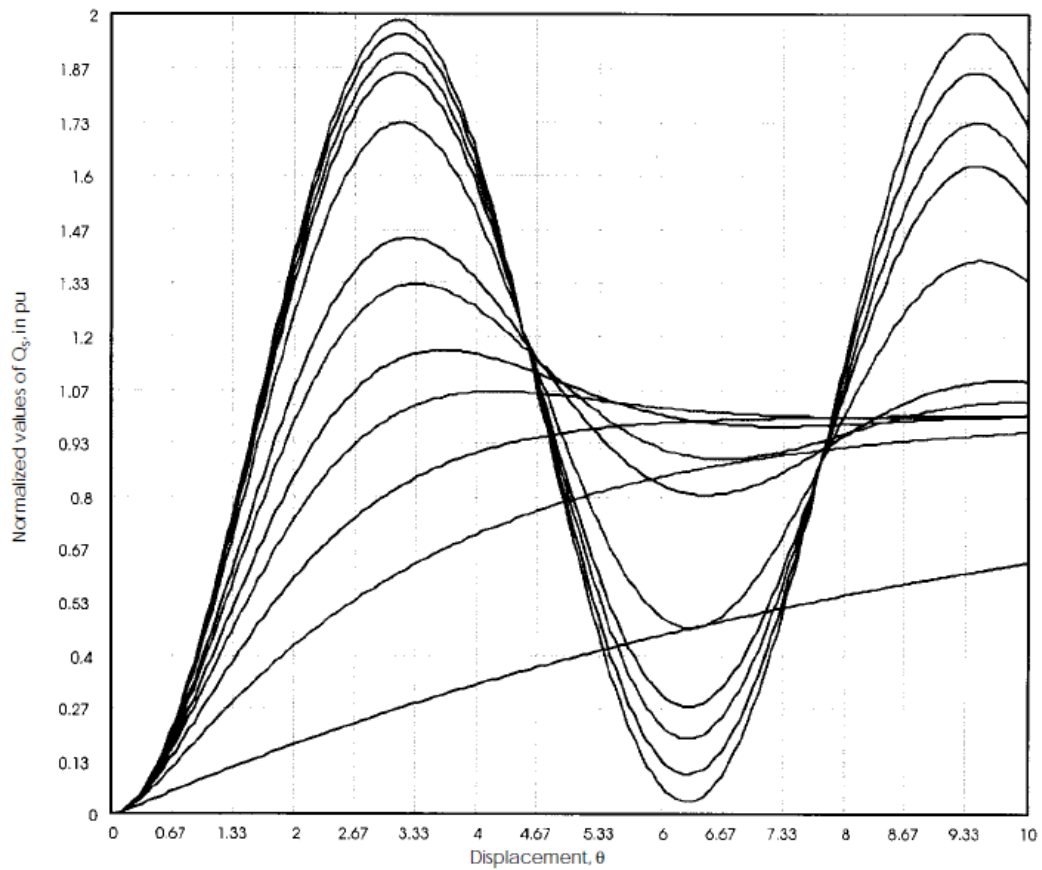Equations 54 through 56 are plotted in Figure 7 for various values of Q_s.

Figure 7—Normalized damping curves, $0.10 \leq Q_s \leq 100$ 0.10, 0.30, 0.50, 0.75, 1.0, 1.5, 2.0, 5.0, 10.0, 15.0, 30.0, and 100.0 with Q_s (100) = 1.99

Switching Transient Examples

In the previous clauses, some simple circuits were examined that can be used to model many switching problems in electrical power systems. Very often, practical switching transient problems can be reduced to either parallel or series *RLC* circuits for the purpose of evaluating the response of the network to a particular stimuli on a first-trial basis. To gain familiarity with the normalized damping curves developed in the previous sub-clauses, some typical switching problems in power systems will be examined. Consider, for example, a 1000 kVA unloaded transformer that, when excited from the 13.8 kV side with its rated voltage of 13.8 kV, draws a no-load current of 650 mA with a power factor of 10.4%. A test circuit for the transformer is shown in Figure 8. The battery voltage, *V*, and the resistance, *R,* are chosen such that, with the switch closed, the battery delivers 10 mA. For this example, a shunt capacitance of 2.8 nF per phase is assumed. The goal is to find the voltage across the capacitance to ground, when the switch is suddenly opened and the flow of current is interrupted.
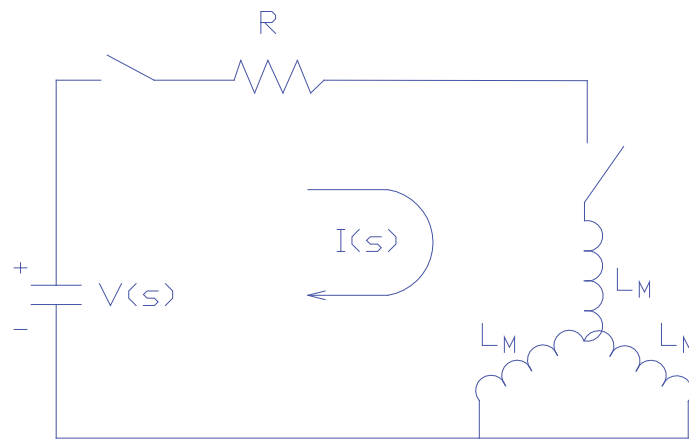

Figure 8—Test setup of unloaded transformer

From the information provided, the no-load current of the transformer is:

$I_{NL} = 0.067794 - j0.64644$ A

The magnetizing reactance X_M per phase is:

$$X_M = \frac{13.8\ kV}{\sqrt{3} \cdot 0.64644} = 12.325\ k\Omega$$

The magnetizing inductance L_M per phase is:

$$L_M = \frac{X_M}{2\pi f} = \frac{12.325\ k\Omega}{377} = 32.693\ H$$

With a shunt capacitance of C_{SH} = 2.8 nF, the shunt capacitive reactance is:

$$X_{SH} = \frac{1}{2\pi f C_{SH}} = \frac{1}{377 \cdot 2.8\ nF} = 947.33\ k\Omega$$

Since $X_{SH} > X_M$, the effects of the shunt capacitive reactance at the power frequency are negligible. The resistance R_C is:

$$R_C = \frac{13.8\ kV}{\sqrt{3} \cdot 0.067794} = 117.524\ k\Omega$$

Using delta-wye transformation impedance conversion, the circuit in Figure 8 can be redrawn as shown in Figure 9.
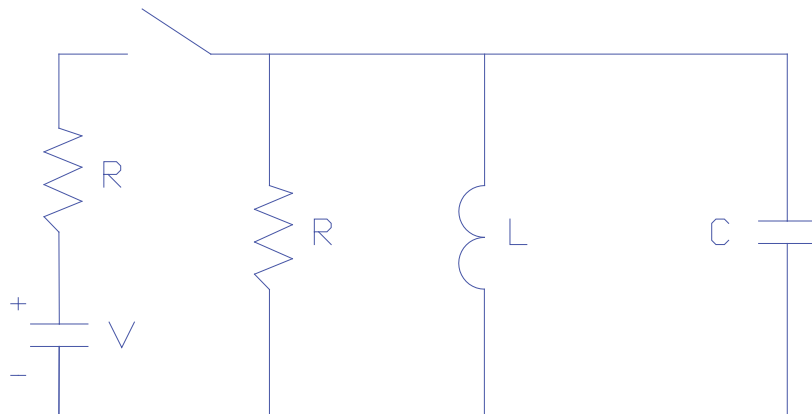

Figure 9—Equivalent RLC circuit for unloaded transformer

In the Laplace transform notation, the equation describing the circuit at $t = 0^+$ is:

$$0 = \frac{I_L(0^-)}{sL} + \frac{V_c(s)}{s} + sCV_c(s) - CV_c(s) - CV_c(0^-) + \frac{V_c(s)}{R}$$

$$L = \frac{3L_M}{2} = 49.035\ H$$

$$C = \frac{2C_{SH}}{3} = 1.867\ nF$$

$$R = \frac{3R_c}{2} = 176.286 \ k\Omega$$

Assuming that dc steady-state was obtained before the switch opened, the term $CV_c(0^-) = 0$ and the initial current in the inductor at $t = 0^+$ is $I_L(0^-) = 10$ mA. Solving for $V_c(s)$ and after rearranging the terms, gives:

$$V_c(s) = -\frac{I_L(0^-)}{C}\left(\frac{1}{s^2 + \frac{s}{RC} + \frac{1}{LC}}\right)$$

The time-response solution for this expression has already been obtained and, depending on the values of the circuit parameters, is shown in Equations 26, 27, and 28. The values for R, L, and C could be inserted into one of those equations to obtain the capacitor voltage for this problem. But this has also been done through the normalized damping curves shown in Figure 5. Therefore, the answers for this particular problem are obtained as follows:

The surge impedance of the circuit is:

$$Z_0 = \sqrt{\frac{L}{C}} = 162.07 \ k\Omega$$

Without damping, the peak transient voltage would be:

$$V_{peak} = I(0^-)Z_0 = -10mA \cdot 162.076 \ k\Omega = -1.621 \ kV$$

But since there is damping, the quality factor of the parallel circuit QP is:

$$Q_P = \frac{R}{Z_0} = \frac{176.286 \ k\Omega}{162.076 \ k\Omega} = 1.087$$

From the curves shown in Figure 5 and with QP ≈ 1.0, the maximum per unit voltage is 0.57. Therefore, from previous step, the maximum voltage developed across the capacitor is:

$$V_{max} = -1.621 \ kV \cdot 0.57 = -924 \ V$$

The maximum peak occurs at approximately θ = 1.2 radians. Since $\omega_0 t = \theta$ and

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad \text{or} \qquad \omega_0 = 3305\,\frac{rad}{s}$$

Figure 10 depicts the actual voltage across the capacitance to ground as calculated by a computer program.
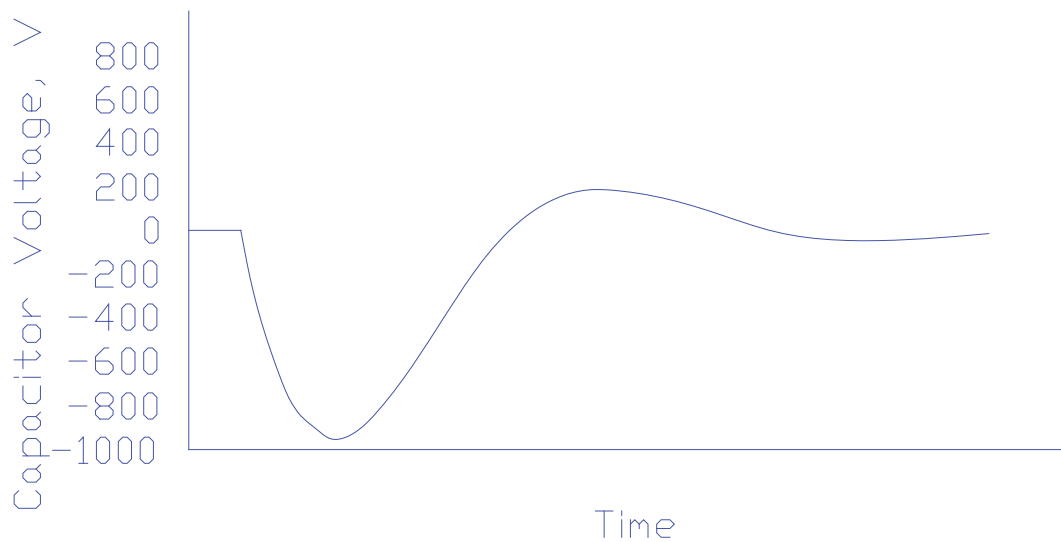

Figure 10 – Actual capacitor voltage

Another practical case will be examined, which concerns capacitor bank switching as depicted in Figure 11. Capacitor C_1 is rated 30 Mvar, three-phase, at 13.8 kV. C_2 is initially uncharged and is rated 10 Mvar, three-phase, also at 13.8 kV. The cable connecting capacitor C_2 to the bus has an inductance L of 35 μ H. The following procedure is used to determine the magnitude of the inrush current and the size of the resistor required to limit this current to a maximum of 5800 A (peak) during energization.
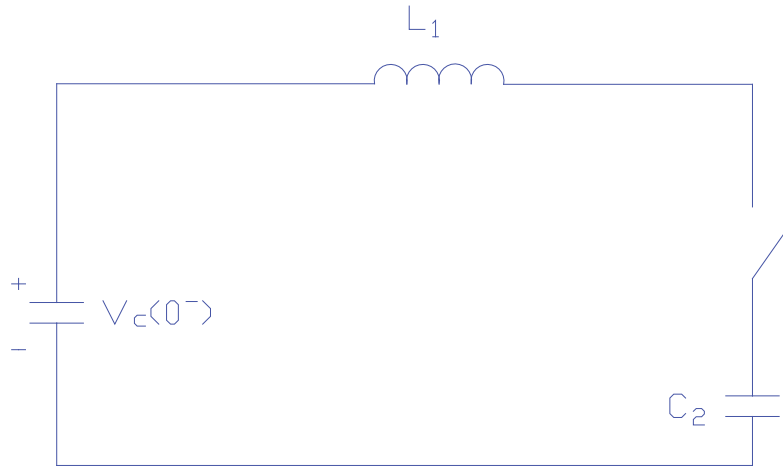
Figure 11 Capacitor bank switching

From the problem statement, the capacitive reactance of the capacitors is:

$$X_{C1} = \frac{kV^2}{C_1} = \frac{13.8^2}{30} = 6.348 \ \Omega$$

$$X_{C2} = \frac{kV^2}{C_2} = \frac{13.8^2}{10} = 19.044 \ \Omega$$

and the capacitance is:

$$C_1 = \frac{1}{2\pi f X_{c1}} = \frac{1}{2\pi \cdot 60 \cdot 6.348 \ \Omega} = 417.861 \ \mu F$$

$$C_1 = 139.287 \ \mu F$$

Assuming worst-case conditions, that is, C_1 charged to peak system voltage or:

$$V_{C1} = \frac{kV \cdot \sqrt{2}}{\sqrt{3}} = \frac{13.8 \cdot \sqrt{2}}{\sqrt{3}} = 11.268 \ kV$$

and with a surge impedance of:

$$Z_0 = \sqrt{\frac{L(C_1 + C_2)}{C_1 C_2}} = 0.579 \ \Omega$$

then, with no damping, the inrush current would be:

$$i_{peak} = \frac{V_{c(0)}}{Z_0} = \frac{11.268 \; kV}{0.579 \; \Omega} = 19.467 \; kA$$

Redrawing the circuit of Figure 11 to show the necessary addition of a resistor to limit the inrush current yields the circuit as shown in Figure 12.
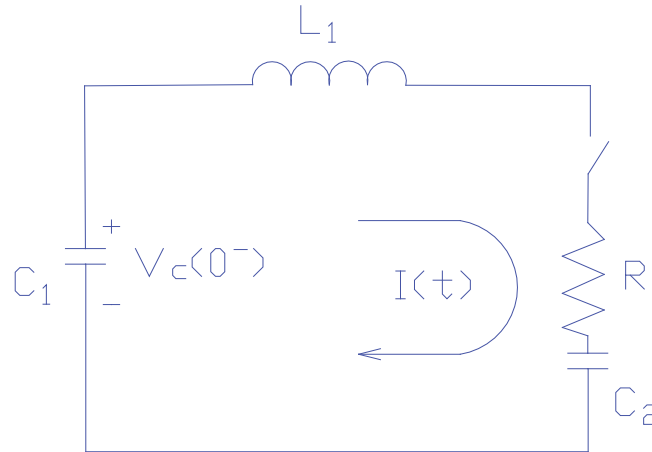
Figure 12—Equivalent circuit for capacitor switching with pre-insertion resistor

The problem requires that the inrush current should not exceed 5800 A. This represents a per-unit value of:

$$I_{pu} = \frac{I_{max}}{I_{peak}} = \frac{5800 \; A}{19467 \; A} = 0.3$$

Referring to Figure 5, since the current problem concerns a series circuit, Q_s replaces Q_P. With a per-unit value requirement of 0.30 (vertical axis), Figure 5 shows that a $Q_P = 0.30$ will reduce the current to 5800 (19467 × 0.30) A or less. Now, since

$$Q_s = 0.3$$

and

$$Q_s = \frac{Z_0}{R} = 0.3$$

then

$$R = \frac{Z_0}{Q_s} = \frac{0.579 \; \Omega}{0.3} = 1.93 \; \Omega$$

Therefore, to limit the inrush current to 5800 A, a 1.9 Ω resistor must be placed in series with capacitor C_2 as shown in Figure 12.

The results of a computer simulation are depicted in Figure 13 and Figure 14. While Figure 13 shows the current without the pre-insertion resistor, Figure 14 reflects the current with the 1.9 Ω resistor.
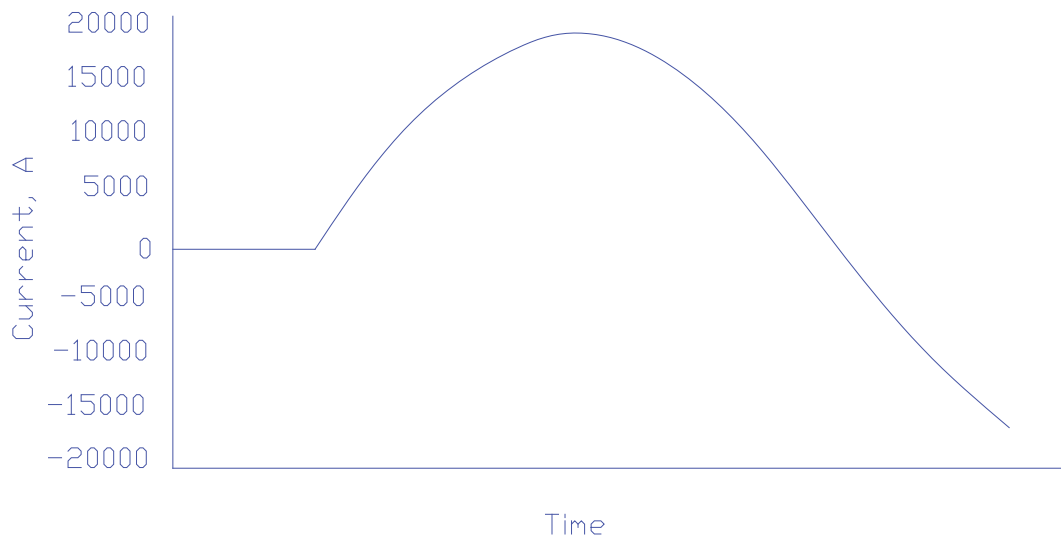

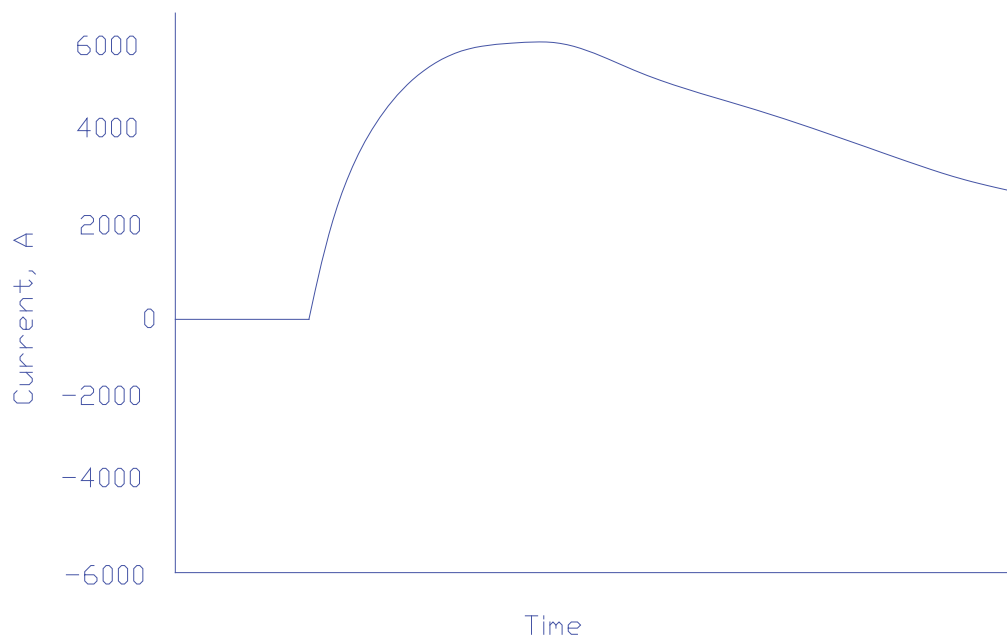Figure 13—Current in circuit without damping resistor

Figure 14—Current in circuit with damping resistor

Transient Recovery Voltage

Circuit breakers provide the mechanism to interrupt the short-circuit current during a system fault. When the breaker contacts open, the fault current is not interrupted instantaneously. Instead, an electric arc forms between the breaker contact, which is maintained as long as there is enough current flowing. Since the fault current varies sinusoidally at the power frequency, the arc will extinguish at the first current zero. However, at the location of the arc, there are still hot, ionized gases and, if voltages exceeding the dielectric capability of the contact gap develop across the open contacts of the circuit breaker, it is possible that the arc will reignite. Circuit interruption is a race between the increase of dielectric strength of the contact gap of the circuit breaker or switch and the recovery voltage. The latter is essentially a characteristic of the circuit itself.

For inductive circuits, we know that the current lags the voltage by an angle less than ninety electrical degrees. Thus, when the current is zero, the voltage is at its maximum. This means that, immediately after interruption of the arc, a rapid buildup of voltage across the breaker contacts may cause the arc to reignite and re-establish the circuit. The rate by which the voltage across the breaker rises depends on the inductance and capacitance of the circuit.

The simplest form of single-phase circuit that is useful to illustrate this phenomenon is that shown in Figure 15.
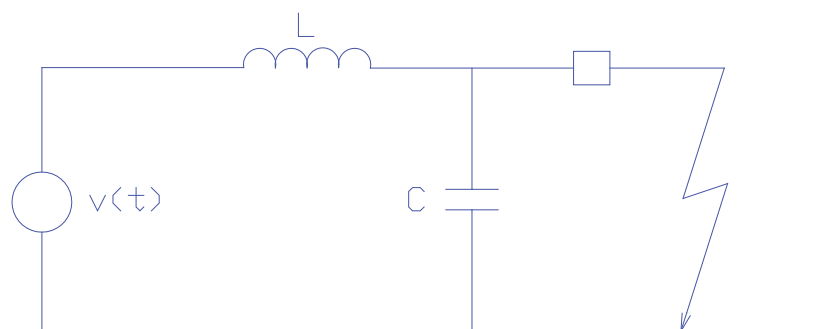

Figure 15—Simplified diagram to illustrate TRV

In the circuit, L is the inductance of the source and C is the natural capacitance of the circuit in the vicinity of the circuit breaker. It may include capacitance to ground through bushings, current transformers, etc. The voltage source is assumed to vary

sinusoidally and, since it is at its peak at the time the short-circuit current is interrupted, it can be expressed as

$$v(t) = \sqrt{2} \cdot V \cdot \cos(\omega t) \tag{57}$$

where ω is the power frequency in radians per second (rad/s). If the switch opens, the flow of current is interrupted at the first current zero and a voltage known as the transient recovery voltage (TRV) will appear across the breaker contacts. This voltage is essentially the voltage across the capacitance. It is zero during the fault but, when the circuit breaker opens to clear the fault, the voltage across the contacts builds up to approximately twice the peak of the voltage at the power frequency.

The equivalent circuit of Figure 15 may be analysed by means of the Laplace transform. The network equation in the s-domain for $t = 0^+$ is:

$$V(s) = I(s)sL - LI(0^-) + \frac{I(s)}{sC} \tag{58}$$

Solving the current I(s) with $I(0^-) = 0$ (current interruption assumed to occur at zero current, no current chopping) yields the following:

$$I(s) = \frac{V(s)}{L}\left[\frac{s}{s^2+\omega_0^2}\right] \tag{59}$$

Substituting sCV_c(s) for I(s), the result is:

$$V_c(s) = V(s)\frac{\omega_0^2}{s^2+\omega_0^2} \tag{60}$$

The Laplace transform of the driving function described by Equation 57 is:

$$V(s) = V_{max}\frac{s}{s^2+\omega^2} \tag{61}$$

Combining Equations 60 and 61, the recovery voltage or the voltage across the capacitor is:

$$V_c(s) = V_{max}\frac{s\omega_0^2}{(s^2+\omega^2)(s^2+\omega_0^2)} \tag{62}$$

From the table of the inverse Laplace transforms, the transient response is:

$$V_c(t) = \frac{V_{max}}{1-\frac{\omega^2}{\omega_0^2}}[\cos\omega t - \cos\omega_0 t] \tag{63}$$

The events before and after the fault are depicted in Figure 16 with damping. However, without damping as described by Equation 63, the recovery voltage reaches a maximum of twice the source voltage (the peak occurs at one half cycle of the natural frequency, after the switch is opened). This is true when the natural frequency is high as compared with the fundamental frequency and when losses are insignificant. Losses (damping) will reduce the maximum value of V_c, as shown in Figure 16.
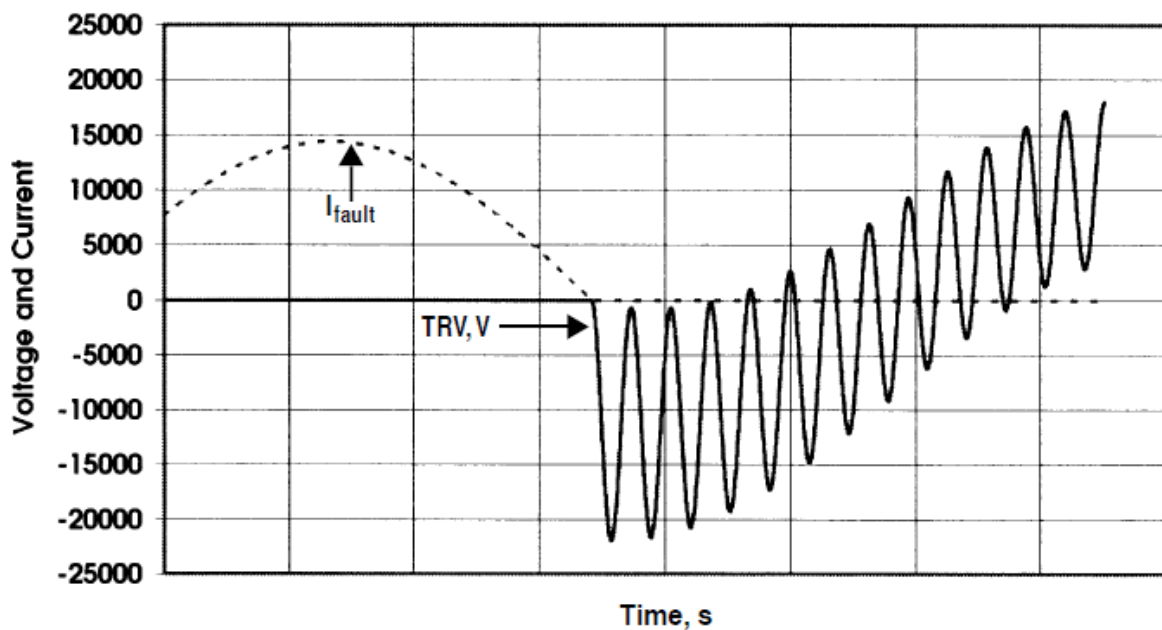
Figure 16—Transient recovery voltage

Upon interruption of the fault current by the circuit breaker, the source attempts to charge the capacitor voltage to the potential of the supply. As a matter of fact, without damping, the capacitor voltage will overshoot the supply voltage by the same amount as it started below. If the natural frequency of the circuit is high (*L* and *C* very small), the voltage across the breaker contacts will rise very rapidly. If this rate-of-rise exceeds the dielectric strength of the medium between the contacts, the breaker will not be able to sustain the voltage and re-ignition will occur.

2. Switching Transient Studies

Introduction

Unlike classical power system studies, i.e., short circuit, load flow, etc., switching

transient studies are conducted less frequently in industrial power distribution systems. Capacitor and harmonic filter bank switching in industrial and utility systems account for most of such investigations, to assist in the resolution of certain transient behavioural questions in conjunction with the application or failure of a particular piece of equipment.

Two basic approaches present themselves in the determination and prediction of switching transient duties in electrical equipment: direct transient measurements (to be discussed later in this chapter) and computer modelling. The latter can be divided into transient network analyser (TNA) and digital computer modelling.

In fact, experienced transient analysts use known circuit-response patterns, based on a few basic fundamentals, to assess the general transient behaviour of a particular circuit and to judge the validity of more complex switching transient results. Indeed, simple configurations consisting of linear circuit elements can be processed by hand as a first approximation. Beyond these relatively simple arrangements, the economics and effective determination of electrical power system transients require the utilization of TNAs or digital computer programs.

Switching Transient Study Objectives

The basic objectives of switching transient investigations are to identify and quantify transient duties that may arise in a system as a result of intentional or unintentional switching events, and to prescribe economical corrective measures whenever deemed necessary. The results of a switching transient study can affect the operating procedures as well as the equipment in the system. The following include some specific broad objectives, one or more of which are included in a given study:

- Identify the nature of transient duties that can occur for any realistic switching operation. This includes determining the magnitude, duration, and frequency of the oscillations.

- Determine if abnormal transient duties are likely to be imposed on the equipment by the inception and/or removal of faults.

- Recommend corrective measures to mitigate transient over-voltages and/or

over-currents. This may include solutions such as resistor pre-insertion, tuning reactors, appropriate system grounding, and application of surge arresters and surge-protective capacitors.

- Recommend alternative operating procedures, if necessary, to minimize transient duties.

- Document the study results on a case-by-case basis in readily understandable form for those responsible for design and operation. Such documentation usually includes reproduction of waveshape displays and interpretation of, at least, the limiting cases.

Control of Switching Transients

The philosophy of mitigation and control of switching transients revolves around the following:

- Minimizing the number and severity of the switching events

- Limitation of the rate of exchange of energy that prevails among system elements during the transient period

- Extraction of energy

- Shifting the resonant points to avoid amplification of particular offensive frequencies

- Provision of energy reservoirs to contain released or trapped energy within safe limits of current and voltage

- Provision of discharge paths for high-frequency currents resulting from switching

In practice, this is usually accomplished through one or more of the following methods:

- Temporary insertion of resistance between circuit elements; for example, the insertion of resistors in circuit breakers

- Synchronized closing control for vacuum and SF_6 breakers and switches

- Inrush control reactors

- Damping resistors in filter and surge protective circuits

- Tuning reactors

- Surge capacitors

- Filters

- Surge arresters

- Necessary switching only, with properly maintained switching devices

- Proper switching sequences

3. Transient Network Analyser (TNA)

Introduction

Through the years, a small number of TNAs have been built for the purpose of performing transient analysis in power systems. A typical TNA is made of scaled-down power system component models, which are interconnected in such a way as to represent the actual system under study. The inductive, capacitive, and resistive characteristics of the various power system components are modelled with inductors, capacitors, and resistors in the analyser. These have the same oersted ohmic value as the actual components of the system at the power frequency. The analyser generally operates in the range of 10 to 100 V_{rms} line-to-neutral, which represents 1.0 per-unit voltage on the actual system.

The model approach of the TNA finds its virtue in the relative ease with which individual components can duplicate their actual power system counterparts as compared with the difficulty of accurately representing combinations of nonlinear interconnected elements in a digital solution. Furthermore, the switching operation that produces the transients is under the direct control of the operator, and the circuit can easily be changed to show the effect of any parameter variation. TNA simulation

is also faster than digital simulation especially for larger systems with many nonlinear elements to model.

Modelling Techniques

Typical hardware used in a TNA to model the actual system components will be described now. However, it should be fully recognized that any specific set of components can be modelled in more than one way, and considerable judgment on the part of the TNA staff is necessary to select the optimum model for a given situation. Also, it should be recognized that, while there is a great similarity among the components of the various TNAs in existence today, there are also unique hardware approaches to any given system. The following is a general description of some of the hardware models.

- Transmission lines are modelled basically as a four-wire system, with three wires associated with the phase conductors and the fourth wire encompassing the effects of shield wire and earth return.

- Circuit breakers consist of a number of independent mercury-wetted relay contacts or solid-state electronic circuitry. The instant of both closing and opening of each individual switch can be controlled by the operator or the computer system. The model has the capability of simulating breaker actions like pre-striking, re-striking, and re-ignition.

- Shunt reactors can be totally electronic or analog with variable saturation characteristics and losses.

- Transformers are a critical part of the TNA. This is because many temporary over-voltages include the interaction of the nonlinear transformer magnetizing branch with the system inductance and capacitance. Modelling of the nonlinear magnetic representation of the transformer is very critical to analyzing ferroresonance and dynamic over-voltages. The model consists of both an array of inductors, configured and adjusted to represent the linear inductances of the transformer, and adjustable saturable reactors, representing the nonlinear portion of the saturation characteristics.

- Arresters of both silicon carbide and metal oxide can be modelled. The models for both types of arresters can be totally electronic and provide energy dissipation values to safely size the surge arresters.

- Secondary arc, available in some TNA facilities, is a model that can simulate a fault arc and its action after the system circuit breakers are cleared.

- Power sources can be three-phase motor-generator sets or three-phase electronic frequency converters. The short-circuit impedance of these sources is such that they appear as an infinite bus on the impedance base of the analyzer.

- Synchronous machines can be either totally electronic or analog models, and are used to study the effects of load rejection or other events that could be strongly affected by the action of the synchronous machine.

- Static var systems include an electronic control circuit, a thyristor-controlled reactor, and a fixed capacitor with harmonic filters. The control logic circuit monitors the three-phase voltages and currents and can be set to respond to the voltage level, the power factor, or some combination of the two.

- Series capacitor protective devices are used in conjunction with series compensated ac transmission lines. When a fault occurs, the voltage on the series capacitor rises to a high value unless it is bypassed by protective devices, such as power gap or metal-oxide varistors. The TNA can represent both of these devices.

4. Electromagnetic Transients Program (EMTP)

Introduction

EMTP is a software package that can be used for single-phase and multiphase networks to calculate either steady-state phasor values or electromagnetic switching transients. The results can be either printed or plotted.

Network and Device Representation

The program allows for arbitrary connection of the following elements:

- Lumped resistance, inductance, and capacitance

- Multiphase (π) circuits, when the elements *R*, *L*, and *C* become symmetric matrixes

- Transposed and untransposed distributed parameter transmission lines with wave propagation represented either as distortionless, or as lossy through lumped resistance approximation

- Nonlinear resistance with a single-valued, monotonically increasing characteristics

- Nonlinear inductance with single-valued, monotonically increasing characteristics

- Time-varying resistance

- Switches with various switching criteria to simulate circuit breakers, spark gaps, diodes, and other network connection options

- Voltage and current sources representing standard mathematical functions, such as sinusoidals, surge functions, steps, ramps, etc. In addition, point-by-point sources as a function of time can be specified by the user.

- Single- and three-phase, two- or three-winding transformers

Switching Transient Problem Areas

Switching of predominantly reactive equipment represents the greatest potential for creating excessive transient duties. Principal offending situations are switching capacitor banks with inadequate or malfunctioning switching devices and energizing and de-energizing transformers with the same switching deficiencies. Capacitors can store, trap, and suddenly release relatively large quantities of energy. Similarly, highly inductive equipment possesses an energy storage capability that can also release large quantities of electromagnetic energy during a rapid current decay. Since transient voltages and currents arise in conjunction with energy redistribution following a switching event, the greater the energy storage in associated system elements, the greater the transient magnitudes become.

Generalized switching transient studies have provided many important criteria to enable system designers to avoid excessive transients in most common circumstances. The criteria for proper system grounding to avoid transient over-voltages during a ground fault are a prime example. There are also several not very common potential transient problem areas that are analyzed on an individual basis. The following is a partial list of transient-related problems, which can and have been analyzed through computer modelling:

- Energizing and de-energizing transients in arc furnace installations

- Ferroresonance transients

- Lightning and switching surge response of motors, generators, transformers, transmission towers, cables, etc.

- Lightning surges in complex station arrangements to determine optimum surge arrester location

- Propagation of switching surge through transformer and rotating machine windings

- Switching of capacitors

- Restrike phenomena during line dropping and capacitor de-energization

- Neutral instability and reversed phase rotation

- Energizing and reclosing transients on lines and cables

- Switching surge reduction by means of controlled closing of circuit breaker, resistor pre-insertion, etc.

- Statistical distribution of switching surges

- Transient recovery voltage on distribution and transmission systems

- Voltage flicker

Significant transients often occur when inductive loads are rapidly transferred

between two out-of-phase sources. Transients can also occur when four-pole transfer switches are both used for line and neutral switching, as may be necessary for separately derived systems. Typical solutions for such problem areas often require transfer switch designs that include in-phase monitors and overlapping neutral conductor switching.

The behaviour of transformer and machine windings under transient conditions is also an area of great concern. Due to the complexities involved, it would be almost impossible to cover the subject in this chapter.

5. Switching Transients - Field Measurements

Introduction

The choice of measuring equipment, auxiliary equipment selection, and techniques of setup and operation are in the domain of practiced measurement specialists. No attempt will be made here to delve into such matters in detail, except from the standpoint of conveying the depth of involvement entailed by switching transient measurements and from the standpoint of planning a measurement program to secure reliable transient information of sufficient scope for the intended purpose.

Field measurements seldom, if ever, include fault switching, and often, recommended corrective measures are not in place to be used in the test program except on a follow-up basis. For systems still in the design stage or when fault switching is required, the transient response is usually obtained with the aid of a TNA or a digital computer program. There are basically three types of transients to consider in field measurements:

The first category includes transients incurred when switching a device on or off. The second category covers the transients occurring regularly, for example, commutation transients. The final category that refers to transients are those of usually unknown origin, generated by extraneous operations on the system. These may include inception and interruption of faults, lightning strikes, etc. To detect and/or record random transients, it is necessary to monitor the system continuously.

Signal Derivation

The ideal result of a transient measurement, or for that matter, any measurement at all, is to obtain a perfect replica of the transient voltage and current as a function of time. Quite often, the transient quantity to be measured is not obtained directly and must be converted, by means of transducers, to a voltage or current signal that can be safely recorded. However, measurements in a system cannot be taken without disturbing it to some extent. For example, if a shunt is used to measure current, in reality, voltage is being measured across the shunt to which the current gives rise. This voltage is frequently assumed to be proportional to the current, when, in fact, this is not always true with transient currents. Or, if the voltage to be measured is too great to be handled safely, appropriate attenuation must be used. In steady-state measurements, such errors are usually insignificant. But in transient measurements, this is more difficult to do. Therefore, since switching transients involve natural frequencies of a very wide range (several orders of magnitude), signal sourcing must be by special current transformers (CTs), non-inductive resistance dividers, non-inductive current shunts, or compensated capacitor dividers, in order to minimize errors. While conventional CTs and potential transformers (PTs) can be suitable for harmonic measurements, their frequency response is usually inadequate for switching transient measurements.

Signal Circuits, Terminations and Grounding

Due to the very high currents with associated high magnetic flux concentrations, it is essential that signal circuitry be extremely well shielded and constructed to be as interference-free as possible. Double-shielded low loss coaxial cable is satisfactory for this purpose. Additionally, it is essential that signal circuit terminations be made carefully with high-quality hardware and assure proper impedance match in order to avoid spurious reflections.

It is desirable that signal circuits and instruments be laboratory-tested as an assembly before field measurements are undertaken. This testing should include the injection of a known wave into the input end of the signal circuit and comparison of this waveshape with that of the receiving instruments. Only after a close agreement between the two waveshapes is achieved should the assembly be approved for

switching transient measurements. These tests also aid overall calibration.

All the components of the measurement system should be grounded via a continuous conducting grounding system of the lowest practical inductance to minimize internally induced voltages. The grounding system should be configured to avoid ground loops that can result in the injection of noise. Where signal cables are unusually long, excessive voltages can become induced in their shields. Industrial switching transient measurement systems have not, as yet, involved such cases.

Equipment for Measuring Transients

The complement of instruments used depends on the circumstances and purpose of the test program. Major items comprising the total complement of display and recording instrumentation for transient measurements are one or more of the following:

- One or more oscilloscopes, including a storage-type scope with multichannel switching capability. When presence of the highest speed transients (that is, those with front times of less than a microsecond) is suspected, a high speed, single trace surge test oscilloscope with direct cathode ray tube (CRT) connections is sometimes used to record such transients with the least possible distortion.

- Multichannel magnetic light beam oscillograph with high input impedance amplifiers.

- Peak-holding digital readout memory voltmeter (sometimes called "peakpicker") that is manually reset.

The occurrence of most electrical transients is quite unpredictable. To detect and/or record random disturbances, it is necessary to monitor the circuit on a continuous basis. There are many instruments available in the market today for this purpose. Most of these instruments are computer based; that is, the information can be captured digitally and later retrieved for display or computer manipulation. These instruments vary in sophistication depending on the type and speed of transient measurements that are of interest.

6. Typical Circuit Parameters for Transient Studies

Introduction

Compared to conventional power system studies, switching transient analysis data requirements are often more detailed and specific. These requirements remain basically unchanged regardless of the basic analysis tools and aids that are employed, whether they are digital computer or transient network analysers.

To determine the transient response of a circuit to a specific form of excitation, it is first necessary to reduce the network to its simplest form composed of Rs, Ls, and Cs. After solving the circuit equations for the desired unknown, values must be assigned to the various circuit elements in order to determine the response of the circuit.

System and Equipment Data Requirements

The following generalized data listed encompass virtually all information areas required in an industrial power system switching transient study:

- Single-line diagram of the system showing all circuit elements and connection options.

- Utility information, for each tie, at the connection point to the tie. This should include:

  1) Impedances R, XL, XC, both positive and zero sequence representing minimum and maximum short-circuit duty conditions.

  2) Maximum and minimum voltage limits.

  3) Description of reclosing procedures and any contractual limitations, if any.

- Individual power transformer data such as rating, connections, no-load tap voltages, LTC voltages if any, no-load saturation data, magnetizing current, positive and zero sequence leakage impedances, and neutral grounding details.

- Capacitor data for each bank, connections, neutral grounding details,

description of switching device and tuning reactors, if any.

- Impedances of feeder cables or lines, that is, R, XL, and XC (both positive and zero sequence).

- Information about other power system elements, such as:

  1) Surge arrester type, location and rating.

  2) Grounding resistors or reactors, rating and impedance of buffer reactors.

  3) Rating, subtransient and transient reactance of rotating machines, grounding details, etc.

- Operating modes and procedures.