R 636

Technical Report

LOW-FREQUENCY POWER TRANSIENT FILTERS

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LOW-FREQUENCY POWER TRANSIENT FILTERS

Technical Report R-636

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by

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ABSTRACT

Transients in electrical power systems at various military installations are reported to cause malfunctions in and damage to electronic equipment. Investigations to date indicate that harmful transients are injected into the critical power bus by both external and internal transient producers. Oscilloscope recordings show that the harmful transients consist of oscillatory voltages having predominant frequency components as low as 400 Hertz and high-frequency disturbances in the form of spike voltages as short as 10 μsec in duration. A study was conducted on the feasibility of developing power filters which could prevent the externally produced transients from reaching transient-sensitive electronic equipment, and prevent load-caused transients from reaching the critical power bus. This report describes that study. Based on the findings, a three-phase filter was designed, fabricated, and experimentally evaluated.

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INTRODUCTION

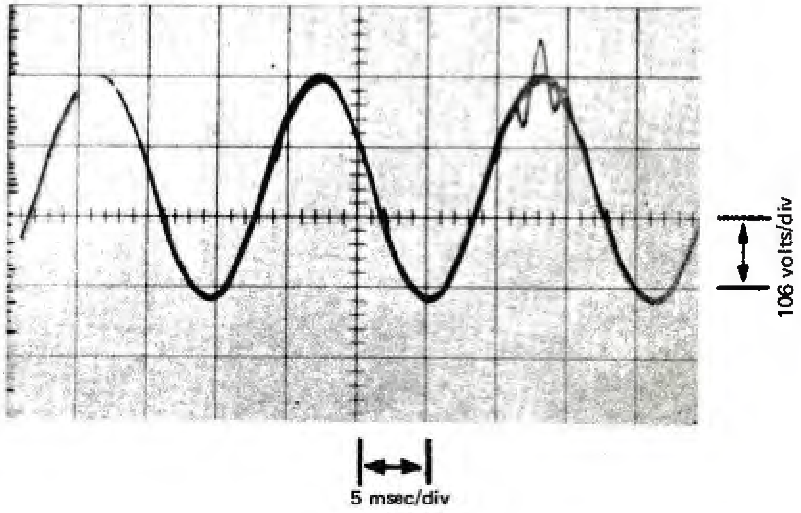
Transients in electrical power systems at military installations cause operational malfunctions in and damage to such critical items as computers and synchronous communications equipment. The transients injected in the facility power system are created by both external and internal sources. Figures 1a, 1b, and 1c show the waveform disturbances caused by external sources, resulting in computer operational problems. Figures 1d and 1e show waveform disturbances caused by internal sources, resulting in synchronous equipment operating problems.

The disturbances consist of voltage spikes and voltage dips that vary in magnitude and duration. Both are characterized by a very fast rise time, 10 to 100 μsec, and are usually associated with a low-frequency oscillatory voltage superimposed on the basic 60-Hertz power sine wave. The oscillatory voltage frequency of the disturbances varied from a few kilocycles to about 400 Hertz.

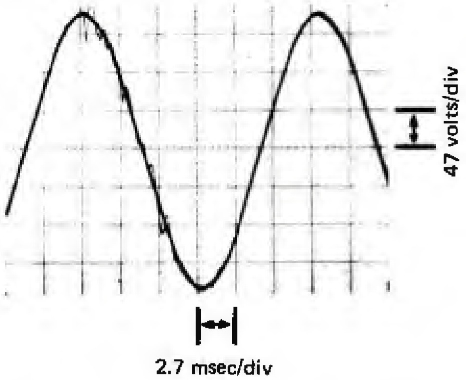
In response to the need for preventing harmful transients from reaching transient-sensitive loads and from being fed back onto the critical power bus, the Naval Civil Engineering Laboratory (NCEL) studied the feasibility of developing power filters which suppress these harmful transients. This report describes the formulation of filter criteria, an analysis of the transient-suppressing effectiveness of resistance-capacitance and inductance-capacitance filters, the design and performance data illustrating the design curves and design procedures, and the performance data of a 10-ampere, 120-volt power filter.

POWER FILTER REQUIREMENTS

Power filters must attenuate all the harmful transients to a level harmless to the load without at the same time attenuating the 60-Hertz line voltage. They must also produce a minimal rise or drop in the output voltage as the load varies from light to full. They should not overheat under full-load operational conditions. In addition, they should be economical, simple, compact, and rugged.

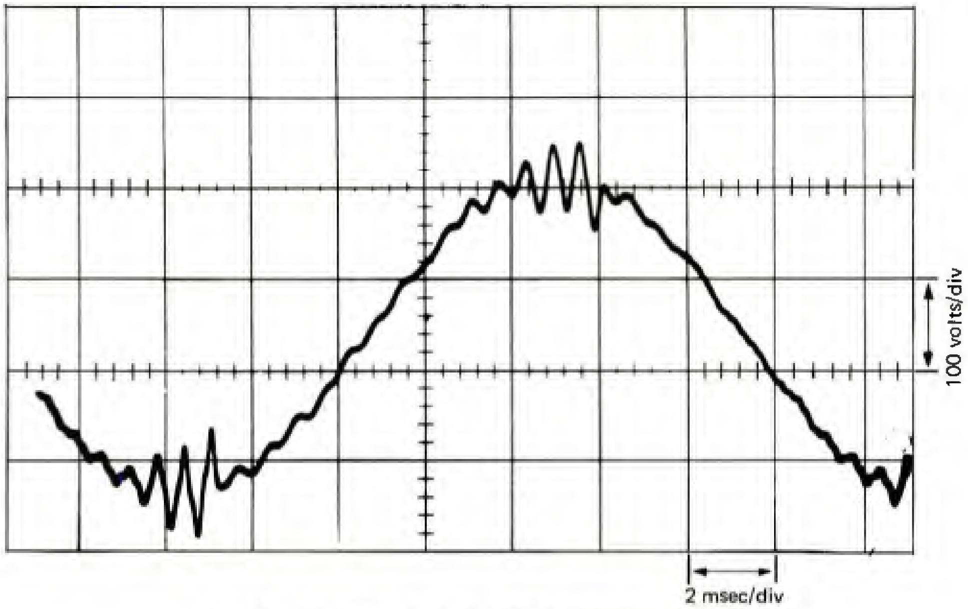


(a) Caused by a utility company switching on 100-kva power factor correction capacitors.

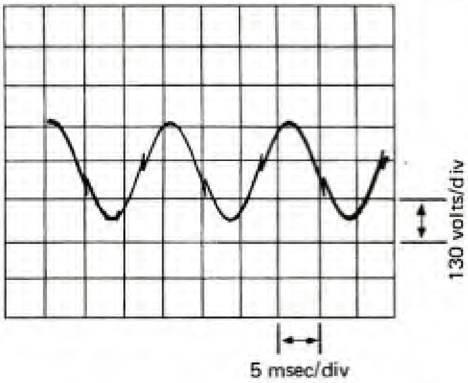


(b) Caused by the switching on of 37.5-kw runway lights.

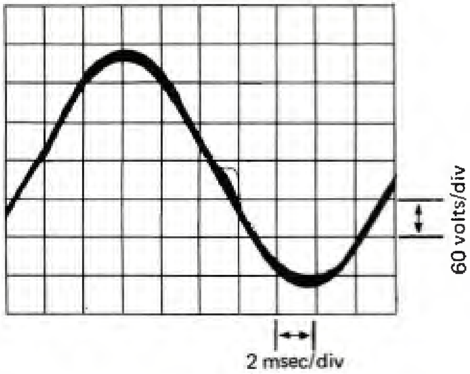
Figure 1. Voltage waveform disturbances.



(c) Caused by ringing in an RFI power line filter.



(d) Caused by one element of a computer.



(e) Caused by intermittent operation of a 25-hp air conditioning motor.

Figure 1. Continued.

To get the maximum attenuation of the harmful transients, the filter cutoff frequency should be selected substantially below the lowest frequency component of the transients. However, the requirement for nonamplification and nonattenuation of the 60-Hertz voltage places a limit on the selection of the lowest possible cutoff frequency. To prevent overheating one must choose the proper wire size in the inductors and a capacitor with a low dielectric loss. The economy, simplicity, compactness, and ruggedness requirements suggest a passive component filter having the minimal number of elements. In view of these requirements, resistance-capacitance filters are first analyzed.

RESISTANCE-CAPACITANCE FILTERS

A resistance-capacitance filter, shown in Figure 2, can be obtained by connecting a capacitor across the power source. The cutoff frequency, f_c, is given by Equation 1:

$$f_c = \frac{1}{2\pi R_{eq} C} \qquad (1)$$

where* $R_{eq} = R_S R_L / R_S + R_L$, that is, the equivalent paralleled impedance of R_S and R_L

R_S = source impedance

R_L = load impedance

Since $R_S \ll R_L$, R_{eq} in Equation 1 may be replaced by R_S.

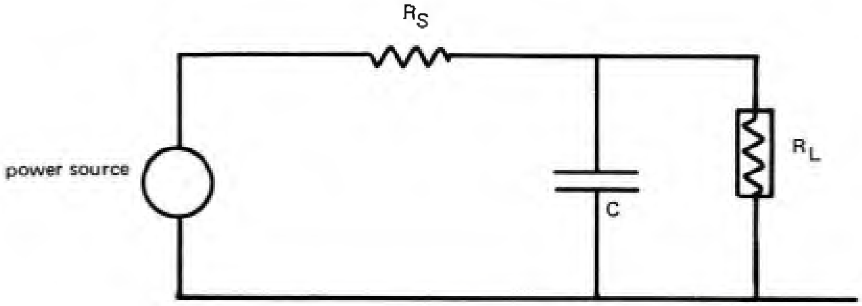


Figure 2. Resistance-capacitance filter network.

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* See List of Symbols at end of report.

For an f_c of 400 Hertz and an R_S typically between 0.1 and 0.01, the values of the required capacitance are between 3,981 and 39,810 μf. The reactive current at 120 volts and 60 Hertz is between 180 and 1,800 amperes. These values show that for suppressing low-frequency transients resistance-capacitance filters are neither practical nor realistic. Resistance-capacitance filters are satisfactory only when the required cutoff frequency is in the high kilocycle range.

The inability of resistance-capacitance filters to meet the requirements of a low cutoff frequency suggests the examination of inductance-capacitance filters.

INDUCTANCE-CAPACITANCE FILTERS

Two- and Three-Element Power Filters

Because of its simplicity, economy, and compactness, a two-element L-filter network is examined first. This filter network, with its terminal impedances, is shown in Figure 3. The impedances R_S and R_L represent the internal source impedance and the load impedance, respectively. This L filter is capable of suppressing transients propagating towards the load designated as forward filtering action. The capacitance C_1, shown in Figure 3, is added to the filter network to suppress transients that may originate on the load side and propagate back onto the critical bus, designated as reverse filtering action. By this network arrangement, forward and reverse filtering action is achieved.

The forward voltage attenuation characteristics of the filter network of Figure 3 are given by Equation 2:

$$\alpha_1 = 20 \log_{10} \frac{E_S}{E_L}$$

$$= 20 \log_{10} \left\{ \frac{[(R_L + X_{C_2})(R + X_{C_1} + X_{C_2} + X_L) - X_{C_2}{}^2](R_S + X_{C_1}) - X_{C_1}{}^2(R_L + X_{C_2})}{R_L X_{C_1} X_{C_2}} \right\} \quad (2)$$

where α_1 = forward voltage attenuation

E_S = input voltage

E_L = load voltage

X_{C_1} = $1/j\omega C_1$ = capacitive reactance

X_{C_2} = $1/j\omega C_2$ = capacitive reactance

X_L = $j\omega L$ = inductor reactance

R = inductor resistance

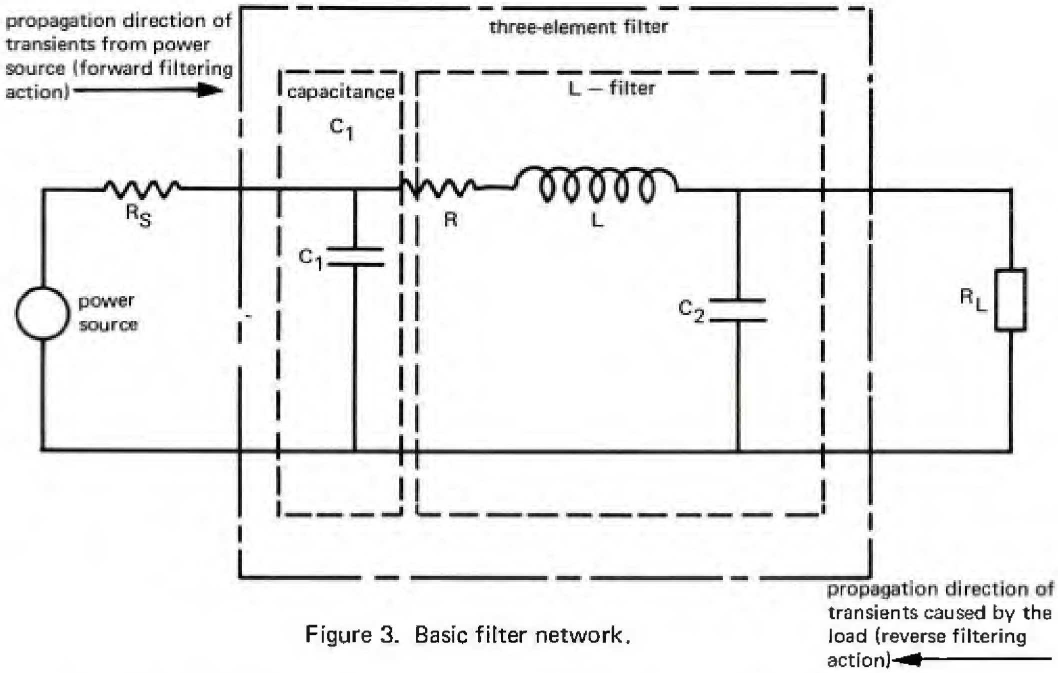


Figure 3. Basic filter network.

With R_S and R_L as known parameters, and by varying L and C_2 in Equation 2, a set of voltage attenuation curves is obtained. From this set the best attenuation curve that satisfies the filter requirements is selected. The proper values of inductance L and capacitance C_2 are then determined.

Since the internal power source impedance R_S is usually much less than unity, Equation 2 may be reduced to Equation 3 and X_{C_1} vanishes:

$$\alpha_1 = 20 \log_{10}\left[\frac{R_L(R + X_L + X_{C_2}) + X_{C_2}(R + X_L)}{R_L X_{C_2}}\right] \tag{3}$$

X_{C_1} is essential only for reverse filter action; capacitor C_1 can be eliminated if reverse filter action is not needed.

The reverse voltage attenuation, α_2, is given by

$$\alpha_2 = 20 \log_{10}\left[\frac{R_t(R + X + X_{C_1} + X_{C_2}) + X_{C_2}(R + X + X_{C_1})}{X_{C_1} X_{C_2}}\right] \tag{4}$$

where R_t = internal transient source impedance.

The dominant factor in Equation 4 is X_{C_1}. The value of C_1 depends on the frequency of the fundamental component of the transients, f_t, created by the load. The value of the capacitance C_1 is not critical and it may be selected by choosing the resonant frequency of the LC_1 circuit to be equal to $1/2 f_t$. C_1 is given by Equation 5:

$$C_1 = \frac{1}{L f_t^2} \tag{5}$$

Figure 4 shows a set of voltage attenuation curves obtained by solving Equation 1 for a 10-ampere, 120-volt, three-element filter. Each curve represents a possible design value for L and C_2. In solving Equation 1, R_S is assumed to be constant and is given the realistic value of 0.01 ohm. R_L is taken to be 10.4 ohms and the inductor resistance R is taken as 0.01 Ω/mh. The computer program used for solving Equation 1 is given in Appendix A.

It can be seen from the voltage attenuation curves that the cutoff frequency is decreased by increasing the values of either L or C_2. In addition the choice of values for L and C_2, and thus the cutoff frequency, is greatly limited by the requirement of nonappreciable voltage loss or gain at 60 Hertz. The attenuation performance of this filter in the frequency range of interest is typically 40 db per decade slope. If more attenuation is needed for special application, other filter elements must be added.

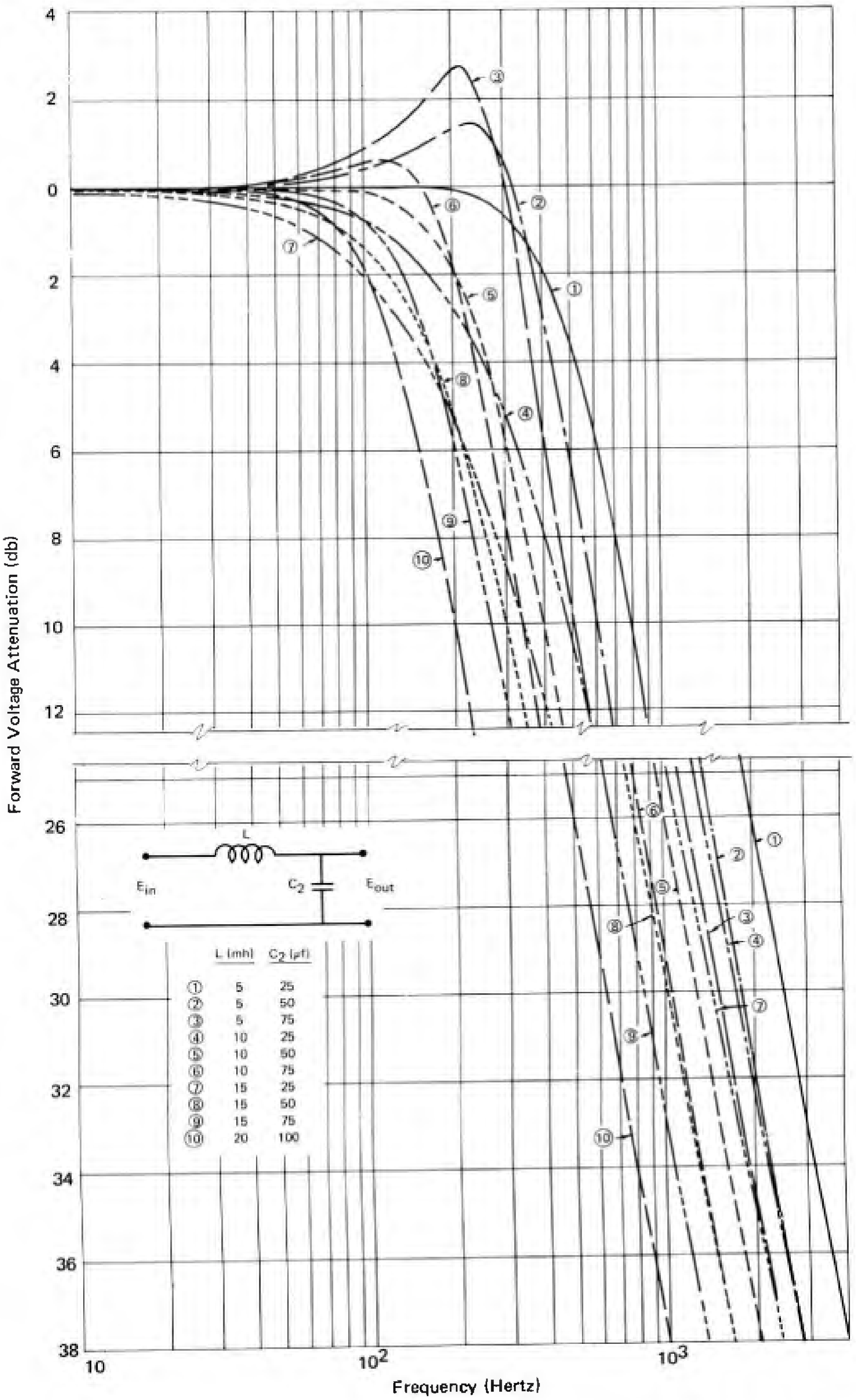
n-Element Power Filters

Figure 5 shows the equivalent circuit diagram of a five-element filter. The forward voltage attenuation, which is obtained by analyzing the equivalent circuit, is given by Equation 6:

$$\begin{aligned}\alpha_1 &= 20 \log_{10} \frac{E_S}{E_L} \\ &= 20 \log_{10} \left(\left\{ \frac{X_{C_3}}{R_L} - \left(\frac{1}{R_L} + \frac{1}{X_{C_3}} \right) \left[X_1 - \frac{X_{C_2}{}^2 (R_S + X_{C_1})}{Y} \right] \right\} \frac{Y}{X_{C_1} X_{C_2}} \right)\end{aligned} \tag{6}$$

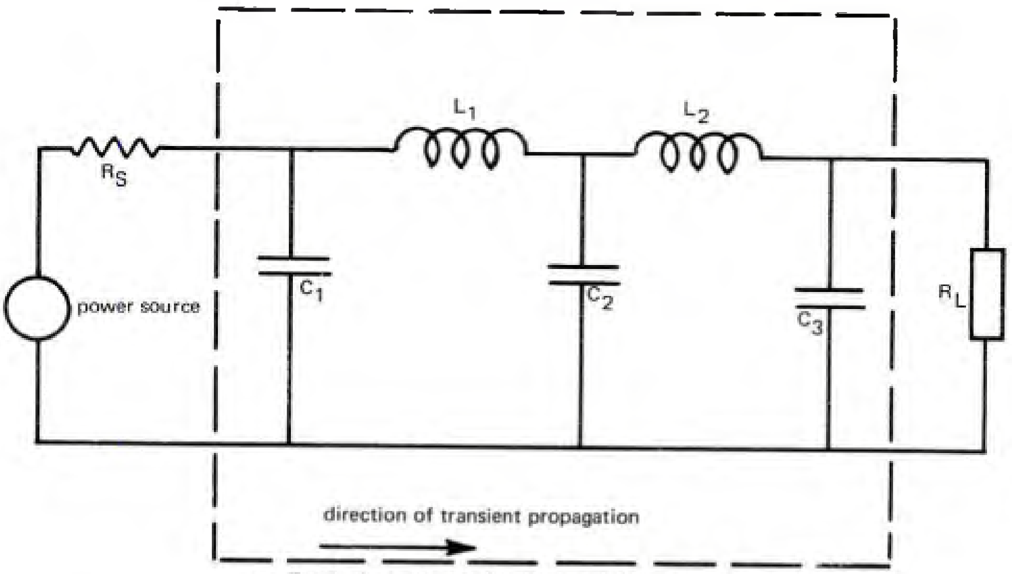
where $X_1 = X_{C_1} + X_{C_3} + X_{L_2}$

and $Y = (R_S + X_{C_1})(X_{C_1} + X_{C_2} + X_{L_1}) - X_{C_1}{}^2$

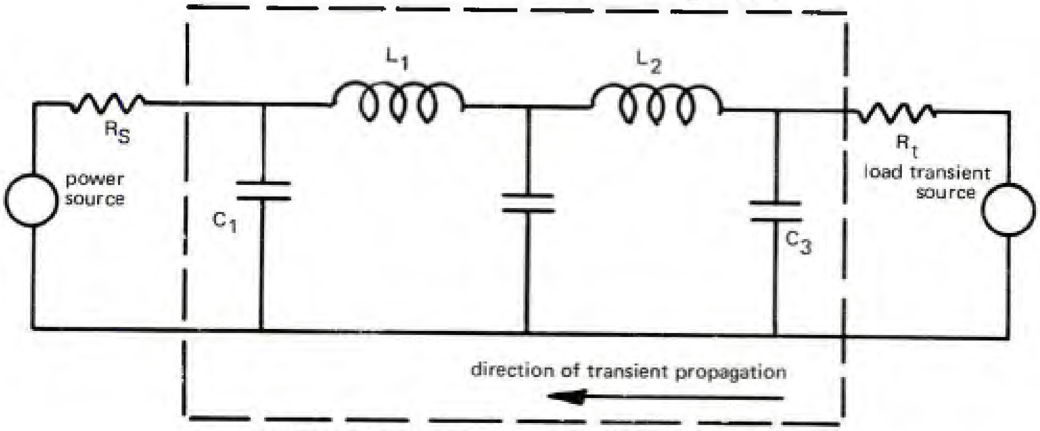


	L (mh)	C_2 (μf)
①	5	25
②	5	50
③	5	75
④	10	25
⑤	10	50
⑥	10	75
⑦	15	25
⑧	15	50
⑨	15	75
⑩	20	100

Figure 4. Voltage attenuation curves of a 10-ampere, 120-volt, three-element filter.



a. Equivalent circuit for forward filtering action.



b. Equivalent circuit for reverse filtering action.

Figure 5. Five-element filter network.

The reverse voltage attenuation can be obtained from Equation 7:

$$\alpha_2 = 20\log\left\{\left(\frac{1}{X_{C_1}}\right)\left[\frac{X_{C_2}^{\,2}(R_t+X_{C_3})}{Y_1} - X_2\right]\left(\frac{Y_1}{X_{C_3}X_{C_2}}\right)\right\} \tag{7}$$

where $X_2 = X_{C_1} + X_{C_3} + X_{L_1}$

and $Y_1 = (R_t + X_{C_3})(X_{C_3} + X_{C_2} + X_{L_2}) - X_{C_3}^{\,2}$

The computed attenuation curves for various values of L_1, L_2, C_1, and C_2 of a 10-ampere, 120-volt, five-element filter are plotted in Figure 6. Appendix A shows the computer program used in obtaining the curves. It is seen from these curves that the imposition of the requirement to maintain minimal deviation of filter output voltages from no load to full load restricts the choice of the Ls and Cs. The attenuation performance, however, is twice that of the L-filter (80 db per decade). Yet, the attenuation characteristics of the n-element filter are quite sensitive to small variations in the values of Ls and Cs. The filter output voltage is also very sensitive to load variations. This sensitivity restricts the use of the filter to near full load. Figure 7 shows the effect of load variations on the attenuation performance.

The basic two-element L-filter has the advantage of being simple, compact, and economical. It has enough attenuation for equipment safety. Furthermore, the two-element filter has the advantage over the n-element filter of keeping the output voltage relatively constant irrespective of load variations (Figure 8). Thus, the two-element L-filter is preferred over the five-element filter except for those highly specialized applications that require very high attenuation performance.

FILTER DESIGN PROCEDURE

Selection of Filter Component Values

The attenuation performance for a 10-ampere, 120-volt, three-element filter is shown in Figure 4. Each attenuation curve represents a possible design value for L and C_2. The design attenuation curve must be selected to satisfy the filter requirements described previously. The selection criteria may be summarized as follows:

1. The attenuation curve should not have any voltage gain at any frequency. This guarantees the suppression of all transient harmonics as well as avoiding the amplification of any harmonics that may exist in the power supplied.
2. There should not be any appreciable voltage loss or gain at 60 Hertz.
3. The cutoff frequency should be lower than the fundamental component frequency of the incoming transients.

Attenuation curves 4 and 5 in Figure 4 satisfy all design criteria. They establish an inductance L of about 10 mh and a capacitance C_2 between 25 and 50 μf. The attenuation curves also show that these values are not critical, and variations of plus or minus 10% in component values will not appreciably alter the filter characteristics. The cutoff frequency of the filter is 220 Hertz, which is far below the lowest transient observed.

Inductor Design

To obtain economical and compact inductors with large values, such as 10 mh, it is necessary to choose high-permeability iron core rather than low-permeability powdered iron or moderate-permeability ferrite core materials. Since the frequencies of the transients requiring suppression are predominantly below 20 kHz, the high-frequency application problems associated with iron core do not exist.

In designing such inductors, the following factors must be considered:

1. The inductor should be as linear as possible.
2. It should not saturate at full load.
3. It should carry the full load on a continuous basis without heating problems.

Inductor linearity is usually obtained so that the inductance value is relatively independent of the property of the core material. In the basic inductance design formula, Equation 8, if l_g is chosen much larger than l_c/μ_Δ, the inductance L is determined primarily by the air gap, and the effect of the nonlinear iron core permeability μ_Δ becomes negligible.

$$L = \frac{3.19 N^2 A_c \times 10^{-8}}{l_g + \dfrac{l_c}{\mu_\Delta}} \tag{8}$$

where A_c = core cross-sectional area

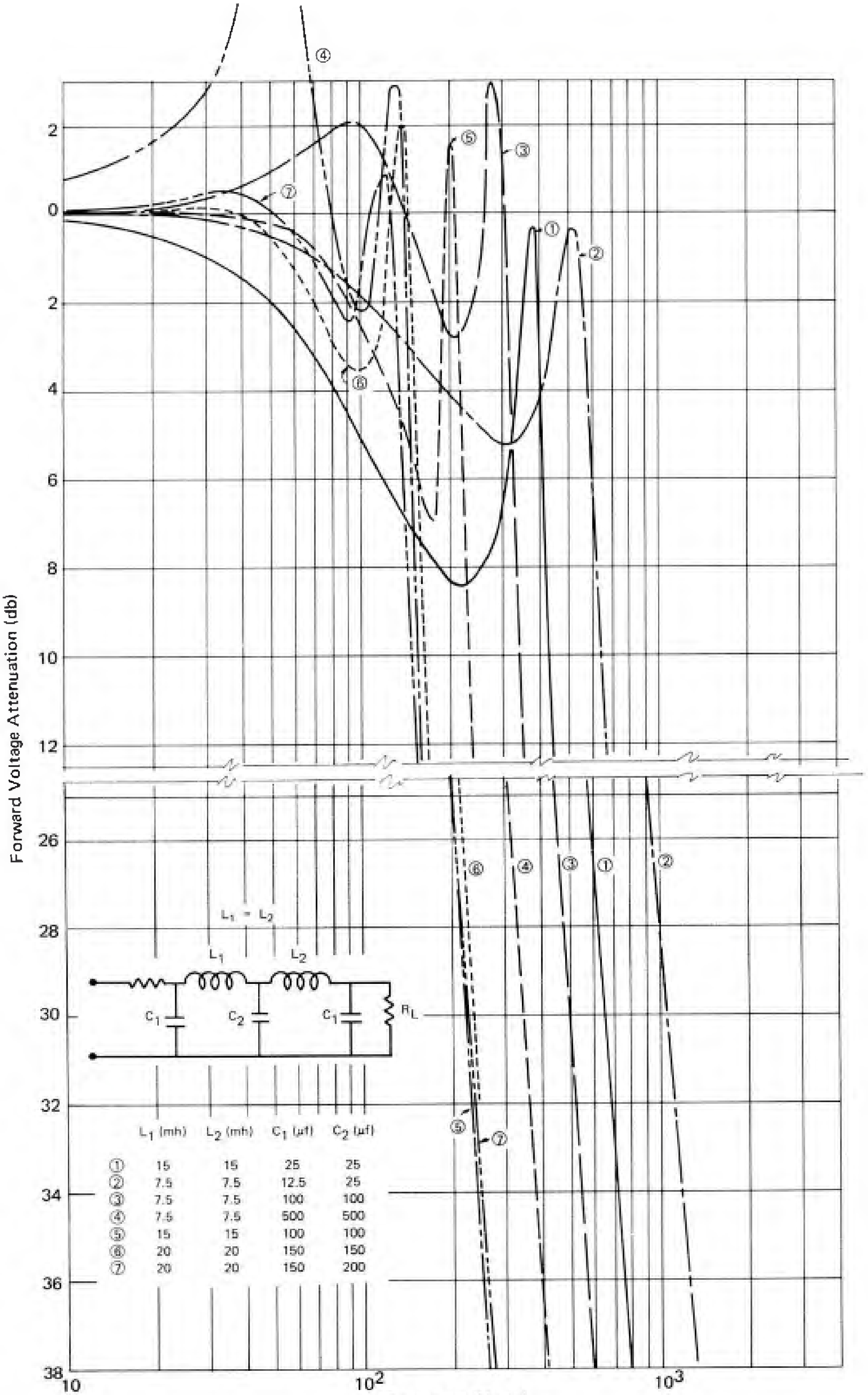
N = number of turns of inductor

l_c = iron core length, in.

l_g = length of inductor air gap

μ_Δ = incremental permeability of the iron core

The derivation of Equation 8 is given in Appendix B.



	L_1 (mh)	L_2 (mh)	C_1 (μf)	C_2 (μf)
①	15	15	25	25
②	7.5	7.5	12.5	25
③	7.5	7.5	100	100
④	7.5	7.5	500	500
⑤	15	15	100	100
⑥	20	20	150	150
⑦	20	20	150	200

Figure 6. Voltage attenuation curves of a 10-ampere, 120-volt, five-element filter.

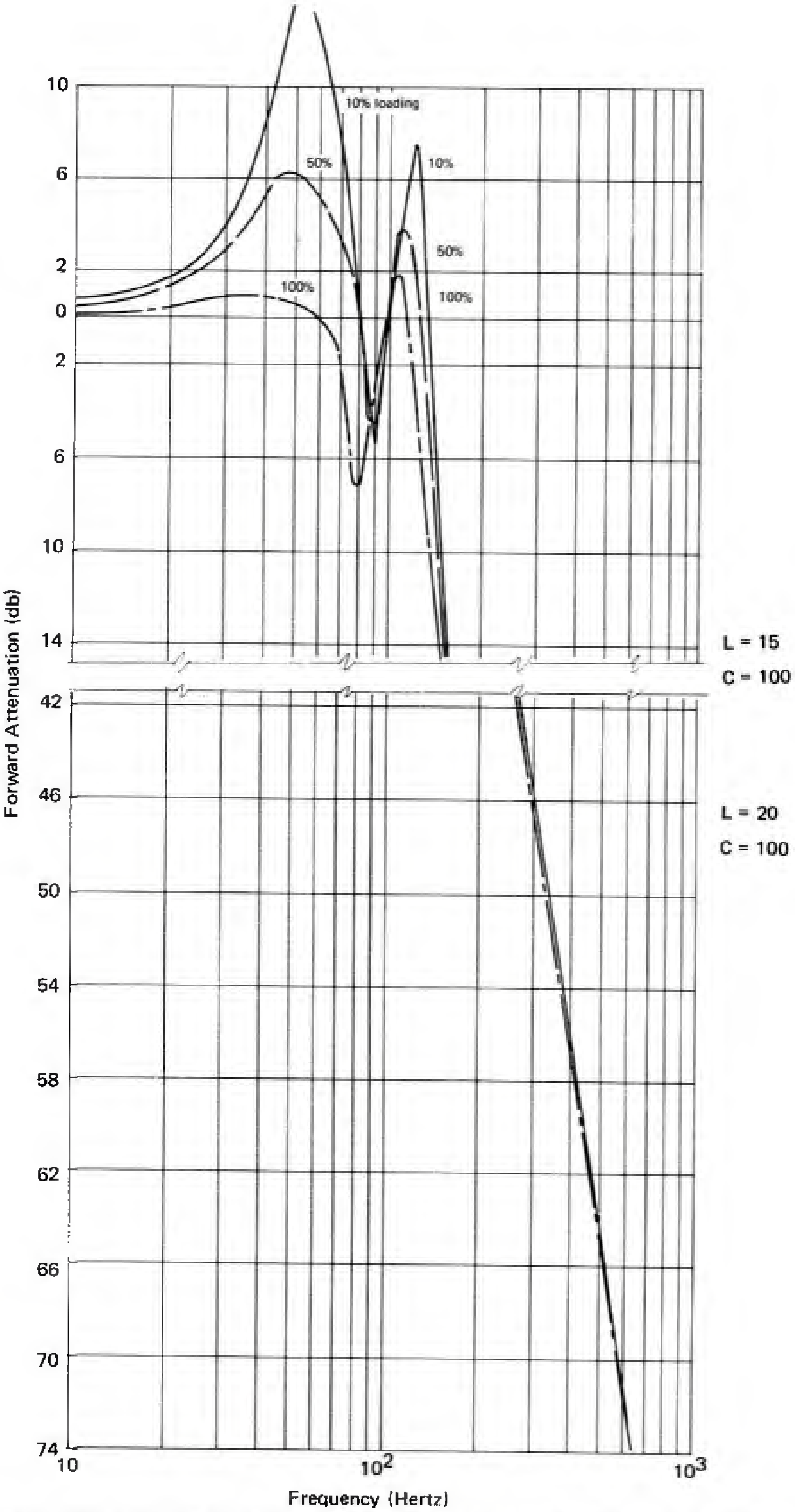


Figure 7. Effects of load variations on the attenuation characteristics of the five-element filter.

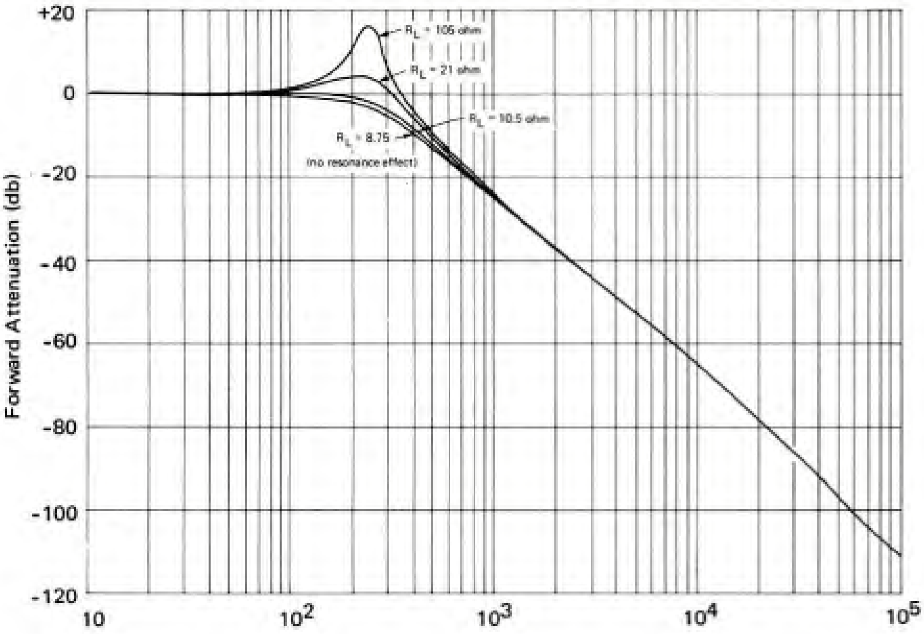


Figure 8. Effects of load variations on the attenuation characteristics of the two-element filter.

To prevent iron core saturation, the flux density at full load, B_{AC}, must not exceed the saturation value. The full-load flux density is computed from Equation 9. The derivation of this equation is shown in Appendix B.

$$B_{AC} = \frac{3.49\,E \times 10^6}{N\,f\,A_c} \qquad (9)$$

where $E = I \omega L$

I = the full load current

$\omega = 2\pi f$ radian frequency

The heating problem can be eliminated by minimizing the copper losses. This is achieved by selecting the proper wire size to obtain a low-resistance coil. For the 10-mh, 10-ampere inductor a 12-AWG wire should be chosen. The resistance for this wire is 0.00162 Ω/ft. It was determined from conventional inductor design procedures that a 78-turn coil should be wound on a 1.5-inch stack of standard 150 EI selectron laminations. The resistance of this coil is calculated as 0.1 ohm. The air gap of the inductor is calculated as 0.030 inch to obtain 10 mh and assure linearity. With 10 amperes flowing at 60 Hertz, the voltage across the 10-mh inductor is 37.7 volts. Substituting into Equation 9, the full load flux density is 14,500 gauss, which is below the saturation value of 16,000 gauss.

EVALUATION

In order to experimentally evaluate the suppression capability of the three-element power filter, a breadboard model of the 10-ampere, 120-volt, single-phase power filter was fabricated (Figure 9). Figure 10 shows the measured voltage attenuation plot. This plot agrees well with the theoretically calculated curve. The filter was connected as shown in Figure 11 and subjected to a family of deliberately created transients. Figures 12a-12c are filter input-output waveforms. These figures show the effectiveness of the breadboard filter in suppressing various low- and high-frequency transients. Figures 13a and 13b show the reverse filtering action capability. In this case, transients created on the load side were prevented from reaching the power bus, thus protecting the bus from transients caused by loads. Figure 14a shows an actual power transient occurring on the power bus to the Electrical Systems laboratory at NCEL. Its voltage amplitude and fundamental frequency are 100 volts and 400 Hertz, respectively. Figure 14b shows that the transients have been effectively suppressed.

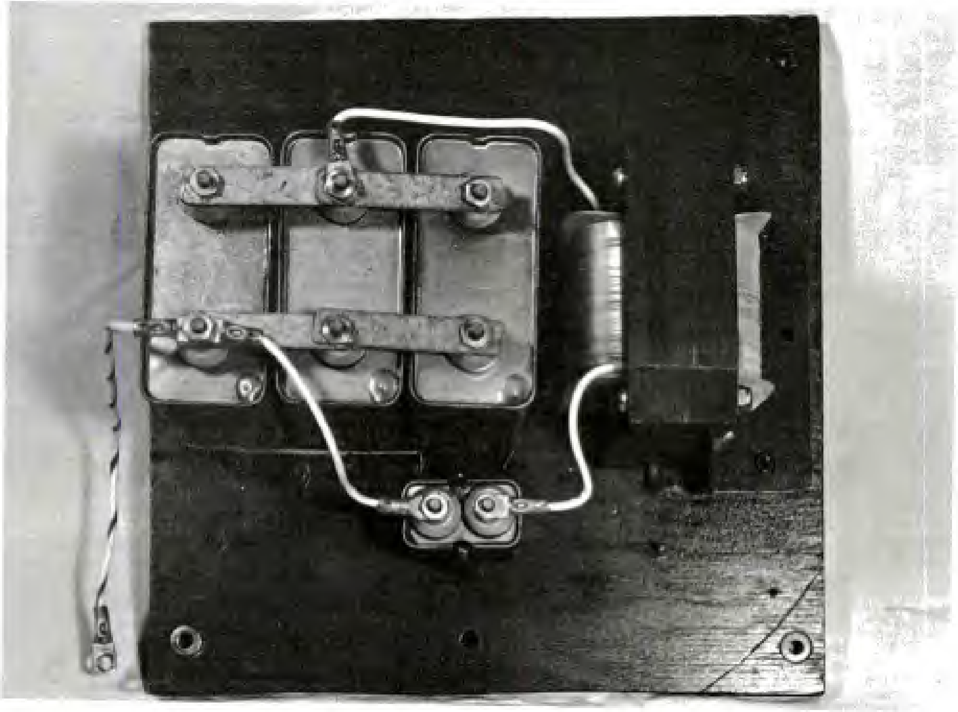


Figure 9. Breadboard model of a 10-ampere, 120-volt power filter.

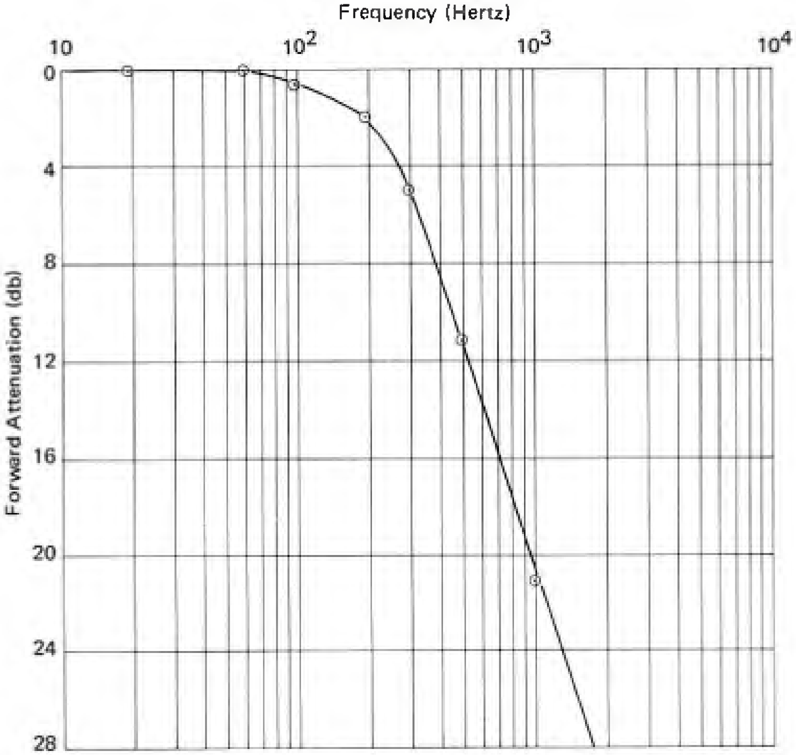


Figure 10. Measured attenuation characteristics of the 10-ampere, three-element power filter.

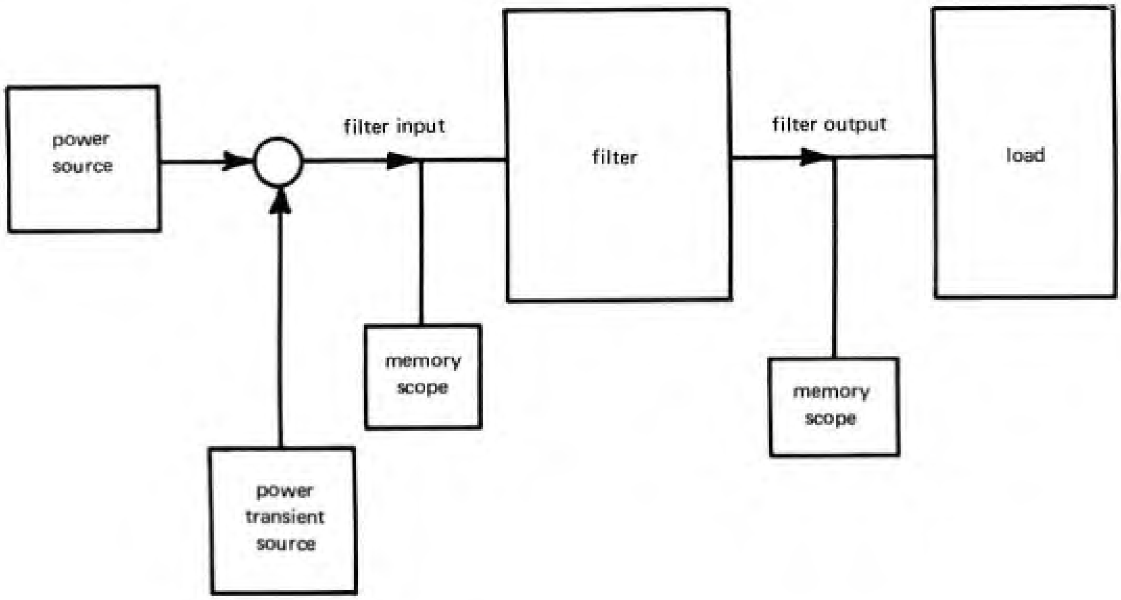
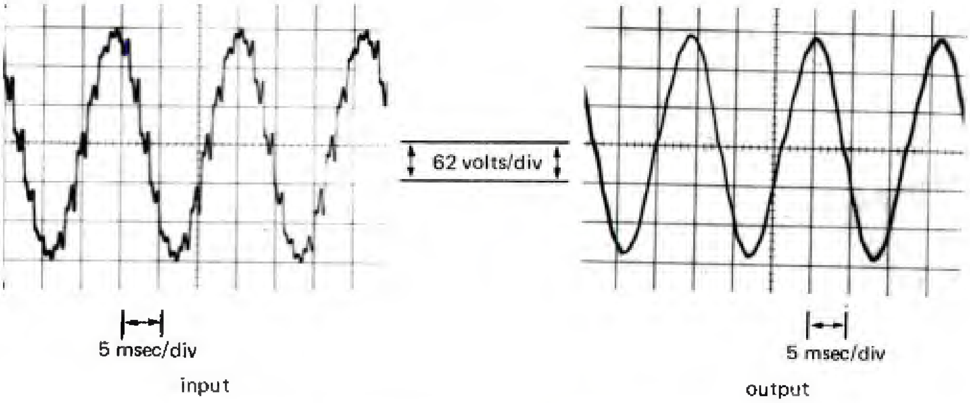
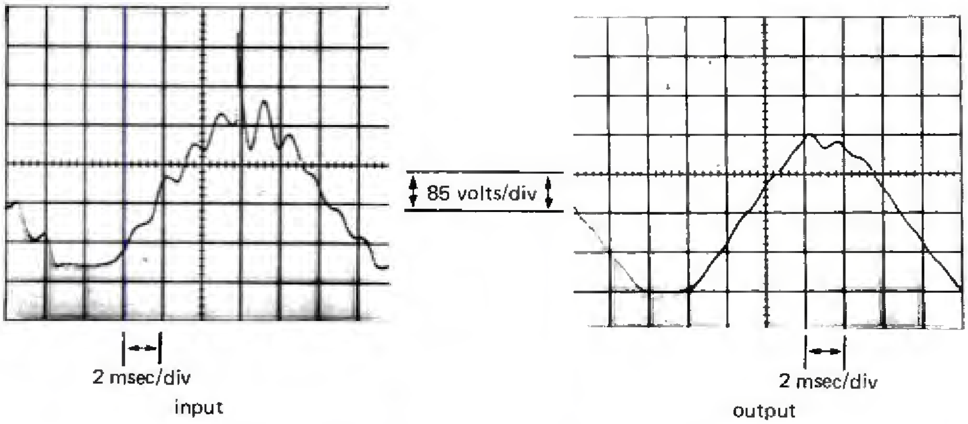


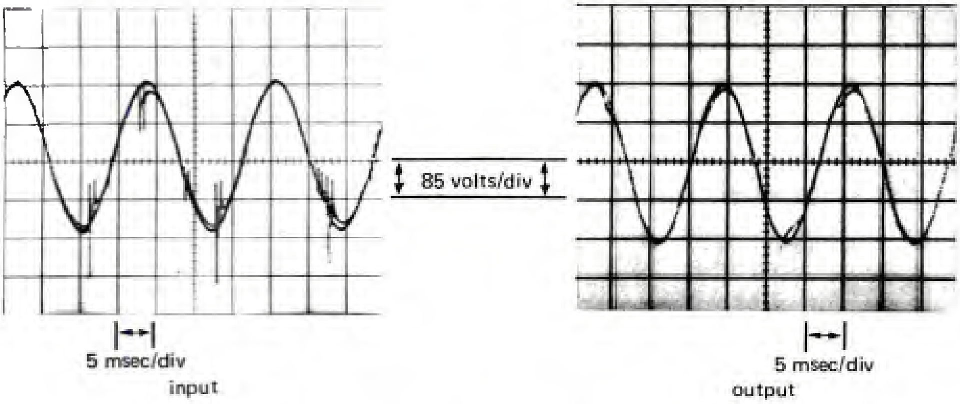
Figure 11. Filter testing block diagram.



(a) Input-output voltage waveforms with input containing low-frequency transients.

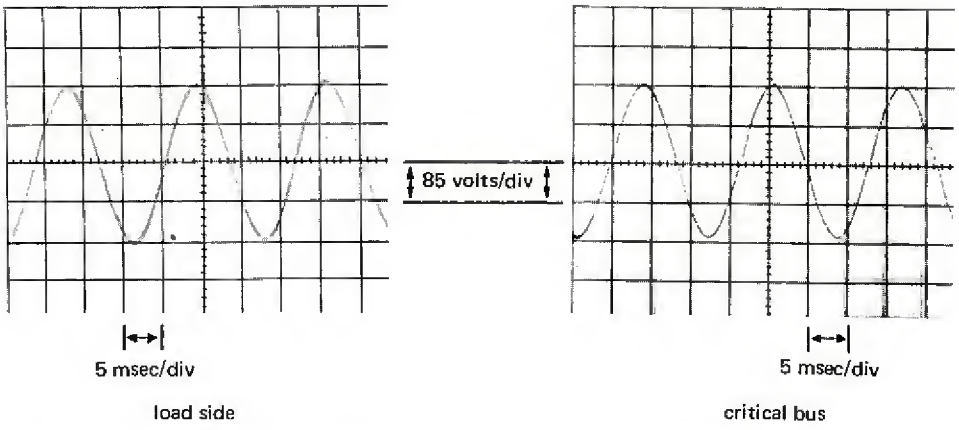


(b) Input-output voltage waveform with input containing a high-voltage pulse associated with low-frequency oscillatory voltage.



(c) Input-output voltage waveforms with input containing spike voltage transients.

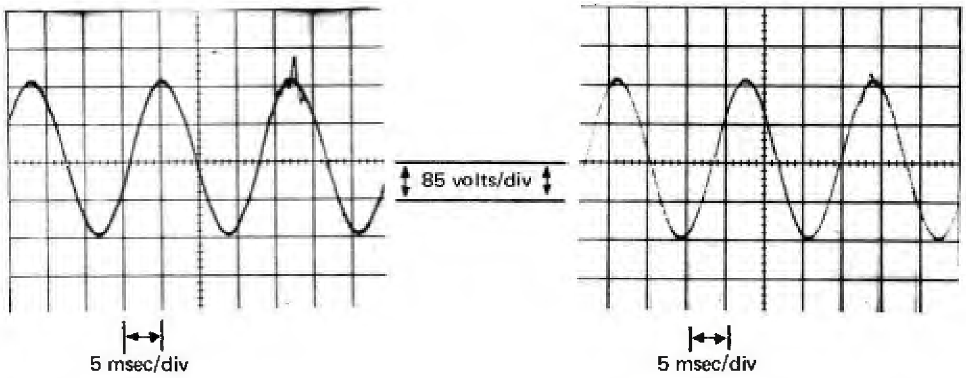
Figure 12. Filter performance.



(a) Filter output waveform containing a transient created at the load side.

(b) Filter input waveform.

Figure 13. Filter performance showing reverse filtering action.



(a) Input.

(b) Output.

Figure 14. Voltage waveforms of 120-volt, 10-ampere breadboard power filter, with input voltage containing transient caused by utility company power factor correction capacitors.

THREE-PHASE FILTER

A three-phase filter is shown in Figure 15. The value of each of the three inductors is equal to that of the single-phase inductor, and the value of each of the three capacitors, C_2', is equal to that of the single-phase capacitor C_2. Similarly, C_1' is equal to C_1. With this arrangement the performance of each line-to-line filter will be at least equivalent to that of a single-phase filter.

Figure 16 shows a fabricated prototype three-phase, three-wire output power filter. This filter is designed for 208 volts, 12 amperes in line 1 and 10 amperes in lines 2 and 3. Figure 17 shows a typical line-to-line input transient and the transient-free filtered output.

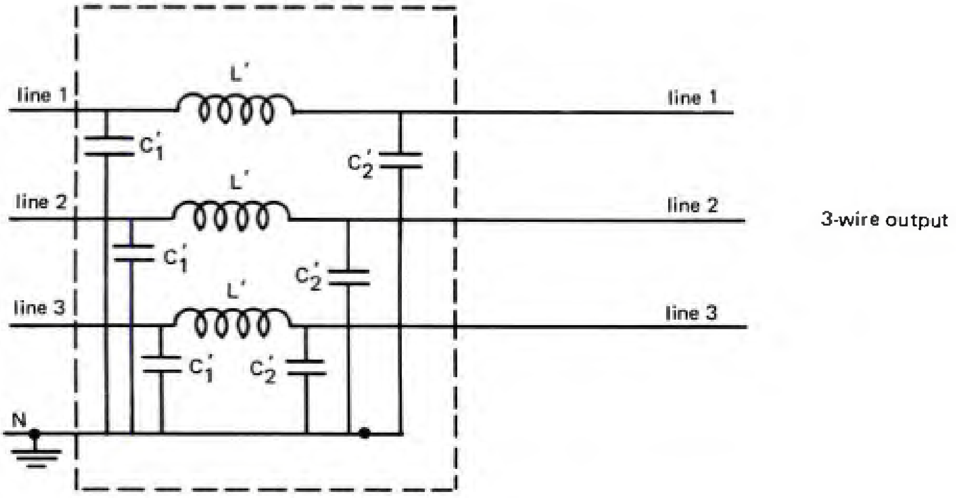
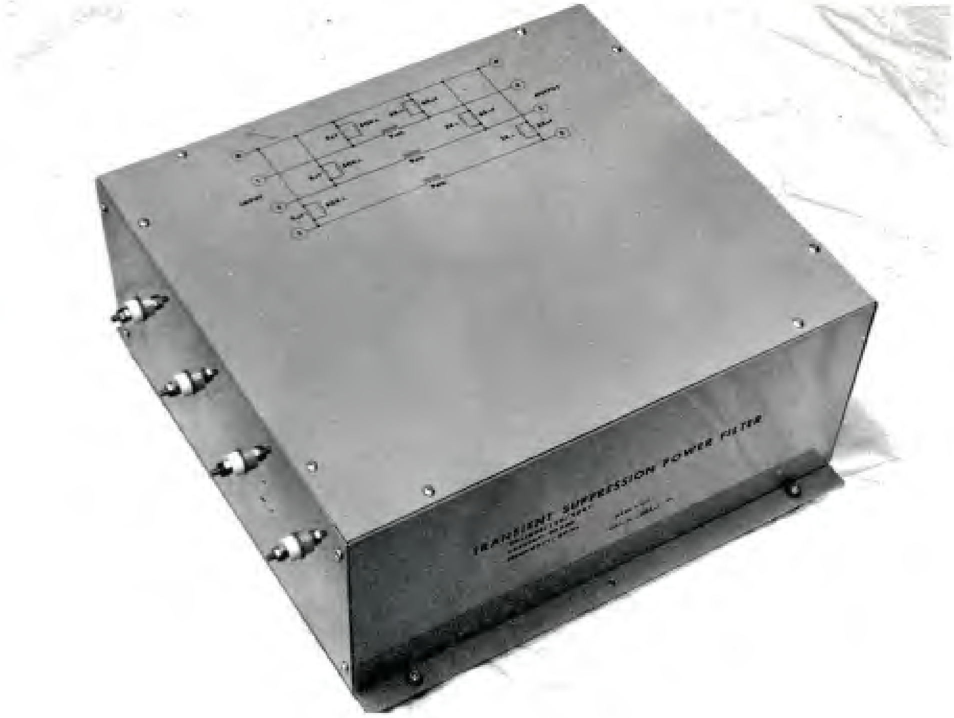


Figure 15. Three-phase filter network.



(a) External view

(b) Internal view.

Figure 16. Prototype of the three-phase filter.

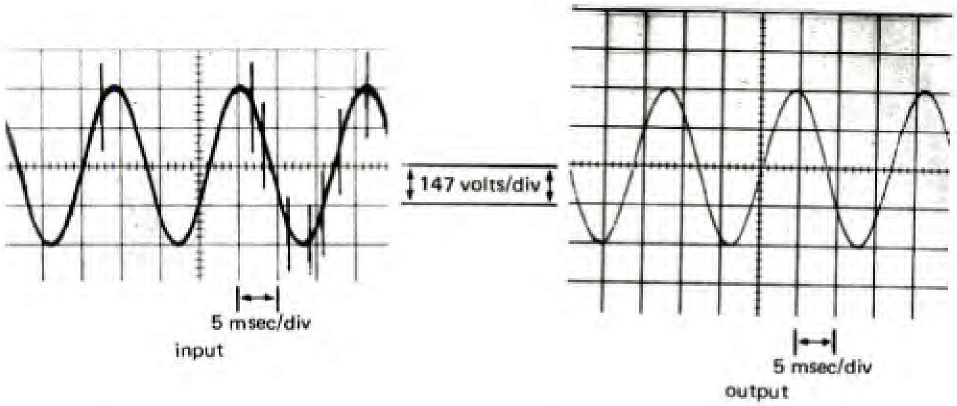


Figure 17. Typical line-to-line input transients and the transient-free output waveforms.

FINDINGS

1. Resistance-capacitance filters are not practical for protecting transient-sensitive equipment against commonly occurring low-frequency harmful power transients.

2. A two-element inductance-capacitance filter is capable of protecting electronic equipment against commonly occurring harmful power transients.

CONCLUSIONS

The use of a two-element inductance-capacitance power filter is an economical means by which transient-sensitive electronic equipment can be effectively protected against harmful power transients. With the addition of a capacitor across the filter input, load-originated transients are effectively suppressed from feeding back onto the critical power bus.

RECOMMENDATION

The feasibility of designing compact and economical high power level filters characterized by a low cutoff frequency should be investigated.

Appendix A

COMPUTER PROGRAM FOR DESIGNING POWER FILTERS

The 1620 FORTRAN II programs used in designing power filters are given below.

1. Two-element L-filter.

```
      READ100,RL,RS,H,C
  100 FORMAT(5E16.4)
      PI=+3.1416E+00
      Y=+8.6858E+00
      FREQ=10.
    6 OMEGA=2.*PI*FREQ
      A=RL+RS
      B=RL*RS
      XL=OMEGA*H
      Y1=OMEGA*C
      XC=1./Y1
      X=XL-XC
      X2=X*X
      Y2=Y1*Y1
      Y3=XC/RL
      ONE=(Y2*A*X)**2
      TWO=Y2*(B-X2)
      THREE=1.+TWO
      Z1=THREE*THREE
      Z2=ONE+Z1
      Z=SQRTF(Z2)
      VRATIO=Y3*Z
      DB=Y*LOGF(VRATIO)
      PUNCH200,FREQ,VRATIO,DB
  200 FORMAT(5E16.4)
      IF(FREQ-500.) 20,5,5
   20 FREQ=FREQ+10.
      GO TO 6
    5 IF(FREQ-1000.) 21,7,7
   21 FREQ=FREQ+100.
      GO TO 6
    7 IF(FREQ-10000.) 22,8,8
   22 FREQ=FREQ+500.
      GO TO 6
    8 IF (FREQ-100000.) 24,10,10
   24 FREQ=FREQ+10000.
      GO TO 6
   10 IF(FREQ-1000000.)25,11,11
   25 FREQ=FREQ+100000.
      GO TO 6
   11 IF(FREQ-10000000.) 26,12,12
   26 FREQ=FREQ+1000000.
      GO TO 6
   12 STOP
      END
```

where RL = load impedance (ohms)

R = inductor resistance (ohms)

RS = source impedance (ohms)

H = inductance **L** (henrys)

CL = capacitance C_2 (farads)

CS = capacitance C_1 (farads)

PI = 3.1414

Y = decibel conversion factor = 8.6858

VRATIO = $V_O/V_I = V_{Out}/V_{Input}$

2. Five-element power filter.

```
      RS=.01
      RL=10.4
      H1=.010
      F1=.000025
      F2=.000100
      PI=3.1415927*2.
   90 FORMAT(58H                            TWO PI SECTION SYMMETRICAL FILTE
     1R  )
   95 FORMAT(/3X3HL1=E10.3,3X3HC1=E10.3,3X3HC2=E10.3,3X3HRS=E10.3,3X3HRL
     1=E10.3)
  100 FORMAT(/3X2HHZ5X5HVO/VI9X2HDB)
  110 FORMAT(I5,2XE11.4,1XE11.4,1XE11.4)
      PUNCH 90
      PUNCH 95,H1,F1,F2,RS,RL
      PUNCH 100
      M1=20
      M2=480
      M3=20
    2 DO 3 I=M1,M2,M3
      CC=I
      W=CC*PI
      W2=W*W
      DA=1.-W2*H1*F1
      FB=F2+F1/DA
      DB=1.-W2*H1*FB
      C11=FI+FB/DB
      C12=C11*DA*DB
      DD=W*C11*C12
      B=DD*C11*RL
      C=C12*C12-C11*C11
      D=DD*C12*RL
      E1=C*C+D*D
      A1=B*D/E1
      B1=B*C/F1
      AM1=SQRTF(A1*A1+B1*B1)
      DB1=8.6858896*LOGF(AM1)
    3 PUNCH 110,I,AM1,DB1
      IF(CC-5.E2) 4,5,5
    4 M1=500
      M2=5000
      M3=100
      GO TO 2
    5 STOP
      END
```

where RS = source impedance (ohms)

RL = load impedance (ohms)

H1 = L_1 = L_2 = inductance (henrys)

F1 = C_1 = C_3 = capacitance (farads)

F_2 = C_2 = capacitance (farads)

Various frequency ranges may be obtained by changing the values of M_1, M_2, and M_3.

Appendix B

DERIVATION OF INDUCTOR DESIGN EQUATIONS

The induced voltage due to flux variation in a coil is given by

$$e = N \frac{d\phi}{dt} \times 10^{-8} \qquad \text{(B-1)}$$

where t = time

ϕ = the total flux

If the flux variation is sinusoidal, then

$$\phi = \phi_{max} \sin(\omega t) \qquad \text{(B-2)}$$

where ϕ_{max} is the maximum amplitude of the flux and Equation B-1 becomes

$$e = -N \phi_{max} \omega \cos(\omega t) \times 10^{-8} \qquad \text{(B-3)}$$

This voltage has an effective value of

$$E = 0.707 \times 2\pi f N \phi \times 10^{-8} \qquad \text{(B-4)}$$

$$= 4.44 N \phi_{max} f \times 10^{-8}$$

Transforming ϕ_{max} into gauss, Equation B-4 becomes

$$E = \frac{1}{3.49} N f \phi_{max} \times 10^{-6} \qquad \text{(B-5)}$$

but $\phi_{max} = B_{AC} A_c$

Then, the AC flux density is given by

$$B_{AC} = \frac{3.49 E \times 10^{6}}{N f A_c} \qquad \text{(B-6)}$$

In a magnetic circuit, the flux is defined by Equation B-7:

$$\phi = \frac{\text{mmf}}{\text{reluctance } (\mathcal{R})} \qquad \text{(B-7)}$$

where the magneto motive force, **mmf**, $= 0.4\pi NI$; and the reluctance, $\mathcal{R}$, $= l_g + l_c/\mu_\Delta$.

Therefore, Equation B-7 may be rewritten as

$$\phi = \frac{0.4\pi NI}{\dfrac{l_g}{A_c} + \dfrac{l_c}{\mu_\Delta A_c}} \qquad \text{(B-8)}$$

The value of the inductance is obtained by the definition

$$L = \frac{\text{flux linkage}}{\text{ampere}} \qquad \text{(B-9)}$$

Combining Equations B-8 and B-9 and simplifying, the value of **L** becomes

$$L = \frac{3.19 N^2 A_c \times 10^{-8}}{l_g + \dfrac{l_c}{\mu_\Delta}} \qquad \text{(B-10)}$$

Equations B-10 and B-6 are the basic Equations 8 and 9 used in the body of the report.

BIBLIOGRAPHY

R. Lee. "Electronic transformers and circuits. New York, Wiley, 1947.

H. M. Schlicke and H. Weidmann. "Compatible EMI filters," IEEE Spectrum, vol. 4, no. 10, Oct. 1967, pp. 59-68.

White Electromagnetics, Inc. A handbook on electrical filters; synthesis, design and applications. Rockville, Md., 1963.

A. I. Zverev. "The golden anniversary of electric wave filters," IEEE Spectrum, vol. 3, no. 3, Mar. 1966, pp. 129-131.

———. Handbook of filter synthesis. New York, Wiley, 1967.

LIST OF SYMBOLS

A_c	core cross-sectional area (in.^{2})
B_{AC}	full load flux density (gauss)
C C_1 C_2 C_3 C_1' C_2'	AC capacitors
E	$I\omega L$ = voltage across inductor **L**
E_L	load voltage or filter output voltage
E_S	source voltage or input voltage
e	induced voltage
f	frequency
f_c	cutoff frequency
f_t	frequency of the fundamental component of transients
I	full load current
j	$\sqrt{-1}$
L L_1 L_2	inductors
l_c	iron core length (in.)
l_ν	length of inductor air gap
N	number of turns of inductor **L**
R	resistance of inductor **L**
R_{eq}	equivalent paralleled impedance of R_S and R_L
R_L	load impedance
R_S	internal source impedance
R_t	internal transient source impedance
$\mathcal{R}$	reluctance
t	time
X_1 X_2 Y Y_1	dummy variables
X_{C_1} X_{C_2} X_{C_3}	reactance of C_1, C_2, and C_3, respectively
X_L X_{L_1} X_{L_2}	reactance of L, L_1, and L_2, respectively
α_1	forward voltage attenuation in db = **20** $\log_{10}(E_S/E_L)$
α_2	reverse voltage attenuation (db)
μ_Δ	incremental permeability of the iron core
ϕ	total flux
ϕ_{max}	maximum instantaneous flux
ω	$2\pi f$ radian frequency

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TR-636 31 p. illus August 1969 Unclassified
1. Transient suppression I. YF 38.534.005.01.001

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