BIBLIOGRAPHY

AIEE Committee Report. " Automatic Load Shedding," AIEE Transactions. (Power Apparatus and Systems), 74:1143-46, December, 1955.

Bauman,H.A.,G.R.Hahn, and C.N. Metcalf. " The Effect of Frequency Reduction on Plant Capacity and on System Operation," AIEE Trans. (Power Apparatus and Systems), 73:1632-37, February, 1955.

Berry, D.H. and others. "Underfrequency Protection of the Ontario Hydro System," CIGRE, 32-14, 1970 Session -- 24 August-2 September.

Berdy , J. "Load Shedding -- Application Guide," General Electric Company, Trans. 1968.

Crary, Selden B. Power System Stability. Vol. 2, New York: John Wiley & Sons, Inc., 1955.

Concordia, C. "Panel on Load Shedding and Bail-Out Frequencies," EEI System Planning Committee, Feb. 13-14, 1969.

Dalziel, Charles F., Edward W. Steinback. " Underfrequency Protection of Power Systems for System Relief, " AIEE Transactions, Pt. III-B (Power Apparatus and Systems), 78:1227-37, December, 1959.

Friedlander, Gordon D. " The Northeast Power Failure, " IEEE Spectrum, February, 1966, pp. 54-73.

______ . "Prevention of Power Failures-- The FPC Report of 1967, " IEEE Spectrum, Feb. 1968, pp.54-61.

Fountain,L.L., and J.L. Blackburn. "Application and Test of Frequency Relays for Load Shedding," AIEE Trans. (Power Apparatus and Systems), 73:1660-64, February, 1955.

IEEE Committee Report. " Survey of Underfrequency Relay Tripping of load Under Energency Conditions, " IEEE Transactions on Power Apparatus and Systems, Vol. PAS-87, No.5, May, 1968,pp. 1362-66.

Kimbark, Edward W. Power System Stability. Vol.1, New York : John Wiley & Sons, Inc., 1961.

Lokay, H.E., and V. Burtnyk. "Developing Automatic Load-Shedding Programs with Underfrequency Relay ," Westinghouse Engineer Vol.28, No.2, March, 1968, pp. 52-57.

______ ___ ______. " Application of Underfrequency Relays for Automatic Load Shedding, " IEEE Transactions on Power Apparatus and Systems, Vol. PAS-87, No.3, March, 1968, pp. 776-783.

New, Warren C. " Load Conservation by Means of Underfrequency Relays. " Presented at Nineteenth Annual Conference for Protective Relay Engineers, Texas A & M University, 1966.

Porretta, B.,and R.D.Brown. " Underfrequency Protection of Electrical Power System. " Presented to Power System Planning and Operating Section at Spring Meeting Canadian Electrical Association, Toronto, Ontario, April, 1968.

Squire P.J. " Operation at Low Frequency in Great Britain, " AIEE Trans. (Power Apparatus and Systems), 73:1647-50, February, 1955.

Swanson, J.O.,and J.P.Jolliffe. "Load Shedding Program in the Pacific Northwest," AIEE Transaction (Power Apparatus and Systems), 73:1655-60,February,1955.

APPENDIX

APPENDIX A

Derivation of the Frequency Decrement Equations

The torque versus frequency characteristic of generator prime movers and of the electric load is such that as the frequency starts to change because of an unbalance between load and generation, the magnitude of the unbalance is diminished and eventually is reduced to zero. The relationship which defines the variation of frequency with time after a sudden loss of generation, is derived from the basic equation for the motion of a rotating machine:

$$Ta = I \frac{d^2\theta}{dt^2} = \frac{WR^2}{32.2} \cdot \frac{d^2\theta'}{dt^2} \text{ lb-ft (pound-feet)} \qquad (1)$$

Definition of terms: see Figs A.1 and A.2

Ta = net accelerating torque

θ' = displacement angle, mechanical radians from a fixed axis

θ = displacement angle, electrical radians from a fixed axis

δ' = displacement angle, mechanical radians from a synchronous rotating axis

δ = displacement angle, electrical radians from a synchronous rotating axis

Wo' = synchronous velocity, mechanical radians per second

Wo = synchronous velocity, electrical radians per second

P = number of poles

fo = base frequency, Hz.

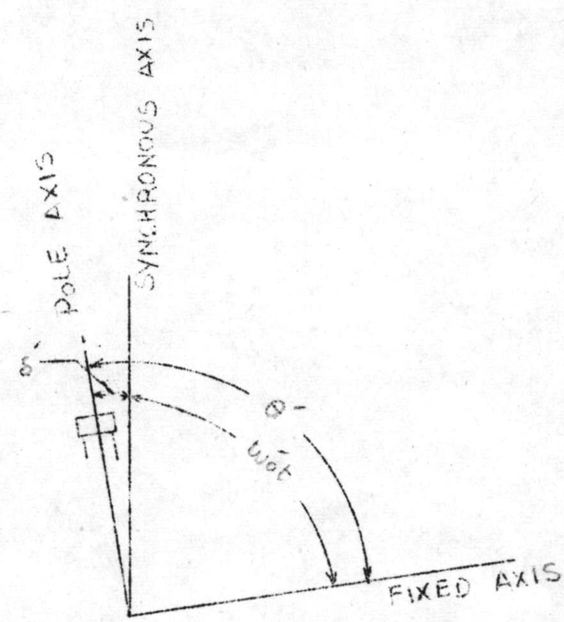

Fig. A.1 Angles in mechanical unit

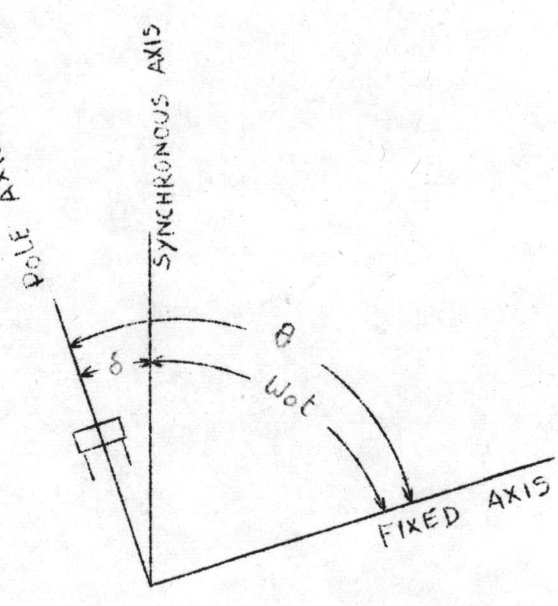

Fig. A.2 Angles in electrical unit

f = actual frequency, Hz.

rpmo = base or synchronous speed

t = time in seconds

From Fig. A.1 $\theta' = \delta' + W_o' t$

Taking the derivative of both sides of the equation with respect to time,

$$\frac{d\theta'}{dt} = \frac{d\delta'}{dt} + W_o'$$

and taking the derivative again

$$\frac{d^2\theta'}{dt^2} = \frac{d^2\delta'}{dt^2} \qquad (2)$$

Substituting equation (2) in equation (1)

$$Ta = \frac{WR^2}{32.2} \frac{d^2\delta'}{dt^2} \text{ lb-ft} \qquad (3)$$

Now $\delta = \frac{P}{2} \delta'$

and $\frac{P}{2} = \frac{60\ fo}{rpmo}$

$$\therefore \delta' = \frac{rpmo}{60fo} \delta$$

$$\frac{d\delta'}{dt} = \frac{rpmo}{60fo} \frac{d\delta}{dt}$$

and $$\frac{d^2\delta'}{dt^2} = \frac{rpmo}{60fo} \frac{d^2\delta}{dt^2} \qquad (4)$$

Substituting equation (4) in equation (3)

$$Ta = \frac{WR^2}{32.2} \cdot \frac{rpmo}{60fo} \cdot \frac{d^2\delta}{dt^2} \text{ lb-ft} \qquad (5)$$

Base torque are $\frac{33,000 \text{ hp}}{2\pi \text{ rpmo}}$ lb-ft or $\frac{33,000 \text{ base KW}}{2\pi \text{ rpmo } 0.746}$ lb-ft

$$\text{per unit torque} = \frac{\text{actual torque}}{\text{base torque}}$$

Hence p-u accelerating torque, $Ta = \frac{WR^2 \text{rpmo } 2\pi \text{ rpmo } 0.746}{32.2 \; 60fo \; 33,000 \text{ base KW}} \frac{d^2\delta}{dt^2}$

In p-u system base KW = base KVA

$$\therefore Ta = \frac{0.231 WR^2 (rpmo)^2 10^{-6}}{\text{KVA base}} \cdot \frac{1}{\pi fo} \cdot \frac{d^2\delta}{dt^2}$$

or
$$Ta = T_G - T_L = \frac{H}{\pi fo} \frac{d^2\delta}{dt^2} \text{ p-u torque} \qquad (6)$$

where $H = \frac{0.231 WR^2 (rpmo)^2 10^{-6}}{\text{KVA base}}$ = generator inertia constant

= the kinetic energy of rotation in KW seconds per KVA

T_G = per unit mechanical torque

T_L = per unit electrical torque on T_G base

From Fig. A.2
$$\theta = \delta + Wot$$

$$\frac{d\theta}{dt} = \frac{d\delta}{dt} + Wo$$

The velocity of the machine is $W = \frac{d\delta}{dt} + Wo = 2\pi f$

Taking the derivative
$$\frac{d^2\delta}{dt^2} = 2\pi \frac{df}{dt} \qquad (7)$$

Substituting equation (7) in equation (6) and **rearranging**

$$\frac{df}{dt} = \frac{(T_G - T_L) fo}{2H} = \frac{Ta\ fo}{2H} \qquad (8)$$

This expression can be used to give system frequency when there is sudden change in generation and when generator and load torques remain constant.

In this case:

$\frac{df}{dt}$ = rate of change of frequency in Hz/sec.

H = system inertia constant. This is equal to the sum of all of the generator inertia constants in per-unit on the total remaining generation base.

T_G = per unit torque of the remaining system generation.

T_L = per unit load torque on the remaining system generation base.

Ta = net accelerating torque. When $T_G > T_L$, Ta is positive and accelerating. When $T_G < T_L$, Ta is negative and decelerating.

Since Ta is constant, this equation represents a straight line, (starting at f = fo and t = 0), having a slope of $\frac{Ta\ fo}{2H}$.

When load and generator torque varied with frequency. Load power will vary directly as some power of frequency.[1]

$$\therefore \quad P_L = kf^D$$

where

P_L = per unit load power

k = constant

f = frequency

D = factor which is a function of the composition of the load or load reduction rate.

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[1] J. Berdy, "Load Shedding--Application Guide," General Electric Company, Trans, 1968, p.4; and charles F. Dalzied and Edward W. Steinback, "Underfrequency Protection of Power Systems for System Relief," AIEE Transactions, Pt. III-B, December, 1959, 1237.

Per unit load torque (T_L) is equal to load power devided by frequency

$$T_L = \frac{P_L}{f} = \frac{kf^D}{f}$$

$$T_L = kf^{D-1} \tag{10}$$

For small changes in frequency, the load torque may be obtained by the following procedure:

$$T_L = kf^{D-1}$$

$$\frac{dT_L}{df} = (D-1)kf^{D-2}$$

$$\Delta T_L = (D-1)kf^{D-2} \Delta f$$

$$T_{LO} + \Delta T_L = kf^{D-1} + (D-1)kf^{D-2} \Delta f$$

$$= kf^{D-2} \left[f + (D-1) \Delta f \right]$$

$$= \frac{kf^{D-1}}{f} \left[f + (D-1) \Delta f \right]$$

substituting $kf^{D-1} = T_{LO}$

$$T_{LO} + \Delta T_L = T_{LO} \left[1 + (D-1) f' \right]$$

Then $$T_L = T_{LO} \left[1 + (D-1) f' \right] \tag{11}$$

where

$f' = \frac{\Delta f}{f}$ per unit change in frequency

f' is negative for a change below 50 Hz

f' is positive for a change above 50 Hz

D = function of load composition-damping factor

T_{LO} = initial per unit load torque

T_L = per unit load torque after a per unit frequency change of f'

Assuming constant input power to the local prime mover when loss of generation occured. Generator torque will vary inversely as the first power of frequency.[2]

$$\therefore \quad T_G = \frac{k}{f} = kf^{-1} \tag{12}$$

For small changes in frequency, the generator torque may be obtained by the following procedure:

$$\frac{dT_G}{df} = - kf^{-2}$$

$$\Delta T_G = - kf^{-2} \Delta f$$

$$T_{GO} + \Delta T_G = kf^{-1} - kf^{-2} \Delta f$$

$$T_{GO} + \Delta T_G = \frac{kf^{-1}}{f}(f - \Delta f)$$

substituting $kf^{-1} = T_{GO}$

Then $$T_G = T_{GO}(1 - f') \tag{13}$$

where

f' = per unit change in frequency

f' is negative for a change below 50 Hz.

f' is positive for a change above 50 Hz.

T_{GO} = initial per unit generator torque.

T_G = per unit generator torque after a per unit frequency change of f'.

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[2]Berdy, loc. cit.

From equation (8) gives

$$2H \frac{df'}{dt} = Ta = T_G - T_L$$

in substituting the torque expressions equation (11) and (13) in this equation

$$2H \frac{df'}{dt} = T_{GO}(1 - f') - T_{LO}\left[1 + (D-1)f'\right]$$

$$= T_{GO} - T_{LO} - \left[T_{GO} + (D-1)T_{LO}\right] f'$$

Let $D_T = T_{GO} + (D-1)\, T_{LO}$ = total damping factor

$$2H \frac{df'}{dt} + D_T f' = T_{GO} - T_{LO} = Ta \qquad (14)$$

Solving this differential equation

$$2H(Df') + D_T f' = Ta$$

Set $D = 0$, Particular Integral $= \frac{Ta}{D_T}$

Set $Ta = 0$, $D = -\frac{D_T}{2H}$

∴ Complementary function $= Ke^{-\frac{D_T}{2H}t}$

∴ Solution of the differential equation is $f' = Ke^{-\frac{D_T}{2H}t} + \frac{Ta}{D_T}$

At $t = 0$, $f' = 0$ gives $K = -\frac{Ta}{D_T}$

∴ The solution of the differential equation (14) is

$$f' = \frac{Ta}{D_T}\left(1 - e^{-\frac{D_T}{2H}t}\right) \qquad (15)$$

where f' = per unit frequency change

T_a = accelerating torque in per unit on remaining generation base

D_T = total damping factor

H = system inertia constant. This is the inertia of remaining system generation on the remaining generation base

The change in frequency (f') times base frequency (f_o) gives the change in Hz. If Ta is negative, the change in frequency will be negative and the frequency at any instant of time will be equal to ($f_o - f'$).

The above discussion assumes that the frequency decay starts at 50 Hz. The frequency decay starting at some other frequency level (after some load has been shed) can be obtained using the same expression. In this case, the net accelerating torque at the new frequency must be determined using the generator and load torques equations.

APPENDIX B

Derivation of equations for calculating curves of final frequency due to system overload for different percent load reductions per one percent drop in frequency (d).

Given d = percent load reduction per one percent of frequency reduction or load reduction rate.

fo = base frequency, Hz

f = final frequency, Hz

$$OL = \frac{\text{Load - Sum of unit loading remain in service}}{\text{Sum of unit loading remain in service}}, \text{p-u}$$

$$= \frac{\text{Deficient generation}}{\text{Remaining generation}}, \text{ in p-u of remaining area generation.}$$

$$= \frac{\text{Deficient generation}}{\text{1 - Deficient generation}}, \text{ in p-u of remaining area generation}$$

$\therefore$ Deficient generation $= \frac{OL}{1 + OL}$ in p-u of initial area load before deficiency occured. Suppose that this amount of deficiency in generation caused the system frequency to settle out at f Hz. At this frequency, the load was reduced by $(\frac{fo - f}{fo}) \cdot d$ in p-u of initial area load.

So that,

$$\frac{OL}{1 + OL} = \left[\frac{fo - f}{fo}\right] d \qquad (1)$$

Rearranging,

$$f = fo\left[\frac{1 + (\frac{d-1}{d})OL}{1 + OL}\right] \qquad (2)$$

or

$$OL = \frac{(1 - \frac{f}{fo})\,d}{\left[1 - d(1 - \frac{f}{fo})\right]} \qquad (3)$$

APPENDIX C

Derivation of equation for load shedding requirements to have frequency settle out at f Hz.

Given L_D = Load required to be shed in p-u of initial area load

OL = System overload in p-u of remaining area generation

OLf = System overload in p-u of remaining area generation that allow system frequency to settle at f, Hz.

fo = base frequency, Hz.

f = settle out frequency, Hz.

$\therefore$ L_D = (OL - OLf)/(1 + OL) in p-u of initial area load. (1)

$$L_D = \frac{(OL - OLf)}{(1 + OL)} \cdot \frac{1}{(1 + OLf)(1 - d(1 - \frac{f}{fo}))}$$

$$\therefore \quad d(1 - \frac{f}{fo}) = \frac{OLf}{1 + OLf}$$

$$(1 + OLf)(1 - d(1 - \frac{f}{fo})) = (1 + OLf)(1 - \frac{OLf}{1+OLf})$$

$$= 1$$

$$\therefore \quad L_D = \frac{(OL + OL.OLf - OLf - OL.OLf)}{(1 + OL)(1 + OLf)(1 - d(1 - \frac{f}{fo}))}$$

$$= \frac{OL(1 + OLf) - OLf(1 + OL)}{(1 + OL)(1 + OLf)(1 - d(1 - \frac{f}{fo}))}$$

$$L_D = \frac{OL - \dfrac{OLf(1 + OL)}{(1 + OLf)}}{(1 + OL)(1 - d(1 - \frac{f}{fo}))}$$

$$= \frac{OL - d - dOL - \dfrac{OLf(1 + OL)}{1 + OLf} + dOL + d}{(1 + OL)(1 - d(1 - \frac{f}{fo}))}$$

$$= \frac{OL - d(1 + OL) + \dfrac{d(1 + OL)(1 + OLf) - OLf(1 + OL)}{1 + OLf}}{(1 + OL)(1 - d(1 - \frac{f}{fo}))}$$

$$= \frac{OL - d(1 + OL) + \dfrac{(d + dOLf - OLf)(1 + OL)}{1 + OLf}}{(1 + OL)(1 - d(1 - \frac{f}{fo}))}$$

$$= \frac{OL - d(1 + OL) + \frac{df}{fo}(1 + OL)}{(1 + OL)(1 - d(1 - \frac{f}{fo}))}$$

$$= \frac{OL - d(1 - \frac{f}{fo})(1 + OL)}{(1 + OL)(1 - d(1 - \frac{f}{fo}))}$$

$$L_D = \frac{\dfrac{OL}{1 + OL} - d(1 - \frac{f}{fo})}{(1 - d(1 - \frac{f}{fo}))} \qquad (2)$$

APPENDIX D

Derivation of equation for calculating the area under the minimum load shed curve.

Given L_d = Load required to be shed in p-u of initial area load

OL = Initial system overload in p-u of remaining area generation

OL_f = System overload that will cause frequency to setlle at frequency f if no load is shed (in p-u of remaining area generation)

OL_m = Maximum overload that the load shedding program is designed to protect and settle at frequency f.

$\therefore$ L_d = $(OL-OL_f)/(1+OL)$ in p-u of initial area load

$$\text{Area under the minimum load shed curve} = \int_{OL_f}^{OL_m} L_d \, d(OL)$$

$$= \int_{OL_f}^{OL_m} \frac{OL-OL_f}{1+OL} \, d(OL)$$

$$= \int_{OL_f}^{OL_m} \frac{OL}{1+OL} \, d(OL) - \int_{OL_f}^{OL_m} \frac{OL_f}{1+OL} \, d(OL)$$

$$= \int_{OL_f}^{OL_m} \frac{1+OL}{1+OL} \, d(1+OL) - \int_{OL_f}^{OL_m} \frac{d(1+OL)}{1+OL}$$

$$- OL_f \int_{OL_f}^{OL_m} \frac{d(OL)}{1+OL}$$

$$= (1+OL)\Big|_{OL_f}^{OL_m} - \ln(1+OL)\Big|_{OL_f}^{OL_m}$$

$$- OL_f \ln(1+OL)\Big|_{OL_f}^{OL_m}$$

Area under the minimum load shed curve

$$= (1+OL_m)-(1+OL_f)-\ln(1+OL_m)+\ln(1+OL_f)$$

$$-OL_f \ln(1+OL_m)+OL_f \ln(1+OL_f)$$

$$= (OL_m-OL_f)-\ln\frac{(1+OL_m)}{(1+OL_f)} - OL_f \ln\frac{(1+OL_m)}{(1+OL_f)}$$

$$= (OL_m - OL_f)-(1+OL_f)\ln\frac{(1+OL_m)}{(1+OL_f)} \qquad (1)$$

APPENDIX E

Sample calculation of relay setting coordination

System inertia constant, H = 2.25 p-u

Load reduction = 0.79 % per one percent frequency reduction

Maximum overload to be protected, 92.3 percent

Minimum settle out frequency, 50 Hz

Total load to be shed, 48 percent

Number of load shedding steps, 4

Frequency at which last step is shed, 44 Hz

Circuit breaker operating time and aux. relay time = 0.37 sec.

Relay settings selected for first trial:

relay 1 - 49.0 Hz, 7 percent load shed

relay 2 - 48.5 Hz, 14 percent load shed

relay 3 - 47.5 Hz, 14 percent load shed

relay 4 - 46.5 Hz, 13 percent load shed

A) Check Coordination between adjacent relay settings.

A.1) Relay 1 and 2.

a) Determine the overload for which the frequency would settle out just above the setting of relay 2, allowing for the load shed by relay 1

Initial overload for which frequency would settle out at 48.5 Hz with 7-percent load dropped at 49.0 Hz can be calculated from the equation (1) of Appendix C. For convenience, the equation can be rearranged to give the following :

$$\text{Initial overload} = \frac{OL_f + L_d}{1-L_d} \qquad (1)$$

where OL_f is the overload which would result in a final frequency of f if no load had been shed and is obtained from equation (3) of Appendix B or Fig. 3, and L_d is the amount of load shed.

$$OL_f = \frac{(1-\frac{48.5}{50})0.79}{1-0.79(1-\frac{48.5}{50})} = 0.0243$$

$$\text{OL initial} = \frac{0.07+0.0243}{1-0.07} = 0.1014$$

$\therefore$ Initial load torque, T_L = 1+OL initial = 1.1014

Initial generator torque, T_G = 1.0

Accelerating torque, Ta = $T_G - T_L$ = -0.1014

Total damping, D_T = $\left[T_G + (D-1)\ T_L\right]$

= $T_G + (0.79-1)\ T_L$

= 1-0.23

= 0.77

1. Substituting the value of D_T and Ta in equation (15) of Appendix A will give the initial frequency variation with time:

$$f = fo + \frac{Ta\ fo}{D_T}(1-e^{-\frac{D_T}{2H}t})$$

2. At frequency 49 Hz, relay 1 is pick up and the time will be

$$t = \frac{\ln\left[1-\frac{(49.0-50.0)x\ D_T}{Ta\ x\ 50}\right]}{-\frac{D_T}{2H}}$$

= 0.963 sec.

3. The accelerating torque and total damping at frequency 49 Hz can be obtained as follows:

At 49 Hz, the frequency change is $- \frac{1.0}{50} = -0.02$ p-u

Using equation (11) and (13) of Appendix A, the new torques can be calculated

$$T_L = 1.1014\left[1+(0.79-1)\ (-0.02)\right]$$

$$T_G = 1.0\left[1-(-0.02)\right]$$

$$Ta = T_G - T_L = -0.082$$

$$D_T = (T_G-(0.21)\ T_L) = 0.79$$

4. The time at which load step 1 is shed,

t = pick up time + breaker operating time + aux.relay time

= 0.963 + 0.37

= 1.333 sec.

5. The frequency at which load step 1 is shed,

$$f = 49.0 + \frac{Tafo}{D_T}\left[1-e^{-\frac{D_T}{2H}x\cdot 0.37}\right]$$

$$= 48.657 \text{ Hz}$$

Since, this frequency is above the setting of relay 2, coordination is satisfactory and final rate of change of frequency can be obtained as follows:

6. At frequency 48.657 Hz, the frequency change is $- \frac{0.343}{50} = -0.00686$ p-u. Then adjust the load torque and generator torque to this frequency according to the precedure described in step 3 above.

The equivalent load shed is also calculated using equation (11) of Appendix A.

$$T_{SL} = \frac{0.07}{1-0.07}\left[1+(0.79-1)\ \left(\frac{48.657-50}{50}\right)\right] = 0.076$$

Subtracted T_{SL} from adjusted load torque gives net load torque. Then accelerating torque and total damping can be determined.

7. Substituting t = 0 in the differential equation of equation (15) of Appendix A will give the final rate of change of frequency after load is shed.

Then,
$$\frac{df}{dt} = \frac{Ta\ fo}{D_T} \cdot \frac{D_T}{2H} \cdot e^{-\frac{D_T}{2H}t}$$

$$\left.\frac{df}{dt}\right|_{t=0} = \frac{Ta\ fo}{2\ H}$$

$$= -0.026 \quad Hz/sec.$$

A.2) Relay 2 and 3

$$OL\ initial = \frac{OL_{f=47.5} + 0.07+0.14}{1-(0.07+0.14)} = 0.3$$

Initial load torque, T_L = 1.0+0.322 = 1.322

Initial generator torque, T_G = 1

$$Ta = T_G - T_L$$

$$D_T = T_G - (0.21)\ (T_L)$$

Following the procedures in steps 1 through 5 above, the frequency at which load step 1 is shed is 47.79 Hz with time 0.659 sec. after deficiency occurred. The time between the pickup of relay 1 and relay

2 is also calculated according to procedure step 2. Now, the net load torque, the generator torque, the accelerating torque and total damping after first step load was shed can be determined according to procedure step 6. Procedure step 5 is repeated using t = time between pickup of relay 1 and 2 + breaker operating time of relay 2 - breaker operating time of relay 1. The frequency at which load step 2 is shed is found to be 47.45 Hz which is lower than setting of relay 3, coordination is unsatisfactory. To obtain proper coordination, the setting of relay 3 should be changed to 47.3 Hz. Now, all the procedures of section A.2 are repeated and the frequency at which relay 2 shed load is 47.44 Hz with time 0.8037 sec. after deficiency occurred. Repeated procedures step 6 and 7 give final rate of change of frequency = -0.149 Hz/sec.

A.3) Relay 3 and 4

$$\text{OL initial} = \frac{OL_{f=46.5} + 0.07+0.14+0.14}{1-(0.07+0.14+0.14)} = 0.6$$

Similarly, using the procedures described in section A.2, the frequency at which load step 3 is shed is found to be 45.5 Hz and the setting of relay 4 should be changed to 45.3 Hz. Then, all the procedures are repeated and the frequency at which relay 3 shed load is 45.49 Hz with time 0.747 sec, final rate of change of frequency is -0.544 Hz/sec.

B) Check coordination at maximum overload.

Using the new relay setting of section A and the procedure described previously, relay 4 will drop its load when frequency is

43.99 Hz with time 0.843 sec and final rate of change of frequency is 1.1 Hz/sec. This is only 0.01 Hz below the desired value of 44 Hz and for this example is satisfactory.

C) Find the area under load shedding step curve and area under minimum load shed curve.

Area under the minimum load shed curve can be calculated by using equation (1) of Appendix D. Because settle out frequency is 50 Hz, so $OL_f = 0$ and maximum overload (OL_m) for this case is equal to

$$\frac{0+0.07+0.14+0.14+0.13}{1-(0.07+0.14+0.14+0.13)} = 0.923$$

Therefore, $$\text{Area (1)} = 0.923 - \ln(1.923) = 0.269 \text{ p-u}$$

Area under load shedding step curve can be calculated by using equation (3) of Appendix B and equation (1) of Appendix E as follow :

$$OL(1) = OL_{f=49} = 0.016$$

$$OL(2) = \frac{OL_{f=48.5} + 0.07}{1-0.07} = 0.101$$

$$OL(3) = \frac{OL_{f=47.3} + 0.07+0.14}{1-(0.07+0.14)} = 0.338$$

$$OL(4) = \frac{OL_{f=45.3} + 0.07+0.14+0.14}{1-(0.07+0.14+0.14)} = 0.662$$

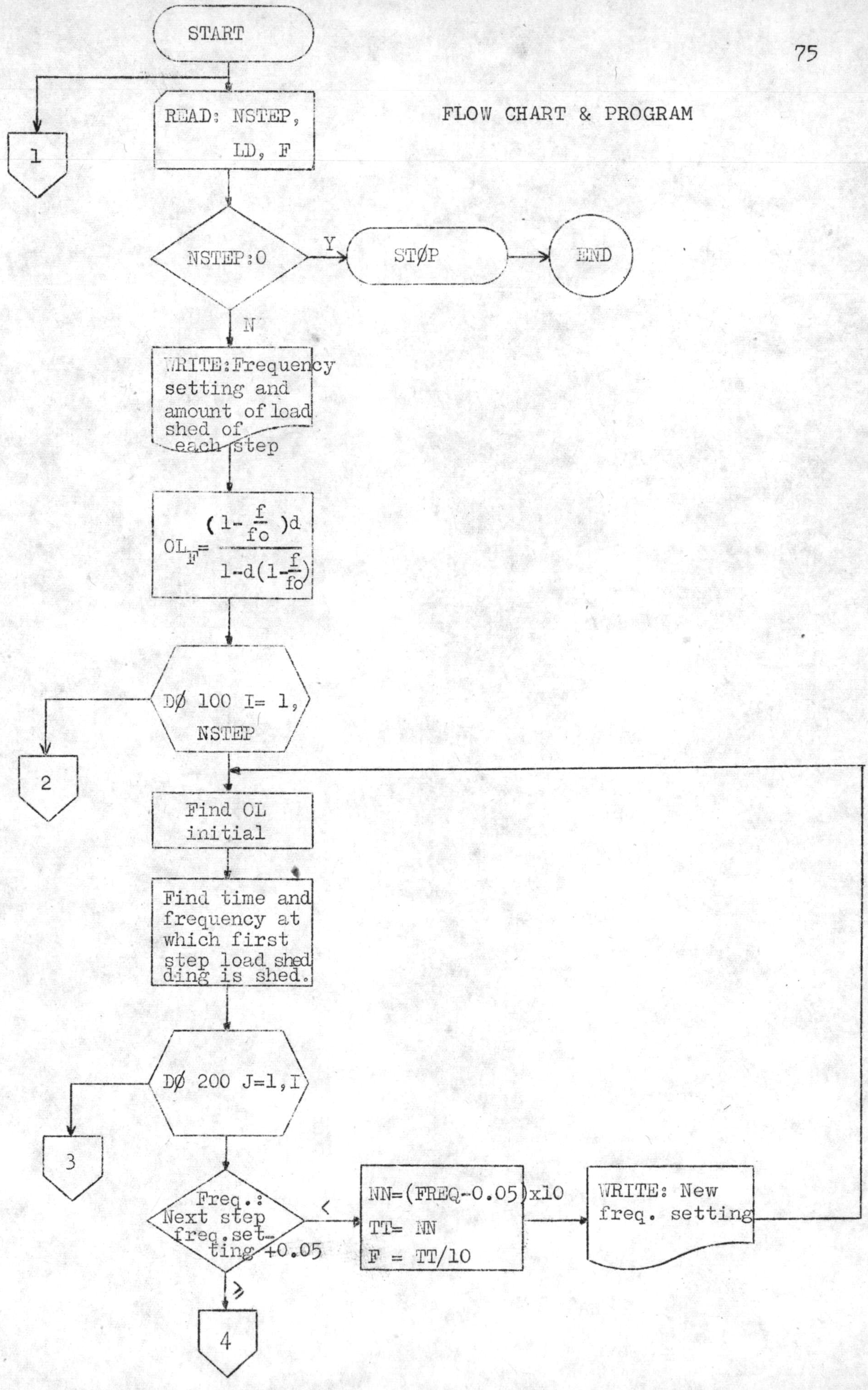
$$OL(5) = OL_m$$

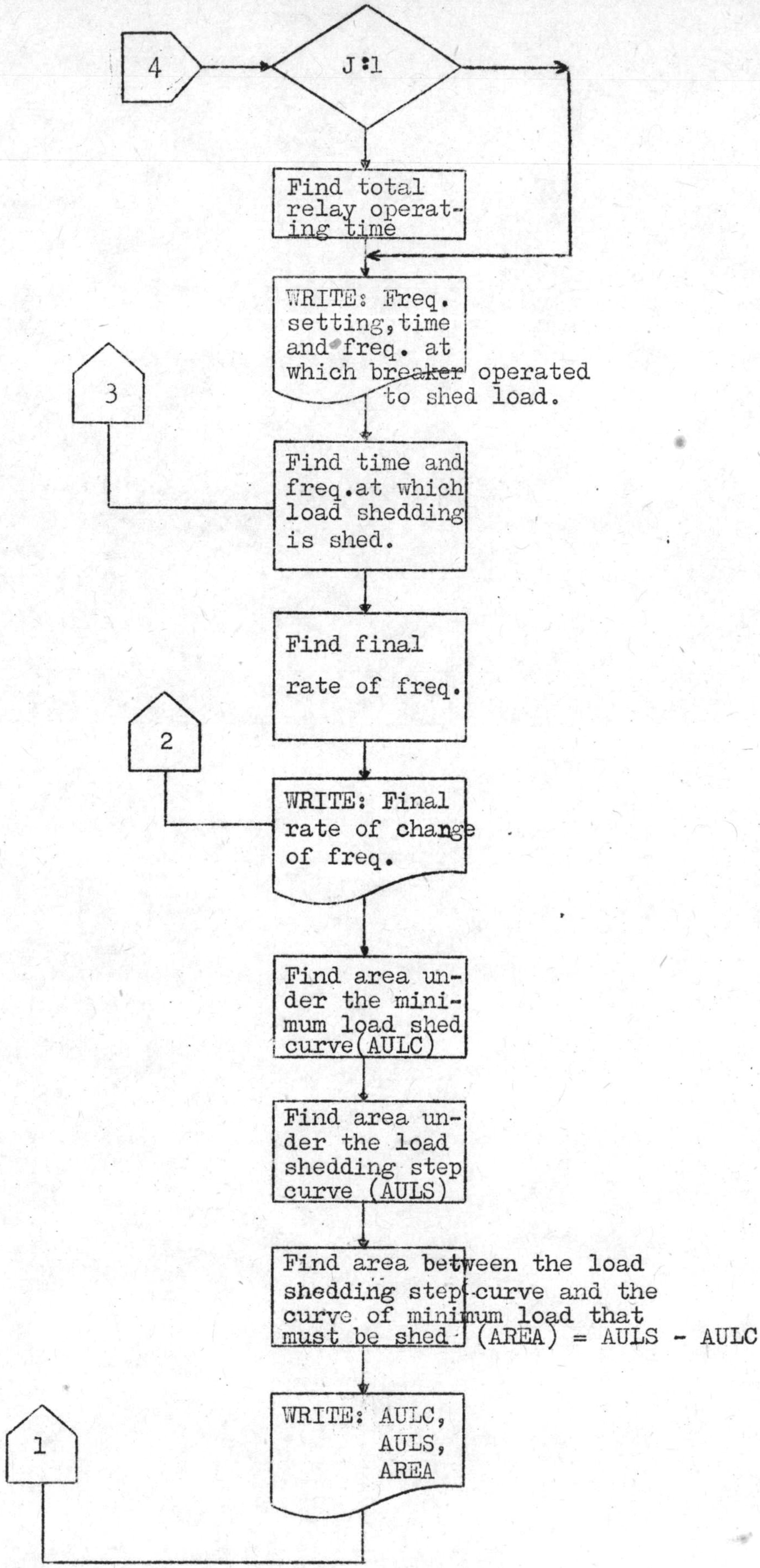
$$\text{Area}(2) = 0.07[OL(2)-OL(1)] + 0.14[OL(3)-OL(2)] +0.14[OL(4)-OL(3)] +0.13[OL(5)-OL(4)]$$

Area (2) = 0.118 p-u

The area between the load shedding step curve and the minimum load shed curve can be calculated using Area(2) - Area(1). Since area under the minimum load shed curve is constant for all case, the combination of number and size of load shedding steps that gives the minimum area of the load shedding step curve is the optimum.

FLOW CHART & PROGRAM




4
J : 1
Find total relay operating time
WRITE: Freq. setting, time and freq. at which breaker operated to shed load.
3
Find time and freq. at which load shedding is shed.
Find final rate of freq.
2
WRITE: Final rate of change of freq.
Find area under the minimum load shed curve (AULC)
Find area under the load shedding step curve (AULS)
Find area between the load shedding step-curve and the curve of minimum load that must be shed (AREA) = AULS - AULC
WRITE: AULC, AULS, AREA
1

```
C        PROGRAM FOR LOAD SHEDDING
C        NSTEP = NUMBER OF LOAD SHEDDING STEP
C        LD = P-U LOAD SHED FOR EACH STEP
C        F = FREQUENCY SETTING FOR EACH STEP
C        F(NSTEP+1) = SETTLE OUT FREQUENCY
C        FO = BASE FREQUENCY
C        M=2H, INERTIA TIME CONSTANT OF THE REMAINING SYSTEM
C        DL = LOAD DAMPING FACTOR
C        D = TOTAL DAMPING FACTOR
C        TCB = RELAY AUX. TIME & C.B. OPERATING TIME
C        OLIN = INITIAL OVERLOAD
C        OLF = OVERLOAD THAT WILL SETTLE AT SETTLE
C              OUT FREQUENCY IF NO LOAD IS SHED
C        OLM=OVERLOAD LOAD SHEDDING PROGRAM TO PROTECT
C            AND SETTLE AT SETTLE OUT FREQUENCY
C        AREA = AREA BETWEEN THE LOAD SHEDDING
C                STEP CURVE AND THE CURVE OF MINIMUM
C                LOAD THAT MUST BE SHED
C        AULS = AREA UNDER THE LOAD SHEDDING STEP CURVE
C        AULC = AREA UNDER THE MINIMUM LOAD SHED CURVE
C        TL = LOAD TORQUE
C        TG = GENERATOR TORQUE
C        TA = ACCELERATING TORGUE
         IMPLICIT REAL (L ,M)
         DIMENSION LD(5),F(6),T(5),OL(5),FREQ(6)
         DIMENSION TIME(5),OLF(6),OLIN(6)
         DATA DL/0.21/,TCB/0.36/,FO/50.0/,KK/1/,M/5.06/
     300 READ(1,3)NSTEP,LD,F
       3 FORMAT(I2,5F6.3,6F5.1)
         IF(NSTEP.EQ.0) GO TO 7
         IF(NSTEP.EQ.3.OR.NSTEP.EQ.2) M = 4.2
      85 WRITE(8,4)
       4 FORMAT('1',//,5X,'***',3X,'LOAD SHEDDING STEPS ARE')
         DO 5 NN =1,NSTEP
       5 WRITE(8,6)NN,F(NN),LD(NN)
       6 FORMAT(//,17X,'STEP',I2,' FREQUENCY SETTING IS',
        1F6.2,' HZ, AMOUNT OF LOAD SHED IS',
        2F7.3,'  P-U OF INITIAL AREA LOAD')
         FREQ(1) = F(1)
         DOL = ((FO-F(1))/FO)*(1.-DL)
         OLF(1) = DOL/(1.-DOL)
         DO 100 I=1,NSTEP
         SUMLD = 0.
         OLIN(1) = 0.
         DO 10 J = 1,I
      10 SUMLD = SUMLD + LD(J)
         DO 11 K = 1,I
         OL(K) = LD(K)/(1.-SUMLD)
      11 OLIN(1) = OLIN(1) +OL(K)
         JJ = I+1
      16 DOL = ((FO-F(JJ))/FO)*(1.-DL)
         OLF(JJ) = DOL/(1.-DOL)
         IF(I.EQ.NSTEP) GO TO 1
         OLIN(JJ) = OLIN(1) +(OLF(JJ)/(1.-SUMLD))
         GO TO 2
       1 OLM = OLIN(1)
         OLIN(JJ) = OLIN(1)
       2 TG = 1.
         TL = 1.+OLIN(JJ)
         TA = TG-TL
          D = TG-(DL*TL)
         T(1) = (-M)*ALOG(1.-((F(1)-FO)*D)/(TA*FO))/D
         DF = (FO-F(1))/FO
```

```
      TL = TL*(1.+(DL*DF))
      TG = TG*(1.+DF)
      TA = TG-TL
      D = TG-(DL*TL)
      FREQ(2)=F(1)+(TA*FO/D)*(1.-EXP((-D)*TCB/M))
      TIME(1) = T(1) +TCB
      IF(I.EQ.NSTEP) GO TO 16
      GO TO (12,14,15,27),I
   12 WRITE(8,70)
   70 FORMAT(//,8X,'**  CHECK COORDINATION',
     1' OF RELAY1 & RELAY2')
      GO TO 17
   14 WRITE(8,71)
   71 FORMAT(//,8X,'**  CHECK COORDINATION',
     1' OF RELAY2 & RELAY3')
      GO TO 17
   15 WRITE(8,72)
   72 FORMAT(//,8X,'**  CHECK COORDINATION',
     1' OF RELAY3 & RELAY4')
      GO TO 17
   27 WRITE(8,84)
   84 FORMAT(//,8X,'**  CHECK COORDINATION',
     1' OF RELAY4 & RELAY5')
      GO TO 17
   16 WRITE(8,73)
   73 FORMAT('1',//,8X,
     1'**  CHECK COORDINATION FOR MAXIMUM OVERLOAD')
   17 N = 1
      DO 200 J =1,I
      IF(J.NE.I.OR.I.EQ.NSTEP) GO TO 25
      JJ = J+1
      IF(FREQ(JJ).GE.(F(JJ)+0.05)) GO TO 25
      NN = (FREQ(JJ)-0.05)*10.
      TT = NN
      F(JJ) = TT/10.
      WRITE(8,78)JJ,F(JJ)
   78 FORMAT(//,15X,'*** FREQUENCY SETTING',
     1' OF RELAY STEP',I3,'  MUST CHANGE TO',
     2F6.2,'  HZ ***')
      GO TO 18
   25 IF(J.EQ.1) GO TO 20
      TIME(J) = T(1)+TCB+T(J)
   20 WRITE(8,74) J,F(J)
   74 FORMAT(//,15X,'STEP',I2,'  OF UNDERFREQUENCY',
     1' RELAY WAS SET AT FREQUENCY',F10.6,'  HZ')
      WRITE(8,75) J,TIME(J),FREQ(J+1)
   75 FORMAT(/,15X,'RELAY STEP  ',I2,'  TRIP AT TIME',
     1F10.6,'  SEC. AND FREQUENCY =',F10.6,'  HZ')
      IF(N.GE.2.OR.J.EQ.I) GO TO 22
      JJ = I-1
      DO 21 K = 1,JJ
   21 T(K+1) = (-M)*ALOG(1.-((F(K+1)-F(1))*D/(TA*FO)))/D
      GO TO (22,22,88,88,88),I
   88 TI = (-M)*ALOG(1.-((47.0-F(1))*D/(TA*FO)))/D
      TI = T(1) +TI
      WRITE (8,87) TI
   87 FORMAT(/,30X,'ZZZZ  T(F=47.0) =',F10.6,'  SEC.   ZZZZ')
   22 DF = (FREQ(J)-FREQ(J+1))/FO
      TL = TL*(1.+(DL*DF))
      TG = TG*(1.+DF)
      TSL = OL(J)*(1.+DL*(FO-FREQ(J+1))/FO)
      TL = TL-TSL
      TA = TG-TL
```

```
      IF(J.EQ.NSTEP) GO TO 19
      D = TG -(DL*TL)
      IF(J.EQ.I) GO TO 13
      IF(J.EQ.1) GO TO 23
      GO TO 24
   23 TT = T(J+1)
      GO TO 30
   24 TT = T(J+1) -T(J)
   30 FREQ(J+2) =FREQ(J+1)+(TA*FO/D)*(1.-EXP((-D)*TT/M))
      N =N+1
  200 CONTINUE
   13 DF = (FREQ(J+1)-F(J+1))/FO
      TL = TL*(1.+(DL*DF))
      TG = TG*(1.+DF)
      TA = TG-TL
   19 DFDT = TA*FO/M
   26 WRITE(8,76)DFDT
   76 FORMAT(/,15X,'FINAL RATE OF CHANGE OF FREQUENCY',
     1' AFTER SHEDDED LAST STEP LOAD IS',F10.6,'   HZ/SEC')
  100 CONTINUE
      N = NSTEP+1
      IF(NSTEP.EQ.3.OR.KK.EQ.2) GO TO 9
      AULC=OLM-OLF(N)-(1.+OLF(N))*ALOG((1.+OLM)/(1.+OLF(N)))
      KK = 2
    9 OLIN(1) =OLF(1)
      OLIN(N) =OLM
      AULS = 0.
      DO 8 NN = 1,NSTEP
    8 AULS = AULS +LD(NN)*(OLIN(NN+1)-OLIN(NN))
      AREA = AULS-AULC
      WRITE(8,80)(OLIN(I),I=1,N)
   80 FORMAT(//,8X,'**  INITIAL OVERLOAD ARE ',
     1F13.9,5(' , ',F13.9))
      WRITE (8,79) F(N)
   79 FORMAT(//,10X,'SETTLE OUT FREQUENCY WAS',F6.2,'  HZ')
      WRITE (8,81)AULC,AULS
   81 FORMAT(//,10X,'AREA UNDER THE MINIMUM LOAD',
     1' SHED CURVE IS',F13.9,'  P-U  , AREA UNDER',
     2' THE LOAD SHEDDING STEP CURVE IS',F13.9,'   P-U')
      WRITE(8,82)
   82 FORMAT(//,10X,'AREA BETWEEN THE LOAD SHEDDING ',
     1'STEP CURVE AND THE CURVE OF MINIMUM LOAD ',
     2'THAT MUST BE SHED')
      WRITE(8,83)AREA
   83 FORMAT(11X,'TO SETTLE AT SETTLE OUT ',
     1'FREQUENCY IS',F13.9,'  P-U')
      GO TO (300,77,77,300,300),NSTEP
   77 II = NSTEP+1
      NSTEP = NSTEP+2
      NN = (FREQ(II)-0.05)*10.
      TT = NN
      F(II) = TT/10.
      M = 5.06
      GO TO 85
    7 STOP
      END
```

TABLE E.1

COMPARISON OF NUMBER OF STEP AND SIZES OF LOAD SHEDDING

Number of Step	Frequency setting & size of load shed at each step					Area under load shedding step curve	Relay operating time to protect maximum overload	Frequency at which last step load was shed	Rate of frequency change when last step load was shed
	STEP 1	STEP 2	STEP 3	STEP 4	STEP 5				
5	49.0 Hz 0.11 p-u	48.4 Hz 0.07 p-u	47.7 Hz 0.06 p-u	47.1 Hz 0.12 p-u	45.6 Hz 0.12 p-u	0.095029 p-u	0.85102 SEC.	44.4509 Hz	0.912 Hz/SEC.
5	49.0 Hz 0.11 p-u	48.4 Hz 0.07 p-u	47.7 Hz 0.06 p-u	47.1 Hz 0.14 p-u	45.3 Hz 0.10 p-u	0.098679 p-u	0.88560 SEC.	44.4804 Hz	0.907 Hz/SEC.
5	49.0 Hz 0.10 p-u	48.4 Hz 0.08 p-u	47.6 Hz 0.06 p-u	47.1 Hz 0.12 p-u	45.6 Hz 0.12 p-u	0.094575 p-u	0.85102 SEC.	44.4260 Hz	0.917 Hz/SEC.
4	49.0 Hz 0.10 p-u	48.4 Hz 0.08 p-u	47.6 Hz 0.06 p-u	47.1 Hz 0.24 p-u		0.159867 p-u	0.68028 SEC.	44.6763 Hz	0.872 Hz/SEC.
5	49.0 Hz 0.09 p-u	48.5 Hz 0.09 p-u	47.7 Hz 0.06 p-u	47.1 Hz 0.12 p-u	45.6 Hz 0.12 p-u	0.094550 p-u	0.85102 SEC.	44.4449 Hz	0.913 Hz/SEC.
4	49.0 Hz 0.09 p-u	48.5 Hz 0.09 p-u	47.7 Hz 0.06 p-u	47.1 Hz 0.24 p-u		0.159843 p-u	0.68028 SEC.	44.6957 Hz	0.869 Hz/SEC.
5	49.0 Hz 0.08 p-u	48.6 Hz 0.10 p-u	47.7 Hz 0.06 p-u	47.2 Hz 0.12 p-u	45.7 Hz 0.12 p-u	0.095272 p-u	0.83952 SEC.	44.4978 Hz	0.904 Hz/SEC.
5	49.0 Hz 0.075p-u	48.6 Hz 0.105p-u	47.7 Hz 0.06 p-u	47.1 Hz 0.12 p-u	45.6 Hz 0.12 p-u	0.095608 p-u	0.85102 SEC.	44.4512 Hz	0.912 Hz/SEC.
5	49.0 Hz 0.085p-u	48.5 Hz 0.095p-u	47.6 Hz 0.06 p-u	47.1 Hz 0.12 p-u	45.6 Hz 0.12 p-u	0.094837 p-u	0.85102 SEC.	44.6775 Hz	0.917 Hz/SEC.
5	49.0 Hz 0.105p-u	48.4 Hz 0.075p-u	47.7 Hz 0.06 p-u	47.1 Hz 0.11 p-u	45.7 Hz 0.13 p-u	0.094724 p-u	0.83952 SEC.	44.4306 Hz	0.917 Hz/SEC.
5	49.0 Hz 0.08 p-u	48.6 Hz 0.08 p-u	47.8 Hz 0.08 p-u	47.1 Hz 0.12 p-u	45.6 Hz 0.12 p-u	0.094325 p-u	0.85102 SEC.	44.4347 Hz	0.915 Hz/SEC.
5	49.0 Hz 0.08 p-u	48.2 Hz 0.08 p-u	47.3 Hz 0.08 p-u	46.7 Hz 0.12 p-u	45.2 Hz 0.12 p-u	0.093958 p-u	0.89716 SEC.	44.1352 Hz	0.972 Hz/SEC.
5	49.0 Hz 0.08 p-u	48.2 Hz 0.08 p-u	47.3 Hz 0.08 p-u	46.7 Hz 0.12 p-u	45.1 Hz 0.12 p-u	0.093958 p-u	0.91534 SEC.	44.1340 Hz	0.958 Hz/SEC.

TABLE E.1 (Continued)

Number of Step	Frequency setting & size of load shed at each step					Area under load shedding step curve	Relay operating time to protect maximum overload	Frequency at which last step load was shed	Rate of frequency change when last step load was shed
	STEP 1	STEP 2	STEP 3	STEP 4	STEP 5				
4	49.0 Hz 0.07 p-u	48.5 Hz 0.14 p-u	47.3 Hz 0.14 p-u	45.3 Hz 0.13 p-u		0.118399 p-u	0.84304 SEC.	43.9886 Hz	1.099 Hz/SEC.
4	49.0 Hz 0.05 p-u	48.6 Hz 0.10 p-u	47.7 Hz 0.10 p-u	46.6 Hz 0.23 p-u		0.154509 p-u	0.70912 SEC.	44.0000 Hz	1.096 Hz/SEC.
4	49.0 Hz 0.06 p-u	48.5 Hz 0.12 p-u	47.5 Hz 0.06 p-u	46.7 Hz 0.24 p-u		0.161505 p-u	0.69891 SEC.	44.0367 Hz	1.089 Hz/SEC.
4	49.0 Hz 0.08 p-u	48.4 Hz 0.12 p-u	47.3 Hz 0.14 p-u	45.4 Hz 0.14 p-u		0.117226 p-u	0.83265 SEC.	43.9254 Hz	1.112 Hz/SEC.
4	49.0 Hz 0.08 p-u	48.4 Hz 0.14 p-u	47.1 Hz 0.13 p-u	45.2 Hz 0.13 p-u		0.115243 p-u	0.85344 SEC.	43.9215 Hz	1.113 Hz/SEC.
3	49.0 Hz 0.08 p-u	48.4 Hz 0.16 p-u	47.0 Hz 0.24 p-u			0.180541 p-u	0.66840 SEC.	44.2800 Hz	1.041 Hz/SEC.
3	49.0 Hz 0.09 p-u	48.4 Hz 0.18 p-u	46.7 Hz 0.21 p-u			0.167578 p-u	0.69891 SEC.	44.2750 Hz	1.042 Hz/SEC.
4	49.0 Hz 0.09 p-u	48.4 Hz 0.13 p-u	47.2 Hz 0.13 p-u	45.3 Hz 0.13 p-u		0.113459 p-u	0.84304 SEC.	43.9796 Hz	1.101 Hz/SEC.
4	49.0 Hz 0.10 p-u	48.3 Hz 0.10 p-u	47.3 Hz 0.15 p-u	45.3 Hz 0.13 p-u		0.116347 p-u	0.84304 SEC.	43.9529 Hz	1.107 Hz/SEC.
4	49.0 Hz 0.11 p-u	48.3 Hz 0.13 p-u	47.0 Hz 0.11 p-u	45.3 Hz 0.13 p-u		0.109529 p-u	0.84304 SEC.	43.9803 Hz	1.101 Hz/SEC.
4	48.9 Hz 0.11 p-u	48.2 Hz 0.13 p-u	46.9 Hz 0.11 p-u	45.2 Hz 0.13 p-u		0.109301 p-u	0.85346 SEC.	43.8897 Hz	1.119 Hz/SEC.
4	49.0 Hz 0.12 p-u	48.2 Hz 0.12 p-u	47.0 Hz 0.12 p-u	45.1 Hz 0.12 p-u		0.108842 p-u	0.86386 SEC.	43.9756 Hz	1.102 Hz/SEC.
4	48.7 Hz 0.12 p-u	48.0 Hz 0.12 p-u	47.0 Hz 0.12 p-u	45.4 Hz 0.12 p-u		0.108250 p-u	0.87400 SEC.	44.3190 Hz	0.935 Hz/SEC.
4	48.4 Hz 0.12 p-u	47.7 Hz 0.12 p-u	46.7 Hz 0.12 p-u	45.1 Hz 0.12 p-u		0.107656 p-u	0.90879 SEC.	44.0437 Hz	0.983 Hz/SEC.

VITA

The author of this thesis, Khanchit Nimmanant, was born in Bangkok, Thailand, on July 18, 1950. He received a Bachelor's Degree of Engineering (Electrical) from Chulalongkorn University in 1972.

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