# 3 Electrical Transients

## 3.1 INTRODUCTION

In Chapter 1, a *transient* is defined as a subcycle disturbance in the AC waveform that is discernible as a sharp discontinuity of the waveform. The definition states that transients are subcycle events, lasting less than one cycle of the AC waveform. Inclusion of the term *subcycle* is for the sake of definition only. Routinely we see transients that span several cycles. To satisfy the absolute definition, the transient occurring in the next cycle is not considered an extension of the transient in the previous cycle. This approach allows us to isolate the disturbance on a cycle-by-cycle basis for ease of analysis and treatment.

Subcycle transients are some of the most difficult anomalies to detect and treat. Their occurrence can be random, and they can vary in degree depending on the operating environment at the time of occurrence. Their effect on devices varies depending on the device itself and its location in an electrical system. Transients are difficult to detect because of their short duration. Conventional meters are not able to detect or measure them due to their limited frequency response or sampling rate. For example, if a transient occurs for 2 msec and is characterized by a frequency content of 20 kHz, the measuring instrument must have a frequency response or sampling rate of at least 10 times 20 kHz, or 200 kHz, in order to fairly describe the characteristics of the transient. For faster transients, higher sampling rates are necessary. In Chapter 9, we will look into what is involved in selecting and setting up instrumentation for measuring electrical transients.

Many different terms are associated with transients, such as *spikes*, *bumps*, *power pulses*, *impulses*, and *surges*. While some of these terms may indeed describe a particular transient, such terms are not recommended due to their ambiguity. We will use the term *transient* to denote all subcycle events and ascribe certain characteristics to these events, such as overvoltage, notch, noise, and ring. It may be that what we call transient is not as important as remembering that the underlying causes of the various transient events differ, as do the cures for the ill effects produced by the transients.

Why is an understanding of the transient phenomenon important? Large electromagnetic devices such as transformers and motors are practically impervious to the effects of transients. Problems arise because of the sensitivity of the microelectronic devices and circuits that make up the control elements of the power system. The microprocess controller is the nerve center of every present-day manufacturing or commercial facility. Medical electronic instruments used in healthcare facilities are becoming more sophisticated and at the same time increasingly susceptible to electrical transients. Because the performance of any machine is only as good as its weakest link, expansive operations can be rendered vulnerable due to the susceptibility of the most inexpensive and seemingly insignificant of the components comprising the system. We will examine some specific examples of such vulnerability later in this chapter.

## 3.2 TRANSIENT SYSTEM MODEL

Steady-state systems are the opposite of transient systems. In steady state, the operation of a power system is characterized by the fundamental frequency or by some low-frequency harmonic of the fundamental frequency. The three passive parameters of the system — resistance ($R$), inductance ($L$), and capacitance ($C$) — determine how the steady-state system will respond when under the influence of an applied voltage. This situation is somewhat analogous to the steady-state thermodynamics model, in which thermal energy supplied is equal to energy stored plus energy dissipated, and by using traditional laws of physics the temperature rise of devices can be accurately calculated. However, in a transient state, traditional laws of equilibrium do not apply. The circuit model of a transient electrical system will appear considerably different from the steady-state model. Passive parameters $R$, $L$, and $C$ are still major determinants of the transient response, but their effect on the transient can change with the duration of the transient. In an electrical system, inductance and capacitance are the energy-storing elements that contribute to the oscillatory nature of the transient. Resistance is the energy-dissipating element that allows the transient to dampen out and decay to the steady-state condition. Figure 3.1 illustrates an electrical power source feeding a resistive–inductive load (e.g., a motor) via circuit breaker S and transformer T. Figure 3.2 is a steady-state representation of the power circuit, and Figure 3.3 is a transient model of the same circuit. In the transient model, the capacitance across the poles of the circuit breaker, the capacitance

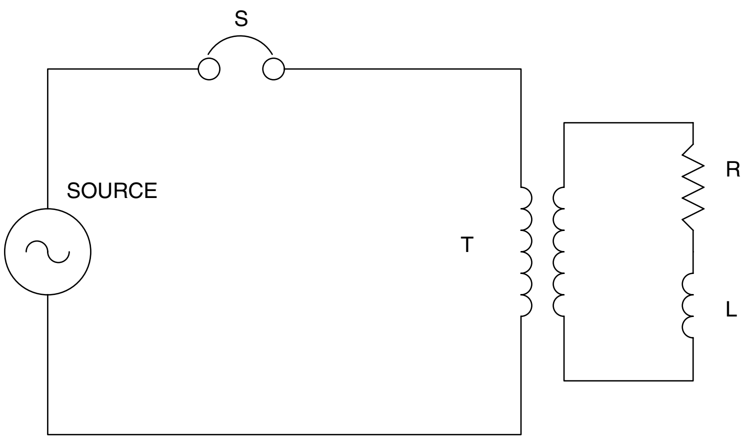



**FIGURE 3.1** Power system consisting of source, circuit breaker, transformer, and load.

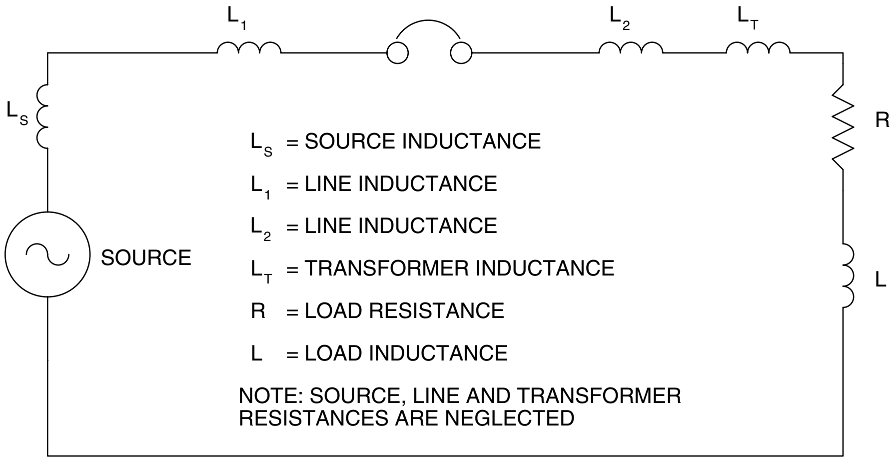



**FIGURE 3.2** Low-frequency representation of the circuit shown in Figure 3.1.

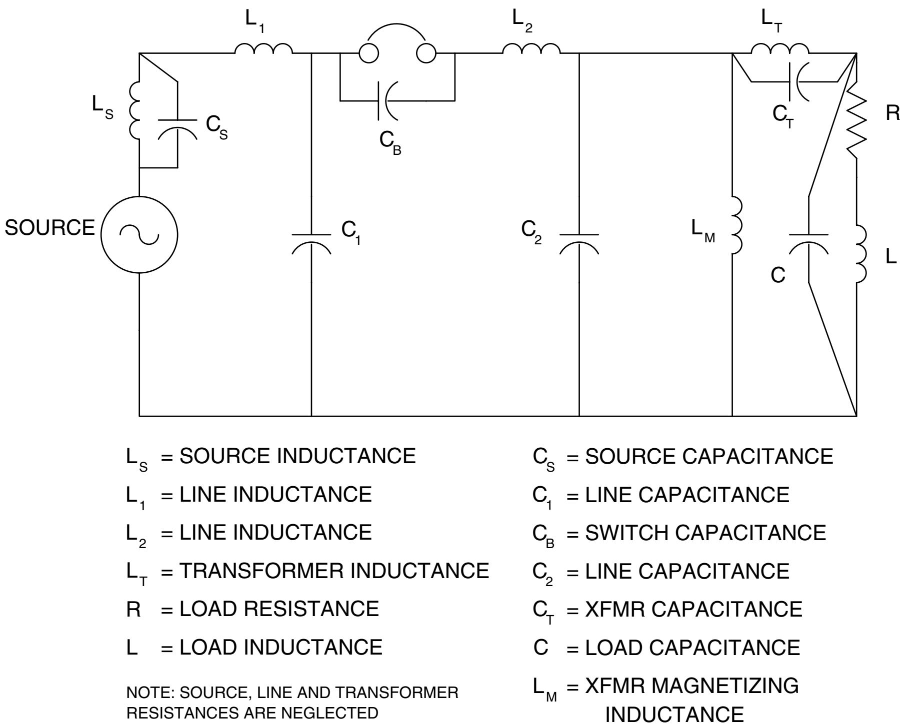



**FIGURE 3.3** Transient model of circuit in Figure 3.1.

of the power lines feeding the motor, and the capacitance of the source and the motor windings become significant. Once the transient model is created, some of the elements may be systematically eliminated depending on their magnitude, the transient duration, and the relevance of a specific element to the problem being addressed. This brings up some important points to consider while solving electrical transient-related problems. First, determine the total transient model, then remove elements in the model that are not relevant to the problem at hand. Also, develop a mathematical model of the transient circuit, and then derive a solution for the needed parameter.

## 3.3 EXAMPLES OF TRANSIENT MODELS AND THEIR RESPONSE

Some examples of transient models and transient response are included in this section. The examples are simple but nonetheless are intended to provide the reader with a better grasp of the basics of electrical transients.

### 3.3.1 Application of DC Voltage to a Capacitor

Figure 3.4 depicts a capacitor to which a DC voltage ($V$) is suddenly applied. Figure 3.5 represents in graphical form the transient response for the current and voltage across the capacitor. The expressions for $V_C$ and $I_C$ assume that the capacitor has zero initial charge:

$$V_C = V(1 - e^{-t/RC}) \tag{3.1}$$

$$I_C = (V/R)e^{-t/RC} \tag{3.2}$$

where $RC$ is the time constant ($T$) of the resistance–capacitance circuit and is expressed in seconds. The time constant is the time it would take for an exponentially decaying parameter to reach a value equal to 36.79% of the initial value. This is explained by noting that the parameter would be reduced to a value given by $1/e^1$ or 0.3679 of the initial value. In a time interval equal to two time constants, the parameter will be reduced to $1/e^2$ or 13.5% of the initial value. After five time constants, the parameter will be reduced to 0.67% of the initial value. As time increases, the value $e^{-t/T}$ becomes smaller and smaller and approaches zero. In this example, the current through the capacitor is $V/R$ at time $t = 0$. At time $t = T$, the current will diminish to $0.3679(V/R)$; at time $t = 2T$, the current will be $0.1353(V/R)$, and so on.

In the same example, if the capacitance has an initial voltage of $+V_0$, then the expressions become:

$$V_C = V - (V - V_0)e^{-t/RC} \tag{3.3}$$

$$I_C = [(V - V_0)/R]e^{-t/RC} \tag{3.4}$$

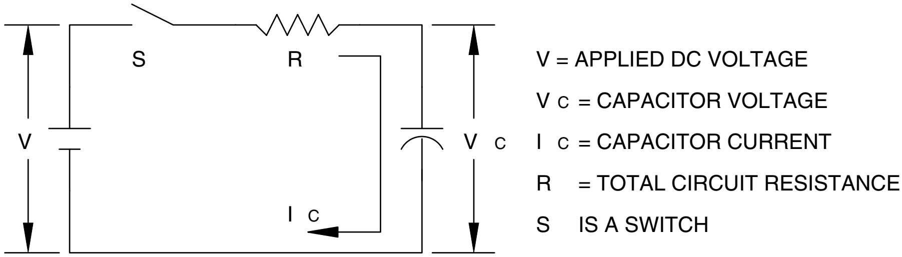



**FIGURE 3.4** Application of DC voltage to an *R–C* circuit.

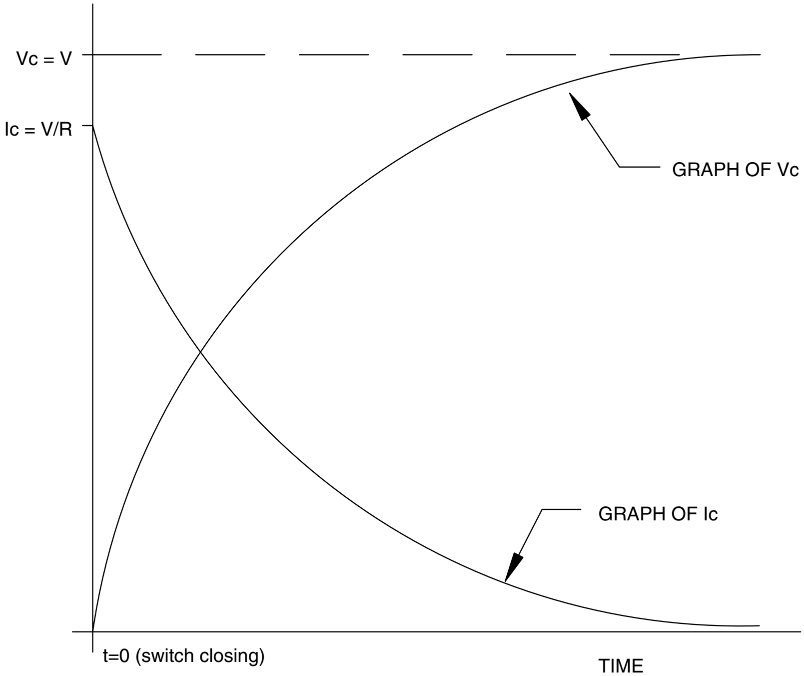



**FIGURE 3.5** Capacitor voltage and capacitor current with time.

### 3.3.2 Application of DC Voltage to an Inductor

Figure 3.6 shows an inductor with $R$ representing the resistance of the connecting wires and the internal resistance of the inductor. The variation of voltage and the current in the inductor are shown in Figure 3.7 and expressed by:

$$V_L = Ve^{-tR/L} \tag{3.5}$$

$$I_L = (V/R)(1 - e^{-tR/L}) \tag{3.6}$$

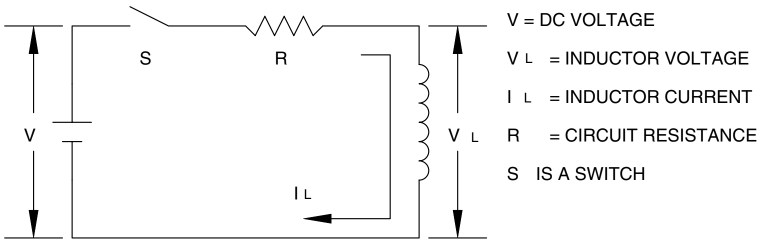



**FIGURE 3.6** Application of DC voltage to a *R–L* circuit.

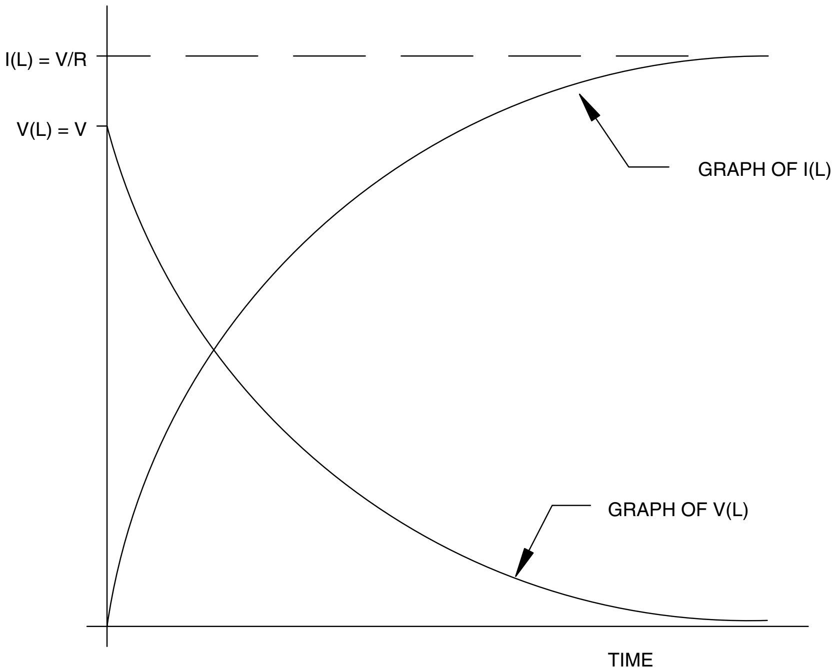



**FIGURE 3.7** Inductor voltage and inductor current with time.

At time $t = 0$, the voltage across the inductor is $V$; in an ideal inductor, current cannot change instantly, so the applied voltage appears across the inductor. At time $t = \infty$, voltage across the inductor is zero. The current through the ideal inductor at time $t = 0$, and at time $t = \infty$ the current through the inductor is equal to $V/R$.

For an inductive circuit, the time constant $T$ in seconds is equal to $L/R$, and the expressions for $V_L$ and $I_L$ become:

$$V_L = Ve^{-t/T} \tag{3.7}$$

$$I_L = (V/R)\,(1 - e^{-t/T}) \tag{3.8}$$

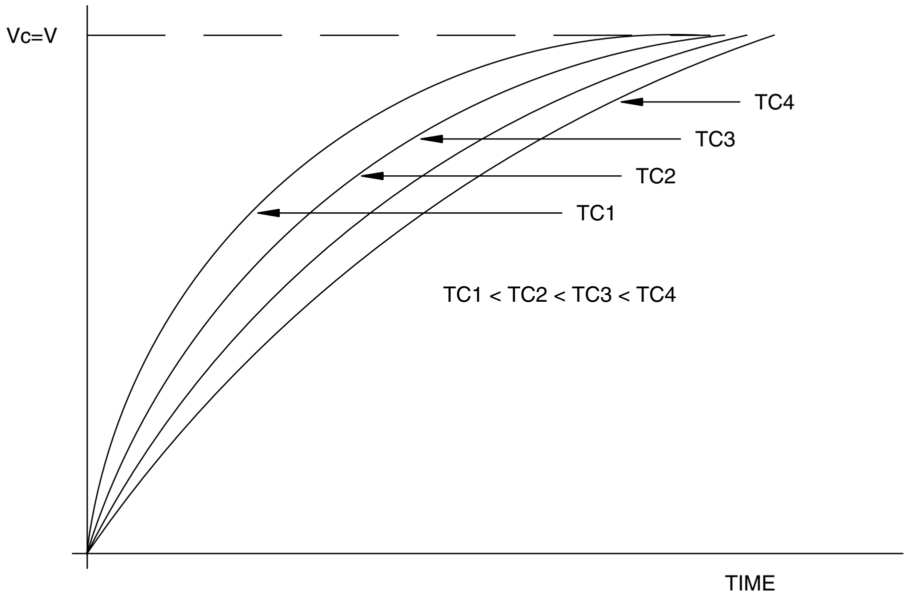



**FIGURE 3.8** Variation of $V_C$ with time and with time constant *RC*.

The significance of the time constant is again as indicated under the discussion for capacitors. In this example, the voltage across the inductor after one time constant will equal 0.3679 V; in two time constants, 0.1353 V; and so on.

The significance of the time constant *T* in both capacitive and inductive circuits is worth emphasizing. The time constant reflects how quickly a circuit can recover when subjected to transient application of voltage or current. Consider Eq. (3.1), which indicates how voltage across a capacitor would build up when subjected to a sudden application of voltage *V*. The larger the time constant *RC*, the slower the rate of voltage increase across the capacitor. If we plot voltage vs. time characteristics for various values of time constant *T*, the family of graphs will appear as shown in Figure 3.8. In inductive circuits, the time constant indicates how quickly current can build up through an inductor when a switch is closed and also how slowly current will decay when the inductive circuit is opened. The time constant is an important parameter in the transient analysis of power line disturbances.

The *L–C* combination, whether it is a series or parallel configuration, is an oscillatory circuit, which in the absence of resistance as a damping agent will oscillate indefinitely. Because all electrical circuits have resistance associated with them, the oscillations eventually die out. The frequency of the oscillations is called the natural frequency, $f_O$. For the *L–C* circuit:

$$f_O = 1/2\pi\sqrt{LC} \tag{3.9}$$

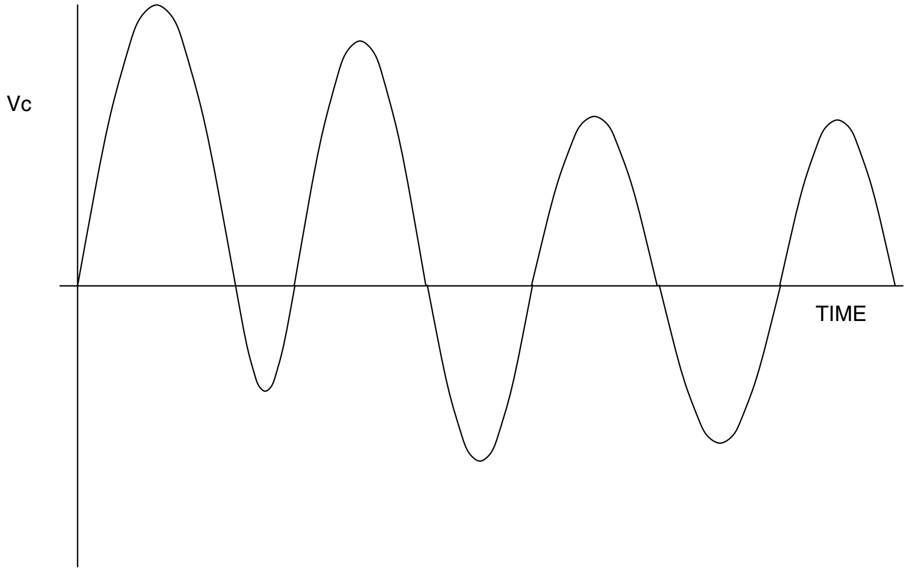



**FIGURE 3.9** Oscillation of capacitor voltage when *L–C* circuit is closed on a circuit of DC voltage *V*.

In the *L–C* circuit, the voltage across the capacitor might appear as shown in Figure 3.9. The oscillations are described by the Eq. (3.10), which gives the voltage across the capacitance as:

$$V_C = V - (V - V_{CO})\cos\omega_O t \tag{3.10}$$

where $V$ is the applied voltage, $V_{CO}$ is the initial voltage across the capacitor, and $\omega_O$ is equal to $2\pi f_O$.

Depending on the value and polarity of $V_{CO}$, a voltage of three times the applied voltage may be generated across the capacitor. The capacitor also draws a considerable amount of oscillating currents. The oscillations occur at the characteristic frequency, which can be high depending on the value of $L$ and $C$. A combination of factors could result in capacitor or inductor failure. Most power systems have some combination of inductance and capacitance present. Capacitance might be that of the power factor correction devices in an electrical system, and inductance might be due to the power transformer feeding the electrical system.

The examples we saw are for *L–C* circuits supplied from a direct current source. What happens when an *L–C* circuit is excited by an alternating current source? Once again, oscillatory response will be present. The oscillatory waveform superimposes on the fundamental waveform until the damping forces sufficiently attenuate the oscillations. At this point, the system returns to normal operation. In a power system characterized by low resistance and high values of $L$ and $C$, the effects would be more damaging than if the system were to have high resistance and low $L$ and $C$ because the natural frequencies are high when the values of $L$ and $C$ are low. The

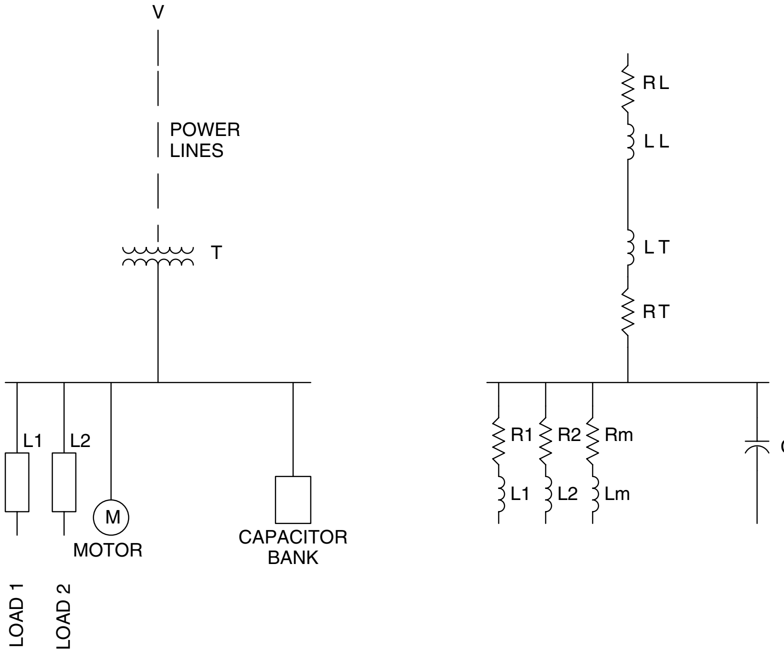



**FIGURE 3.10** Lumped parameter representation of power system components.

resistance of the various components that make up the power system is also high at the higher frequencies due to the skin effect, which provides better damping characteristics. In all cases, we are concerned about not only the welfare of the capacitor bank or the transformer but also the impact such oscillations would have on other equipment or devices in the electrical system.

## 3.4 POWER SYSTEM TRANSIENT MODEL

At power frequencies, electrical systems may be represented by lumped parameters of *R*, *L*, and *C*. Figure 3.10 shows a facility power system fed by 10 miles of power lines from a utility substation where the power is transformed from 12.47 kV to 480 V to supply various loads, including a power factor correction capacitor bank. Reasonable accuracy is obtained by representing the power system components by their predominant electrical characteristics, as shown in Figure 3.10. Such a representation simplifies the calculations at low frequencies. To obtain higher accuracy as the frequency goes up, the constants are divided up and grouped to form the π or T configurations shown in Figure 3.11; the computations get tedious, but more accurate results are obtained. Yet, at high frequencies the power system should be represented by distributed parameters, as shown in Figure 3.12. In Figure 3.12, r, l, and c represent the resistance, inductance, and capacitance, respectively, for the unit distance. The reason for the distributed parameter approach is to produce results that more accurately represent the response of a power system to high-frequency transient phenomena.

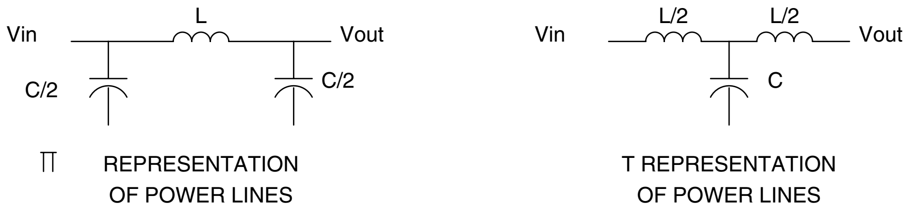



**FIGURE 3.11** Representation of power lines at high frequencies where L is the total inductance and C is the total capacitance of the power lines.

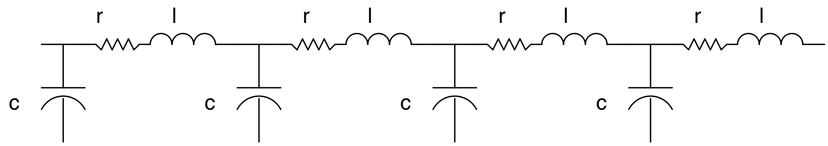



**FIGURE 3.12** Distributed constant representation of power lines at high frequencies where c, l, and r are electrical constants for unit distance.

The wavelength of a periodic waveform is given by:

$$\lambda = C/f$$

where $C$ is the velocity of light in vacuum and is equal to $300 \times 10^6$ msec or 186,400 miles/sec. For 60-Hz power frequency signals, $\lambda$ is equal to 3106 miles; for a 1-MHz signal, $\lambda$ is equal to 393 ft.

All alternating current electrical signals travel on a conducting medium such as overhead power lines or underground cables. When a signal reaches the end of the wiring, it reflects back. Depending on the polarity and the phase angle of the reflected wave, the net amplitude of the composite waveform can have a value between zero and twice the value of the incident wave. Typically, at 1/4 wavelength and odd multiples of 1/4 wavelength, the reflected wave becomes equal in value but opposite in sign to the incident wave. The incident and the reflected waves cancel out, leaving zero net signal. The cable, in essence, acts like a high-impedance circuit. For transient phenomena occurring at high frequencies, however, even comparatively short lengths of wire might be too long to be effective.

Several quantities characterize the behavior of power lines as far as transient response is concerned. One important quantity is the characteristic impedance, expressed as:

$$Z_O = \sqrt{(L/C)} \tag{3.11}$$

In a power line that has no losses, the voltage and the current are linked by the characteristic impedance $Z_O$.

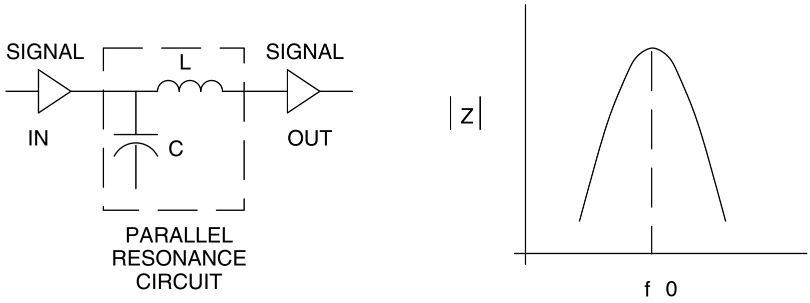



**FIGURE 3.13** Parallel resonance circuit and impedance graph indicating highest impedance at the frequency of resonance.

Another important characteristic of power systems is the natural frequency, which allows us to calculate the frequency of a disturbance produced in the *L–C* circuit when it is excited by a voltage or current signal. Why is this important? Transient phenomena are very often oscillatory, and the frequencies encountered are higher than the power frequency. By knowing the circuit constants *L* and *C* and the amplitude of the exciting voltage and current, the response of a transient circuit might be determined with reasonable accuracy. Also, when two circuits or power lines are connected together, the characteristic impedance of the individual circuits determines how much of the transient voltage or current will be reflected back and what portion will be refracted or passed through the junction to the second circuit. This is why, in transient modeling, impedance mismatches should be carefully managed to minimize large voltage or current buildups. The natural frequency is given by:

$$f_O = 1/2\pi\sqrt{LC} \tag{3.12}$$

Because any electrical signal transmission line has inductance and capacitance associated with it, it also has a natural frequency. The phenomenon of resonance occurs when the capacitive and inductive reactances of the circuit become equal at a given frequency. In transmission line theory, the resonant frequency is referred to as the characteristic frequency. Resonance in a parallel circuit is characterized by high impedance at the resonant frequency, as shown in Figure 3.13. The electrical line or cable has a characteristic resonance frequency that would allow the cable to appear as a large impedance to the flow of current. These typically occur at frequencies corresponding to 1/4 wavelengths. The significance of this becomes apparent when cables are used for carrying high-frequency signals or as ground reference conductors. Conductor lengths for these applications have to be kept short to eliminate operation in the resonance regions; otherwise, significant signal attenuation could result. If the cable is used as a ground reference conductor, the impedance of the cable could render it less than effective.

The velocity of propagation ($v$) indicates how fast a signal may travel in a medium and is given by:

$$v = 1/\sqrt{(\mu\varepsilon)} \tag{3.13}$$

where $\mu$ is the permeability of the medium and $\varepsilon$ is the dielectric permittivity. For example, in a vacuum, the permeability = $\mu$ = $4\pi 10^{-7}$ H/m, and the dielectric permittivity = $\varepsilon$ = $8.85 \times 10^{-12}$ F/m. Therefore,

$$v = 1/\sqrt{(4\pi 10^{-7} \times 8.85 \times 10^{-12})} \cong 300 \times 10^{6} \text{ msec} = \text{velocity of light}$$

For other media, such as insulated cables or cables contained in magnetic shields (conduits, etc.), the velocity of propagation will be slower, as these items are no longer characterized by the free air qualities of $\mu$ and $\varepsilon$.

The quantities $Z_O$, $f_O$, and $v$ are important for examining transient phenomenon because high-speed, high-frequency events can travel through a conductive path (wire) or may be coupled to adjacent circuits by propagation through a dielectric medium. How effective the path is at coupling the transient depends on these factors.

## 3.5 TYPES AND CAUSES OF TRANSIENTS

Transients are disturbances that occur for a very short duration (less than a cycle), and the electrical circuit is quickly restored to original operation provided no damage has occurred due to the transient. An electrical transient is a cause-and-effect phenomenon. For transients to occur, there must be a cause. While they may be many, this section will look at some of the more common causes of transients:

- Atmospheric phenomena (lightning, solar flares, geomagnetic disturbances)
- Switching loads on or off
- Interruption of fault currents
- Switching of power lines
- Switching of capacitor banks

### 3.5.1 Atmospheric Causes

Over potential surge due to lightning discharge is the most common natural cause of electrical equipment failure. The phenomenon of lighting strike can be described as follows. A negative charge builds up on a cloud, as indicated in Figure 3.14. A corresponding positive charge can build up on the surface of the earth. A voltage difference of hundreds of millions of volts can exist between the cloud and the earth due to the opposing charges. When the voltage exceeds the breakdown potential of air (about $3 \times 10^{6}$ V/m or 75 kV/inch), a lightning flash occurs. The exact physics of the lightning phenomenon will not be discussed here, as it is sufficient to know that a lightning strike can typically produce a voltage rise in about 1 or 2 µsec that can decline to a value of 50% of the peak voltage in approximately 50 to 100 µsec. A typical lightning impulse wave might appear as shown in Figure 3.15. A common misconception is that a direct lightning strike is needed to produce destructive overvoltages. In fact, it is rare that a failure in an electrical system is due to a direct lightning strike. More often, the electrical and magnetic fields caused by indirect lightning discharge induce voltages in the power lines that result in device failures. Also, lightning discharge current flowing through the earth creates a potential dif-

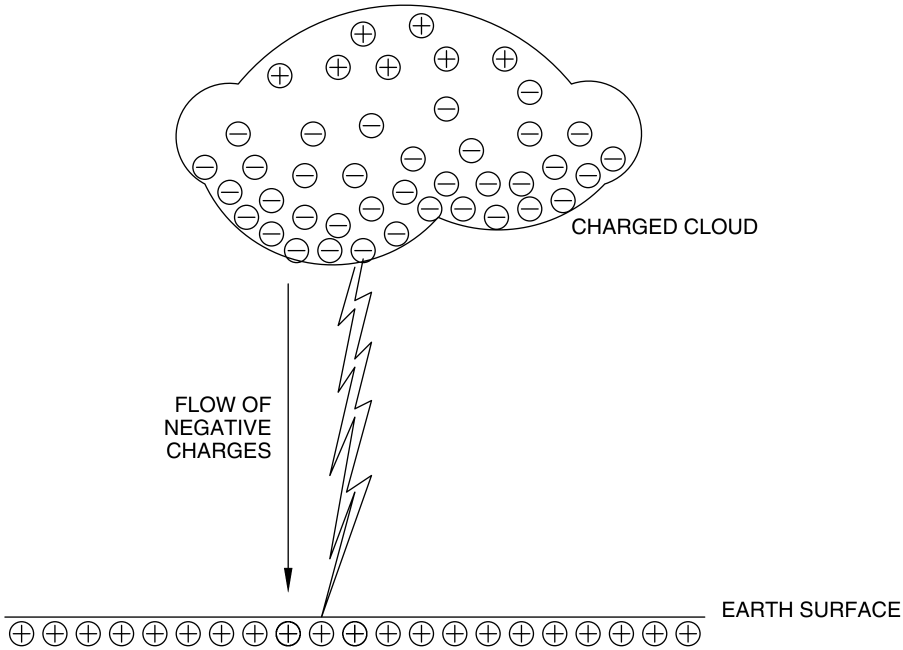



**FIGURE 3.14** Lightning discharge due to charge buildup in the clouds.

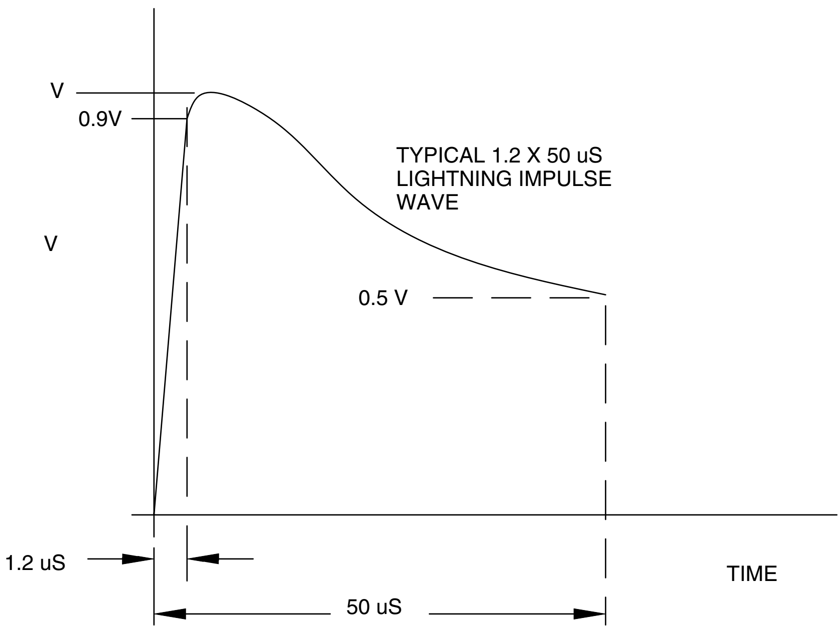



**FIGURE 3.15** Lightning impulse waveform characterized by a rise to 90% value in 1.2 μs and a fall to 50% value in 50 μs.

ference between the power lines and ground and in extreme cases causes equipment failure.

Isolation transformers provide limited protection from lightning strikes. Because lightning is a short-duration, high-frequency phenomenon, a portion of the lightning energy will couple directly from the primary winding to the secondary winding of the transformer through the interwinding capacitance. This is why equipment supplied from the low-voltage winding of a transformer that is exposed to lightning energy is also at risk. The amount of voltage that will be coupled through the transformer will depend on the transformer interwinding capacitance itself. The higher the capacitance, the higher the transient energy coupled to the secondary. Transformers provided with a grounded shield between the primary and the secondary windings provide better protection against lightning energy present at the transformer primary winding.

Lightning arresters, when properly applied, can provide protection against lightning-induced low voltages. Arresters have a well-defined conduction voltage below which they are ineffective. This voltage depends on the rating of the arrester itself. For optimum protection, the arrester voltage should be matched to the lightning impulse withstand of the equipment being protected. Table 3.1 provides typical voltage discharge characteristics of arresters for various voltage classes.

### 3.5.2 Switching Loads On or Off

Switching normal loads in a facility can produce transients. The majority of plant loads draw large amounts of current when initially turned on. Transformers draw

**TABLE 3.1**
**Typical Surge Arrester Protective Characteristics**

| Arrester Rating (kV rms) | Maximum Continuous Operating Voltage[a] (kV rms) | 1-sec Temporary Overvoltage (kV rms) | Maximum Front of Wave Protective Level[b] (kV crest) |
|---|---|---|---|
| 3 | 2.55 | 4.3 | 10.4 |
| 6 | 5.1 | 8.6 | 20.7 |
| 9 | 7.65 | 12.9 | 31.1 |
| 12 | 10.2 | 17.2 | 41.5 |
| 15 | 12.7 | 21.4 | 51.8 |
| 18 | 15.3 | 25.8 | 62.2 |
| 21 | 17.0 | 28.7 | 72.6 |
| 24 | 19.5 | 32.9 | 82.9 |

*Note:* For proper protection, the impulse level of all protected equipment must be greater than the front of wave protective level by a margin of 25% or greater.

[a] Maximum continuous operating voltage is the maximum voltage at which the arrester may be operated continuously.

[b] Maximum front of wave protective level is the kilovolt level at which the arrester clamps the front of the impulse waveform.

inrush currents that range between 10 and 15 times their normal full-load current. This current lasts between 5 and 10 cycles. Alternating current motors draw starting currents that vary between 500 and 600% of the normal full-load running current. Fluorescent lights draw inrush currents when first turned on. Large current drawn through the impedance of the power system sets up transient voltages that affect electrical components sensitive to sags, subcycle oscillations, or voltage notch. There are instances when conditions are such that harmonic frequency currents in the inrush current interact with the power system inductance and capacitance and cause resonance conditions to develop. During resonance, substantial overvoltages and overcurrents might develop. In the strict sense, these are not subcycle events and therefore may not be classified as transients, but their effects are nonetheless very detrimental.

Large inrush currents drawn by certain loads produce other negative effects. Consider a conductor carrying a large current. The magnetic field due to the surge current could induce large potentials in adjacent signal or data cables by inductive coupling. This is why it is preferable to keep signal or data cables physically distant from power cables. Data and signal wires that run near power cables should be contained in metal conduits made of steel. Steel, due to its magnetic properties, is a better shield at low frequencies than nonferrous metals such as aluminum or copper. Nonferrous metals make better shields at high frequencies.

When discussing inductive coupling due to transient current, the loop area of the susceptible circuit should not be overlooked (see Figure 3.16), as the larger the area of the loop, the higher the noise voltage induced in the susceptible circuit. In Figure 3.16, the voltage induced in circuit 2 depends on the magnetic field linking the circuit; the larger the loop area, the larger the flux linkage and, therefore, the higher the noise voltage induced in circuit 2. Twisted pairs of wires minimize the loop area and reduce noise voltage pickup, thus signal and data circuits for sensitive, low-level signal applications installed in close proximity to power wires should use twisted sets of wires to reduce noise coupling.

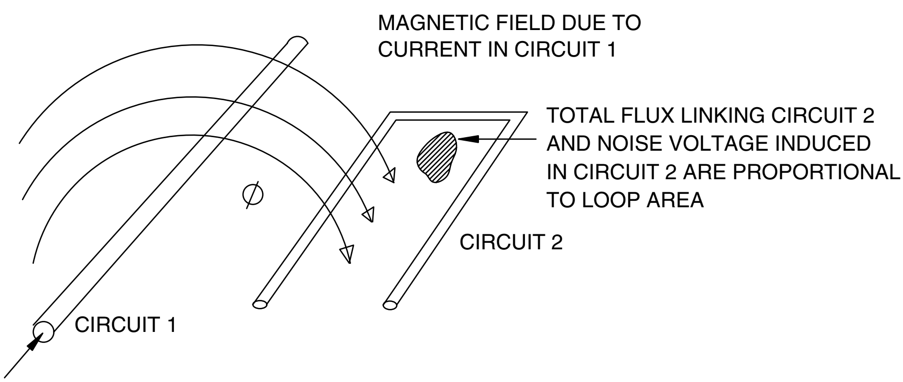



**FIGURE 3.16** Voltage induced in circuit 2 due to current in circuit 1. The voltage depends on the loop area of circuit 2 and proximity between the circuits.

So far we have examined the effects of switching power to loads during normal operation. Switching power off also generates transients due to the fact that all devices carrying electrical current have inductances ($L$) associated with them. The current flowing in an inductive device cannot abruptly change when the circuit is opened. The voltage produced in an electrical device due to a sudden change of current is given by:

$$e = L \times \mathrm{d}i/\mathrm{d}t$$

where $\mathrm{d}i/\mathrm{d}t$ is the rate change of current and $L$ is the inductance associated with the device.

For example, if 50 A of current flowing through a coil of inductance $L = 20$ mH drops to zero in 2 msec, then the voltage generated across the coil is given by:

$$\mathrm{E} = (20 \times 10^{-3} \times 50)/(2 \times 10^{-3}) = 500 \text{ V}$$

It is easy to see that substantial voltages can be developed while switching inductive devices off. The transient voltage produced can easily couple to other circuits via stray capacitance between the inductive device and the susceptible circuit. This voltage can appear as noise for the second circuit. The closer the two circuits are spaced, the higher the amount of noise that is coupled. Voltages as high as 2000 to 5000 V are known to be generated when large inductive currents are interrupted. In low-voltage power and signal circuits, this can easily cause damage.

### 3.5.3 Interruption of Fault Circuits

During fault conditions, large currents are generated in an electrical system. The fault currents are interrupted by overcurrent devices such as circuit breakers or fuses. Figure 3.17 shows a simplified electrical circuit where an electrical fault is cleared by a circuit breaker. C represents the capacitance of the electrical system up to the point where the overcurrent device is present. Interruption of the fault current generates overvoltage impulse in the electrical system, and the magnitude of the voltage depends on the amount of fault current and the speed with which the fault is interrupted. Older air circuit breakers with slower speed of interruption produce lower impulse voltages than vacuum or $SF_6$ breakers, which operate at much faster

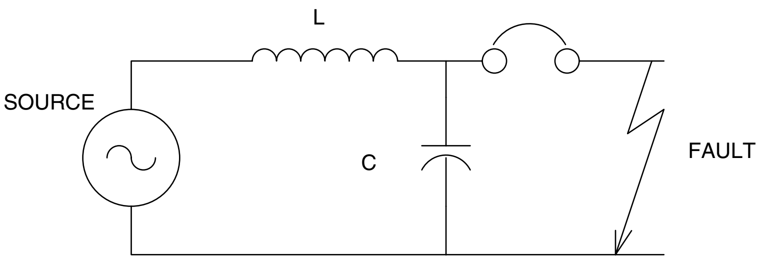



**FIGURE 3.17** Electrical fault at the output side of a circuit breaker.

speeds during a fault. While using vacuum or $SF_6$ technology to clear a fault quickly and thereby limit damage to equipment is an important advantage, a price is paid by the generation of higher level voltage transients. Once the fault is interrupted, the generated voltage impulse can interact with the inductance and capacitance of the electrical system and produce oscillation at a frequency much higher than the fundamental frequency. The oscillations are slowly damped out by the resistance associated with the system. The response of the system might appear somewhat like what is shown in Figure 3.18. The voltage can build up to levels equal to twice the peak value of the voltage waveform. The overvoltage and associated oscillations are harmful to electrical devices.

A very serious case of overvoltages and oscillations occurs when the overcurrent device is supplied from overhead power lines that connect to long lengths of underground cables. Underground cables have substantial capacitance to ground. The combination of the inductance due to overhead lines and capacitance due to underground cables could generate high levels of overvoltage and prolonged oscillations at low frequencies. Such transients are very damaging to transformers, cables, and motors supplied from the lines. In extreme cases, voltages as high as three to four times the AC peak voltage may be generated.

### 3.5.4 Capacitor Bank Switching

One of the more common causes of electrical transients is switching of capacitor banks in power systems. Electrical utilities switch capacitor banks during peak load hours to offset the lagging kVAR demand of the load. The leading kVARs drawn

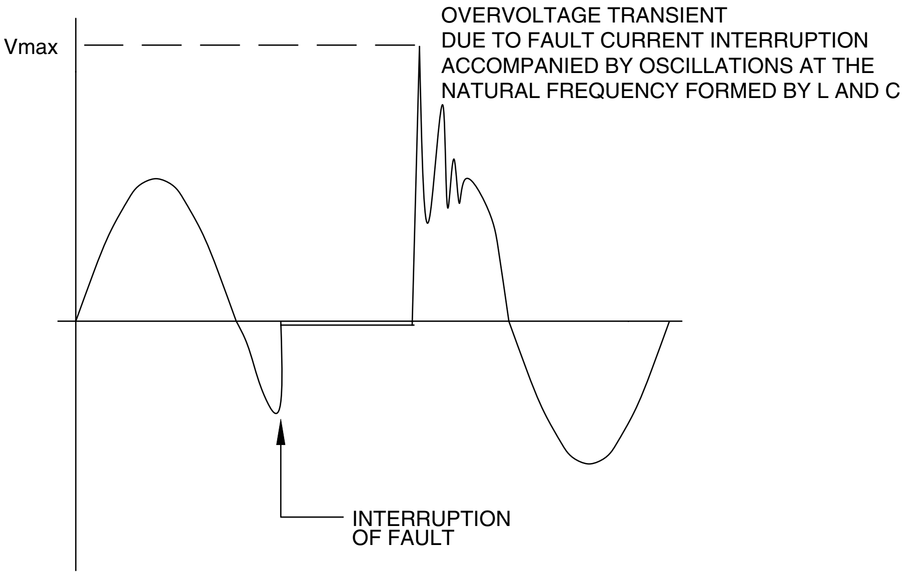



**FIGURE 3.18** Overvoltage transient due to fault current interruption shown in Figure 3.17.

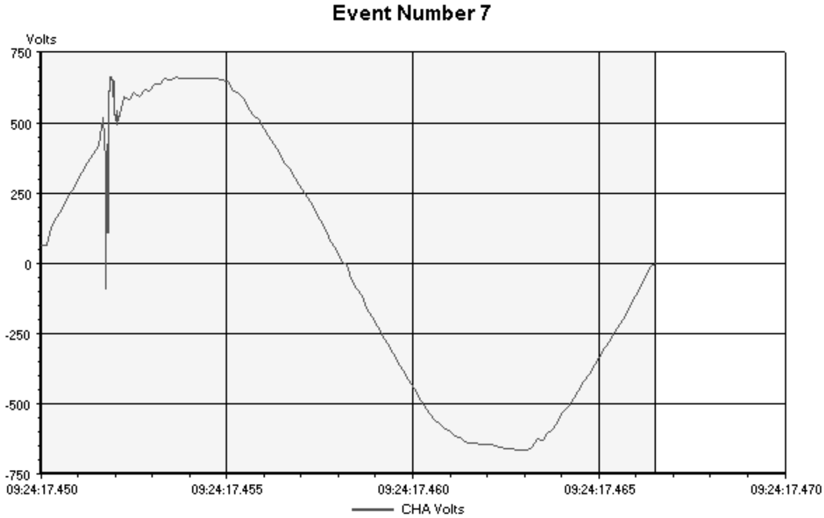
by the capacitor banks offset the lagging kVAR demand of the load, reducing the net kVA load on the circuit. Switching of capacitor banks is accompanied by a surge of current which is initially limited by the characteristic impedance of the power system and resistance of the line. A sharp reduction in the voltage is followed by a voltage rise, which decays by oscillation at a frequency determined by the inductance and capacitance of the circuit. Several cases of power system component failures and malfunctions due to capacitor bank switching operations have been seen by the author. Typically, the voltage rise due to capacitor switching operation can attain values 1.5 to 2 times the nominal voltage. Power equipment can withstand only a limited number of exposures to such rises in voltage magnitude. With time, the insulation systems of such devices weaken, and a point is reached when the devices can fail. In one particular instance, two power distribution transformers failed at the same time; the cause was traced to large capacitor bank switching operations by the utility at a substation located adjacent to the affected facility.

Adjustable speed drives (ASDs) and solid-state motor controllers are quite sensitive to voltage rises resulting from capacitor bank switching operations. The ASD might shut down the motor due to voltage on the system rising beyond the maximum tolerance. In some cases, capacitor switching causes the voltage waveform to undergo oscillations and produce stray crossings of the time axis. This is unacceptable for devices that require the precise number of zero time crossings for proper performance.

*Example:* A 2000-kVAR, 13.8-kV, Y-connected capacitor bank is connected at the end of a 25-mile transmission line with an inductive reactance of 0.5 Ω per mile. Find the natural frequency of the current that would be drawn during turn on:

Total inductive reactance = $X_L = 25 \times 0.5 = 12.5\ \Omega$
Inductance ($L$) = $12.5/120\pi = 0.033$ H
Current through the capacitor bank ($I_C$) = 83.7 A
Capacitive reactance ($X_C$) = $7967/83.7 = 95.18\ \Omega$
Capacitance ($C$) = 27.9 μF
Characteristic frequency ($f_0$) = $1/(2X\pi \sqrt{0.033 \times 0.0000279}) \cong 166$ Hz

The current drawn from the source will have a frequency of 166 Hz which will decay as determined by the power system resistance. Due to impedance drops associated with the currents, the voltage waveform would experience similar oscillations prior to settling down to nominal levels. The series resonance circuit formed by the system inductance and the capacitance could produce a voltage rise in the electrical system. Depending on the severity of the voltage rise and the time to decay, equipment damage can result, especially if the switching operations are frequent. The condition is made worse if a second capacitor bank is brought online. The natural frequencies associated with this action are higher and so is the time to decay. Considerable energy is exchanged between the two capacitors before steady-state operation is attained.




AV,BV,CV Impulse event at 08/22/95 09:24:17.45

| | PrevRMS | MinRMS | MaxRMS | WorstIMP | Phase | HFHits |
|---|---|---|---|---|---|---|
| AV Volts | 481.9 | 476.0 | 476.0 | -612.0 | 42 deg | 1 |
| BV Volts | 480.0 | 475.7 | 475.7 | -486.0 | 184 deg | 2 |
| CV Volts | 481.1 | 477.4 | 477.4 | 671.0 | 282 deg | 2 |
| DI Amps | 1.534 | 1.395 | 1.395 | 0.000 | 0 deg | 0 |

**FIGURE 3.19** Transient due to motor starting. The motor had an input capacitor for power factor correction, and the motor and capacitor were turned on simultaneously.

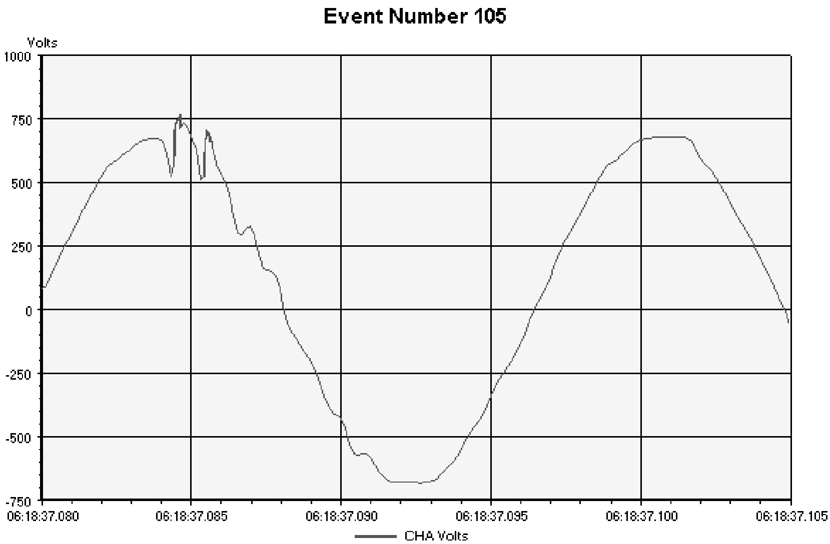
## 3.6 EXAMPLES OF TRANSIENT WAVEFORMS

### 3.6.1 Motor Start Transient

Figure 3.19 shows a transient produced when a 50-hp induction motor with integral power factor correction was started across the line. The notch in the voltage waveform at the instant of starting was produced by the presence of the capacitor. The quick voltage recovery was followed by ringing characteristics. The transient lasted less than half of a cycle, but it was sufficient to affect the operation of large chillers located nearby which contained solid-state starters with sensitive voltage-sensing circuitry. Because of the severity of the motor-starting transient, the chillers started to shut down. In a situation such as this, it is often prudent to apply correction to the sensitive circuitry rather than try to eliminate the problem itself or apply correction to the power system as a whole.

### 3.6.2 Power Factor Correction Capacitor Switching Transient

Figure 3.20 shows the transient voltage response at the main electrical switchboard for a commercial building due to capacitor bank switching by the utility. A moderate




AV Impulse event at 02/22/97 06:18:37.08

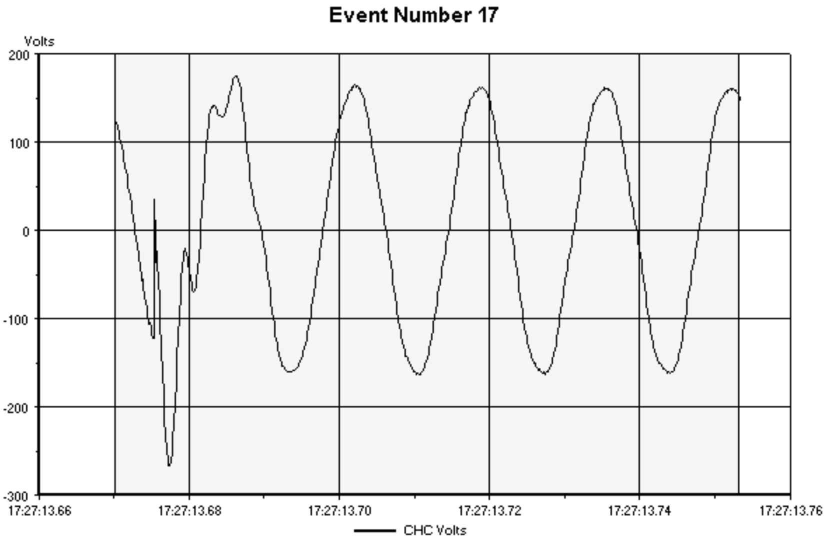
| | PrevRMS | MinRMS | MaxRMS | WorstIMP | Phase | HFHits |
|---|---|---|---|---|---|---|
| AV Volts | 484.5 | 486.6 | 487.4 | 198.0 | 99 deg | 2 |
| BV Volts | 485.9 | 488.1 | 490.1 | 0.0 | 0 deg | 0 |
| CV Volts | 483.1 | 484.6 | 489.6 | 0.0 | 0 deg | 0 |

**FIGURE 3.20** Transient due to capacitor bank switching by the utility. The waveform was recorded at the main electrical switchboard for a commercial building.

rise in system voltage is followed by ringing at the characteristic frequency of the utility source inductive reactance and capacitance due to the power factor correction equipment.

### 3.6.3 Medium Voltage Capacitor Bank Switching Transient

The transient shown in Figure 3.21 was the result of a 5-MVAR capacitor bank switching at an industrial facility. The facility suffered from poor power factor due to plant loads which necessitated connection of the capacitor bank. The initial rise in voltage reached peak amplitude equal to 160% of the system nominal peak voltage. This practice had been going on in this facility for approximately 5 years before failures were observed in underground cables and a power transformer. At this point, the electrical system in the facility was monitored for transient voltages by installing power quality analyzers at select locations. Once the nature of the transients and their cause were determined, corrective steps were taken to retrofit the capacitor bank with pre-insertion resistors, which helped to attenuate the amplitude of the impulse. Also, all replacement equipment at the facility was specified to be of a higher basic insulation level (BIL) than the minimum specified in standards.




**CV Impulse event at 07/16/98 17:27:13.67**

| | PrevRMS | MinRMS | MaxRMS | WorstIMP | Phase | HFHits |
|---|---|---|---|---|---|---|
| AV Volts | 108.2 | 114.4 | 118.1 | 0.0 | 0 deg | 0 |
| BV Volts | 108.3 | 111.7 | 115.6 | 0.0 | 0 deg | 0 |
| CV Volts | 109.3 | 115.5 | 122.6 | 138.0 | 225 deg | 1 |

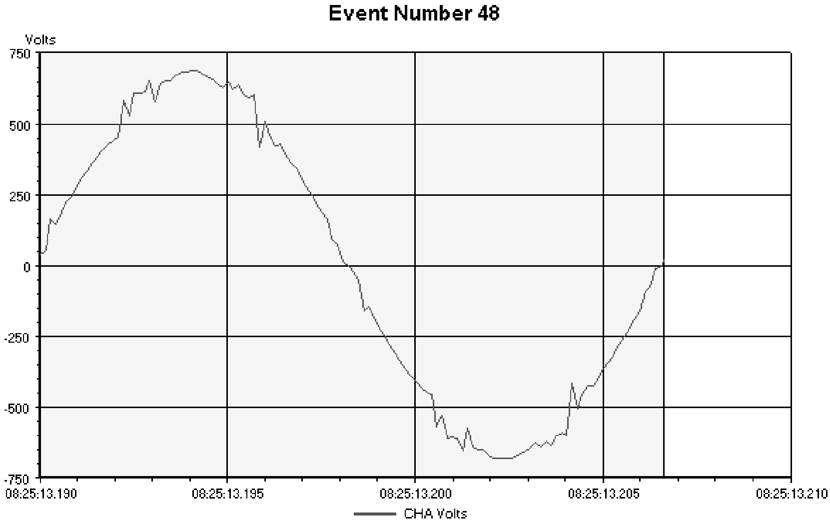
**FIGURE 3.21** Voltage waveform at a 12.47-kV power system during switching in of a 5-MVAR capacitor bank. The voltage-to-transformer ratio is 60:1.

### 3.6.4 Voltage Notch Due to Uninterruptible Power Source Unit

Typically, we associate voltage notches with adjustable speed drives. Voltage notches are also common with the outputs of uninterruptible power source (UPS) units due to power electronic switching circuitry associated with the UPS units. Unless provided with wave-shaping and filtering circuitry, the output of the UPS can contain substantial notches. Figure 3.22 shows the output waveform of a UPS unit supplying 480-V output to a computer center at a financial institution. If the notch levels become excessive, problems can arise in the operation of sensitive communication or data-processing loads. The voltage notch phenomenon is a repetitive event. Even though we defined transients as subcycle events, the repetitive notching shown is included in this section for the sake of completeness.

### 3.6.5 Neutral Voltage Swing

The event shown in Figure 3.23 was observed in a computer laboratory at a university. Normally, neutral voltage should be within 0.5 V with respect to the ground. This is because in a four-wire power distribution system the neutral of the power source




**Waveform event at 09/27/96 08:25:13.19**

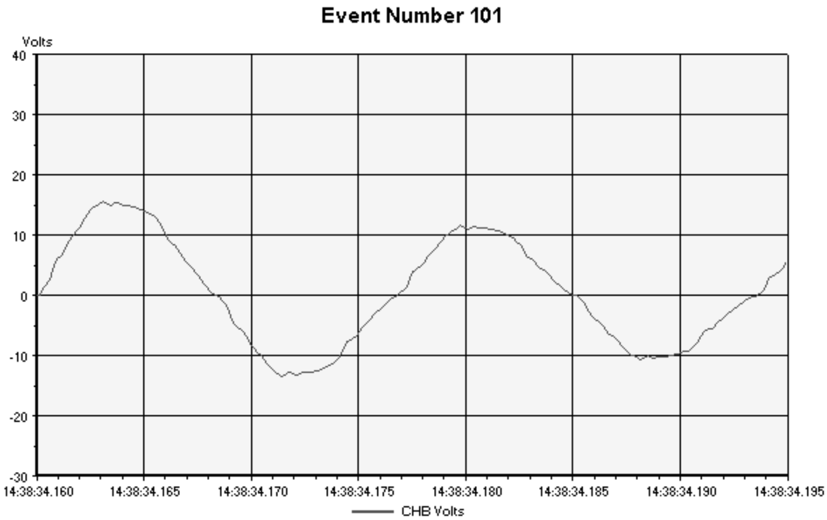
| | PrevRMS | MinRMS | MaxRMS | WorstIMP | Phase |
|---|---|---|---|---|---|
| AV Volts | 476.3 | 476.3 | 476.3 | 0.0 | 0 deg. |
| BV Volts | 479.0 | 480.3 | 480.3 | 0.0 | 0 deg. |
| CV Volts | 479.3 | 479.2 | 479.2 | 0.0 | 0 deg. |
| DI Amps | 0.007 | 0.007 | 0.007 | 0.000 | 0 deg. |

**FIGURE 3.22** Voltage notches produced at the output of an uninterruptible power source (UPS) unit.

is connected to the ground at the source. This tends to hold the neutral potential close to the ground. In a typical building, neutral-to-ground voltages become higher as we move away from the source feeding the facility. In some instances, depending on the loads and the distance between the source and the load, neutral-to-ground voltage can measure 2 to 3 V. The case illustrated by Figure 3.23 is an extreme one where neutral-to-ground voltages reached levels higher than 10 V. The computer laboratory experienced many problems with the computers locking up, in some instances during critical times when tests were being administered to the students.

### 3.6.6 Sudden Application of Voltage

Fast rise time transients are produced when voltage is suddenly applied to a load. Figure 3.24 shows an example of 480 V being applied to the primary of a power distribution transformer. Typical waveform characteristics include fast rise time and ringing due to the inductance and capacitance of the load circuitry. Normally, power system should ride through such occurrences, but, if the load circuit includes capacitor banks or power supplies with capacitors, large inrush currents may be produced with possible overcurrent protection operation. In situations where the capacitors have an initial charge present, some overvoltage events may be produced.




Waveform event at 12/17/96 14:38:34.16

| | PrevRMS | MinRMS | MaxRMS | WorstIMP | Phase |
|---|---|---|---|---|---|
| AV Volts | 119.1 | 96.1 | 106.6 | 0.0 | 0 deg. |
| BV Volts | 0.81 | 5.56 | 10.16 | 0.00 | 0 deg. |
| CV Volts | 119.3 | 96.3 | 106.8 | 0.0 | 0 deg. |
| DV Volts | 0.80 | 5.55 | 10.13 | 0.00 | 0 deg. |

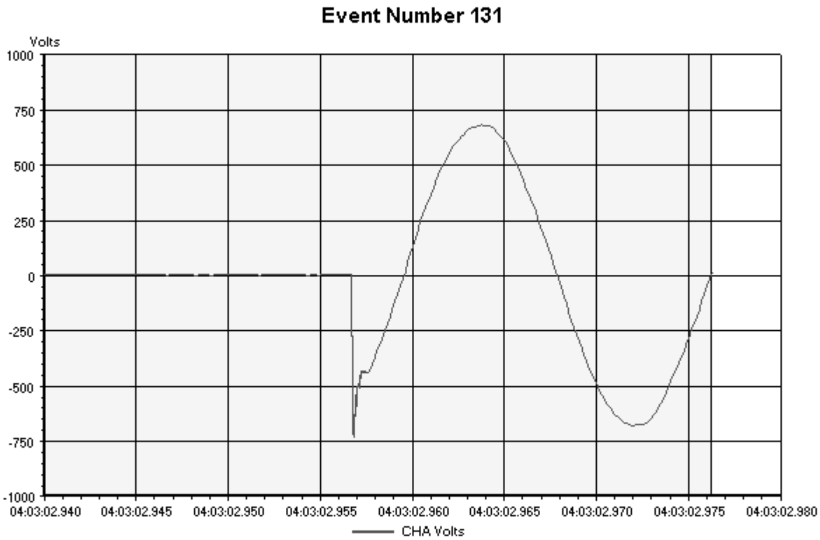
**FIGURE 3.23** Large neutral voltage swings responsible for problems in a university computer laboratory.

### 3.6.7 Self-Produced Transients

Some machines by nature generate transients that can affect machine operation if they contain sensitive circuits. Figure 3.25 shows a waveform produced by a food-processing machine. The transients occurred several times each day as the machine automatically turned on and off. Severe transients caused the machine to go into a lockout mode which required the operator to manually reset the machine. The problem was fixed by providing a dedicated circuit of low impedance for the machine. This reduced the transient to levels that could be lived with.

## 3.7 CONCLUSIONS

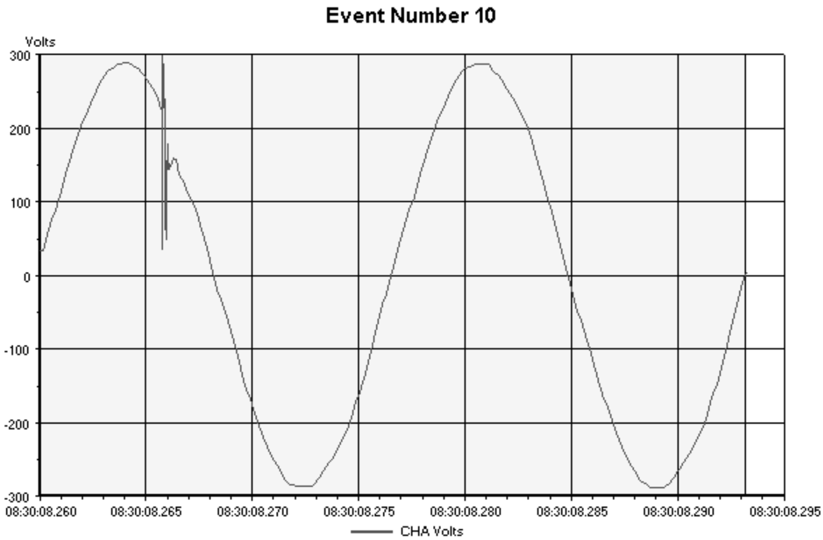
A power system during normal operation is in a steady-state condition even though some voltage fluctuations may be present as the result of facility or utility switching operations. The voltage stays within tolerances that would normally be expected. All electrical and electronic devices are designed to function within these tolerances. Some level of degradation of the useful life of the equipment is to be expected even though the operating voltages are within tolerances. Transients are abnormal, short-duration power system events that have a specific cause behind them, such as switching operations or electrical faults or even nature-induced events. Very few devices are designed specifically with transients in mind, and most devices can handle a limited number of transients. The exact number would depend on the nature of the transient and the age of the equipment. The effects of transients on equipment are cumulative, with every succeeding transient having a greater effect on the equipment. Electrical devices installed in a typical home environment are relatively safe as far as exposure to transients is concerned. Devices installed in an industrial environment are more susceptible due to the possibility of severe transient activity in such an environment. It is important for a facility designer or operator not only to know what type of transients might be present in an electrical system, but also to be aware of the sensitivity of the installed equipment to such transients.




**AV,CV Impulse event at 11/14/00 04:03:02.94**

| | PrevRMS | MinRMS | MaxRMS | WorstIMP | Phase | HFHits |
|---|---|---|---|---|---|---|
| AV Volts | 64.1 | 0.5 | 482.5 | -669.0 | 297 deg | 1 |
| BV Volts | 67.7 | 1.0 | 484.5 | 0.0 | 0 deg | 0 |
| CV Volts | 116.3 | 259.2 | 469.8 | 625.0 | 136 deg | 1 |

**FIGURE 3.24** Fast rise transient generated when a 480-V feeder was energized. The transient produced ringing due to system inductance and capacitance.




**AV,CV Impulse event at 03/22/01 08:30:08.26**

| | PrevRMS | MinRMS | MaxRMS | WorstIMP | Phase | HFHits |
|---|---|---|---|---|---|---|
| AV Volts | 204.5 | 202.0 | 204.2 | -189.0 | 129 deg | 1 |
| BV Volts | 203.2 | 199.5 | 205.7 | 0.0 | 0 deg | 0 |
| CV Volts | 203.7 | 197.4 | 203.5 | 251.0 | 246 deg | 1 |

**FIGURE 3.25** Transient produced by a machine itself. This event was recorded at the supply lines to a food-processing machine. At the start of each operation, the machine generated transients, which, when severe enough, shut down the machine.