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Coral Springs, FL 33065

December, 1984
New Information
Mailed to: E, D, C/41-000A

SSO Relay

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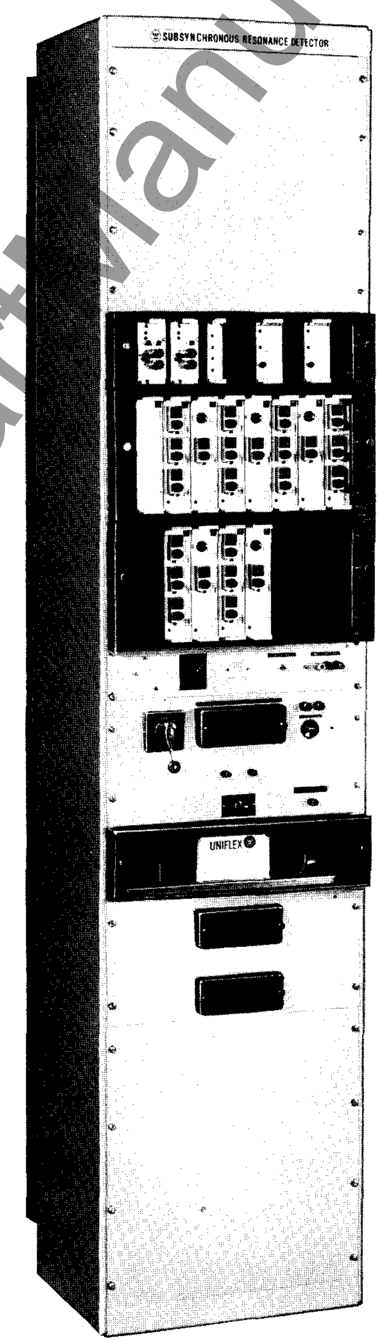

Problem and Background

The increased cost and unavailability of right-of-way, and also escalating construction costs have forced utilities to look for alternate methods to increase power transfer. One very economical means of transmitting electrical power at high voltages over long distances and achieving stability is by the use of series capacitors. In most situations, series compensation will prove to be the economical choice over other approaches to this problem. However, even though economics and stability may dictate this approach, other problems may be encountered which merit some consideration. One such problem is known as subsynchronous resonance. Subsynchronous resonance is a phenomena which occurs when a frequency below electrical rated frequency produces electrical torques acting on the shaft at a natural torsional frequency of the turbine-generator. As a result, the turbine-generator shaft will experience severe oscillatory vibrations. The problem of subsynchronous resonance can be dealt with in many ways. For instance, series capacitor controls, filters, and dynamic stabilizers can be used to reduce the occurrence of this problem. However, there is a need to trip the generator in the case where subsynchronous resonance persists despite the use of the above measures. A relay, type SSO, was developed with the required sensitivity to monitor the subsynchronous resonance phenomena, and to respond in a time adequate to prevent extensive shaft damage.

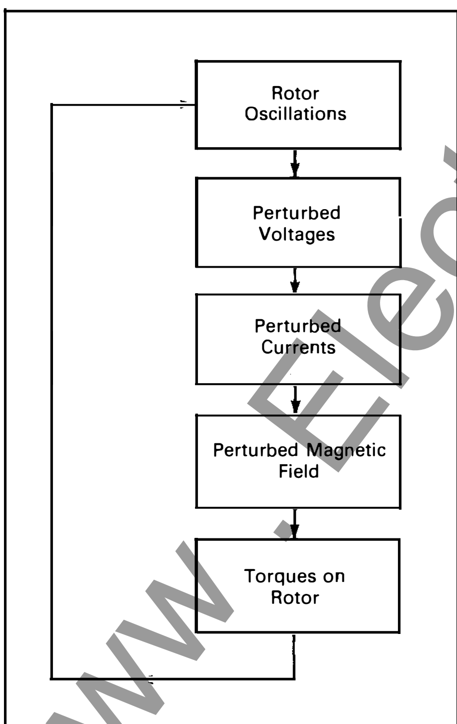

Fig. 1. Torsional Interaction Phenomena

SSR Phenomena

The subsynchronous resonance phenomena can be analyzed from the standpoint of Torsional Interaction, Transient Torques, and the Induction Generator effects. The Torsional Interaction effect can be explained with the aid of the flow chart shown in Figure 1.

Mechanical oscillations cause flux variations producing rotating flux fields at other than synchronous speed. The resulting perturbed voltages cause subsynchronous currents to flow in the generator stator. These subsynchronous currents give rise to perturbed magnetic fields which produce torques on the rotor. If these torques acting on the rotor are at a natural torsional frequency of the turbine-generator, and the system subsynchronous frequency corresponds to a resonance frequency, the resulting stresses due to growing oscillations can be damaging to the turbine-generator shaft. Note that the frequency of the torques acting on the rotor is the complement of the system subsynchronous resonance frequency.

A second component of subsynchronous resonance is the Transient Torque effect. Whereas torsional interaction is a form of self-excitation, the transient torque effect is caused by disturbances in the power system due to faults, switching, or load changes. These disturbances produce transient subsynchronous currents in the transmission system at the electrical system resonant frequency which flow in the generator stator causing a magnetic field rotating at some subsynchronous speed similar to the phenomena mentioned above. If the resulting oscillatory torques are excessive, they can also cause damaging stresses in the turbine-generator shaft.

A third component of subsynchronous resonance is known as the induction generator effect. The induction motor/generator equivalent circuit shown in Figure 2 can help visualize the induction generator effect.

Whenever subsynchronous stator currents occur, they produce a magnetic field which rotates at a corresponding subsynchronous speed. However, the rotor is turning at a speed faster than the rotating subsynchronous magnetic field which causes the slip to be negative. As a result, the generator's rotor resistance appears negative (refer to the Induction Motor/Generator equivalent circuit in Figure 2). This is the induction generator phenomena. If the magnitude of this apparent negative rotor resistance is greater than the sum of the other associated resistances, then the means for electrical damping has been eliminated. Thus, the occurrence of subsynchronous currents at a resonant frequency under these conditions would result in sustained resonant oscillations. Besides possible damage to the turbine-generator shaft, overheating in the generator, transformer, and other elements in the transmission system may occur.

Rotor Failure

The chief concern with subsynchronous resonance is the possibility of rotor damage due to excessive shaft torques. Generally, the analysis for potential shaft failure is divided into two areas. The first area deals with a high torque level where the stress at critical locations along the rotor approaches the yield point. The second area deals with lower levels of torque in which the stress at critical locations along the rotor exceeds the endurance limit.

For high torque levels in which the steel has reached the yield point, the resulting shaft deformation can result in shaft misalignment. The resultant lateral bending stresses could ultimately lead to shaft failure if not corrected.

For lower torque levels, in which the endurance limit has been exceeded, the main concern is cyclic torques causing fatigue in the shaft. The amount of fatigue life expended is calculated using a stress life or S-N curve[2]

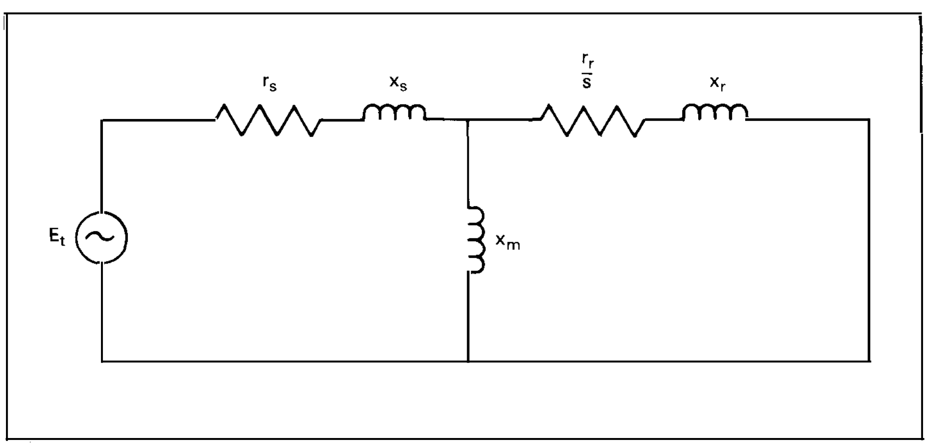

Fig. 2. Induction Motor/Generator Equivalent Circuit

Relay Detection Theory

The SSO relay system, as illustrated in Figure 3, was developed to detect the presence of each of the three components of subsynchronous resonance previously discussed. The relay utilizes several modules to monitor, examine, and trip if necessary to prevent damage to the turbine-generator shaft. The modules are designated as MM, TT, SET and IGE. The subsynchronous signals are extracted from line currents. This function is performed by the MM module. The output of the MM module, which is the extracted SSO signal, is the input to the other modules (see Figure 4). The MM module obtains its input from the auxiliary CT's. It extracts and processes the SSO signal based on the positive sequence component of the armature current. The filter circuits in the MM module screen out frequencies below 6 Hertz and above 45 Hertz. This frequency range should cover all the frequencies which may be critical to the turbine-generator shaft.

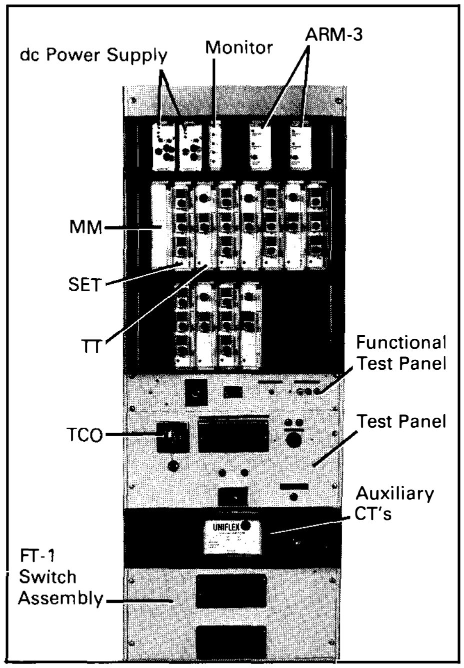

Fig. 3. SSO Relay System

The SET module was designed to protect the turbine-generator shaft from the self-excited or torsional interaction effect. It is used to detect subsynchronous oscillation signals whose magnitude is constant or growing and whose frequency corresponds to a torsional natural frequency of the turbine-generator with the intent to limit the loss-of-life to the shaft to a maximum of one percent per incident. The SET module contains a SRRT circuit and a FRRT circuit for monitoring. The SRRT (slow rate-of-rise trip) circuit provides the logic to monitor oscillating signals which are slowly growing with time. The FRRT (fast rate-of-rise trip) circuit monitors those oscillations which are fast growing and exceeding a predetermined rate. A narrow band filter with a bandwidth of ±2 Hertz can be tuned to a natural torsional frequency of the turbine-generator shaft to provide the input to the SRRT and FRRT circuits so that only those critical frequencies which pose a danger to the turbine-generator shaft would be monitored and examined (refer to Figure 5).

The tripping time for the SRRT circuit is determined from the equation below:

$$T = T_{01} + \frac{K}{I_S}$$

where

T_{01} = fixed time delay
I_S = subsynchronous current
K = a preset constant

The inverse time characteristic controlled by the K constant is programmable. To initiate circuit response, I_S, the subsynchronous armature current, must be above a preset level I_{SS}. For the process to continue, each peak of I_S must be equal to or greater than the peak immediately preceding it. A trip will occur at time T if I_S reaches the final setting I_{SF}. The FRRT circuit has a shorter trip time than the SRRT circuit with a preset value of T_2. The FRRT circuit will respond to any subsynchronous signal which is greater than a preset value I_{SFR}. Similar to the SRRT circuit logic, the FRRT circuit will continue processing if each succeeding peak increases at a rate δ above the preceding one. To ensure the security, a trip only occurs if one more rising peak is encountered after completing the trip time whether the trip mode is FRRT or SRRT.

From the above information it can be observed that the SET module has a minimum trip time of T_2. Note that the SRRT cir-

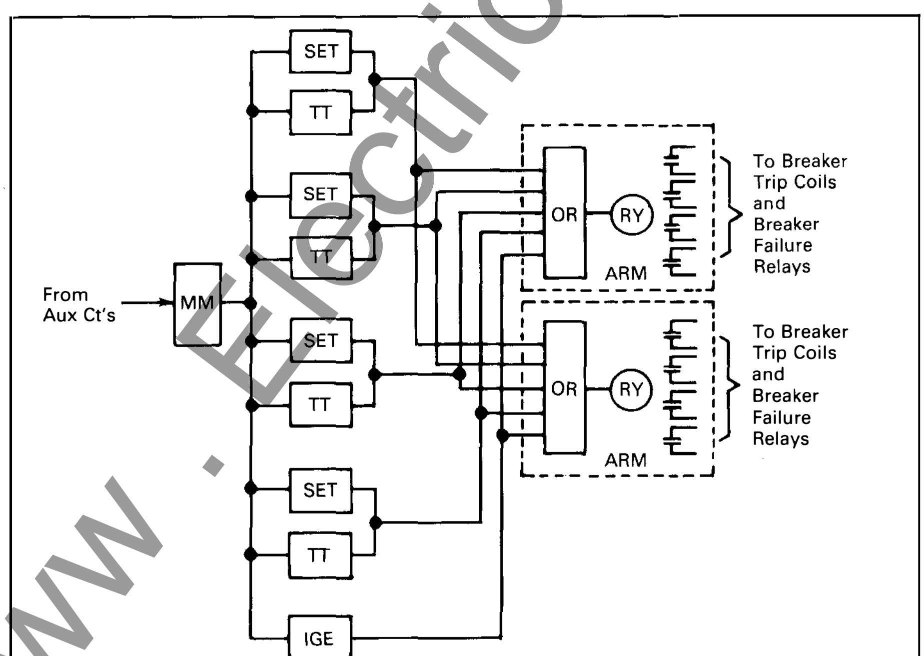

Fig. 4. SSO Relay Block Diagram

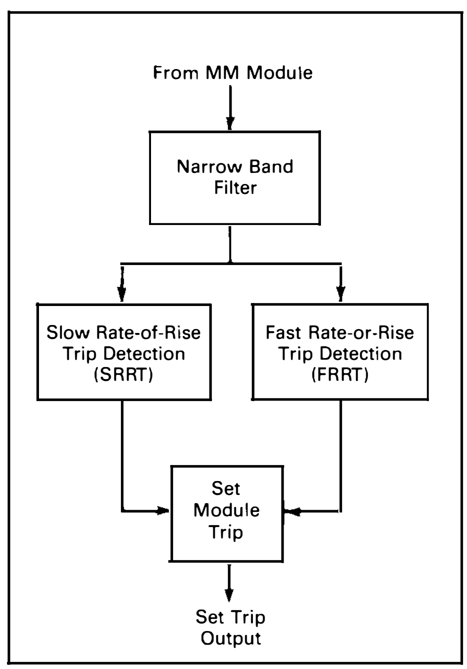

Fig. 5. Set Module

cuit can interact with the FRRT circuit for cases where a slowly growing subsynchronous signal develops into a faster one, and vice versa. Thus, the total trip time can be divided between the SRRT circuit and the FRRT circuit. In this case, the total trip time would be between T and T_2. For instances where two close frequencies within the bandwidth of the narrow band filter are encountered, the relay will respond to the resulting waveform as in the case of a single modal frequency. Special evaluation circuits were implemented to ensure security and reliability for these cases.

The TT module function is to detect a transient subsynchronous oscillation signal that is decaying with time. It provides two trip functions, the instantaneous transient trip (ITT) and the mid-range transient trip (MRTT). The functional block diagram shown in Figure 6 can be used to illustrate how the TT module works. A gross frequency detector (GFD) using an odd-even zero-crossing evaluation technique determines if a frequency corresponds to a natural torsional frequency of the turbine-generator shaft. When the magnitude of the full wave rectified subsynchronous signal reaches a preset monitoring level, an exponentially decaying guard signal is generated which simulates the expected decay rate for the mode being monitored. If three consecutive odd or even zero crossings are encountered indicating the correct modal frequency and if two peaks of the subsynchronous oscillation signal crosses the guard signal all within a predefined time period, then a trip output will occur. The MRTT trip detection logic is outlined as follows:

1. A Guard Crossing (GC) is considered "VALID" if:
   A. The GC occurred within a fixed time ΔT_1 before a correct frequency detection (GFD). OR
   B. The GC occurred within a fixed time ΔT_2 (Set equal to ΔT_1) after a GFD.
2. If two valid guard crossings are detected before the trip logic is reset the relay will trip.
3. The trip logic will reset if for two cycles of the modal frequency (ΔT_3) neither a correct frequency nor a guard crossing is detected. The trip logic will also reset if the guard signal is reset.
4. The guard signal is reset only when the incoming signal drops below approximately 0.16 P.U., the monitoring pickup level.
5. $\Delta T_1 = \Delta T_2 = \Delta T_3$ is set for approximately 2 cycles of the modal frequency.

The MRTT logic also accommodates those cases which involve multi-modal subsynchronous oscillation signals.

As seen in the block diagram of Figure 6, an instantaneous transient trip (ITT) circuit is also included in the TT module. Whenever the subsynchronous signal exceeds the ITT setting, or the MRTT circuit requirements are satisfied, a TT trip will be initiated.

The IGE module was incorporated into the relay system to detect growing subsynchronous oscillations which do not occur at a turbine-generator modal frequency, but do occur in the 6-45 Hz band range. The IGE module is identical to the SET module except without the narrow band filter (refer to Figure 7). Its primary function is to protect the generator rotor from overheating resulting from magnetic fields rotating at subsynchronous speeds inducing currents in the rotor circuit. However, the IGE module can also be considered a backup to the SET modules as a measure of additional security.

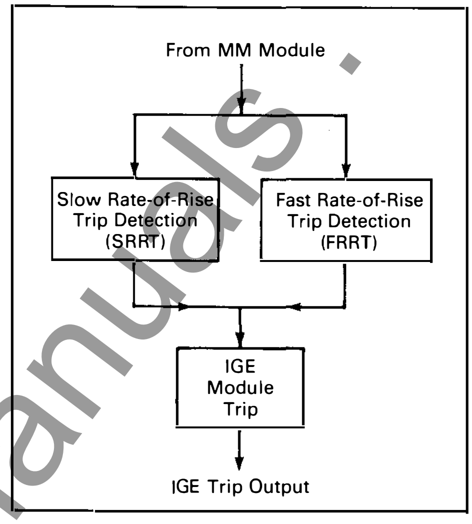

Fig. 7. IGE Module

Further Information:
I.L. 41-170, I.L. 41-171, I.L. 41-174

References

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2. B. L. Agrawal and R. G. Farmer, "Application of Subsynchronous Oscillation Relay – Type SSO," presented at the Joint Power Generation Conference, Phoenix, AZ, Sept. 28-Oct. 1, 1980.
3. "Proposed Terms and Definitions for Subsynchronous Oscillations," by IEEE Subsynchronous Resonance Working Group of the System Dynamic Performance Subcommittee: IEEE Transactions on Power Apparatus and Systems, PAS-99, No. 2 March/April 1980.

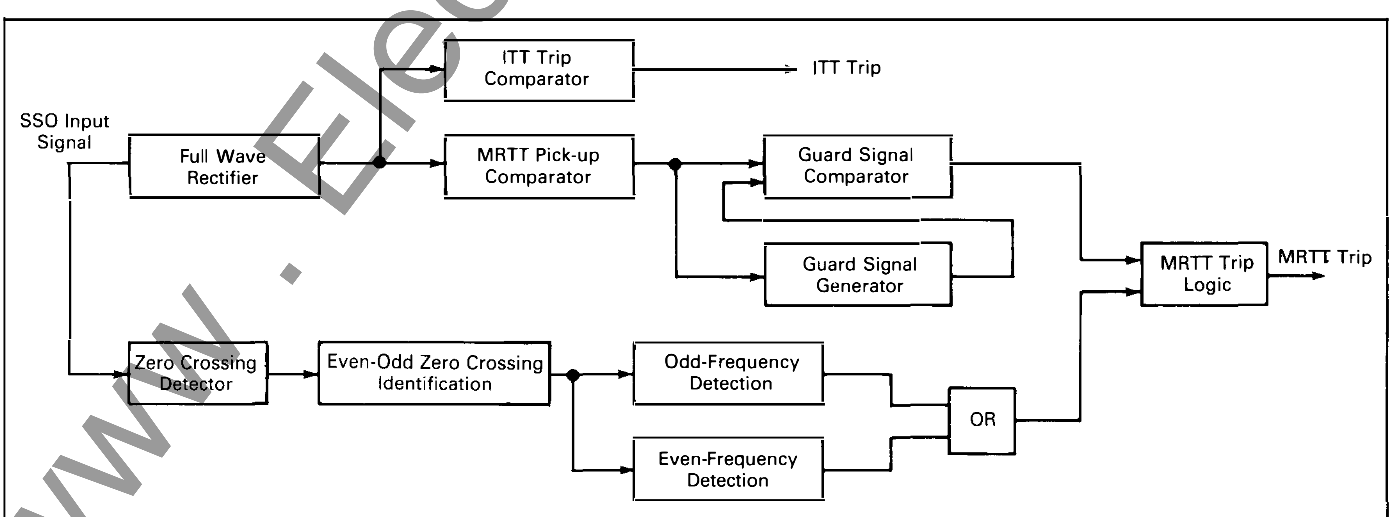

Fig. 6. Simplified TT Module Logic Diagram

SSO Relay Setting Calculations

General Setting Recommendations

The SSO relay may be applied to provide either primary or secondary protection for a turbine-generator against subsynchronous oscillations of the rotating shaft sections. Because the subsynchronous oscillations correspond to shaft natural frequencies, they may be associated with extremely small values of armature current. Then, the desired settings for the SET module may be so small as to cause undesirable trips of the unit. If the relay settings must be increased to improve the security of the system, care should be taken to assure that the relay is still sufficiently sensitive to provide adequate protection of the turbine-generator.

Before the settings of the SSO relay can be calculated, the following information is needed:

1. Inertia constants of each lumped mass of the rotor, H_i.
2. Spring constants of the shaft between each mass, K_s.
3. Mode shape for each subsynchronous torsional natural frequency, θ_i.
4. Per-unit values of shaft torque which correspond to the torsional endurance limit (EL) and the torsional yield limit (T_{eim}) for each shaft section.
5. No-load mechanical damping of each mode, σ_m.
6. Breaker trip time, t_b.
7. Inverse electrical time constant, σ_e.
8. Continuous permissible I_2 of generator.
9. The critical shaft section for each mode. Note that the critical shaft is selected by computing the allowed generator velocity deviation for each mode. The following equations are used for this calculation:

$$\Delta\omega_{ij} = \frac{T_{eim}}{K_S} \bullet \omega_n$$

where

$\Delta\omega$ = allowed velocity deviation for shaft-section i-j

T_{eim} = per-unit limiting torque for shaft-section at 1000 cycles to failure

K_S = spring constant of the shaft-section

ω_n = modal frequency

$$\Delta\omega_g = \frac{\theta_g}{\theta_i - \theta_j} \bullet \Delta\omega_{ij}$$

where

$\Delta\omega_g$ = allowed generator velocity deviation

θ_g = relative angular displacement of the generator (radians)

$\theta_i - \theta_j$ = angular displacement across shaft-section i-j

$\Delta\omega_{ij}$ = allowed velocity deviation for shaft-section i-j

The minimum allowed generator velocity deviation for each mode dictates the critical shaft section of that mode.

SET Module

For each SET module, calculate the armature current which corresponds to the endurance limit of the critical shaft for that particular mode of oscillation using the following equation:

$$I_o = \frac{4 \bullet \sigma_m \bullet H_m \bullet \theta_g \bullet EL \bullet f_m}{f_s \bullet K_s \bullet (\theta_j - \theta_k)}$$

where

σ_m = no-load mechanical damping (1/sec)

H_m = effective inertia constant (sec)

$$= \sum_{i=1}^{n} H_i \left(\frac{\theta_i}{\theta_g}\right)^2$$

n = number of lumped masses in the system

θ_i = relative angular displacement of the mass at the mode of concern (radians)

θ_g = relative angular displacement of the generator (radians)

EL = endurance limit of the critical shaft (per-unit torque)

f_m = natural frequency of the shaft oscillations (hertz)

f_s = system frequency (hertz)

K_s = spring constant of critical shaft (p.u. Torque/rad)

$(\theta_j - \theta_k)$ = angular displacement across critical shaft (radians)

Set the pickup current for the SRRT section (I_{SS}) equal to half of I_o ($I_o/2$). Set the pickup current for the FRRT section (I_{SFR}) equal to I_o. Set the trip-initiating current of the SRRT section (I_{SF}) also equal to I_o.

To find the value of K such that the loss of life in the critical shaft will be limited to a percentage equal to LL when the subsynchronous component of the armature current is of a constant magnitude equal to γI_o, use the following equation:

$$K = \gamma I_o \left(\frac{A \bullet LL}{100\,(\gamma^B)\,f_m} - T_{o1} - t_b\right)$$

where

K = Programmable relay setting to adjust the trip time to correspond to the fatigue-life curve.

γ = I_s/I_o at a given modal frequency f_m

γI_o = magnitude of subsynchronous current (p.u.)

LL = loss of life (percent)

f_m = natural frequency of the shaft oscillations (hertz)

T_{o1} = relay time delay (sec)

t_b = breaker opening time (sec)

A, B = constants in equation approximating loss-of-life curve in the region γI_o

i.e., equation in the following form:

$N = A\,(I_o/I_s)^B$

N = number of cycles till failure

I_o = p.u. subsynchronous armature current corresponding to the endurance limit

I_s = p.u. subsynchronous armature current

For exponentially growing subsynchronous currents, the time required for the current to increase from the pickup level, I_{SS}, to I_{SF}, is

$$t_s = \frac{\ln\left(\frac{I_{SF}}{I_{SS}}\right)}{\sigma}$$

where

σ = Total undamping of electrical-mechanical system (1/sec)

The additional time, t_c, required for the loss-of-life to reach LL when the subsynchronous current grows exponentially from I_{SF} is:

$$t_c = \frac{\ln\left(\frac{A \bullet B \bullet \sigma \bullet LL}{100 \bullet f_m} + 1\right)}{B\sigma}$$

To assure that the loss-of-life does not exceed LL, the sum of t_s and t_c should be greater or equal to the total clearing time. That is,

$$t_c + t_s \geq t_R + t_b$$

where

t_R = relay operate time

t_b = breaker opening time

$$\frac{\ln\left(\frac{A \cdot B \cdot \sigma \cdot LL}{100 \cdot f_m} + 1\right)}{B\sigma} + \frac{\ln(I_{SF}/I_{SS})}{\sigma} \geq T_{o1} + \frac{K}{I_{SS}e^{\sigma t_1}} + t_b$$

The equality in the above equation will hold for some value $\sigma = \sigma_c$. As a matter of convenience, define t_1 and t_2 as follows:

$$t_1 = t_c + t_s = \frac{\ln\left(\frac{A \cdot B \cdot \sigma \cdot LL}{100 \cdot f_m} + 1\right)}{B\sigma} + \frac{\ln(I_{SF}/I_{SS})}{\sigma}$$

$$t_2 = t_b + t_R = t_b + T_{o1} + \frac{K}{I_{SS}e^{\sigma t_1}}$$

An iterative technique can be applied by choosing a value for σ, calculate t_1, and then substitute σ and t_1 in the second equation to find t_2. If t_2 is not equal to t_1, then continue the iteration by choosing a new σ, and compute the new values for t_1 and t_2. σ_c, the value of σ at which $t_1 = t_2$, can then be substituted into the following equation to compute δ.

$$\delta = 100\,(e^{\sigma_c/2f_m} - 1)\ \%$$

δ is the desired SSO relay setting. The actual subsynchronous current must be increasing from one peak to the next peak by a percentage greater than δ in order for the FRRT circuit to operate. Note that the minimum value of δ by design is 1%. For the case where the calculated value of δ is less than 1%, set δ = 1%, and compute new values for σ,t_1 and K that correspond to δ = 1% according to the following steps:

1. $\sigma_{new} = 2 \cdot f_m \cdot \ln(1 + \delta)$ where δ is in per-unit.
2. $t_1(\sigma_{new})$
3. $K_{new} = \left[\frac{\ln\left(\frac{A \cdot B \cdot \sigma_{new} \cdot LL}{100 \cdot f_m} + 1\right) + B \cdot \ln\left(\frac{I_{SF}}{I_{SS}}\right)}{B\sigma_{new}} - T_{o1} - t_b\right] I_{SS}e^{\sigma_{new} t_1}$

TT Module

Determining the settings for the TT module requires a calculation of the minimum magnitude of exponentially decaying subsynchronous current (I_f) that can cause the growing shaft torques to reach the elastic limit of the shaft. I_f is given by the following equation:

$$I_f = \frac{4 \cdot \sigma_e \cdot H_m \cdot \theta_g \cdot T_{eim} \cdot f_m}{f_s \cdot K_s \cdot (\theta_j - \theta_k)}$$

where

σ_e = inverse electrical time constant (1/sec)

H_m = effective inertia constant (sec)

θ_g = relative angular displacement of the generator (Radians)

T_{eim} = elastic limit of the critical shaft (per-unit torque)

f_m = natural frequency of the shaft oscillations (hertz)

f_s = system frequency (hertz)

K_s = spring constant of critical shaft (p.u. Torque/rad)

$(\theta_j - \theta_k)$ = angular displacement across critical shaft (Radians)

Now set τ_m equal to the time constant of the electrical system. The relay setting A_m, which is defined to be the initial peak magnitude of the guard signal, is calculated using the following equation:

$$A_m = 0.8\, I_f e^{-T_{inhibit}/\tau_m}\ \text{p.u.}$$

where

$T_{inhibit}$ = 50ms – 70ms for **500 KV** system
= 60ms – 70ms for **345 KV** system
= 70ms – 90ms for **230 KV** system

$T_{inhibit}$ is to account for the ring down period following fault clearing and wide band filter transient response. The factory setting for $T_{inhibit}$ will be in the middle of the setting range; $T_{inhibit}$ = 60ms for 500 KV system, 65ms for 345 KV system, and 80ms for 230 KV system.

Set ITT, the instantaneous transient trip value, to the dial setting nearest the value

$$\frac{I_F}{(1 - e^{-t_o/\tau_m})}$$

where

t_o = relay minimum time delay for the TT module plus breaker opening time

$$t_o = (0.022 + t_b)\ \text{sec}$$

Although there is one ITT setting for each modal frequency, the lowest calculated value of the above equation should be used for all ITT settings.

The final settings for the TT module are for the Reset Timers, ΔT_1, ΔT_2, and ΔT_3. The reset timers are adjusted to the following setting:

$$\Delta T_1 = \Delta T_2 = \Delta T_3 = 2 \text{ cycles of the modal frequency.}$$

IGE Module
The IGE module is intended to provide protection from growing oscillations in the range of 6 to 45 Hz that are not at a torsional natural frequency of the turbine-generator unit. For oscillations at frequencies other than torsional natural frequencies, the limiting factors from the generator's viewpoint are rotor heating, and possibly oscillatory torques within the rotor system. Because of its wide frequency detection range, the IGE module has also evolved as a backup for each of the SET modules while at the same time insuring its primary function of protecting the generator from excessive heating or oscillatory torques.

The expression relating the amount of subsynchronous current that produces the same amount of negative sequence heating losses is given as follows:

$$\sqrt{I_S^3 f_m} = \sqrt{I_2^3 f_2}$$

where

f_2 = 120 Hz

f_m = 45 Hz for maximum heating

I_2 = continuous permissible negative sequence current of the generator (per unit)

$$\sqrt{45 I_S^3} = \sqrt{120 I_2^3}$$

$$I_S = 1.39 I_2$$

The suggested settings for the IGE module are listed below. Use the minimum of

I_{SS} = 0.01 p.u. or $I_{SS} = 0.5\ I_S$

I_{SF} = 0.02 p.u. or $I_{SF} = I_S$

I_{SFR} = 0.03 p.u. or $I_{SFR} = I_S$

The other settings are:

$$K = 0.1 \text{ p.u.-sec}$$

$$\delta = 0.01 \text{ or } 1\%$$

These values will serve a dual purpose. The IGE module will act as a backup for each of the SET modules and will also insure that tripping occurs before any appreciable heating or off-resonant frequency oscillatory torques occur.

MM Module
There are two customer-supplied settings in the MM module. The first is a gain control used to calibrate for current transformers having secondary currents not precisely 5.0 amperes with one per unit current in their primaries. Refer to Table #1 for I_{BASE} value. The second setting, f_{BR}, is to enhance the rejection of the supersynchronous frequency closest to the subsynchronous frequency range. This frequency is defined as follows:

$$f_{BR} = 2f_S - f_{m\,(max)}$$

where

f_{BR} = frequency to be rejected (Hz)

f_S = system frequency (Hz)

$f_{m(max)}$ = maximum torsional resonant frequency (Hz)

Table 1. Range of Values used in the SSO MM Module

Value	Range	Units
f_m	Regular wide-band filter for all modal frequencies between $15 \leq f_m \leq 45$ Hz; Expanded wide-band filter for all modal frequencies between $6 \leq f_m \leq 42$ Hz	Hz
f_s	50 or 60 Hz	Hz
I_{BASE} Secondary	$3.7 \leq I_{BASE} \leq 5.0$	Amps
f_{BR}	$60 \leq f_{BR} \leq 90$ Hz	Hz

Table 2. Setting Range for SET Module

Value	Range	Units
I_{SS}, I_{SF}, I_{SFR}	$.001 \leq I_{SS}, I_{SF}, I_{SFR} \leq .100$	p.u.
K	$0 < K \leq 1.0$	sec-p.u.
T_{o1}	for $6 \leq f_m < 15$ Hz $T_{o1} = .860$; for $15 \leq f_m < 25$ Hz $T_{o1} = .640$; for $25 \leq f_m \leq 45$ Hz $T_{o1} = .380$	sec
δ	$\delta_{min} = 1$	%

Table 3. Setting Range for TT Module

Value	Range	Units
τ_m	$.1 \leq \tau_m \leq .5$	sec
A_m	$.25 \leq A_m \leq 1.90$	p.u.
$T_{inhibit}$	$50 \leq T_{inhibit} \leq 70$ for 500 KV system; $60 \leq T_{inhibit} \leq 70$ for 345 KV system; $70 \leq T_{inhibit} \leq 90$ for 230 KV system	msec
ΔT_1, ΔT_2, ΔT_3	2 cycles of modal frequency	sec
ITT	4 distinct settings: 1.0, 1.25, 1.50, 1.75	p.u.

Table 4. Setting Range for IGE Module

Value	Range	Units
I_{SS}, I_{SF}, I_{SFR}	$.005 \leq I_{SS}, I_{SF}, I_{SFR} \leq .500$	p.u.
K	$0 < K \leq 1.0$	sec-p.u.
T_{o1}	for $6 \leq f_m < 15$ Hz $T_{o1} = .860$; for $15 \leq f_m \leq 45$ Hz $T_{o1} = .400$	sec
δ	$\delta_{min} = 1$	%

Table A. Setting Catalog

Unit ____________________

MM Module
Amperes for 1 per unit relay input, I_{BASE} = ______________________________ Amperes
BAND-REJECT FREQUENCY, f_{BR} = ______________________________ Hz

Set Modules	**Mode**				
Quantity	**1**	**2**	**3**	**4**	
F_M					Hz
I_{SS}					p.u.
I_{SF}					p.u.
I_{SFR}					p.u.
T_{o1}					sec
K					sec-p.u.
δ					%

IGE Modules

Module		
Quantity	**1**	
I_{SS}		p.u.
I_{SF}		p.u.
I_{SFR}		p.u.
T_{o1}		sec
K		sec-p.u.
δ		%

TT Modules	**Mode**				
Quantity	**1**	**2**	**3**	**4**	
F_M					Hz
A_M					p.u.
τ_m					sec
I_{TT}					p.u.
$T_{inhibit}$					sec
$\Delta T_1 = \Delta T_2 = \Delta T_3$					sec

Setting Example

The machine for this example has the following characteristics:

Angular Displacements for Each Mode of Oscillation

Lumped Mass	Inertia Constant	Mode 1 18.3 HZ	Mode 2 24.4 HZ	Mode 3 47.3 HZ
1. HP Turbine	0.595	−0.70	1.0	−0.001
2. LP Turbine	2.12	−0.13	−0.45	0.005
3. Generator	0.755	0.84	0.43	−0.088
4. Exciter	0.056	1.0	0.61	1.0

Shaft Section	Mode 1 LP-GEN	Mode 2 HP-LP	Mode 3 GEN-EXC
EL	0.98	0.87	0.42
T_{eim}	2.4	2.1	1.3
K_S	50.1	51.2	24.6
Log Dec	0.006	0.006	0.009
σ_m	0.11	0.15	0.43

Determine A and B constants for each mode. Refer to the appendix.

Mode 1 (18.3 Hz):

$$A = N = 10^6$$

$$B = \frac{1n(N/A)}{1n\ (EL/T_{eim})} = \frac{1n\left(\frac{10^3}{10^6}\right)}{1n\left(\frac{0.98}{2.4}\right)} = 7.71$$

Mode 2 (24.4 Hz):

$$A = N = 10^6$$

$$B = \frac{1n(N/A)}{1n\ (EL/T_{eim})} = \frac{1n\left(\frac{10^3}{10^6}\right)}{1n\left(\frac{0.87}{2.1}\right)} = 7.84$$

Mode 3 (47.3 Hz):

$$A = N = 10^6$$

$$B = \frac{1n(N/A)}{1n\ (EL/T_{eim})} = \frac{1n\left(\frac{10^3}{10^6}\right)}{1n\left(\frac{0.42}{1.3}\right)} = 6.11$$

Other required information for SSO setting calculations include:

Breaker open time = 0.034 second
Inverse electrical time constant = 5/seconds
Continuous Permissible Unbalance Current, I_2 = 8%

Now calculate effective inertia constant for each mode:

Mode 1

$$H_m = \sum_{i=1}^{n} H_i\left(\frac{\theta_i}{\theta_g}\right)^2 = H_1\left(\frac{\theta_1}{\theta_g}\right)^2 + H_2\left(\frac{\theta_2}{\theta_g}\right)^2 + H_3\left(\frac{\theta_3}{\theta_g}\right)^2 + H_4\left(\frac{\theta_4}{\theta_g}\right)^2$$

$$= 0.595\left(\frac{-0.70}{0.84}\right)^2 + 2.12\left(\frac{-0.13}{0.84}\right)^2 + 0.755\left(\frac{0.84}{0.84}\right)^2 + 0.056\left(\frac{1.0}{0.84}\right)^2$$

= 1.3 seconds

Mode 2

$$H_m = \sum_{i=1}^{n} H_i\left(\frac{\theta_i}{\theta_g}\right)^2 = 0.595\left(\frac{1.0}{0.43}\right)^2 + 2.12\left(\frac{-0.45}{0.43}\right)^2 + 0.755\left(\frac{0.43}{0.43}\right)^2 + 0.056\left(\frac{0.61}{0.43}\right)^2$$

= 6.41 seconds

Mode 3

$$H_m = 0.595\left(\frac{-0.001}{-0.008}\right)^2 + 2.12\left(\frac{0.005}{-0.088}\right)^2 + 0.755\left(\frac{-0.088}{-0.088}\right)^2 + 0.056\left(\frac{1.0}{-0.088}\right)^2$$

= 7.99 seconds

Determination of Critical Shaft Section for Each Mode
The critical shaft section for each mode can be determined by computing the allowed generator velocity deviation for each shaft section. These calculations for this example are as follows:

Mode 1
LP-GEN:

$$\Delta\omega = \frac{T_{eim}}{K_S} \bullet \omega_n = \frac{2.4}{50.1} \times 2\pi\,(18.3) = 5.508$$

$$\Delta\omega_g = \frac{\theta_g}{|\theta_i - \theta_j|} \bullet \Delta\omega = \frac{0.84}{|-0.13 - 0.84|} \times 5.508 = 4.77$$

HP-LP:

$$\Delta\omega = \frac{2.1}{51.2} \times 2\pi\,(18.3) = 4.72$$

$$\Delta\omega_g = \frac{0.84}{|-0.70 - (-0.13)|} \times 4.716 = 6.95$$

GEN-EXC:

$$\Delta\omega = \frac{1.3}{24.6} \times 2\pi\,(18.3) = 6.076$$

$$\Delta\omega_g = \frac{0.84}{|0.84 - 1.0|} \times 6.076 = 31.90$$

Thus, for mode 1, the LP-GEN shaft-section is the critical shaft section since it has the minimum allowed generator velocity deviation.

Mode 2
LP-GEN:

$$\Delta\omega = \frac{T_{eim}}{K_S} \bullet \omega_n = \frac{2.4}{50.1} \times 2\pi\,(24.4) = 7.344$$

$$\Delta\omega_g = \frac{\theta_g}{|\theta_i - \theta_j|} \bullet \Delta\omega = \frac{0.43}{|-0.45 - 0.43|} \times 7.344 = 3.59$$

HP-LP:

$$\Delta\omega = \frac{2.1}{51.2} \times 2\pi\,(24.4) = 6.29$$

$$\Delta\omega_g = \frac{0.43}{|1.0 - (-0.45)|} \times 6.29 = 1.87$$

GEN-EXC:

$$\Delta\omega = \frac{1.3}{24.6} \times 2\pi\,(24.4) = 8.102$$

$$\Delta\omega_g = \frac{0.43}{|1.0 - (-0.45)|} \times 6.29 = 1.87$$

Based on the above calculations for mode 2, the HP-LP shaft section has the minimum allowed generator velocity deviation which implies that it is the critical shaft section for this modal frequency.

Mode 3
LP-GEN:

$$\Delta\omega = \frac{T_{eim}}{K_S} \bullet \omega_n = \frac{2.4}{50.1} \times 2\pi\,(47.3) = 14.24$$

$$\Delta\omega_g = \frac{\theta_g}{|\theta_i - \theta_j|} \bullet \Delta\omega = \frac{0.088}{|0.005 - (-0.088)|} \times 14.24 = 13.47$$

HP-LP:

$$\Delta\omega = \frac{2.0}{51.2} \times 2\pi\,(47.3) = 12.19$$

$$\Delta\omega_g = \frac{0.088}{|-0.001 - 0.005|} \times 12.19 = 178.79$$

GEN-EXC:

$$\Delta\omega = \frac{T_{eim}}{K_S} \bullet \omega_n = \frac{1.3}{24.6} \times 2\pi\,(47.3) = 15.71$$

$$\Delta\omega_g = \frac{0.088}{|-0.088 - 1.0|} \times 15.71 = 1.271$$

The results for mode 3 show that the GEN-EXC shaft section is the critical shaft.

SET Module Setting Calculations
The subsynchronous armature current that corresponds to the endurance limit is calculated as follows:

$$I_o = \frac{4 \cdot \sigma_m \cdot H_m \cdot \theta_g \cdot EL \cdot f_m}{f_s \cdot K_s \cdot (\theta_j - \theta_k)}$$

Mode 1 $$I_o = \frac{(4\text{p.u./rad})\ (0.11/\text{sec})\ (1.3\ \text{sec})\ (0.84\ \text{rad})\ (0.98\text{p.u.})\ (18.3\text{Hz})}{(60\ \text{Hz})\ (50.1\ \text{p.u./rad})\ (0.84-(-.13))\ \text{rad}} = 0.0029\ \text{p.u.}$$

Mode 2 $$I_o = \frac{(4\text{p.u./rad})\ (0.15/\text{sec})\ (6.41\ \text{sec})\ (0.43\ \text{rad})\ (0.87\text{p.u.})\ (24.4\text{Hz})}{(60\ \text{Hz})\ (51.2\text{p.u./rad})\ (1.0-(-0.45))\ \text{rad}} = 0.008\ \text{p.u.}$$

Mode 3 $$I_o = \frac{(4\text{p.u./rad})\ (0.43/\text{sec})\ (7.93\ \text{sec})\ (0.088\ \text{rad})\ (0.42\text{p.u.})\ (47.3\text{Hz})}{(60\ \text{Hz})\ (24.6\text{p.u./rad})\ (1.0-(-0.088))\ \text{rad}} = 0.015\ \text{p.u.}$$

The suggested pickup and trip currents for the SET module as found for each mode are:

Mode 1
$I_{SS} = I_o/2 = 0.0029/2 = 0.0015$ p.u.
$I_{SFR} = I_o = 0.0029$ p.u.
$I_{SF} = I_o = 0.0029$ p.u.

Mode 2
$I_{SS} = I_o/2 = 0.008/2 = 0.004$ p.u.
$I_{SFR} = I_o = 0.008$ p.u.
$I_{SF} = I_o = 0.008$ p.u.

Mode 3
$I_{SS} = I_o/2 = 0.015/2 = 0.008$ p.u.
$I_{SFR} = I_o = 0.015$ p.u.
$I_{SF} = I_o = 0.015$ p.u.

Next calculate K for each mode to limit loss-of-life in the critical shaft to a percentage equal to LL. Assume LL = 1% for this example.

$$K = \gamma I_o \left[\frac{A \cdot LL}{100(\gamma^B)f_m} - T_{o1} - t_b\right]$$

Mode 1 (18.3 Hz)
$T_{o1} = 0.640$ seconds for $15\ \text{Hz} \leq f_m \leq 25\ \text{Hz}$

$$K = (2)\ (0.0029\ \text{p.u.}) \left[\frac{(10^6\ \text{cycles})\ (1)}{100(2^{7.71})\ (18.3\ \text{cycles/sec})} - 0.640\ \text{sec} - 0.034\ \text{sec}\right] = 0.0112\ \text{sec-p.u.}$$

Calculate σ_c for the above calculated K. Note that the following three equations must be satisfied:

$$t_1 = \frac{1n\left[\frac{A \cdot B \cdot \sigma_c \cdot LL}{100 \cdot f_m} + 1\right]}{B \cdot \sigma_c} + \frac{1n(I_{SF}/I_{SS})}{\sigma_c} \quad (1)$$

$$t_2 = T_{o1} + t_b + \frac{K}{I_{SS}e^{\sigma_c t_1}} \quad (2)$$

$$t_1 = t_2 \quad (3)$$

In order to compute σ_c, an iterative technique must be applied. The following iterative process will be used in this example.

Choose initial $\sigma_c = 0.5$

$$t_1 = \frac{1n\left[\frac{(10^6 \text{ cycles})\ (7.71)\ (0.5/\text{sec})\ (1)}{(100)\ (18.3 \text{ cycles/sec})} + 1\right]}{(7.71)\ (0.5/\text{sec})} + \frac{1n(0.0029 \text{ p.u.}/0.0015 \text{ p.u.})}{0.5/\text{sec}}$$

$= 3.3038$ seconds

$$t_2 = 0.640 \text{ sec} + 0.034 \text{ sec} + \frac{0.0112 \text{ sec} - \text{p.u.}}{(0.0015 \text{ p.u.})e^{(0.5/\text{sec})\ (3.3038)}}$$

$= 2.1053$ seconds

Thus, $t_1 \neq t_2$

Adjust σ_c for the next iterative step as follows:

$$\sigma_{c_{new}} = \frac{t_1}{t_2}\ \sigma_{c_{old}}$$

OR whichever decreases $|t_2 \text{-} t_1|$

$$\sigma_{c_{new}} = \frac{t_2}{t_1}\ \sigma_{c_{old}}$$

Choose $\sigma_{c_{new}} = \frac{3.3038}{2.1053}(0.5) = 0.7846$

and $t_1 = 2.18$ seconds

$t_2 = 2.02$ seconds

Again $t_1 \neq t_2$

Adjusting σ_c for the next iterative step yields

$$\sigma_{c_{new}} = \frac{2.18}{2.02}(0.7846) = 0.8467$$

and $t_1 = 2.03$

$t_2 = 2.01$

Again $t_1 \neq t_2$

Adjusting σ_c for the next iterative step yields

$$\sigma_{c_{new}} = \frac{2.03}{2.01}(0.8467) = 0.8551$$

and $t_1 = 2.01$

$t_2 = 2.01$

Therefore, $t_1 = t_2$ and the correct value for σ_c is 0.8551

The value for δ can be determined from

$$\delta = 100\ (e^{\sigma_c/2f_m} - 1)$$

$$= 100\ (e^{0.8551/(2\times 18.3)} - 1)$$

$$= 2.36\%$$

Since $\delta > 1\%$, no further calculations are required.

Mode 2 (24.4 Hz)

T_{o1} = 0.640 seconds for 15Hz $\leq f_m <$ 25Hz

$$K = (2)(0.008)\left[\frac{(10^6)(1)}{(100)(2^{7.84})(24.4)} - 0.640 - 0.034\right]$$

$$= 0.0178 \text{ sec-p.u.}$$

Using the same iterative approach as for mode 1 calculations, σ_c is found to be 1.2032. Calculating δ for mode 2 gives

$$\delta = 100\,(e^{\sigma_c/2f_m} - 1)$$

$$= 100\,(e^{1.2032/(2\times24.4)} - 1)$$

$$= 2.50\%$$

Mode 3 (47.3Hz)

T_{o1} = 0.380 seconds for $f_m \geq$ 25Hz

$$K = (2)(0.015)\left[\frac{(10^6)(1)}{(100)(2^{6.11})(47.3)} - 0.380 - 0.034\right]$$

$$= 0.0794$$

Again iterating to compute σ_c for mode 3 yields

$$\sigma_c = 0.8450$$

Solving for δ results as follows:

$$= 100\,(e^{0.8450/(2\times47.3)} - 1)$$

$$= 0.897\%$$

Since δ is less than 1%, set δ = 1% (minimum setting). Based on δ = 1%, σ and K are calculated as follows:

$$\sigma_{new} = 2 \cdot f_m \cdot 1n\,(1 + \delta)$$

$$= (2)(47.3)(1n(1 + .01))$$

$$= 0.9413$$

$$t_1\,(\sigma_{new}) = \frac{1n\left(\frac{A \cdot B \cdot \sigma_{new} \cdot LL}{100 \cdot f_m} + 1\right)}{B\sigma} + \frac{1n(I_{SF}/I_{SS})}{\sigma}$$

$$= \frac{1n\,\frac{(1000000)(6.11)(0.9413)(1)}{(100)(47.3)} + 1}{(6.11)(0.9413)} + \frac{1n\left(\frac{0.015}{0.008}\right)}{0.9413}$$

$$= 1.9030$$

$$K_{new} = \left[\frac{1n\left(\frac{A \cdot B \cdot \sigma_{new} \cdot LL}{100 \cdot f_m} + 1\right) + B \cdot 1n\left(\frac{I_{SF}}{I_{SS}}\right)}{B\sigma_{new}} - T_{o1} - t_b\right] I_{SS}e^{\sigma_{new} t_1}$$

$$= \left[\frac{\left[1n\,\frac{(1000000)(6.11)(0.9413)(1)}{(100)(47.3)} + 1\right] + (6.11)\left(1n\left(\frac{0.015}{0.008}\right)\right)}{(6.11)(0.9413)} - 0.380 - 0.034\right] (0.008)e^{(0.9413)(1.9030)}$$

$$= 0.0714$$

All the settings for the SET modules have now been determined. For convenience, they are summarized in Table A.

TT Module Setting Calculations

Mode 1

The minimum magnitude of the exponentially decaying subsynchronous current, I_f, that can cause the growing shaft torques to reach the elastic limit of the critical shaft is calculated as follows:

$$I_f = \frac{4 \cdot \sigma_e \cdot H_m \cdot \Theta_g \cdot T_{eim} \cdot f_m}{f_s \cdot k_s \cdot (\Theta_j - \Theta_k)}$$

$$= \frac{(4\text{p.u./rad})(5/\text{sec})(1.3\text{p.u.})(0.84 \text{ rad})(2.4\text{p.u.})(18.3\text{Hz})}{(60\text{Hz})(50.1\text{p.u./rad})(0.97 \text{ rad})}$$

$$= 0.329 \text{ p.u.}$$

The initial magnitude of the guard signal, A_m, can now be computed. The values for $T_{inhibit}$ and τ_m are

$$T_{inhibit} = 60 \text{ milliseconds for 500KV system}$$

$$\text{and } \tau_m = \frac{1}{\sigma_e} = \frac{1}{5} = 0.2 \text{ seconds}$$

The calculation of A_m yields

$$A_m = 0.8 I_f \, e^{-T_{inhibit}/\tau_m}$$

$$= 0.8(0.329)e^{-0.060/0.2}$$

$$= 0.195 \text{ p.u.}$$

Choose the minimum setting A_m = 0.25 p.u.

Mode 2

The subsynchronous current I_f is computed to be

$$I_f = \frac{(4)(5)(6.41)(0.43)(2.1)(24.4)}{(60)(51.2)(1.45)}$$

$$= 0.634 \text{ p.u.}$$

The values for $T_{inhibit}$ and τ_m for this case are the same as for mode 1. Thus, A_m for Mode 2 is found to be

$$A_m = 0.8 I_f \, e^{-T_{inhibit}/\tau_m}$$

$$= 0.8\,(0.634)e^{-0.060/0.2}$$

$$= 0.376 \text{ p.u.}$$

Mode 3

The calculation for I_f is

$$I_f = \frac{(4)(5)(7.99)(0.088)(1.3)(47.3)}{(60)(24.6)(1.088)}$$

$$= 0.538 \text{ p.u.}$$

Again, the values for $T_{inhibit}$ and τ_m remain the same, and A_m becomes

$$A_m = 0.8 I_f \, e^{-T_{inhibit}/\tau_m}$$

$$= 0.8(0.538)e^{-0.060/0.2}$$

$$= 0.319$$

The only other required setting for the TT module is the ITT setting. The ITT value should be based on the smallest value of I_f calculated for the modes considered. For this example, the value for ITT should be based on the I_f for Mode 1. The value for t_o is determined from the following expression:

$$t_o = t_{min} + t_b$$

where

t_{min} = 22 milliseconds
t_b = 34 milliseconds

$$t_o = 22\text{ms} + 34\text{ms} = 56\text{ms}$$

The ITT setting is now calculated to be

$$ITT = \frac{I_f}{1 - e^{-t_o/\tau_m}}$$

$$= \frac{0.329}{1 - e^{-0.056/0.2}}$$

$$= 1.347 \text{ p.u.}$$

Use ITT setting = 1.25 p.u. for all three modes.

The settings for the reset timers are

Mode 1: $\Delta t_1 = \Delta t_2 = \Delta t_3 = \dfrac{2 \text{ cycles}}{18.3 \text{ cycles/sec}} = 0.109 \text{ sec}$

Mode 2: $\Delta t_1 = \Delta t_2 = \Delta t_3 = \dfrac{2 \text{ cycles}}{24.4 \text{ cycles/sec}} = 0.082 \text{ sec}$

Mode 3: $\Delta t_1 = \Delta t_2 = \Delta t_3 = \dfrac{2 \text{ cycles}}{47.3 \text{ cycles/sec}} = 0.042 \text{ sec}$

A complete summary of the settings for the TT module is shown in Table A. The only remaining calculations are for setting the IGE module.

IGE Module Setting Calculations

The amount of subsynchronous current, I_s, which produces the same maximum heating as a given amount of negative sequence current I_2 is computed for this example to be:

$$I_S = 1.39\, I_2 = (1.39)(0.08) = 0.111 \text{ p.u.}$$

Thus, the suggested settings for the IGE module are determined as follows:

$I_{SS} = 0.5 I_S = (0.5)(0.111) = 0.056$ p.u.

Since the calculated $I_{SS} > 0.01$, use $I_{SS} = 0.01$ p.u.

$I_{SF} = I_S = 0.111$ p.u. > 0.02 p.u.

Therefore, use $I_{SF} = 0.02$ p.u.

$I_{SFR} = I_S = 0.111$ p.u. > 0.03 p.u.

Thus, set $I_{SFR} = 0.03$ p.u.

The other suggested settings include

$K = 0.1$ p.u. -sec
$\delta = 0.01$ or 1%

Table A also contains a summary of the above recommended IGE settings for the machine in this example.

Table A. Setting Catalog

Unit ____________________

MM Module

Amperes for 1 per unit relay input, $I_{BASE} = 4.3$ ____________________ Amperes
BAND-REJECT FREQUENCY, $f_{BR} = 72.7$ ____________________ Hz

SET Modules

Quantity	Mode 1	Mode 2	Mode 3	Mode 4	
F_M	18.3	24.4	47.3		Hz
I_{SS}	0.0015	0.004	0.008		p.u.
I_{SF}	0.0029	0.008	0.015		p.u.
I_{SFR}	0.0029	0.008	0.015		p.u.
T_{o1}	0.640	0.640	0.380		sec
K	0.0112	0.0178	0.0714		sec-p.u.
δ	2.36	2.50	1.00		%

IGE Modules

Quantity	Module 1	
I_{SS}	0.01	p.u.
I_{SF}	0.02	p.u.
I_{SFR}	0.03	p.u.
T_{o1}	0.40	sec
K	0.10	sec-p.u.
δ	1.00	%

TT Modules

Quantity	Mode 1	Mode 2	Mode 3	Mode 4	
F_M	18.3	24.4	47.3		Hz
A_M	0.250	0.376	0.319		p.u.
τ_m	0.200	0.200	0.200		sec
I_{TT}	1.25	1.25	1.25		p.u.
$T_{inhibit}$	0.060	0.060	0.060		sec
$\Delta T_1 = \Delta T_2 = \Delta T_3$	0.109	0.082	0.042		sec

Appendix

Determination of A and B Constants for Loss-of-Life Curve

A loss-of-life curve is used to estimate the fatigue life expenditure for a shaft section. A typical loss-of-life curve is shown below in figure 8. The vertical axis is usually in terms of Shear Stress (S-N curve) or Torque, but can also be converted to current as a matter of convenience for SSO application. It is assumed that per-unit steady-state oscillating torque and per-unit oscillating current are equal. The equation approximating the loss-of-life curve in the region $I_L \geq I_S \geq I_o$ indicated above is in the following form:

$$N = A(I_o/I_S)^B \qquad \text{(A1)}$$

where

- N = number of cycles till failure
- A,B = constants in equation
- I_o = p.u. subsynchronous armature current corresponding to the endurance limit.
- I_S = p.u. subsynchronous armature current

The A and B constants for equation (A1) can be determined by choosing any two points on the curve. As a matter of convenience, the points corresponding to the endurance limit and elastic limit will be chosen. The equation given for I_o in the SET Module setting section is used for calculating the currents. The A constant can be determined first by simply setting I_S equal to I_o. That is,

$$N = A\left(\frac{I_o}{I_o}\right)^B = A(1)^B = A \qquad \text{(A2)}$$

Thus, the constant A is equal to N, the number of cycles till failure at the endurance limit. The B constant can then be calculated by setting I_S equal to I_L, the per-unit subsynchronous current which will produce shaft torques equalling the elastic limit of the shaft. The equation manipulations for determining the B constant are as follows:

$$N = A\left(\frac{I_o}{I_L}\right)^B$$

$$\ln N = \ln A + B \ln\left(\frac{I_o}{I_L}\right)$$

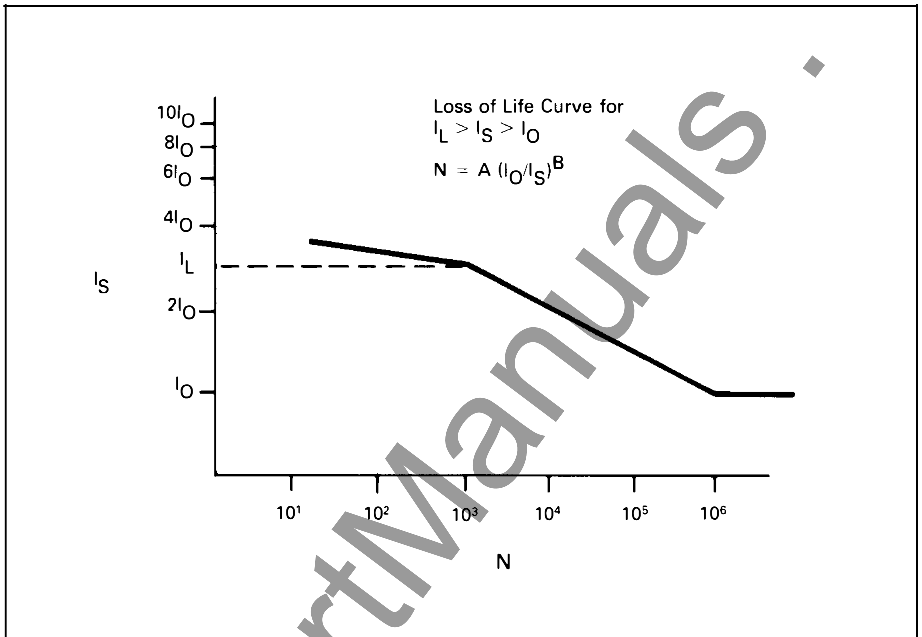

Fig. 8. Typical loss-of-life Curve

$$B \ln\left(\frac{I_o}{I_L}\right) = \ln N - \ln A = \ln\left(\frac{N}{A}\right)$$

$$B = \frac{\ln(N/A)}{\ln(I_o/I_L)} \qquad \text{(A3)}$$

The ratio I_o/I_L in equation (A3) above is equal to EL/T_{eim} where EL is the per-unit value of shaft torque corresponding to the torsional endurance limit, and T_{eim} is the per-unit value of shaft torque corresponding to the torsional yield point (or elastic limit). Thus, equation (A3) can also be written as follows:

$$B = \frac{\ln(N/A)}{\ln(EL/T_{eim})} \qquad \text{(A4)}$$

The following is an example of calculating the A and B constants using the same parameters as in the setting example calculations. Setting $I_S = I_o$ to compute the A constant yields

$$10^6 = A\left(\frac{I_o}{I_o}\right)^B = A(1)^B = A$$

where $N = 10^6$ at the endurance limit

To calculate the B constant, let $I_S = I_L$ as noted above. Assume $N = 10^3$ at the elastic limit. The per-unit values for the endurance limit EL and the elastic limit T_{eim} for mode 1 are 0.98 and 2.4, respectively. Solving equation (A4) gives

$$B = \frac{\ln\left(\frac{10^3}{10^6}\right)}{\ln\left(\frac{0.98}{2.4}\right)} = 7.71$$

Printed in USA

Westinghouse Electric Corporation
Relay and Telecommunications Division
Coral Springs, FL 33065