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High-Speed Reclosing System and Machine Considerations

HIGH-SPEED RECLOSING SYSTEM AND MACHINE CONSIDERATIONS

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While high-speed reclosing (HSR) following transmission faults has been widely used for many years, and discussed in many papers, there is currently a great deal of interest in this subject by utility engineers. The widespread interest has developed as a result of concerns in the industry that some of the HSR practices have a potentially more harmful effect on adjacent turbine-generators than had heretofore been recognized. It had generally been assumed that any excessive machine duties would be readily apparent by inspection of the stator end windings. Studies during the past several years, however, have shown that shaft fatigue damage, which is not an observable quantity prior to crack initiation, may be a greater limitation than stator winding duty.[1,2,3] While the potential for significant shaft fatigue damage for some worst case HSR incidents seems apparent, an assessment of the probability of such damage actually occurring is a complex statistical problem involving many variables. Recently completed studies[2] utilizing Monte Carlo techniques compare the probable shaft fatigue life expenditures for several alternate line reclosing practices. Studies such as these allow utilities to compare and evaluate alternate reclosing practices and implement methods which optimize the reliability of electric powergeneration and transmission.

In so doing, the utility engineer must assess the reclosing needs of the particular system. HSR, at the fastest possible speed, may be neither necessary nor desirable on many systems. A realistic appraisal of both the system switching requirements and the potential turbine-generator damage effects is necessary to achieve a proper balance between these two demands. The purpose of this paper is to present a brief review of some of the main considerations in arriving at this balance and to discuss reclosing concepts which can assist in meeting generator and system requirements,

SYSTEM SWITCHING REQUIREMENTS

A wide variety of switching operations are necessary for operation of a power system. These range from routine planned switching of lines for maintenance or operating reasons to emergency line switching during extreme system emergencies and automatic line reclosing following tripouts due to electrical faults.

It is important to differentiate between system needs for planned switching operations and those associated with unplanned system disturbances. In the former case, the lack of urgency to reclose permits conservative switching rules to be applied and system adjustments to be made, if necessary, which will result in essentially no damage to turbine generator components. Recent work of an IEEE Working Group[4], supported by the General Electric Company, has proposed screening guide limits on planned steady-state switching operations and suggests a criterion that the step change of power seen by the machine not exceed 0.5 per' unit of the generator kVA rating, i.e., $\Delta P \leq 0.5$ per unit. This screening guide level is not intended to apply for fault conditions and HSR. No screening guides have yet been developed for these.

During times of system disturbances, other factors must be considered to maintain transmission system reliability. For example, lines must be reclosed despite greater than normal angles across circuit breakers. During lightning storms, lines must be reclosed promptly after fault tripouts. Most electrical faults are temporary so automatic reclosing of power circuit breakers will generally be successful and thus will play an important role in maintaining transmission system reliability. From a system reliability viewpoint, one would like to restore the circuit as promptly as possible, hence, the historic widespread use of “high-speed reclosing” (HSR), which is typically in the order of 20-30 electrical cycles after the initial disturbance.

While the need for some form of automatic reclosing is generally accepted, opinion varies as to how fast this should be. A number of utilities are presently using 10 second or longer reclosing times to reduce the risk of turbine-generator shaft fatigue damage. They have experienced no reduction in system reliability compared with their previous practice of high-speed reclosing. Other utilities feel that successful high-speed reclosing, in a second or less, is important in avoiding stability problems which might result from simultaneous multiple circuit outages.

STABILITY CONSIDERATIONS

HSR may be either helpful or harmful to stability, depending on the system scenario being considered. Automatic line reclosing is an aid to stability by reducing the risk of multiple outages of circuits. From this viewpoint, the faster the line restoration the better. On the other hand, the system must also be able to maintain transient stability for fault occurrences when high-speed reclosing is unsuccessful (i.e., closure back into a permanent fault). It should be recognized that this second fault may cause instability by aggravating the initial electrical swings which have not had a chance to die out.

Figure 1 illustrates a case where high-speed reclosing is more harmful from a stability standpoint than helpful. In this example, a three-phase fault on the strongest line is cleared in five cycles by breaker tripping. The system is transiently stable for this fault without reclosing, as shown by the dashed curve. On the other hand, if high-speed reclosing is used and the fault happens to be a permanent one, the shock of the second fault coming near the peak of the swing curve causes loss of stability of the plant or unit.

A slight delay in reclosing time for the example of Fig. 1 could make the system stable for the unsuccessful reclosure case. As will be discussed later, short delays such as appear useful to the system in this case, are inherent to reclosing strategies which also greatly reduce turbine-generator duties, as compared with use of unrestricted HSR.

Another situation for which concern is sometimes expressed is that of false tripping of a line adjacent to a faulted circuit. This would result in loss of plant stability if successful high-speed reclosing of at least one circuit is not achieved. Line relaying should be designed to make this scenario one of very low probability. If false tripping of a line adjacent to a faulted circuit does occur, however, this could be readily accommodated by selective reclosing relay procedures which permit high-speed restoration of the unfaulted or temporarily faulted circuits.

In general, fault and reclosing events of most risk to the turbine-generator also carry the greatest risks of system instability – for example – unsuccessful reclosure into nearby multi-phase faults. Relay solutions available which are most effective in reducing the risks of turbine-generator damage can, at the same time, substantially reduce the transient stability problems of the system.

TURBINE-GENERATOR VIBRATION AND FATIGUE

Power system disturbances, such as electrical faults and various line switching or reclosing events, produce a torsional transient stimulus on the generator rotor. For turbine-generators connected to uncompensated transmission lines, transient stimulus on the generator rotor consists of one or more of the following components:

- Step change in torque
- 60 Hz torque
- 120 Hz torque

These stimuli on the generator rotor cause oscillating torques to be induced in the turbine-generator shafts. Depending on the severity of the disturbance, the amplitudes of the multi-modal shaft torque oscillations may significantly exceed the shaft's fatigue endurance limit, resulting in shaft fatigue damage. Because turbine-generator torsional oscillations are damped very lightly, they will persist for many seconds, generally significantly longer than the electrical air-gap torque oscillations which caused them. Therefore, following a major electrical disturbance, the potential exists for the shafts to experience many damaging fatigue cycles before the mechanical oscillations decay to undamaging levels.

The fatigue process is cumulative, so that fatigue life consumption in a shaft is the result of all past events that produced strain oscillations above the endurance limit of the shaft material. If the shaft cumulative fatigue life expenditure exceeds a certain threshold, a surface fatigue crack is likely to be initiated, generally at the point of highest stress concentration in the limiting shaft span. This fatigue crack may ultimately propagate by several mechanisms to a depth which would force the unit to be removed from service due to subsequent abnormal exposures, such as additional electrical disturbances and/or possible cyclic bending stresses due to shaft misalignment.

Severe electrical disturbances also have the potential for causing couplings to become misaligned, rotor transverse vibration to increase, and loosening, fretting, and wear of a variety of turbine-generator rotating and non-rotating components.

Major faults that occur close to a power plant may stimulate levels of shaft torque that are several times the value corresponding to steady state load torque. To illustrate this, consider, as seen in Fig. 2, the specific simulation of a close-in temporary three-phase fault, cleared after 3 cycles with the line successfully reclosed after approximately 25 cycles. The 892 MVA 2-pole turbine-generator that was analyzed here consisted of a high-pressure turbine, two low-pressure turbines, a generator, and a shaft-driven exciter. The generator electrical torque is shown in the upper trace, showing about three cycles of fault torque followed at reclosure of the line by an additional small torque stimulation associated with switching the line back into service. The lower trace shows the response torque for one shaft section and indicates that the peak-to-peak value of almost three per unit of machine rated torque still persists at the time of reclosure, with virtually no reduction in amplitude. This illustrates the very light damping of shaft torsional oscillations which results in the potential for a large number of shaft fatigue cycles for this case.

Figure 3 shows a case in which a permanent fault occurs and, hence, the reclosure was unsuccessful. The electrical torque trace again indicates that a three-phase, close-in fault was applied and cleared in three cycles. As the line recloses, the fault torque is repeated after three cycles. The lower trace shows the same initial peak-to-peak mechanical response torques of 3 per unit; however, this time the peak-to-peak torque after the unsuccessful reclosure is considerably greater, and in this example is in the range of 5 to 6 per unit. This doubling effect is simply a result of the very light torsional damping of the mechanical oscillations, such that there has been insufficient time for the oscillations from the original fault to attenuate appreciably before the reclosure superimposed the second set of oscillations. In this example, reclosure timing was selected to give maximum reinforcement of shaft oscillations.

The problem, however, is more severe than simply an increase of two to one in peak-to-peak shaft torque between a successful and unsuccessful reclosure. Consider a typical stress-life diagram shown in Fig. 4 for a steel structure containing a stress concentration, This curve plots alternating stress on the ordinate and cycles to failure on the abscissa. As shown by the two sets of dotted lines, a doubling of stress amplitude may result in an order of magnitude increase in fatigue life expenditure due to the non-linear nature of the fatigue process. This effect has been largely responsible for the concerns with high-speed reclosing.

HSR for temporary faults, which comprise the vast majority of all line faults, generally results in modest levels of shaft fatigue life consumption for a single event. For severe permanent faults, however, the rapid sequence of torque applications associated with HSR can cause major fatigue damage under worst case conditions.

This potential for large shaft fatigue life expenditures in a single incident is shown in Fig. 5 for a study group of seven large steam turbine-generator units of various mechanical configurations. Shaft life expenditures as high as 100 percent are seen possible for close-in three-phase faults, and as high as 30 percent for double-line-ground faults, where "100 percent loss of fatigue life" corresponds to initiation of a fatigue crack.

While the probability of occurrence of the worst case fatigue damage level shown is quite small, the potential level of damage is so high that means should be applied to completely avoid it. Fortunately, it appears that this can be done with little if any sacrifice in system reliability.

A generalized evaluation of different reclosing strategies requires more than consideration of worst case conditions.

LIFETIME DUTIES

While it is clear from analysis that some of the worst case reclosing scenarios (such as unsuccessful reclosure onto multi-phase faults at the most unfavorable instant) can cause a significant loss of fatigue life of turbine-generator shafts, the severity of actual reclosing events varies over a wide range. Figure 6, for example, shows the wide variation in duty with the particular instant of reclosure. Similar variations of an order of magnitude or more occur for small variations in tripping times. An appraisal of a reclosing strategy requires consideration of these and many other variables and statistical assumptions, as listed in Table 1.

A recent study[2] utilized Monte Carlo simulations to contrast the cumulative shaft fatigue duty for several different reclosing practices and for several machine configurations, over an assumed 40-year turbine-generator fault exposure period. The study system was a two-line configuration into an equivalent system reactance as shown in Fig. 7. A hybrid computer which combines analog and digital facilities was utilized to generate the large quantity of torsional vibration and fatigue data for the Monte Carlo simulations used to estimate lifetime duties.

To explore a range of reclosing possibilities, four practices were compared:

- Unrestricted HSR which refers to reclosure at both ends of the line as rapidly as possible following a line tripout, regardless of fault type or severity.
- Delayed Reclosing, using 10 **second delay time.**
- Sequential Reclosing utilizing initial reclosure of the remote end breaker with check relays permitting plant end reclosure on temporary faults only.
- Selective Reclosing utilizing high-speed reclosing only for the less severe faults. For purposes of this study a simplified assumption for fault severity was used, with HSR permitted only for L-G and L-L faults, regardless of location.

Table 2 shows the assumed fault statistics, based on pub lished utility data.

Figure 8 shows the results of Monte Carlo simulations of the four reclosing practices described for a turbine-generator fault exposure period of 40 years. it is seen that the various practices resulted in widely different cumulative probability distributions for loss of shaft fatigue life. These results are for the machine which generally exhibited the highest fatigue duty in the study population, and for the particular fault statistics of Table 2.

It is seen that all of the alternative practices to unrestricted HSR substantially reduce the risk of excessive shaft fatigue damage. If it is assumed, for example, that 30 percent of the shaft life is reserved for other possible events such as bus faults, out-of-phase synchronizing accidents, and the more remote line faults, the probabilities of exceeding the allotted 70 percent shaft life for these practices is given as follows:

Unrestricted HSR	**21%**
Delayed Reclosing	**0.03%**
Sequential Reclosing	**0.1%**
Selective Reclosing	**0.9%**

Recognizing the potential duties on the turbine-generator, the need then becomes one of balancing these risks against the reliability needs of the power system.

ALTERNATIVE RECLOSING CONCEPTS

There are many possible reclosing strategies, including the four illustrated in Fig. 8. While the generalized studies provide calibration of the effectiveness of different strategies, the particular plant and transmission network, its stability limitations, vulnerability to multiple circuit outages, etc., will dictate the preferred reclosing practice or combination of practices.

One concept to reclosing which offers the possibility of minimizing turbine-generator duties as well as fast restoration of a transmission circuit is a combination of selective and sequential relaying based on fault severity. As noted previously, fault severity from the standpoint of turbine-generator duties and plant stability is a function of fault type and fault location. For example, close-in three-phase and double line-to-ground faults are most severe while remote line-to-line and single line-to-ground faults are least severe. Hence, relaying, which provides a fault severity measurement based on fault type and location, could be used to initiate HSR of the line terminals in a sequence which would minimize duties on the turbine-generator. With this concept, line reclosing could occur in one of the following modes:

- For the least severe faults, conventional HSR would be initiated independently at the two-line terminals.
- For faults that exceed the fauit severity setting at one terminal, high-speed sequential reclosing would occur.
- For faults that exceed the fault severity setting at both terminals, 10 second delayed reclosing would be utilized.

There are two approaches that provide a means for making a fault severity measurement based on fault type and fault location. One approach uses a positive sequence distance relay while the other utilizes a positive sequence voltage relay.

Positive Sequence Distance Relaying

For economy and simplicity, it is preferable to use line relays as a source of information about fault severity in a selective reclosing scheme. One relay that is particularly well-suited for this function is the positive sequence distance relay SLYP used in the General Electric SLYP-SLCN scheme. With the normal settings used for line protection, the SLYP relay will operate for all three-phase faults and for some nearby line-to-ground, line-to-line and double line-to-ground faults. Hence, when the SLYP relay operates, it could be used to block high-speed reclosing at a line terminal for the most severe fault types and locations. Conversely, when the SLYP relay does not operate, HSR of a line terminal would be permitted. Where blocking occurs at one end only, high-speed sequential reclosing would be provided at that end utilizing a high-speed phase angle check and/or a three-phase voltage check.

The impedances seen by a positive sequence distance relay for all types of faults is shown by the equations in Table 3. It should be noted that except for three-phase faults, the apparent impedance seen by the relay includes source impedance in the negative sequence (Z2) and (ZO) terms. Therefore, the impedance seen by the relay will vary to some degree with system configuration. These equations assume sources behind both line terminals.

To illustrate the possible application of the SLYP relay in a selective reclosing scheme, consider the 80-mile and 40-mile lines on the system in Fig. 7 used in the Monte Carlo study. Figure 9 shows the positive sequence impedance seen by the SLYP relay for all types of faults at each terminal of the 80-mile line while Fig. 10 shows the impedances seen by the SLYP relays at the terminals of the 40-mile line. In these and subsequent figures, fault location is given with respect to the source or generating end of the line. The dashed lines In both diagrams indicate typical relay settings used for line protection. For hoth lines, an overreaching relay is used to control reclosing at the sending end of the Iine (generator end) while an under-reaching first zone relay is used to control reclosing at the receiving end. Both types of units are incorporated in the standard SLYP-SLCN scheme.

For the sending end of the 80-mile line (Fig. 9A), the SLYP relay will pick up and block reclosing for any impedance which falls below the relay setting. Therefore, the SLYP relay will block reclosing:

- For all three-phase faults (LLL) .
- For double line-to-ground faults (DLG) on 60 percent of the line
- For line-to-line faults (LLL) on 46 percent of the line
- For nearby single line-to-ground faults (SLG) on 7 percent of the line.

In effect, the SLYP relay will block reclosing for those faults which may impose the greatest duty on the generator. While blocking reclosing for some nearby line-to-ground faults may seem overly pessimistic, it is not uncommon to have line-to-ground faults evolve into permanent double line-to-ground faults due to equipment failures in or near stations.

At the receiving end of the line (Fig. 9B), the first zone SLYP relay will permit reclosing for all line-to-ground faults and block reclosing:

- For three-phase faults on 88 percent of the line.
- For double line-to-ground faults on about 40 percent of the line.
- For line-to-line faults on 30 percent of the line.

While this terminal permits reclosing for some three-phase faults, it should be noted that if the fault is permanent, the fault is physically 110 miles or more away from the generator. Electrically, the fault appears to be even further away from the generator, due to infeed effects, and therefore, the duty on the generator will be reduced. For this case, high-speed reclosing would be blocked at the other terminal.

With the specified setting, high-speed reclosing would be initiated at either one or the other terminal for line-to-ground, double line-to-ground and line-to-line faults anywhere on the line. The other terminal would be reclosed sequentially after a high-speed phase angle check and/or voltage check. For most three-phase faults, HSR would be blocked at both ends. In these cases, a 10 second delayed reclosing could be utilized at both ends.

Figure 10A & B shows the impedance seen by the SLYP relay at the terminals of the 40-mile line. As noted earlier, an over-reaching relay at the generator end of the line and an under-reaching relay at the receiving end are used to control reclosing. With typical settings for this type line as shown by the dashed lines, it is also possible to achieve similar type of coverage and reclosing sequences as for the 80-mile line.

As can be seen in the illustration, the characteristic of the positive sequence distance relay, Type SLYP, is inherently selective as to fault type and location and thereby provides an excellent means for controlling reclosing based on fault severity.

Positive Sequence Voltage Relay

Positive sequence voltage can provide another means for discriminating between different types of faults and their location. For example, Fig, 11 and Fig. 12 show the variation of positive sequence voltage as a function of fault type and location at the terminals of the 80- and 40-mile lines, respectively. Again, fault location is given with respect to the sending end of the line. As can be seen from these diagrams, the more severe the fault, the lower the positive sequence voltage. This characteristic, in conjunction with a positive sequence undervoltage relay, could be used to control reclosing.

To illustrate the possible application of such a relay, consider the variation of positive sequence voltages for the 80-mile line shown in Fig. 11. The dashed lines indicate one possible setting for an undervoltage relay. With this setting, the voltage relay will be picked up under normal conditions. During faults, the relay will remain picked up and initiate reclosing for voltages above the setting. Conversely, the relay will drop out and block reclosing for voltages below the setting. For the settings shown, HSR and sequential HSR could be accomplished for a range of fault severities similar to the distance relay previously illustrated. For the sending end of the 80-mile line (Fig. 11A), the positive sequence undervoltage relay would permit HSR for all line-to-ground faults and would block reclosing:

- For all three-phase faults.
- For double line-to-ground faults on a total of 44 percent of the line.
- For line-to-line faults on 16 percent of the line.

At the receiving end of the line (Fig. 11B), the undervoltage relay would permit HSR for all line-to-ground faults, and would block reclosing:

- For all three-phase faults.

- For double line-to-ground faults on 16 percent of the line.
- For line-to-line faults on 10 percent of the line.

At the sending end of the 40-mile line (Fig. 12A), HSR reclosing would be blocked for all three-phase and double line-to-ground faults and on 20 percent of the line for line-to-line faults. HSR reclosing would be permitted for all line-to-ground faults.

At the receiving end of the 40-mile line, (Fig. 12B), HSR would be permitted for all line-to-ground and line-to-line faults while reclosing would be blocked for double line-to-ground faults on 14 percent of the line and for three-phase faults on 80 percent of the line.

The illustration shows only one possible combination of undervoltage relay settings. The settings could be modified to restrict or to expand the range of HSR for different types of faults as dictated by turbine shaft life requirements. Because of the drooping voltage characteristic and because positive sequence voltage can vary appreciably with system configuration, it is generally more difficult to obtain the same degree of reclosing discrimination with the undervoltage relay approach as with the positive sequence distance relay.

The two approaches discussed provide alternative means for controlling reclosing as a function of fault type and fault location. Either the positive sequence distance relay or the positive sequence undervoltage relay could be used in a sequential reclosing scheme to restore a line to service. For the more severe temporary faults where one terminal is blocked, high-speed phase angle checking relays are available to permit high-speed sequential reclosing. One benefit of such relaying would be to provide safe high-speed restoration of any circuits which had been tripped incorrectly. Where there are generating plants at both ends of a line, as is frequently the case, sequential reclosing on the more severe multi-phase faults would be initiated from the end most remote from the fault. Reclosing which is based on fault severity should reduce turbine generator duties and improve overall system stability.

CONCLUSIONS

- Unrestricted high-speed reclosing may risk major shaft fatigue damage and this practice should not be applied without specific study to assure its safety.
- In particular, high-speed reclosing into nearby three-phase and double-line-ground faults poses a potential for major shaft fatigue damage in a single incident.
- The line reclosing speeds judged necessary to provide adequate reliability varies widely between systems.
- Depending on the perceived needs of the system, different reclosing relay methodsare available which will generally meet these needs and protect the turbine-generator from excessive duties. These methods include:
  - Delayed reclosing of 10 seconds for all faults.
  - Sequential relaying initiated from the remote end of the line with check reclosure at plant end Specific studies may be required to check duties.
  - Selective relaying to permit high-speed reclosing for less severe faults only and delayed reclosing for others.
  - Combined selective and sequential reclosing utilizing fault severity measurement and high-speed phase angle check relaying. This provides high-speed simultaneous reclosing, high-speed sequential reclosing or delayed reclosing based on fault severity considerations. Specific studies may be required to check duties for HSR of severe faults.

With the present availability of reclosing relaying equipment, it should be possible to eliminate or minimize conflict between line switching needs of the system and the duties on large steam turbine-generators. Study methods are available to determine specific needs. A new device, the torsional vibration monitor,[5] could be applied to provide specific fatigue duty measurements on selected units. Such direct measurements will provide invaluable data for achieving the best possible balance for all of the system reliability needs.

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5. E. E. Gibbs and D. N. Walker, "Torsional Vibration Monitoring," GER-3198, presented at Pacific Coast Electrical Association Engineering and Operating Conference, March 13-14, 1980.

Table 1

VARIABLES AFFECTING RECLOSING DUTIES

- System Configuration
- Machine Electrical & Mechanical Parameters
- Fault Frequency
- Fault Type
- Fault Location
- Fault Temporary or Permanent
- Fault Clearing Time Range
- Fault Reclosing Time Range
- Fault Occurrence, Point on Wave (DC Offset)
- Scatter in Shaft Fatigue Properties

Table 2

Fault Statistics

Fault Rate 4/100 Mi./Yr.	Fault Type		
	3ϕ	L-L-G	L-G and L-L
Fault type – %	3	3	94
Percent of faults that are temporary	60	60	87
Percent success of initial automatic reclosures	55	55	80
Percent success of subsequent delayed reclosures	5	5	

Table 3

Impedances Seen By a Positive Sequence Distance Relay for Different Types of Faults with Sources Behind Each Line Terminal

THREE-PHASE FAULT (LLL)

$$Z_{1R} = Z_{1L}$$

SINGLE LINE-TO-GROUND FAULT (SLG)

$$Z_{1R} = Z_{1L} + \frac{Z_2}{C_1} + \frac{Z_0}{C_1}$$

LINE-TO-LINE FAULT (LL)

$$Z_{1R} = Z_{1L} + \frac{Z_2}{C_1}$$

DOUBLE LINE-TO-GROUND FAULT (DLG)

$$Z_{1R} = Z_{1L} + \frac{1}{C_1}\,\frac{Z_2 Z_0}{Z_2 + Z_0}$$

WHERE:

Z_{1R} = Apparent impedance seen by relay

Z_{1L} = Positive sequence impedance of the line to the point of fault.

Z_2 = Negative sequence impedance as viewed from the fault including the effects of source impedance.

Z_0 = Zero sequence impedance as viewed from the fault including the effects of source impedance.

C_1 = Positive sequence current distribution factor.

$$C_1 = \frac{I_1 \text{ Relay}}{I_1 \text{ Fault}}$$

GENERATOR ROTOR ANGLE SWING
WITH HIGH-SPEED RECLOSING

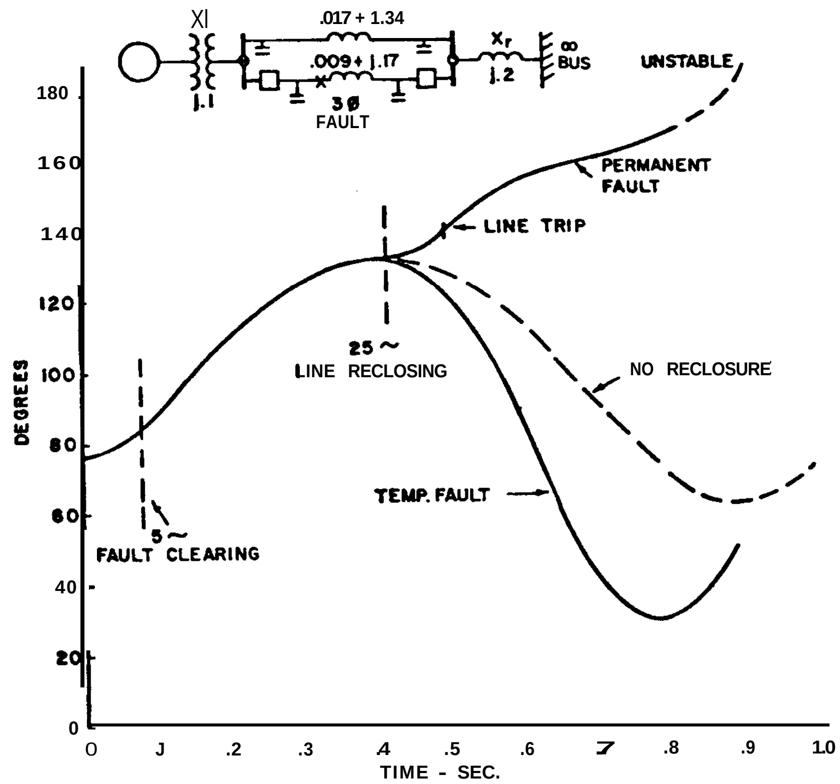


Figure 1

HIGH-SPEED RECLOSING (25 CYCLES)
FOLLOWING A THREE-PHASE FAULT

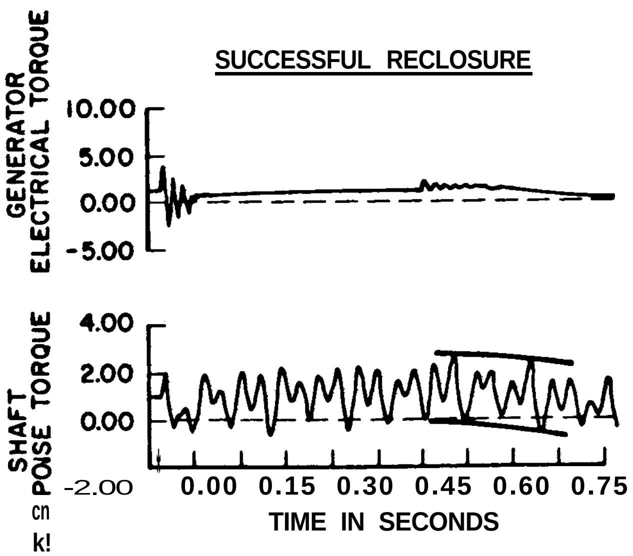


Figure 2

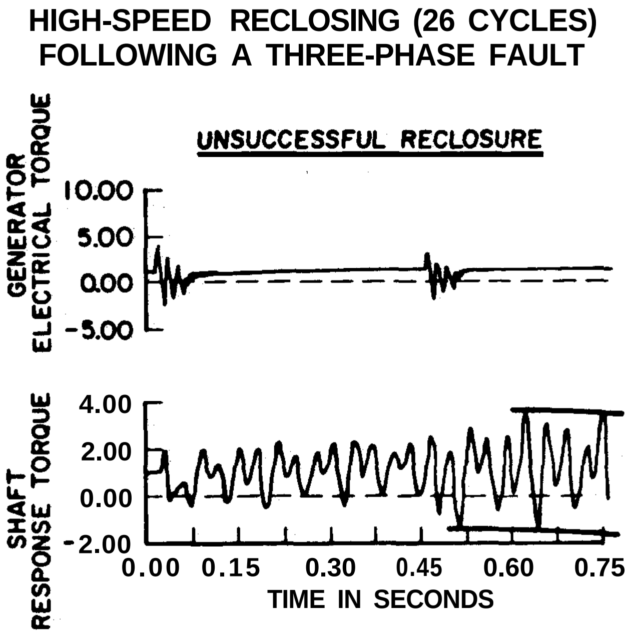


Figure 3

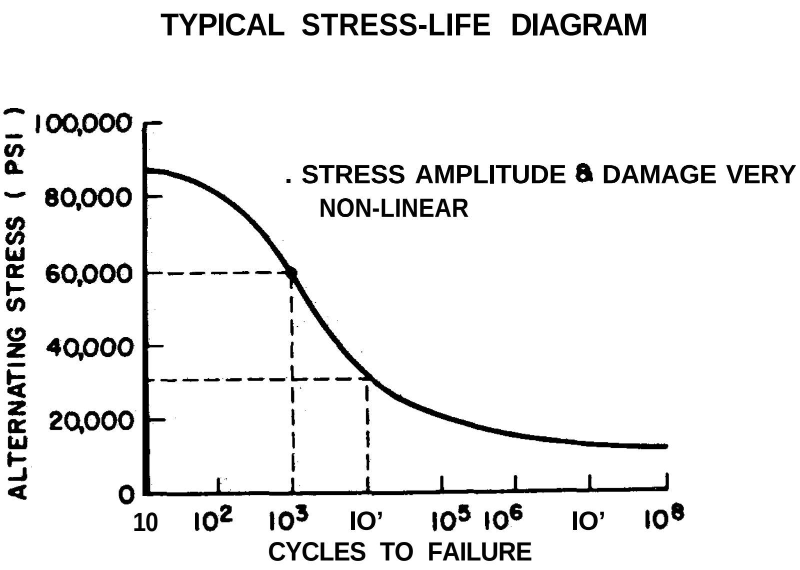


Figure 4

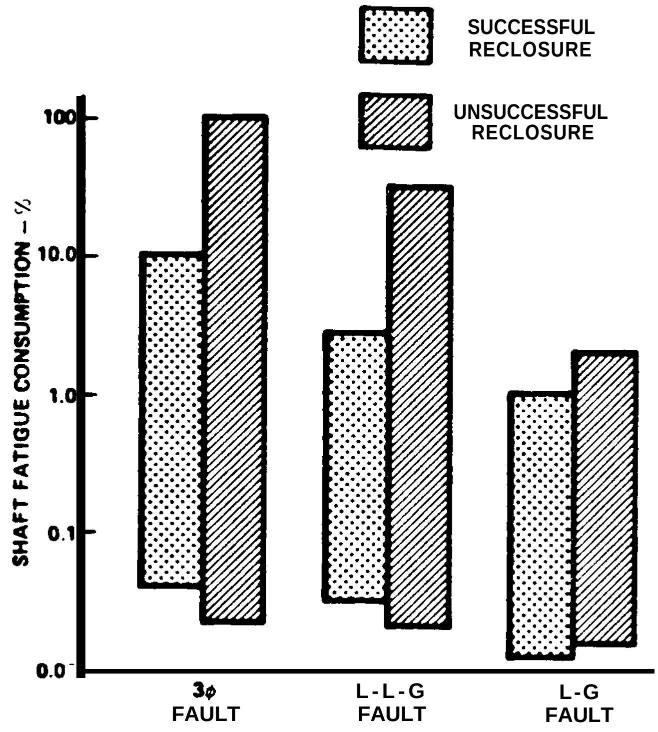


Fig. 5. Ranges of shaft fatigue duty (single incident)

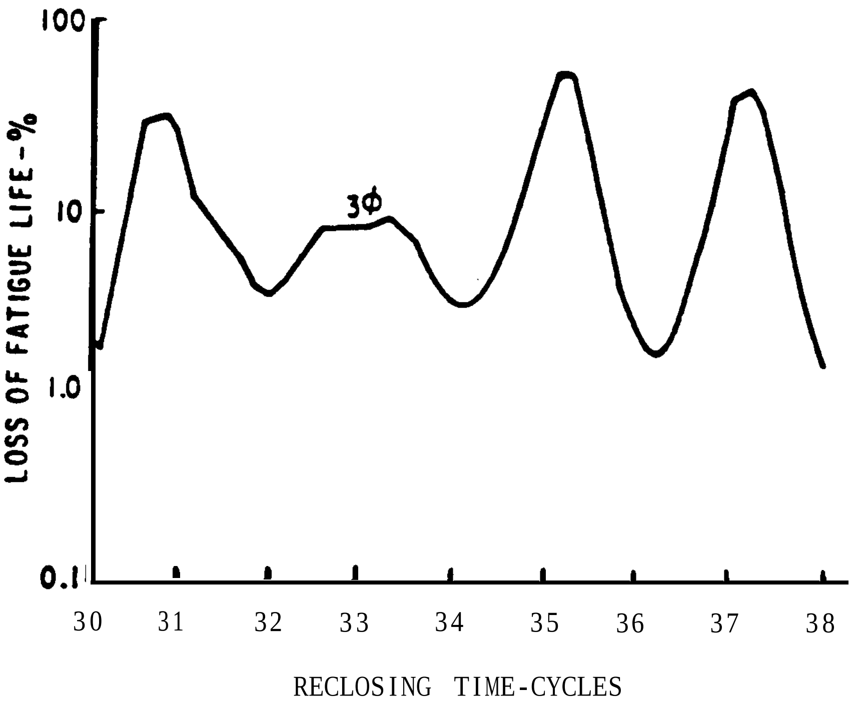


Fig. 6. Effect of breaker reclosing time on shaft fatigue duty

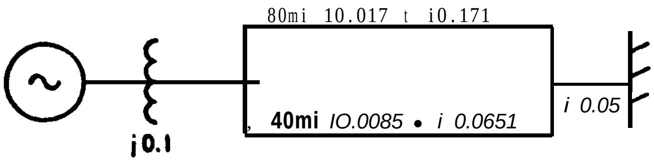


Fig. 7. Electrical system model

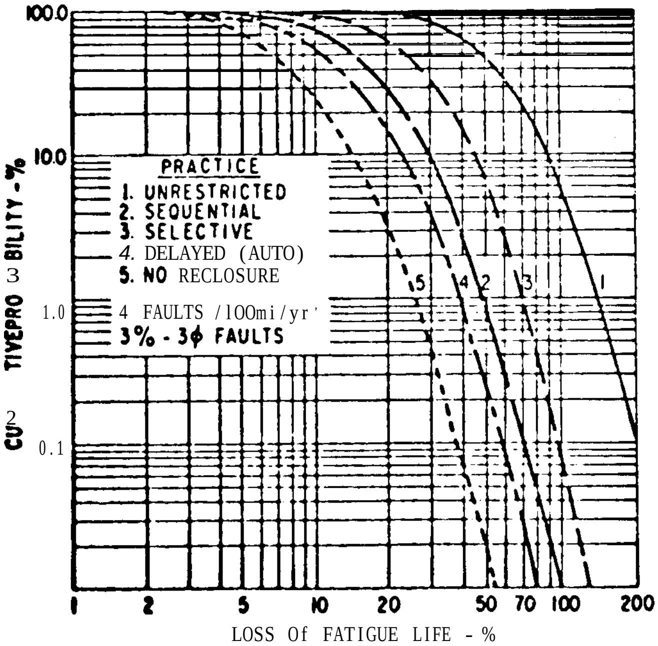
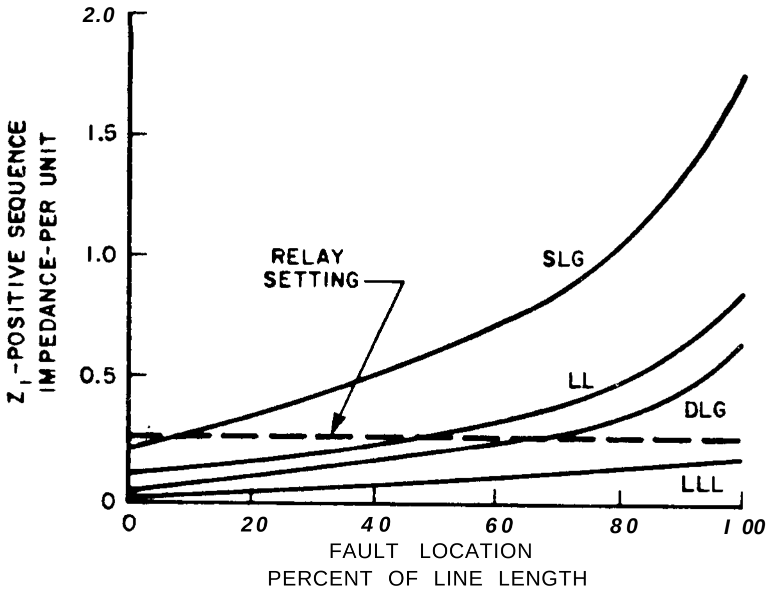
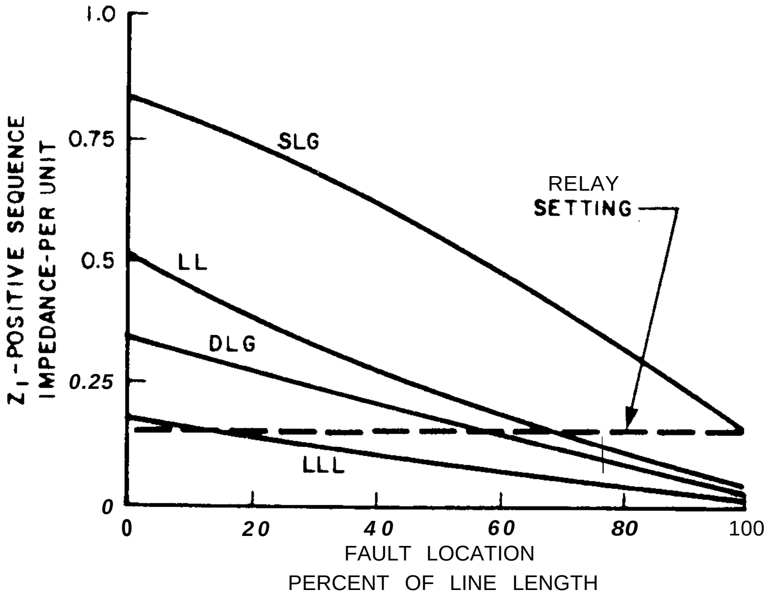


Fig. 8. Fatigue expenditure over 40-year exposure period (3 percent 3φ faults)

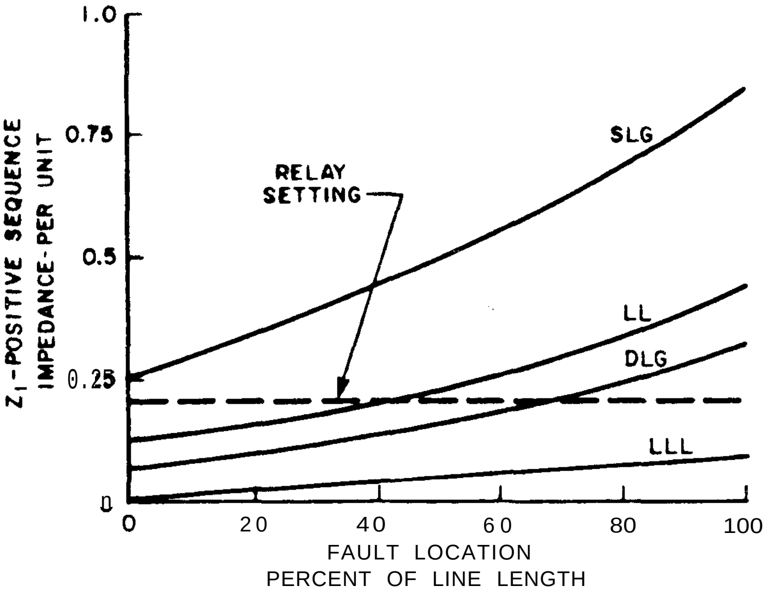


(A) IMPEDANCES AS SEEN AT THE SENDING END (GENERATOR END). (80-MILE LINE)

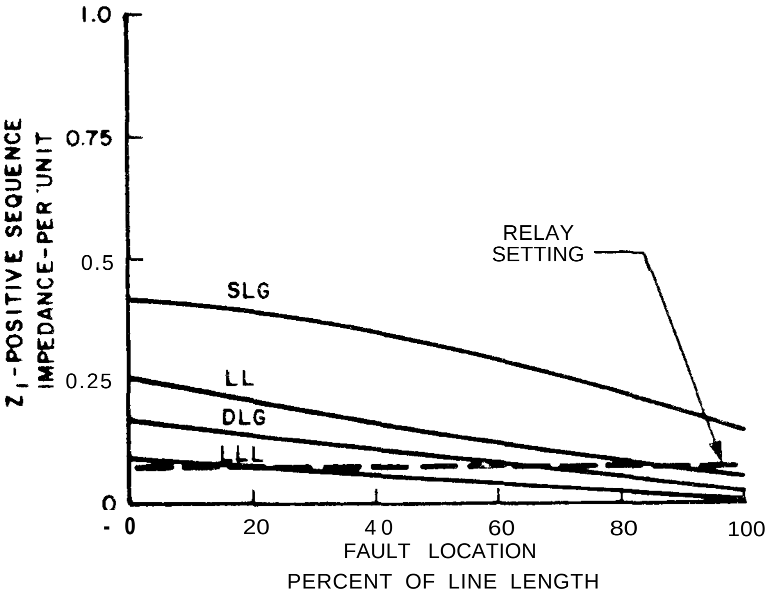


(B) IMPEDANCES AS SEEN AT THE RECEIVING END. (80-MILE LINE)

Fig. 9. Impedances seen by a positive sequence distance relay for all faults on the 80-mile line

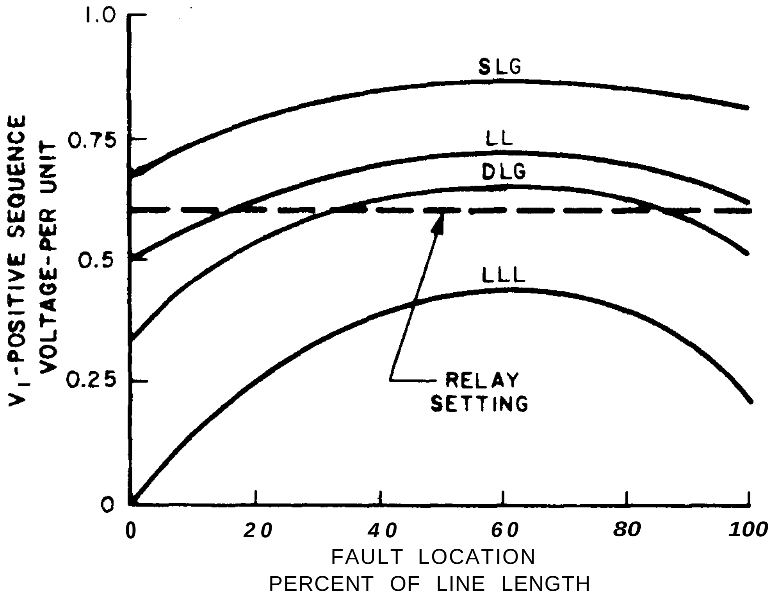


(A) IMPEDANCES AS SEEN AT THE SENDING END (GENERATOR END). (40-MILE LINE)

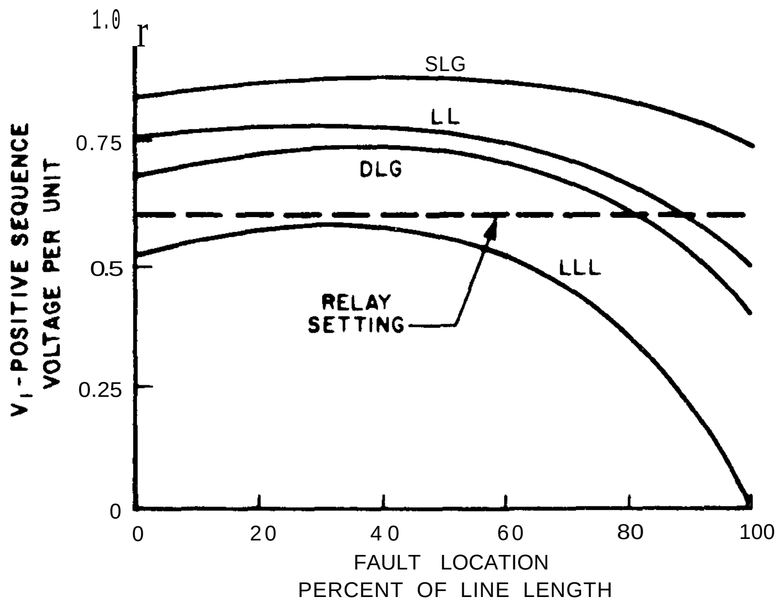


(B) IMPEDANCES AS SEEN AT THE RECEIVING END. (40-MILE LINE)

Fig. 10. Impedances seen by a positive sequence distance relay for all faults on the 40-mile line

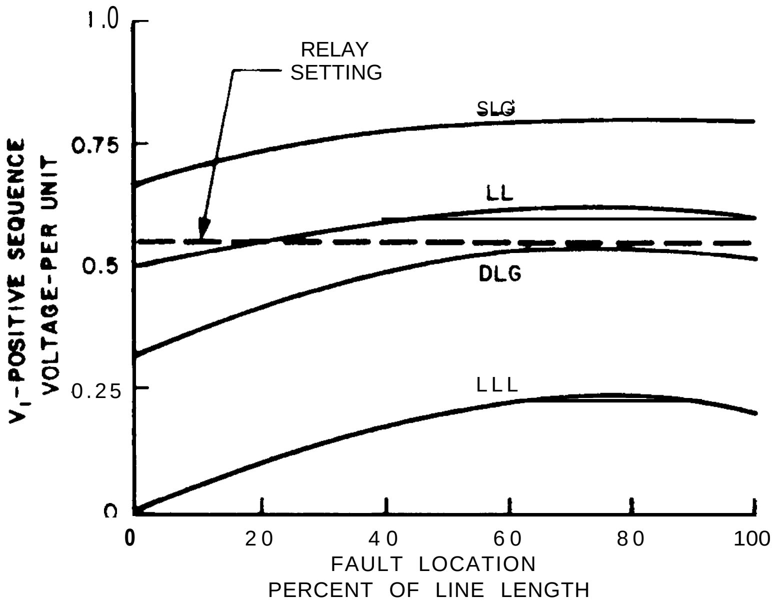


(A) VOLTAGES AS SEEN AT THE SENDING END. (80-MILE LINE)

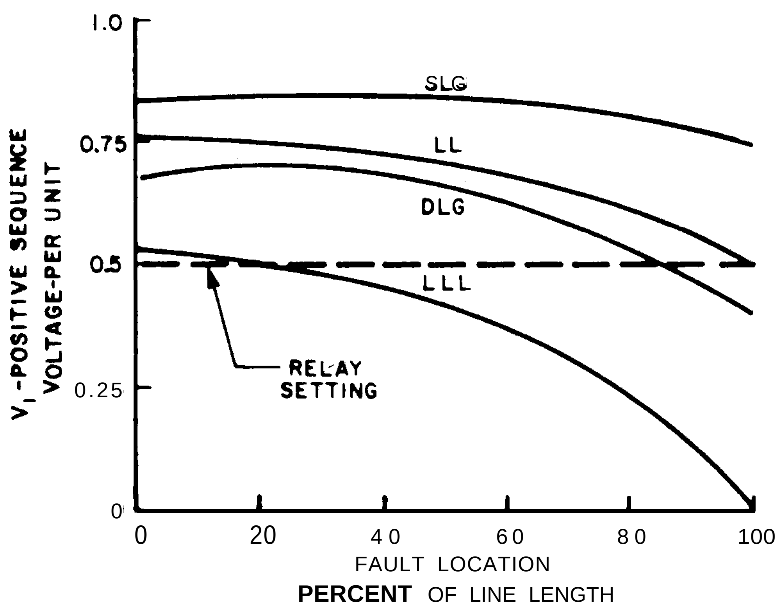


(8) VOLTAGES AS SEEN AT THE RECEIVING END. (80-MILE LINE)

z 17. Positive sequence voltages for all faults as seen at the terminals of the 80-mile line



(A) VOLTAGES AS SEEN AT THE SENDING END. (40-MILE LINE)



(B) VOLTAGES AS SEEN AT THE RECEIVING END. (40-MILE LINE)

Fig. 12. Positive sequence voltages for all faults as seen at the terminals of the 40-mile line

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