EE 5223 - Lecture 12 Fri Feb 3, 2023

Ongoing List of Topics:

- URL: http://www.ece.mtu.edu/faculty/bamork/EE5223/index.htm
- Labs - EE5224 labs will break from Feb 6th-10th (WC).
- Term Project - teams: ~3, incl. Max 1 5224 student
- Software - Aspen 2022 V15.6. Exercise 6 coming up.

Today:

- Radial coordination homework: work through the solution
- MOCTs - Magneto-Optic Current Transformers
  - Faraday effect, “faraday rotators,” Verdet constant
  - shift of polarization angle due to strength of H-field
  - Design kept to low near-linear range
- Linear Couplers, Rogowski Coils
- CCVTs

Next:

- Voltage & Current relationships during faults, §3.5-3.10
  - X/R ratio, dc offset, decay of dc offset
  - relative angles and magnitudes of all Vs & Is during fault

Some Term Project Ideas:

- Browse Table of Contents in your text book for ideas.
- Scope of project? Teams of 1, 2, or 3, scope appropriate.
- Ask online students/engineers for suggestions
  - New technologies to figure out, important problems to solve
  - Important concepts that need to be better understood (beyond tech level)
- Using ATP to model CT saturation and relay performance (actual waveforms)
  - CT saturation effects
  - Full 3-phase connection of CT, CT secondary cables, and relay burdens.
  - Build library of ATP components for this application.
- Application and testing of a protection scheme (many are possible)
  - Choose scheme and relay(s)
  - Design the protection scheme and provide settings
  - Test in relaying lab
- Substation automation (IEC 61850)
- Negative sequence polarization methods

Term Project Ideas (cont'd):

  - Hardware vs. simulation, or both? EE5220 students - use ATP,Comtrade.
  - Relay tester, lab tests of relays?
  - Extend Matlab work? ASPEN? Make educational or engineering tools.
  - Type of protection you're interested in?
    - Distribution (urban, rural, industrial)
    - Transformer (fixed tap, LTC, PS)

- Generator
- Bus
- Cap Banks (Shunt or Series)
- Transmission Lines, Cables
- Motors (Induction, Synchronous)

- Examples of past projects can be looked at. Some topics I can suggest:
  - Capacitor Bank Protection
  - High-Impedance Faults
  - Negative sequence polarization
  - Substation Grounding, Grounding Issues
  - Small/medium gas-turbine gen protection.
  - Other ideas - see course web page and click on Useful Web Links.
  - New technologies - eg. optical VTs?
  - Out of step, load shedding, system separation.
  - Relay settings and system coordination.Pilot schemes.
  - Blocking, permissive, overreach, underreach.
  - End-to-end line relay testing (GPS coordination)
  - Multi-terminal line protection
  - IEC 61850 - use of high bandwidth intranet for peer-peer communications among relays.

severely limited and distorted. This is illustrated in Fig. 5.14 for a 20-times-rated fully offset current with resistive burden. This type of burden causes a sharp drop-off of the secondary current during each cycle.

After saturation occurs, the decay of the dc component results in the CT recovering, so that during each subsequent cycle, the secondary current more nearly approaches the primary. As the dc disappears, the secondary is again a reproduction of the primary. This assumes no ac saturation. It is possible, but rarely occurs, that the secondary current may be practically zero for a few cycles in very severe cases.

Inductance in the burden results in a more gradual drop-off, whereas a lower burden reduces the distortion. These several effects are shown in Fig. 5.14. As shown, this saturation does not occur instantly; hence, initially,

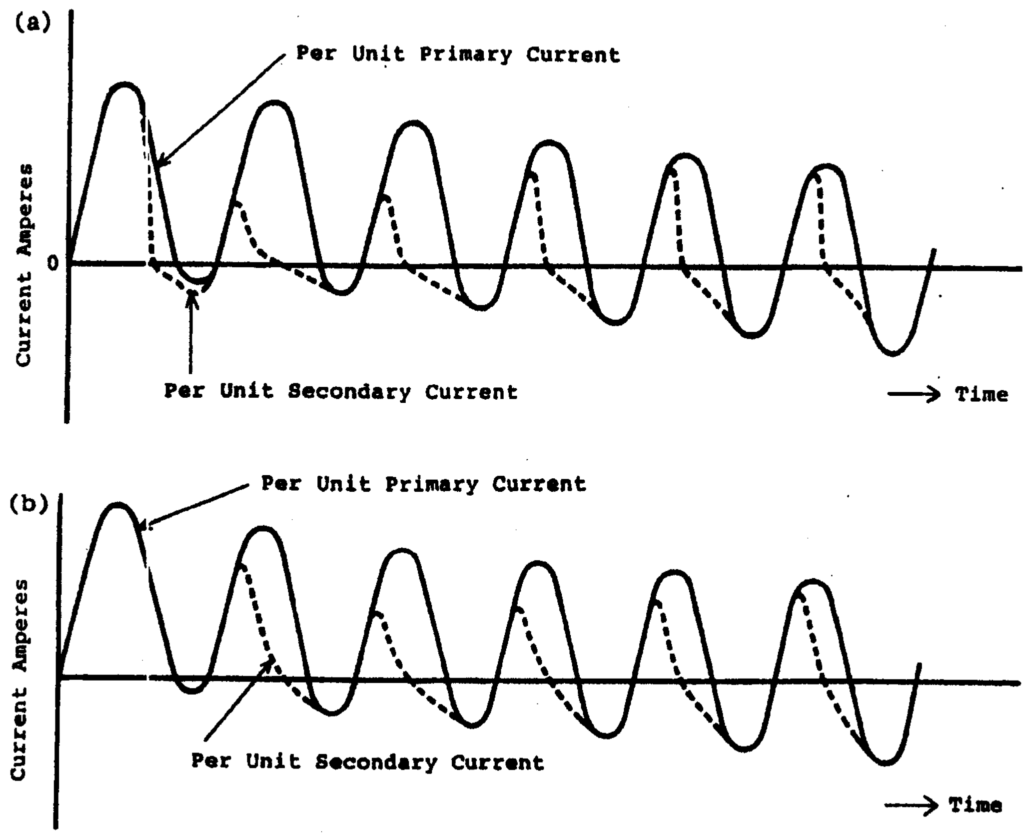
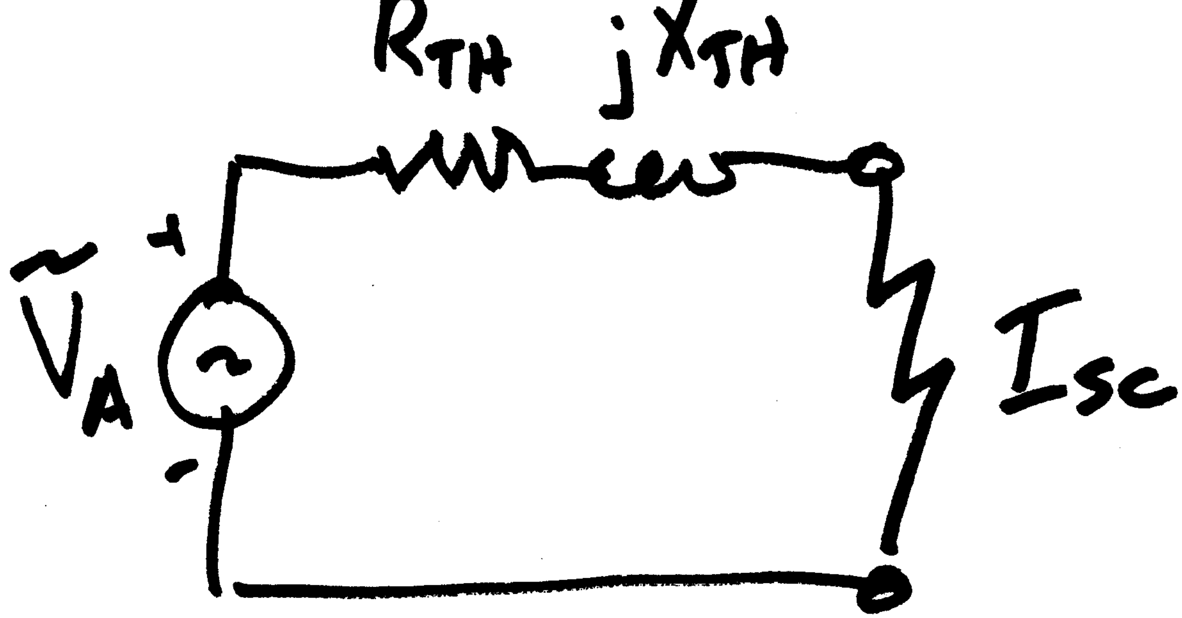
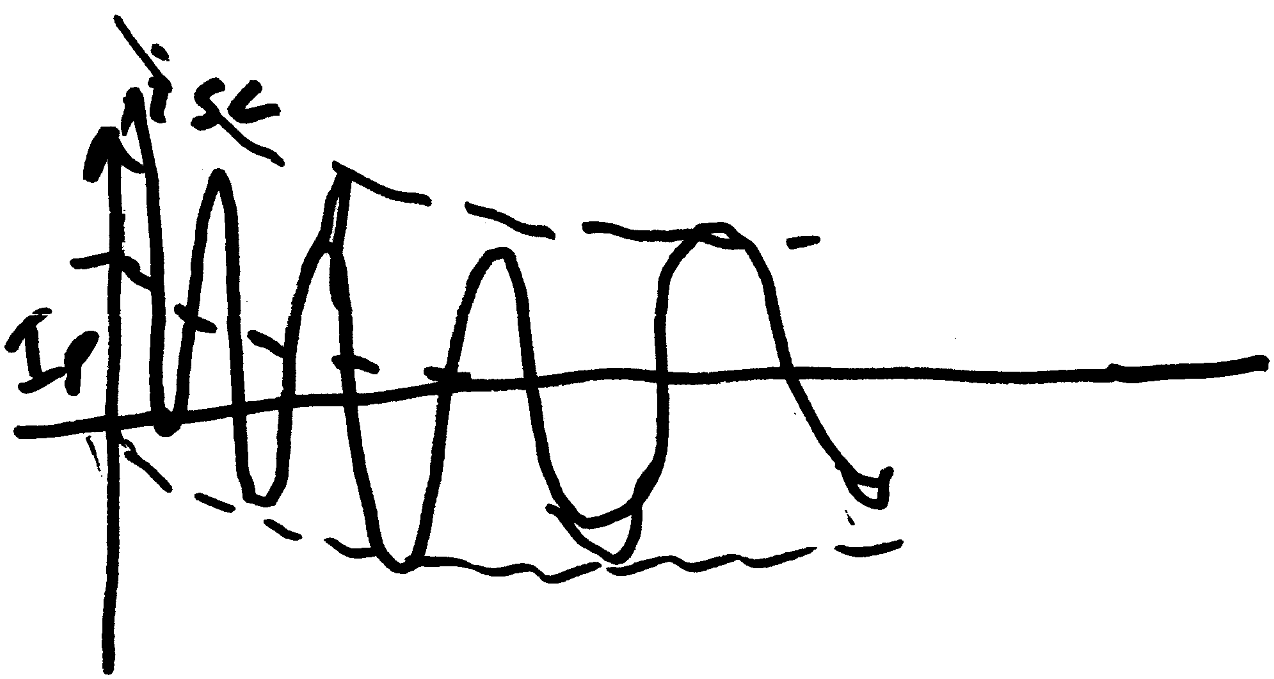


FIGURE 5.14 Typical possible distortion in CT secondary current resulting from dc saturation: (a) large resistive burden; (b) smaller resistive burden. (Fig. 3 of IEEE 76-CH1130-4, *PWR Transient Response of Current Transformers*.)

$\frac{X}{R}$ ratio





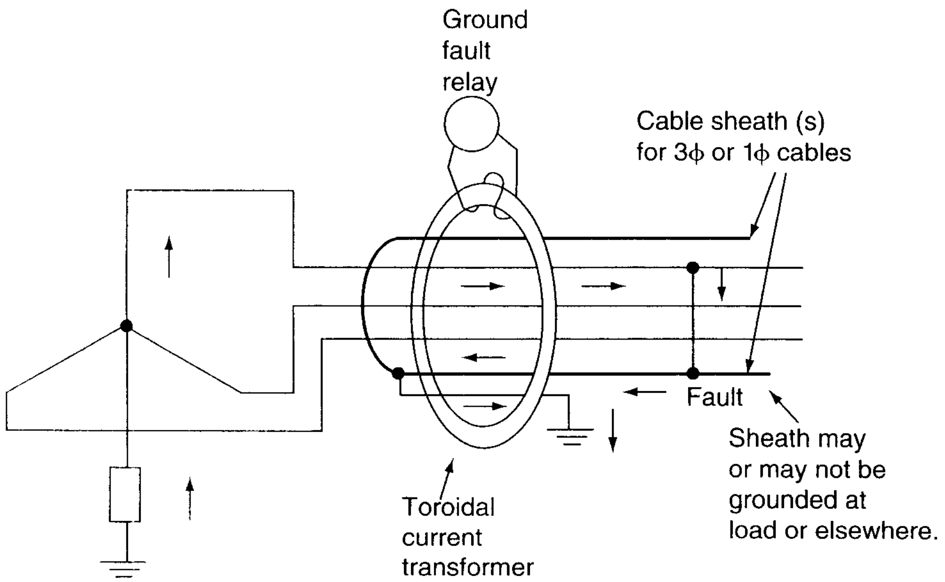


FIGURE 5.13 Typical application of the flux summation current transformer for ground-fault protection with metallic sheath conductors.

exciting current were negligible. Specific applications are discussed in later chapters.

A metallic sheath or shielded cables passed through the toroidal CT can result in cancellation of the fault current. This is illustrated in Figure 5.13. This applies either to three-phase cables, as shown, or to single-phase cables. The cancellation may be partial or complete, depending on the sheath grounding. This sheath component of fault current can be removed from passing through the CT by connecting a conductor, as shown.

5.10 CURRENT TRANSFORMER PERFORMANCE ON THE DC COMPONENT

As transformers are paralyzed by direct current, CT performance is affected significantly by the DC component of the AC current. When a current change occurs in the primary AC system, one or more of the three-phase currents will have some DC offset, although none may be maximum and one could not have much impact. This DC results from the necessity to satisfy two conflicting requirements that may occur: (1) in a highly inductive network of power systems, the current wave must be near maximum when the voltage wave is at or near zero and (2) the actual current at the time of change is that determined by the prior network conditions. For example, energizing a circuit with current zero, before closing the circuit at the instant when the voltage wave is zero presents a problem. By requirement (1) the current should be at or near maximum at that moment. Thus, a countercurrent is produced to provide the zero required by condition (2). This is the DC component equal and opposite

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Figure 4
Remains of main secondary circuit breaker burned down during arcing fault in low-voltage switchgear section of unit substation.

equipment burndown may include personnel fatalities or serious injury, contingent fire damage, loss of vital services (lighting, elevators, ventilation, fire pumps, etc.), shutdown of critical loads, and loss of product revenue. It should be pointed out that the cases reported have involved both industrial and commercial building distribution equipment, without regard to manufacturer, geographical location, operating environment, or the presence or absence of electrical system neutral grounding. Also, the reported burndowns have included a variety of distribution equipment—load center unit substations, switchboards, busway, panelboards, service-entrance equipment, motor control centers, and cable in conduit, for example.

It is obvious, therefore, when all the possible effects of arcing-fault burndowns are taken into consideration, that engineers responsible for electrical power system layout and operation should be anxious both to minimize the probability of arcing faults in electrical systems and to alleviate or mitigate the destructive effects of such faults if they should inadvertently occur despite careful design and the use of quality equipment.

7.1

SERIES R–L CIRCUIT TRANSIENTS

Consider the series R–L circuit shown in Figure 7.1. The closing of switch SW at $t = 0$ represents to a first approximation a three-phase short circuit at the terminals of an unloaded synchronous machine. For simplicity, assume zero fault impedance; that is, the short circuit is a solid or "bolted" fault. The current is assumed to be zero before SW closes, and the source angle α determines the source voltage at $t = 0$. Writing a KVL equation for the circuit,

$$\frac{\mathrm{L}di(t)}{dt} + \mathrm{R}i(t) = \sqrt{2}\mathrm{V}\sin(\omega t + \alpha) \quad t \geqslant 0 \tag{7.1.1}$$

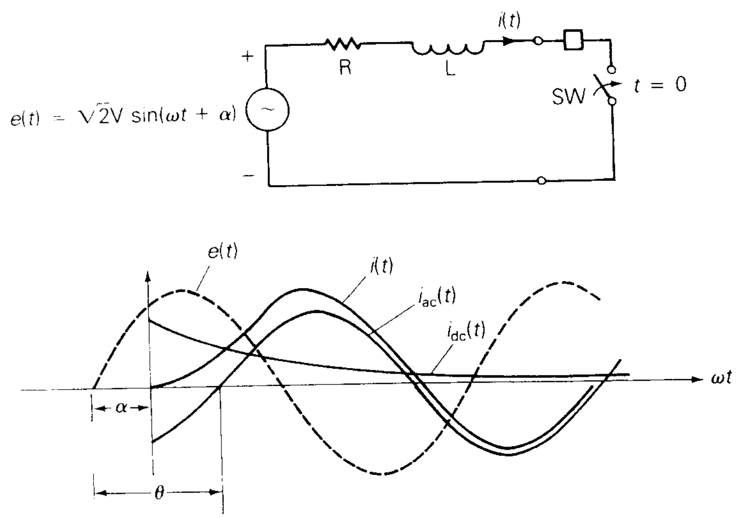
The solution to (7.1.1) is

$$i(t) = i_{\mathrm{ac}}(t) + i_{\mathrm{dc}}(t)$$

$$= \frac{\sqrt{2}\mathrm{V}}{\mathrm{Z}}[\sin(\omega t + \alpha - \theta) - \sin(\alpha - \theta)e^{-t/\mathrm{T}}] \quad \mathrm{A} \tag{7.1.2}$$

FIGURE 7.1

Current in a series R–L circuit with ac voltage source



where

$$i_{ac}(t) = \frac{\sqrt{2}V}{Z}\sin(\omega t + \alpha - \theta) \quad \text{A} \tag{7.1.3}$$

$$i_{dc}(t) = -\frac{\sqrt{2}V}{Z}\sin(\alpha - \theta)e^{-t/T} \quad \text{A} \tag{7.1.4}$$

$$Z = \sqrt{R^2 + (\omega L)^2} = \sqrt{R^2 + X^2} \quad \Omega \tag{7.1.5}$$

$$\theta = \tan^{-1}\frac{\omega L}{R} = \tan^{-1}\frac{X}{R} \tag{7.1.6}$$

$$T = \frac{L}{R} = \frac{X}{\omega R} = \frac{X}{2\pi f R} \quad \text{s} \tag{7.1.7}$$

The total fault current in (7.1.2), called the *asymmetrical fault current*, is plotted in Figure 7.1 along with its two components. The ac fault current (also called *symmetrical* or *steady-state fault current*), given by (7.1.3), is a sinusoid. The *dc offset current*, given by (7.1.4), decays exponentially with time constant $T = L/R$.

The rms ac fault current is $I_{ac} = V/Z$. The magnitude of the dc offset, which depends on α, varies from 0 when $\alpha = \theta$ to $\sqrt{2}I_{ac}$ when $\alpha = (\theta \pm \pi/2)$. Note that a short circuit may occur at any instant during a cycle of the ac source; that is, α can have any value. Since we are primarily interested in the largest fault current, we choose $\alpha = (\theta - \pi/2)$. Then (7.1.2) becomes

$$i(t) = \sqrt{2}I_{ac}[\sin(\omega t - \pi/2) + e^{-t/T}] \quad \text{A} \tag{7.1.8}$$

where

TABLE 7.1

Short-circuit current—series R–L circuit*

Component	Instantaneous Current (A)	rms Current (A)
Symmetrical (ac)	$i_{ac}(t) = \frac{\sqrt{2}V}{Z}\sin(\omega t + \alpha - \theta)$	$I_{ac} = \frac{V}{Z}$
dc offset	$i_{dc}(t) = \frac{-\sqrt{2}V}{Z}\sin(\alpha - \theta)e^{-t/T}$	
Asymmetrical (total)	$i(t) = i_{ac}(t) + i_{dc}(t)$	$I_{rms}(t) = \sqrt{I_{ac}^2 + i_{dc}(t)^2}$ with maximum dc offset: $I_{rms}(\tau) = K(\tau)I_{ac}$

* See Figure 7.1 and (7.1.1)–(7.1.12).

$$I_{ac} = \frac{V}{Z} \quad \text{A} \tag{7.1.9}$$

The rms value of $i(t)$ is of interest. Since $i(t)$ in (7.1.8) is not strictly periodic, its rms value is not strictly defined. However, treating the exponential term as a constant, we stretch the rms concept to calculate the rms asymmetrical fault current with maximum dc offset, as follows:

$$\begin{aligned} I_{rms}(t) &= \sqrt{[I_{ac}]^2 + [I_{dc}(t)]^2} \\ &= \sqrt{[I_{ac}]^2 + [\sqrt{2}I_{ac}e^{-t/T}]^2} \\ &= I_{ac}\sqrt{1 + 2e^{-2t/T}} \quad \text{A} \end{aligned} \tag{7.1.10}$$

It is convenient to use $T = X/(2\pi f R)$ and $t = \tau/f$, where τ is time in cycles, and write (7.1.10) as

$$I_{rms}(\tau) = K(\tau)I_{ac} \quad \text{A} \tag{7.1.11}$$

where

$$K(\tau) = \sqrt{1 + 2e^{-4\pi\tau/(X/R)}} \quad \text{per unit} \tag{7.1.12}$$

From (7.1.11) and (7.1.12), the rms asymmetrical fault current equals the rms ac fault current times an "asymmetry factor," $K(\tau)$. $I_{rms}(\tau)$ decreases from $\sqrt{3}I_{ac}$ when $\tau = 0$ to I_{ac} when τ is large. Also, higher X to R ratios (X/R) give higher values of $I_{rms}(\tau)$. The above series R–L short-circuit currents are summarized in Table 7.1.

EXAMPLE 7.1 Fault currents: R–L circuit with ac source

A bolted short circuit occurs in the series R–L circuit of Figure 7.1 with $V = 20$ kV, $X = 8\ \Omega$, $R = 0.8\ \Omega$, and with maximum dc offset. The circuit breaker opens 3 cycles after fault inception. Determine (a) the rms ac fault current, (b) the rms "momentary" current at $\tau = 0.5$ cycle, which passes through the breaker before it opens, and (c) the rms asymmetrical fault current that the breaker interrupts.

SOLUTION

a. From (7.1.9),

$$I_{ac} = \frac{20 \times 10^3}{\sqrt{(8)^2 + (0.8)^2}} = \frac{20 \times 10^3}{8.040} = 2.488 \quad \text{kA}$$

b. From (7.1.11) and (7.1.12) with $(X/R) = 8/(0.8) = 10$ and $\tau = 0.5$ cycle,

$$K(0.5 \text{ cycle}) = \sqrt{1 + 2e^{-4\pi(0.5)/10}} = 1.438$$

$$I_{momentary} = K(0.5 \text{ cycle})I_{ac} = (1.438)(2.488) = 3.576 \quad \text{kA}$$

c. From (7.1.11) and (7.1.12) with $(X/R) = 10$ and $\tau = 3$ cycles,

$$K(3 \text{ cycles}) = \sqrt{1 + 2e^{-4\pi(3)/10}} = 1.023$$

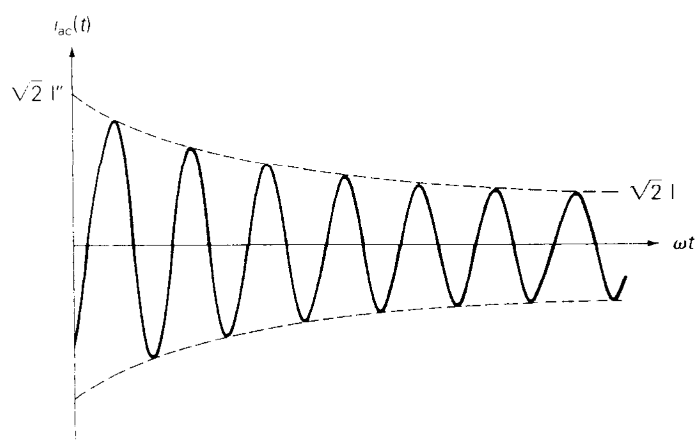
$$I_{rms}(3 \text{ cycles}) = (1.023)(2.488) = 2.544 \quad \text{kA}$$

■

7.2 THREE-PHASE SHORT CIRCUIT—UNLOADED SYNCHRONOUS MACHINE

One way to investigate a three-phase short circuit at the terminals of a synchronous machine is to perform a test on an actual machine. Figure 7.2 shows an oscillogram of the ac fault current in one phase of an unloaded synchronous machine during such a test. The dc offset has been removed

FIGURE 7.2 ac fault current in one phase of an unloaded synchronous machine during a three-phase short circuit (the dc offset current is removed)



from the oscillogram. As shown, the amplitude of the sinusoidal waveform decreases from a high initial value to a lower steady-state value.

A physical explanation for this phenomenon is that the magnetic flux caused by the short-circuit armature currents (or by the resultant armature MMF) is initially forced to flow through high reluctance paths that do not link the field winding or damper circuits of the machine. This is a result of the theorem of constant flux linkages, which states that the flux linking a closed winding cannot change instantaneously. The armature inductance, which is inversely proportional to reluctance, is therefore initially low. As the flux then moves toward the lower reluctance paths, the armature inductance increases.

The ac fault current in a synchronous machine can be modeled by the series R–L circuit of Figure 7.1 if a time-varying inductance $L(t)$ or reactance $X(t) = \omega L(t)$ is employed. In standard machine theory texts [3, 4], the following reactances are defined:

X''_d = direct axis subtransient reactance

X'_d = direct axis transient reactance

X_d = direct axis synchronous reactance

where $X''_d < X'_d < X_d$. The subscript d refers to the direct axis. There are similar quadrature axis reactances X''_q, X'_q, and X_q [3, 4]. However, if the armature resistance is small, the quadrature axis reactances do not significantly affect the short-circuit current. Using the above direct axis reactances, the instantaneous ac fault current can be written as

$$i_{ac}(t) = \sqrt{2}E_g\left[\left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{-t/T''_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{-t/T'_d} + \frac{1}{X_d}\right]\sin\left(\omega t + \alpha - \frac{\pi}{2}\right) \tag{7.2.1}$$

where E_g is the rms line-to-neutral prefault terminal voltage of the unloaded synchronous machine. Armature resistance is neglected in (7.2.1). Note that at $t = 0$, when the fault occurs, the rms value of $i_{ac}(t)$ in (7.2.1) is

$$I_{ac}(0) = \frac{E_g}{X''_d} = I'' \tag{7.2.2}$$

which is called the rms *subtransient fault current*, I''. The duration of I'' is determined by the time constant T''_d, called the *direct axis short-circuit subtransient time constant.*

At a later time, when t is large compared to T''_d but small compared to the *direct axis short-circuit transient time constant* T'_d, the first exponential term in (7.2.1) has decayed almost to zero, but the second exponential has not decayed significantly. The rms ac fault current then equals the rms *transient fault current*, given by

$$I' = \frac{E_g}{X'_d} \tag{7.2.3}$$

TABLE 7.2 Short-circuit current—unloaded synchronous machine*

Component	Instantaneous Current (A)	rms Current (A)
Symmetrical (ac)	(7.2.1)	$I_{ac}(t) = E_g\left[\left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{-t/T''_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{-t/T'_d} + \frac{1}{X_d}\right]$
Subtransient		$I'' = E_g/X''_d$
Transient		$I' = E_g/X'_d$
Steady-state		$I = E_g/X_d$
Maximum dc offset	$i_{dc}(t) = \sqrt{2}I''e^{-t/T_A}$	
Asymmetrical (total)	$i(t) = i_{ac}(t) + i_{dc}(t)$	$I_{rms}(t) = \sqrt{I_{ac}(t)^2 + i_{dc}(t)^2}$ with maximum dc offset: $I_{rms}(t) = \sqrt{I_{ac}(t)^2 + [\sqrt{2}I''e^{-t/T_A}]^2}$

*See Figure 7.2 and (7.2.1)–(7.2.5).

When t is much larger than T'_d, the rms ac fault current approaches its steady-state value, given by

$$I_{ac}(\infty) = \frac{E_g}{X_d} = I \tag{7.2.4}$$

Since the three-phase no-load voltages are displaced 120° from each other, the three-phase ac fault currents are also displaced 120° from each other. In addition to the ac fault current, each phase has a different dc offset. The maximum dc offset in any one phase, which occurs when $\alpha = 0$ in (7.2.1), is

$$i_{dcmax}(t) = \frac{\sqrt{2}E_g}{X''_d}e^{-t/T_A} = \sqrt{2}I''e^{-t/T_A} \tag{7.2.5}$$

where T_A is called the *armature time constant*. Note that the magnitude of the maximum dc offset depends only on the rms subtransient fault current I''. The above synchronous machine short-circuit currents are summarized in Table 7.2.

Machine reactances X''_d, X'_d, and X_d as well as time constants T''_d, T'_d, and T_A are usually provided by synchronous machine manufacturers. They can also be obtained from a three-phase short-circuit test, by analyzing an oscillogram such as that in Figure 7.2 [2]. Typical values of synchronous machine reactances and time constants are given in Appendix Table A.1.

EXAMPLE 7.2 Three-phase short-circuit currents, unloaded synchronous generator

A 500-MVA 20-kV, 60-Hz synchronous generator with reactances $X''_d = 0.15$, $X'_d = 0.24, X_d = 1.1$ per unit and time constants $T''_d = 0.035$, $T'_d = 2.0$, $T_A = 0.20$ s is connected to a circuit breaker. The generator is operating at 5% above rated voltage and at no-load when a bolted three-phase short circuit occurs on the load side of the breaker. The breaker interrupts the fault

3 cycles after fault inception. Determine (a) the subtransient fault current in per-unit and kA rms; (b) maximum dc offset as a function of time; and (c) rms asymmetrical fault current, which the breaker interrupts, assuming maximum dc offset.

SOLUTION

a. The no-load voltage before the fault occurs is $E_g = 1.05$ per unit. From (7.2.2), the subtransient fault current that occurs in each of the three phases is

$$I'' = \frac{1.05}{0.15} = 7.0 \quad \text{per unit}$$

The generator base current is

$$I_{base} = \frac{S_{rated}}{\sqrt{3}V_{rated}} = \frac{500}{(\sqrt{3})(20)} = 14.43 \quad \text{kA}$$

The rms subtransient fault current in kA is the per-unit value multiplied by the base current:

$$I'' = (7.0)(14.43) = 101.0 \quad \text{kA}$$

b. From (7.2.5), the maximum dc offset that may occur in any one phase is

$$i_{dcmax}(t) = \sqrt{2}(101.0)e^{-t/0.20} = 142.9e^{-t/0.20} \quad \text{kA}$$

c. From (7.2.1), the rms ac fault current at $t = 3$ cycles $= 0.05$ s is

$$I_{ac}(0.05\ \text{s}) = 1.05\left[\left(\frac{1}{0.15} - \frac{1}{0.24}\right)e^{-0.05/0.035} + \left(\frac{1}{0.24} - \frac{1}{1.1}\right)e^{-0.05/2.0} + \frac{1}{1.1}\right]$$

$$= 4.920 \quad \text{per unit}$$

$$= (4.920)(14.43) = 71.01 \quad \text{kA}$$

Modifying (7.1.10) to account for the time-varying symmetrical component of fault current, we obtain

$$I_{rms}(0.05) = \sqrt{[I_{ac}(0.05)]^2 + [\sqrt{2}I''e^{-t/T_a}]^2}$$

$$= I_{ac}(0.05)\sqrt{1 + 2\left[\frac{I''}{I_{ac}(0.05)}\right]^2 e^{-2t/Ta}}$$

$$= (71.01)\sqrt{1 + 2\left[\frac{101}{71.01}\right]^2 e^{-2(0.05)/0.20}}$$

$$= (71.01)(1.8585)$$

$$= 132 \quad \text{kA}$$

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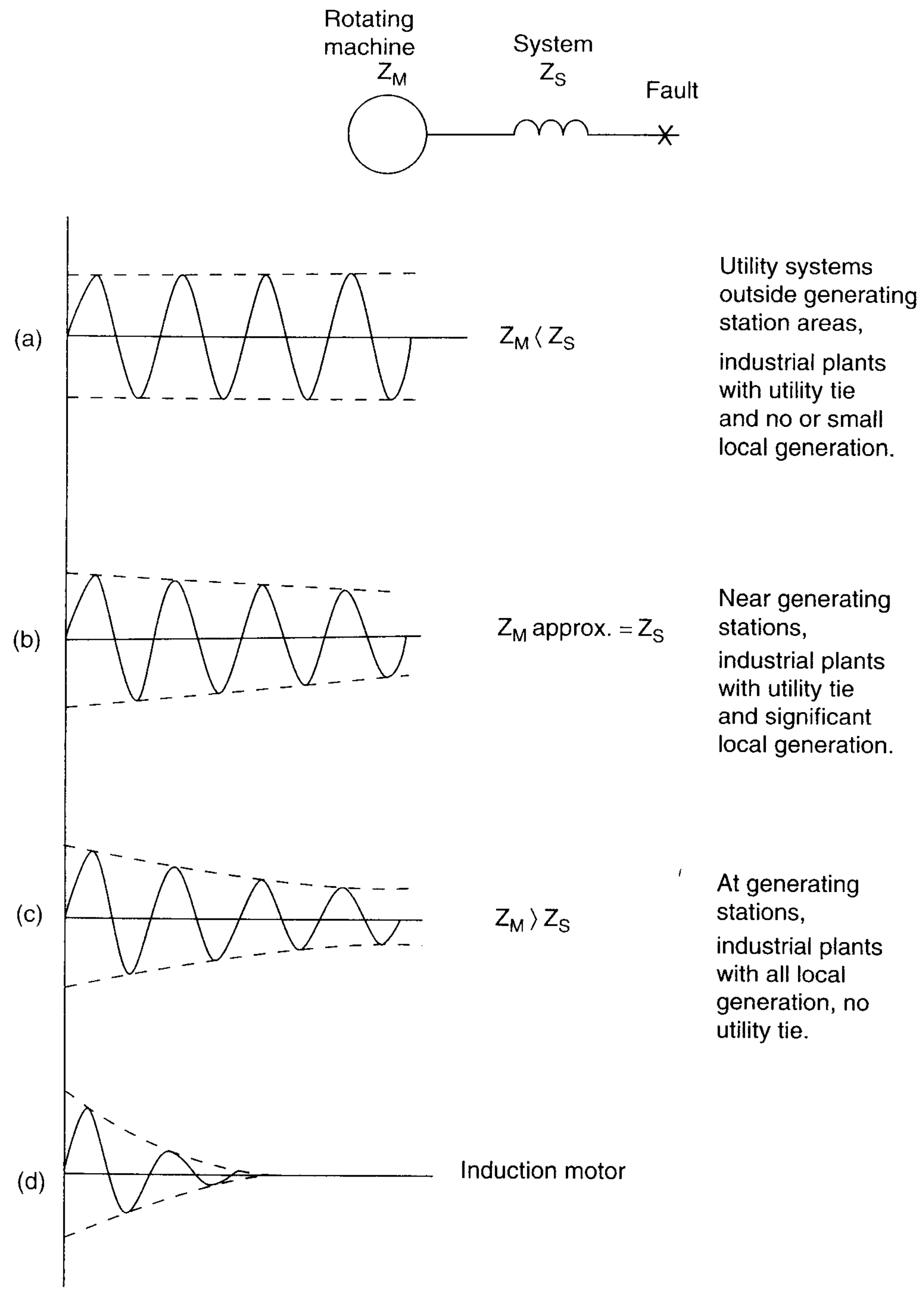
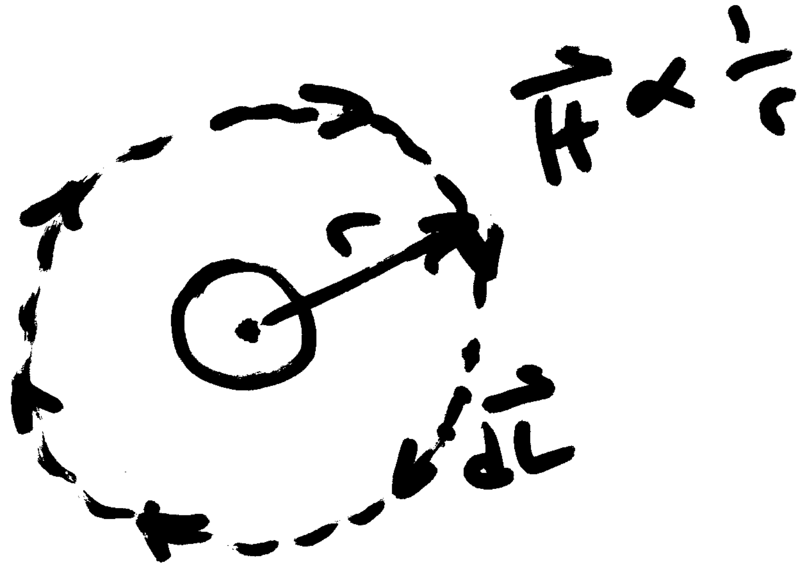
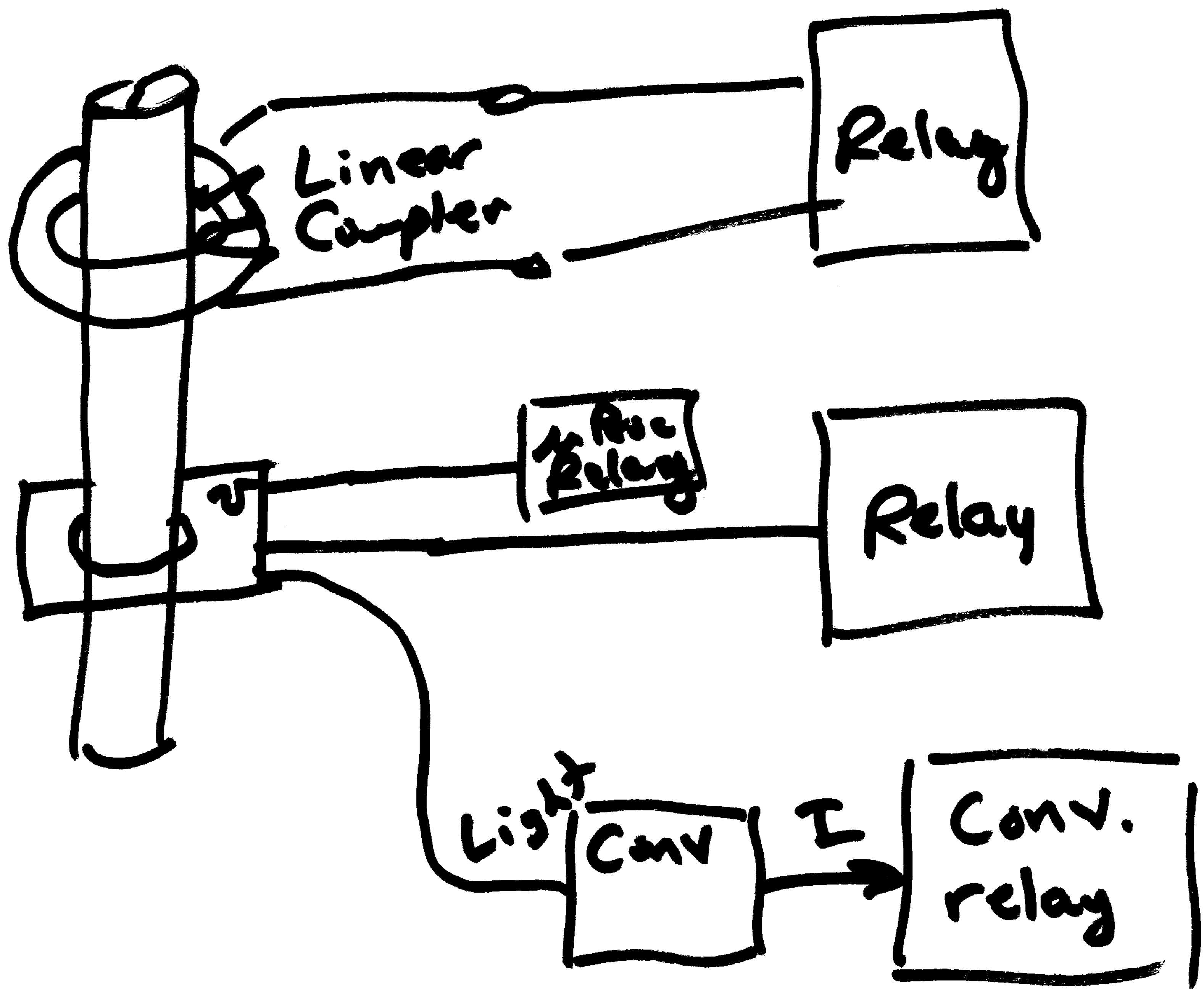


FIGURE 4.6 Guide illustrating the effects of rotating machine decrements on the symmetrical fault current.

Usually, induction motors are not considered as sources of fault current for protection purposes (see Figure 4.6, case D). However, it must be emphasized that these motors must be considered in circuit breakers' applications under the ANSI/IEEE standards. Without a field source, the voltage that is



$$I_{encl} = \oint \vec{H} \cdot \vec{dL}$$



Linear
Coupler
Relay
V
Relay
Relay
Light
Conv
I
Conv.
relay