First Cycle

```
* BUS: 100 :UTIL-69 *****
        8.914 KA AT -87.27 DEG (1065.29 MVA) : X/R = 21.65 KV = 69.000
       Ze =   0.0004472 +j   0.0093764 (Complex)
       SYM kA*1.6 =   14.26       ASYM kA Based on X/R ratio = 14.11 kA

       MAX. HIGH VOLTAGE CLF AND POWER FUSE DUTY = 9.25 SYM, = 14.64 ASY
       MAX. HIGH VOLTAGE DISTRIBUTION FUSE DUTY = 9.77 SYM, = 15.46 ASY

  CONTRIBUTIONS TO FAULT:
  BUS  to  BUS         MAG      ANG      BUS  to  BUS        MAG   ANG
  UTIL     100 :UTIL   8.367   -87.42   01:69-1   100 :UTIL 0.318 -84.53
  02:69-2  100 :UTIL   0.229   -85.54

  * BUS: 04:MILL-2 *****
        7.691 KA AT -85.66 DEG ( 183.83 MVA): X/R = 13.61 KV = 13.800
       Ze =   0.0041165 +j   0.0542433 (Complex)
       SYM kA*1.6 =   12.31       ASYM kA Based on X/R ratio = 11.60 kA

       MAX. HIGH VOLTAGE CLF AND POWER FUSE DUTY = 7.69 SYM, = 11.60 ASY
       MAX. HIGH VOLTAGE DISTRIBUTION FUSE DUTY = 8.03 SYM, = 12.11 ASY

  CONTRIBUTIONS TO FAULT:
  BUS  to   BUS         MAG      ANG    BUS  to   BUS       MAG    ANG
  02:69-2   04:MILL-2   6.338  -85.68  04:MILL-2 15:FDR I  -0.550 -86.35
  04:MILL-2 27:T12 PR  -0.167  -82.49  04:MILL-2 16:T9 PRI -0.091 -84.11
  04:MILL-2 08:FDR L    0.000    0.00  04:MILL-2 24:FDR M  -0.545 -85.95

  * BUS: 24:FDR M *****
       7.562 KA AT -84.68 DEG ( 180.76 MVA) : X/R = 11.17 KV = 13.800
      Ze =   0.0051256 +j   0.0550855 (Complex)
      SYM kA*1.6 =   12.10       ASYM kA Based on X/R ratio =  11.10 kA

      MAX. HIGH VOLTAGE CLF AND POWER FUSE DUTY = 7.56 SYM, = 11.10 ASY
      MAX. HIGH VOLTAGE DISTRIBUTION FUSE DUTY = 7.69 SYM, = 11.29 ASY

  CONTRIBUTIONS TO FAULT:
  BUS  to   BUS        MAG      ANG     BUS  to  BUS       MAG      ANG
  04:MILL-2 24:FDR M   7.016   -84.58  24:FDR M 31:FDER P -0.399   -87.20
  24:FDR M  32:FDR Q  -0.148   -82.86

  * BUS: 31:FDR P *****
        7.474 KA AT -84.02 DEG ( 178.65 MVA): X/R =  10.02 KV =  13.800
       Ze =   0.0058284 +j   0.0556708 (Complex)
       SYM kA*1.6 = 11.96         ASYM kA Based on X/R ratio = 10.80 kA

       MAX. HIGH VOLTAGE CLF AND POWER FUSE DUTY = 7.47 SYM, = 10.80 ASY
       MAX. HIGH VOLTAGE DISTRIBUTION FUSE DUTY = 7.48 SYM, = 10.80 ASY

  CONTRIBUTIONS TO FAULT:
  BUS  to  BUS        MAG      ANG      BUS  to  BUS       MAG      ANG
  31:FDR P 36:T13 SE -0.399   -87.25   24:FDR M  31:FDR P  7.076  -83.84

  * BUS: 36:T13 SEC *****
      11.254 KA AT -85.21 DEG (  46.78 MVA) : X/R =  15.06 KV =  2.400
      Ze =   0.0178490 +j   0.2130016 (Complex)
```

```
    SYM kA*1.6 =   18.01       ASYM kA Based on X/R ratio =  17.18 kA

    MAX. HIGH VOLTAGE CLF AND POWER FUSE DUTY = 11.26 SYM, = 17.18 ASY
    MAX. HIGH VOLTAGE DISTRIBUTION FUSE DUTY = 11.90 SYM, = 18.16 ASY

CONTRIBUTIONS TO FAULT:
BUS  to  BUS        MAG      ANG      BUS  to  BUS        MAG     ANG
Med Ind  36:T13 SE  2.939   -88.08   31:FDR P 36:T13 SE  8.320  -84.20
```

Interrupting time

```
* BUS: 100 :UTIL-69 *****
      8.654 KA AT -87.37 DEG (1034.21 MVA) : X/R =  21.99 KV =  69.000
     Ze =   0.0004440 +j   0.0096591 (Complex)

  CONTRIBUTIONS TO FAULT:
  BUS  to  BUS       MAG      ANG      BUS  to  BUS        MAG      ANG
  UTIL     100 :UTIL 8.367   -87.42   01:69-1  100 :UTIL  0.165   -85.33
  02:69-2  100 :UTIL 0.121   -86.50

  * BUS: 01:69-1 *****
      6.633 KA AT -81.93 DEG ( 792.74 MVA) : X/R =  7.19 KV =  69.000
     Ze =   0.0017702 +j   0.0124897 (Complex)

  CONTRIBUTIONS TO FAULT:
  BUS  to  BUS        MAG      ANG       BUS  to  BUS       MAG     ANG
  01:69-1  03:MILL-1 -0.166   -85.46    01:69-1  100 :UTIL -6.467 -81.84

  * BUS: 04:MILL-2 *****
      6.981 KA AT -85.78 DEG ( 166.87 MVA) : X/R =  13.78 KV =  13.800
     Ze =   0.0044095 +j   0.0597656 (Complex)

  CONTRIBUTIONS TO FAULT:
  BUS  to   BUS         MAG      ANG     BUS  to  BUS       MAG     ANG
  02:69-2   04:MILL-2   6.321   -85.69  04:MILL-2 15:FDR I -0.393 -86.48
  04:MILL-2 27:T12 PR  -0.031   -85.11  04:MILL-2 16:T9 PRI 0.000   0.00
  04:MILL-2 08:FDR L    0.000    0.00   04:MILL-2 24:FDR M -0.236 -86.99

  * BUS: 24:FDR M *****
      6.866 KA AT -84.81 DEG ( 164.12 MVA) : X/R =  11.28 KV =  13.800
     Ze = 0.0055071 +j 0.0606812 (Complex)

  CONTRIBUTIONS TO FAULT:
  BUS  to   BUS        MAG      ANG     BUS  to  BUS        MAG    ANG
  04:MILL-2 24:FDR M   6.630   -84.74  24:FDR M  31:FDR P  -0.184 -87.68
  24:FDR M  32:FDR Q  -0.052   -84.81

  * BUS: 31:FDR P *****
      6.790 KA AT -84.18 DEG ( 162.29 MVA) : X/R =  10.10 KV =  13.800
     Ze =   0.0062527 +j   0.0612986 (Complex)

  CONTRIBUTIONS TO FAULT:
  BUS  to  BUS         MAG      ANG    BUS  to  BUS        MAG     ANG
  31:FDR P 36:T13 SE  -0.184   -87.70 24:FDR M  31:FDR P  6.606  -84.08

  * BUS: 36:T13 SEC *****
      9.374 KA AT -84.72 DEG ( 38.97 MVA) : X/R =  12.41 KV =  2.400
```

```
      Ze =   0.0235982 +j   0.2555270 (Complex)

  CONTRIBUTIONS TO FAULT:
  BUS  to  BUS        MAG      ANG     BUS  to  BUS        MAG     ANG
  Med Ind  36:T13 SE  1.176   -88.08  31:FDR P  36:T13 SE 8.201  -84.24
```

6.13 Bibliography

[B1] ANSI/NEMA Std Pub. No. MG1-2003, Motors and Generators, paragraph MG1-1.58, Dec. 1980.[2, 3]

[B2] Huening, Walter C. Jr., "Calculating Short-Circuit Currents with Contributions from Induction Motors," *IEEE Transactions,* IAS Vol. 1A-18, No. 2, Mar/Apr 1982.

[B3] IEC 909-1988, International Standard, Short-circuit Current Calculation in Three-phase a.c. Systems, First edition.[4]

[B4] IEEE Std C37.010-1999 (Reaff 2005), IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.[5, 6]

[B5] IEEE Std C37.13-1990 (Reaff 1995), IEEE Standard for Low-Voltage AC Power Circuit Breakers Used on Enclosures.

[B6] IEEE Std C37.41-2000, IEEE Standard Design Tests for Distribution Cutouts and Fuse Links, Secondary Fuses, Distribution Enclosed Single-Pole Air Switches, Power Fuses, Fuse Disconnecting Switches, and Accessories.

[2]ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[3]NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (http://global.ihs.com/).

[4]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[5]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[6]The IEEE standards or products referred to in this subclause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

Chapter 7
Capacitor contributions to short-circuit currents

7.1 Introduction

Capacitor discharge currents from power factor correction capacitors or harmonic filters have not previously been considered in the ANSI or IEC calculation procedures. The stresses associated with capacitor discharge currents are different than typical fault conditions due to the high-frequency components present within currents and the extremely fast time constants of the capacitor circuits. These conditions may affect equipment sensitive to high-frequency currents.

This section describes the nature of capacitive discharge currents during fault conditions and the effect of capacitor currents on the total fault current. Guidelines if applicable, will be provided for properly considering and accounting for the fault currents imposed on equipment applied near capacitor banks. Energizing capacitors and back-to-back switching of capacitors is not covered in this chapter.

7.2 Capacitor discharge current

A capacitor in an ac system charges and discharges in a controlled manner every half cycle, based on the sinusoidal driving voltage and system impedances. When a fault occurs, the system voltage is suddenly changed and the capacitor discharges at a rapid rate, with a high discharge current. The current is greatest if the fault occurs when the capacitor is charged to the maximum at a voltage peak. Only the impedance between the capacitor and the fault limits the discharge current. The current will "ring down" based on circuit resistance and reactance. The resistance provides damping and the interaction between the system reactance and capacitor determines the frequency of the oscillating current. The discharge current can be expressed by the Equation (7.1):

$$I_{pk} = \frac{\sqrt{\frac{2}{3}} \times V_{LL} \times e^{-Rt/L} \sin(\omega_0 t)}{Z_0} \tag{7.1}$$

where

V_{LL} = the system line-to-line voltage

L = the inductance between the capacitor bank and the fault

R = the resistance between the capacitor bank and the fault

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

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

In the above expression, ω_0 is the natural frequency of the oscillatory circuit in radians per second. The natural frequency is often relativity high compared to the system frequency. The maximum peak current from the Equation (7.1) is shown in Equation (7.2) below.

$$I_{\max} = \sqrt{\frac{2}{3}} \times V_{\mathrm{LL}} \times \sqrt{\frac{C}{L}} \tag{7.2}$$

Equation (7.2) shows that the worst-case transient fault current depends on the magnitude of the system voltage, the inductance between the capacitor and the fault, and the capacitance of the bank. Thus, an increase in voltage or capacitance increases the discharge current. Since an increase in the inductance decreases the current, the distance from the bank to the fault can be quite significant in determining the discharge current. The magnitude of the discharge current may be negligible for equipment located farther from the capacitor bank.

Equation (7.1) and Equation (7.2) also indicate that both the magnitude and the natural frequency of the discharge current may be relatively high as compared to the magnitude and frequency of the system fault currents, as demonstrated in the following example.

7.2.1 Example

The 10 Mvar capacitor bank shown in Figure 7-1 has the following capacitive reactance and capacitance:

$X_c = 19.04\ \Omega$

$C = 139.3\ \mu\mathrm{F}$

The capacitor bank will draw $|I_c| = 418.4\mathrm{A_{rms}}$ under steady-state rated conditions. The bank is connected to the bus through 30 m of 3-1/C 500 kcmil conductors with the following impedance:

$Z' = 0.0276 + \mathrm{j}0.0520\ \Omega/300\ \mathrm{m}$

$Z = 0.00276 + \mathrm{J}0.0052\ \Omega$

so

$R = 0.00276\ \Omega$ and $L = 13.79\ \mu\mathrm{H}$

This translates to a peak discharge current of 35.8 kA at a frequency of 3.631 kHz. Note that the frequency of the discharge current is over sixty times the fundamental frequency of the fault current. The time constant of the discharge current is the time for the current in the series RLC circuit to reach 36 percent of its final value. In this case, the time constant is as follows:

$2T_s = L/2R = 9.99\ \mathrm{ms}$

which is slightly over 1/2 of a cycle on a 60 Hz system.

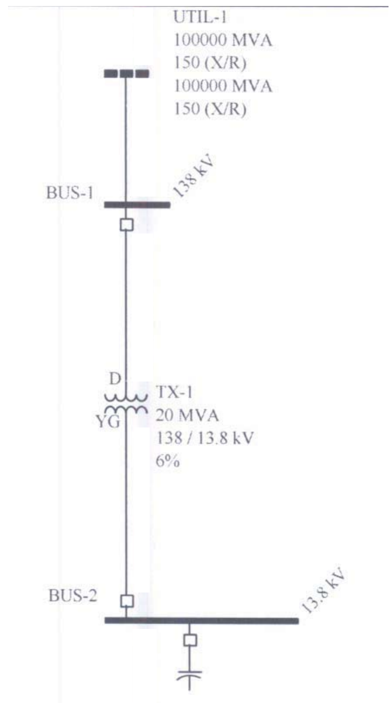

Figure 7-1—One-line diagram for example case

7.3 Transient simulations

To better understand the transient response, several test systems were developed and modeled using time-domain transient simulation software. Use of this type of software allows complete simulation of all types of transient phenomena including the interactions between different circuit elements to a defined disturbance. Modeling guidelines were derived from Greenwood [B1].[1]

7.3.1 Standard capacitor bank

The system of Figure 7-1 was modeled to determine the effects of capacitor discharge as a function of capacitor MVA, circuit length, and interaction with the utility source. The example was chosen as a typical industrial supply with realistic circuit parameters similar to field conditions.

A three-phase bolted fault was placed on the 13.8 kV bus 15 ms into the simulation while the system was in steady-state. The faults were initiated at voltage peak in order to maximize the current offset. The initial fault current without capacitors was calculated as

[1]The numbers in brackets correspond to those of the bibliography in 7.5.

31 340 amperes (with dc offsets included) based on the impedance looking back to the source.

Figure 7-2 shows the results of a simulation for the case described in the previous example. Plot 7-2(a) shows only the capacitor currents on the phase with the largest current. The plot in Figure 7-2(b) shows the fault current contribution from the source, and plot 7-2(c) shows the total fault current on that phase. Notice that the peak capacitor current matches the predicted current of 35 806 A fairly closely, with a peak current of 36 253 A. The total peak fault current is 43 539 A, which occurs during the first cycle when the current contribution from the source reaches its sinusoidal peak. Of this peak current, the capacitor contributes roughly 25 000 A. Note that the capacitor current decays fairly quickly.

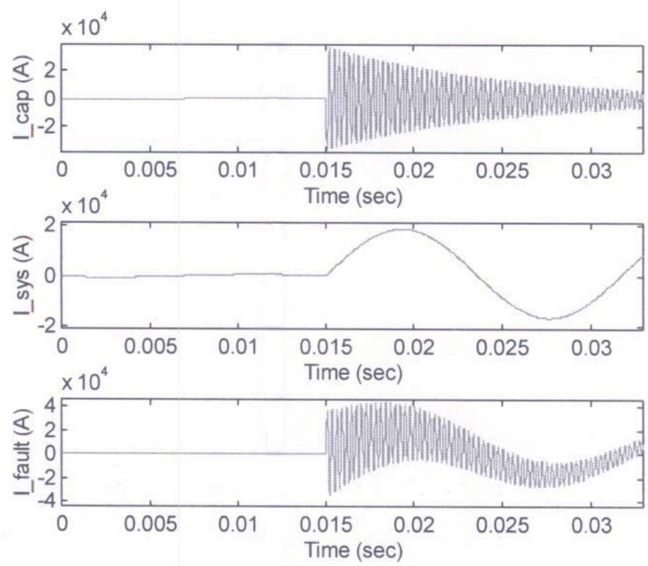

Figure 7-2—Fault study with 10 Mvar capacitor separated from fault by 30 m of cable

Note that the cable model used for these calculations is a fairly simple one. The increased resistance due to skin effect at the natural frequency is not included. The impact of cable capacitance and coupling between phases is also neglected. Including these elements in the model will both increase the magnitude of the initial transient and the speed the decay of the capacitor contribution. Figure 7-3 shows fault current when the cable is modeled first with a single coupled pi section, and second with a distributed parameter traveling wave model (with parameters calculated at 1000 Hz). Both cases have nearly identical maximum currents, but now the peak occurs almost immediately due to the interaction with the cable capacitance. Note also, that the travel times for electromagnetic waves on the 30-meter cable are very short.

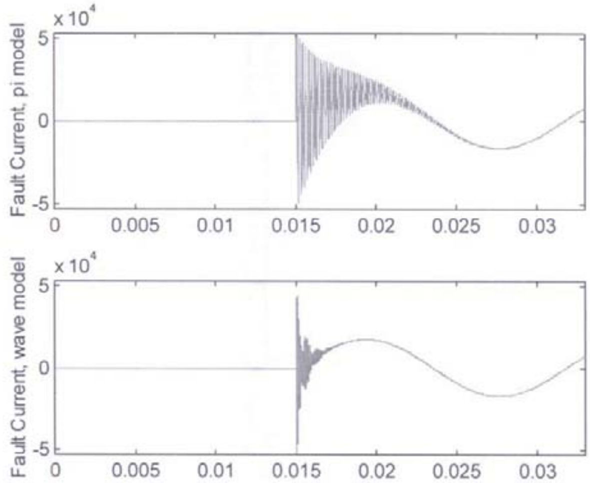

Figure 7-3—Fault currents with coupled-pi and traveling wave models for the 30 m cable and 10 Mvar capacitor bank

Figure 7-4 shows the results of a 10 Mvar capacitor in series with 15 m of 3-1/C-500 kcmil copper conductors. The cable is modeled using a traveling wave model for the cable.

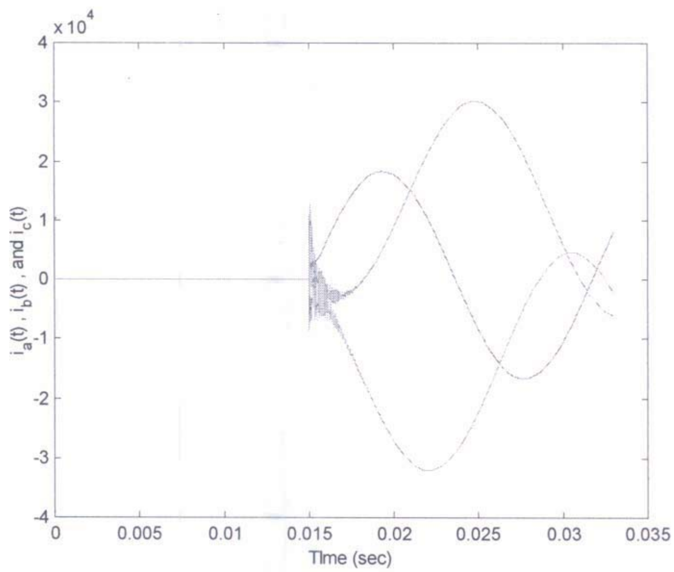

Figure 7-4—Fault current with 15 m cable and 10 Mvar capacitor bank

As can be seen, there is a high initial transient at the onset of the fault that damps quickly down in less than 0.5 ms (1/30 cycle) due to the very short time for the voltage and current waves to traverse the cable between the fault and the capacitor. Nearly complete ring down occurs in approximately 2.0 ms or 1/8 of a cycle. As can be expected, lower values of capacitance reduce the transient and time constant.

Figure 7-5 shows the same system with 300 m of cable in order to determine the effect of the added cable inductance on the response. Note that the peak fault currents are higher in this case.

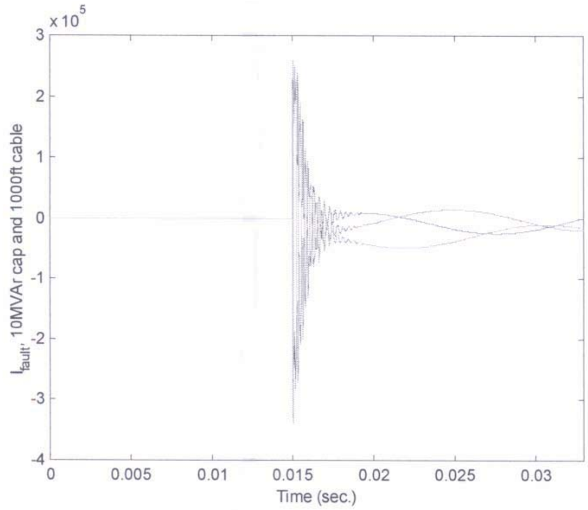

Figure 7-5—Fault current with 300 m cable separating 10 Mvar capacitor from the fault

The initial transient is nearly ten times higher than in the 30 m cable, and takes longer to damp down due to the longer travel times on the longer cable. Complete ring down still occurs in approximately 2.0 ms or 1/8 of a cycle.

Standard capacitor connections show high transient discharge currents that damp quickly before a 1/4 cycle. Low *X/R* ratio cables associated with industrial installations do not increase the time constant significantly to produce extended transient times, which could affect breaker operation.

During fault conditions, the capacitor discharge takes place in the initial 1/30–1/8 cycles, depending on the time constant of the system. Since the breaker protective device and contacts cannot operate in this time frame, the discharge takes place into closed contacts. The electromagnetically induced forces of the discharge current are instantaneously proportional to the current squared. Since the close and latch (momentary) rating of a breaker is the maximum fundamental frequency rms fault current the breaker can withstand, it can also be considered a measure of the forces which may be safely imposed on the various physical members of the breaker during a rated frequency (i.e., 60 Hz) fault condition.

To determine if the capacitor contributions could affect breaker of fuse interrupting capability, the I^2t energy in Joules was calculated for the capacitor and 60 Hz fault current and compared. The energy was calculated for each of the cases described above. The fault

