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OUT OF STEP RELAYING FOR GENERATORS WORKING GROUP REPORT

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ABSTRACT

This paper discusses the need for the methods of accomplishing out-of-step protection of generators. The report describes the loss-of-synchronism impedance characteristics of large generators in a modern EHV system. It is demonstrated that conventional out-of-step relaying schemes as applied to transmission lines can also be used to detect the out-of-step condition at the generator.

I. INTRODUCTION

In the aftermath of the 1965 Northeast Power Failure and other subsequent power system disturbances, attention was focused more acutely than ever on such system problems as low voltage and frequency, and generators operating out-of-synchronism. The need for purposeful automatic sectionalizing of systems into self-sustaining islands was recognized as being desirable for severe system swings for which recovery is not possible. Although out-of -step protection systems were available before 1965, more sophisticated schemes have been developed for application to transmission systems. These schemes provide line relays with sensing elements and control logic to detect the out-of-synchronism condition, the objective being the opening of certain transmission lines or the inhibiting of tripping of these ties to effect the maximum preservation of the system.

In 1970 the Rotating Machinery Subcommittee of the IEEE Power System Relay Committee became aware that some relay engineers were becoming more concerned with sensing the out-of-step condition electrically at the generator terminals or the high voltage terminals of the associated step-up transformer. It was recognized that sensing elements were not generally applied to cover the gap that may exist from the station transmission buses electrically back through the unit transformer and into the generator. This gap usually occurs because relays in the generator zone such as differential and most time delayed back-up relays cannot operate for an out-of step condition. This, along with the possibility of seriously damaging a generator under an out-of-step condition, prompted the Subcommittee to form a Working Group to study this problem. The assignment of the Working Group was defined as "To investigate the need for and the methods of accomplishing out-of-step protection of generators." The results of this study including a survey letter of inquiry are presented in this report.

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II. LOSS OF SYNCHRONISM CHARACTERISTICS

General

The conventional relaying approach to visualize and detect a loss of synchronism condition is to analyze apparent impedance variation as viewed at the terminals of a line or generator. This variation is a function of the system voltages and the angular separation between the systems. The apparent impedance locus also depends on the type of governor and voltage control, and the type of disturbance which initiated the swing. Depending on the rate of slip this variation in impedance can usually be detected by distance-type relaying, and the systems or generator separated before the completion of one slip cycle.

Simplified graphical procedures have been developed (2) and used to determine the variation in apparent impedance during a loss of synchronism condition. These procedures derive an impedance locus which can be plotted for study purposes with the system characteristic on an R-X diagram. Typical impedance loci obtained with this procedure are illustrated in Figure 1. The three impedance loci shown are plotted as a function of the ratio of the system voltages EA/EB which is assumed to remain constant during the swing. Moreover, in this simplified approach, the following assumptions are made: initial transients (dc or 60 Hz components) and effects of generator saliency are neglected; transient changes in impedance due to a fault or clearing of a fault (or due to any other disturbance) have subsided; effects of shunt loads and shunt capacitance are neglected; effects of regulators and governors are neglected; and the voltages E_A and E_B behind the equivalent impedances are balanced sinusoidal voltages of fundamental frequency.

When the voltage ratio $E_A/E_B = 1$, the impedance locus is a straight line PQ which is the perpendicular bisector of the total system impedance between A and B. On this diagram, the angle formed by the intersection of lines AP and BP on line PQ is the angle of separation (δ) between the systems. If system $B(E_B)$ is taken as reference, and if it is assumed E_A advances in phase angle ahead of E_B, the impedance locus moves from point P toward Q and the angle (δ) increases. When the locus intersects the total impedance line AB the systems are 180 degrees out of phase. This point is both the electrical and impedance center of the system. As the locus moves to the left of the system impedance line, the angular separation increases beyond 180 degrees and

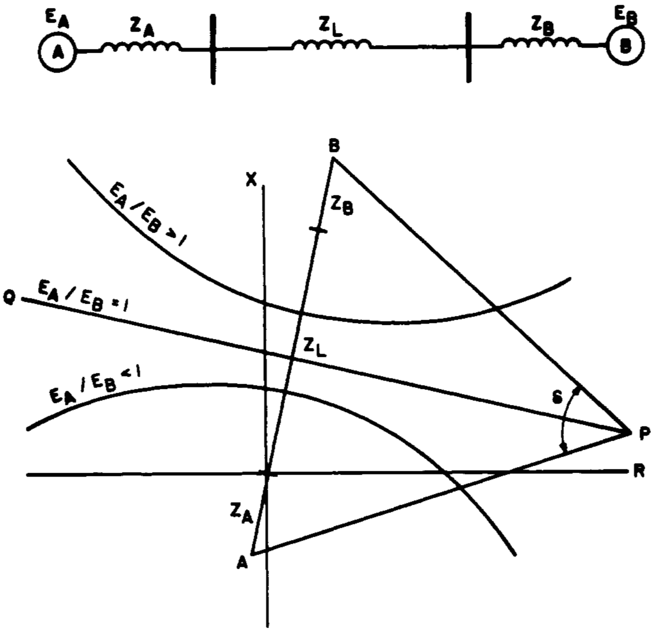


Fig. 1 Typical Out-of-Step Impedance Loci Using Simplified Graphical Procedures

eventually the systems will reach a point where they will be in phase again. If the systems are not separated, system A can continue to move ahead of B again and the whole cycle may repeat itself. When the locus reaches the point where the swing started, say at point P, one slip cycle has been completed.

If system A slows down with respect to B (decreases in phase angle), the impedance locus will move in the opposite direction from Q to the right to P.

When the voltage ratio E_A/E_B is more than or less than one (1), the impedance loci will be circles with their centers on extensions of the total impedance line AB. For the case of $E_A/E_B>1$, the electrical center will be above the impedance center of the system and for $E_A/E_B<1$, the electrical center will be below the impedance center.

It should be noted that the electrical centers of the system are not fixed points. The location of these centers will vary as the system impedances behind the line terminals vary and the equivalent internal generator voltages vary. Therefore, when determining the impedance locus for a system it will be necessary to consider changes in system conditions (that is, variations in Z_A and Z_B of Figure 1) and determine a locus for each condition.

The rate of slip between the two systems is a function of the accelerating torque and inertias of the systems. An estimate of the slip can be obtained from transient stability studies where angular changes of the system voltages may be plotted as a function of time. From these plots, an average rate of slip either in degrees/sec. or cycles/sec. can be determined. The rate of slip between the systems will not be constant during any given slip cycle. However, the general practice in simplified studies is to assume a constant rate of slip for the portion of the first slip cycle which is of interest; namely, the starting point of the swing locus and the point of 180 degrees separation between systems.

Generator Loss of Synchronism Characteristics

Ten to twenty years ago, system and generator impedance characteristics were such that the electrical center during a loss of synchronism condition generally occurred out in the transmission system. The impedance loci generally intersected transmission lines and could readily be sensed by line relaying or out-of-step relaying schemes and the system could be separated without the need for tripping generators.

With the advent of EHV systems, large conductor-cooled generators, with fast response voltage regulators and with the expansion of transmission systems, system and generator impedance characteristics have changed appreciably. Generator and step-up transformer impedances have increased in magnitude while systems impedances have decreased. As a result, on many systems today, the system impedance center and the electrical center during swings can and does occur in the generator or in the generator step-up transformer.

In general, the loss of synchronism impedance loci, as viewed at the generator terminals, follows the swing characteristic where the ratio of generator to system voltage (E_A/E_B) is less than one ($E_A/E_B<1$). This is due to the fact that for most machine loadings, the equivalent internal machine voltage will be less than 1.0 per unit and less than the equivalent system voltage. This will generally be true for leading, unity and even for slightly lagging power factor loadings. Most generators are operated in this power factor range today.

Figures 2 to 4 illustrate the type of loss of synchronism impedance loci that may be encountered for both tandem and cross-compound generators. The impedance loci shown are given as a function of system impedance and were determined in a digital computer study using a comprehensive dynamic model of a turbine generator. Representations of the excitation system and governor response were included, but it was assumed the voltage regulator was out of service. With the omission of voltage regulator response, the internal machine voltages remain low during the disturbance, and therefore, the electrical center of the swings are more likely to fall within the generator zone.

In all cases, it was assumed that the disturbance and instability were caused by the prolonged clearing of a nearby three phase fault on the high voltage side of the generator step-up transformer. All impedances given are in per unit on generator MVA base and all initial loadings and system voltages are shown for each case.

Figure 2 demonstrates the loss of synchronism impedance loci for a tandem generator for system impedances of .05, .2 and .4 per unit, respectively. It should be noted the circle formed by the impedance locus increases in diameter, and the electrical center shifts from within the machine out into the step-up transformer as the system impedance increases. This increase in circle diameter and shift is due to the fact that as system impedance is increased, a higher internal machine voltage and increased reactive power output are required to compensate for the increased losses and to maintain 1.0 per unit voltage on the machine terminals and system bus. All of these loss of synchronism characteristics usually can be detected by available out-of-step relaying schemes, as discussed in Section IV.

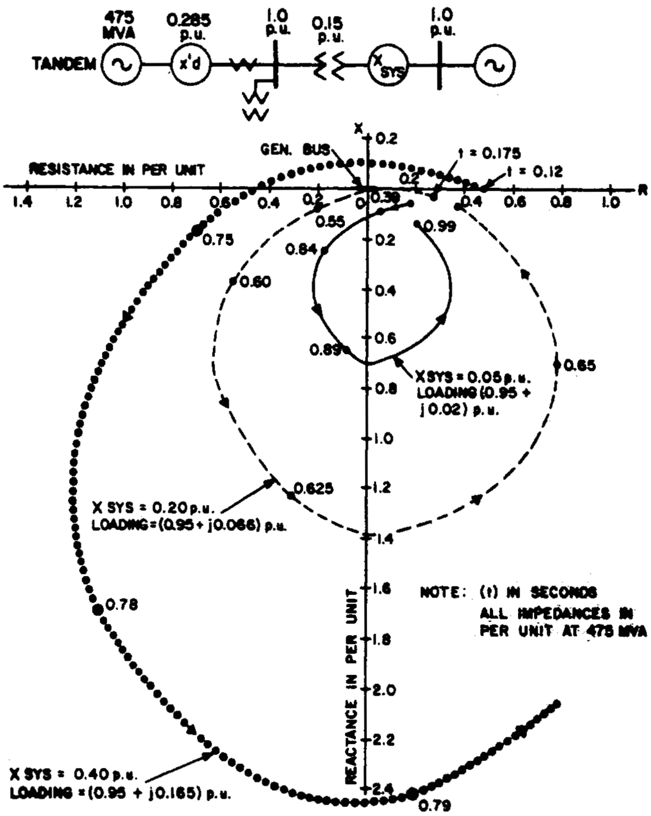


Fig. 2 Loss of Synchronism Characteristic - Tandem Unit

Figures 3 through 4 show the loss of synchronism impedance loci for a typical cross-compound generator as a function of system impedance. Figure 3 gives the impedance loci as viewed at the terminals of high pressure (HP) and low pressure (LP) units for a system impedance of .05 per unit. In this case the impedance loci are similar to those for a tandem generator. The high pressure unit with its lower inertia has completed one slip cycle while the high inertia low pressure unit has only completed a small portion of the slip cycle.

Figure 4 shows the pattern for the impedance loci when the system impedance falls in the range of .2 to .4 per unit. In this case both loci, as viewed from the machine terminals, are above the R axis. Because of the irregularity of these loci, it would be difficult to detect a loss of synchronism at the terminals of either unit with conventional relays. However, Figure 4 also shows the composite impedance locus for this case, as viewed at the low voltage terminals of the step-up transformer. The impedance locus at this point follows the same pattern as for tandem generators and could be used to detect a loss of synchronism.

As noted previously, the above loss of synchronism characteristics do not include the effect of voltage regulators. If a slow response voltage regulator is in service, the impedance locus circle will be larger in diameter but will still fall below the R axis. The increase in circle diameter is due to the increase in machine internal voltage produced by the voltage regulator. While the effect of fast response voltage regulators has not been studied, it is possible that the rapid increase in internal voltage produced may shift the electrical center out of the generator zone into the system.

The advent of the modern generator and the EHV transmission system has also resulted in significant changes in the slip characteristics of the generator during swing conditions. For the tandem generator, the average rate of slip during the first half slip cycle will usually be in the range of 250 to 400 degrees/second while for the cross-compound units, the average initial rate of slip will be 400 to 800 degrees/second. For both types of generators, the average rate of slip during the remainder of the slip cycle will fall in the range of 1200 to 1600 degrees/second. These rates of slip, it should be noted, are approximate values. The actual rate of slip will be a function of the machine inertias, machine load, type of fault and the length of time it takes to clear the fault. In general, the longer the fault clearing time, the higher the initial rate of slip.

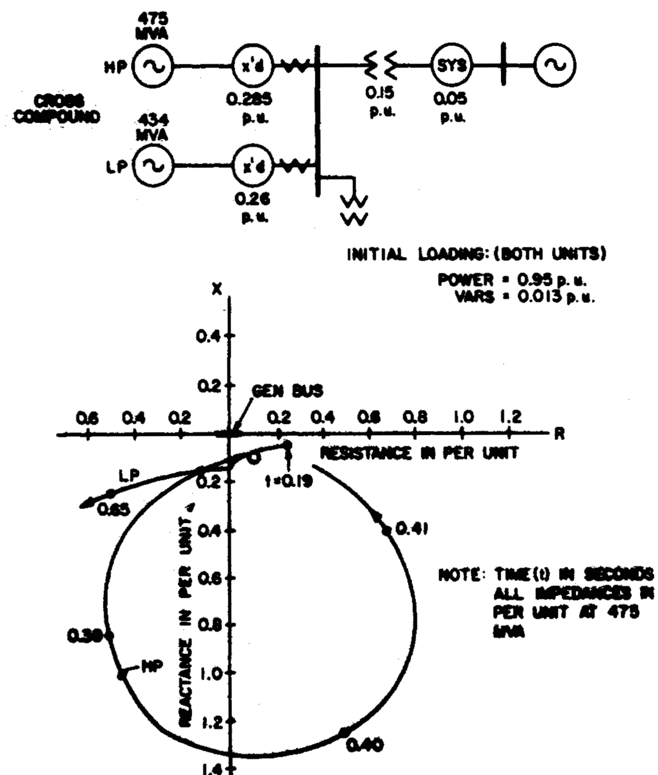


Fig. 3 Loss of Synchronism Characteristic - Cross Compound Unit

III. EFFECT ON GENERATORS OPERATING IN OUT-OF-STEP CONDITION

With the increased probability of incurring an out-of-step operating condition with the modern machine, the problem of possible damage to such a unit needs to be examined.

During an out-of-step condition as the swing angle between the generated voltage of a machine changes with respect to that of other units in the system, the current in any such unit varies in magnitude. The current surges that result are cyclical in nature; the frequency being a function of the relative rate of slip of the poles in the machine. The resulting high peak currents and off-frequency operation can cause winding stresses, and pulsating torques which can excite mechanical resonances that can be potentially damaging to the generator and to the turbine generator shafts. Therefore, it is recommended that for an out-of-step condition the generator be tripped with no intentional delay within the first slip cycle.

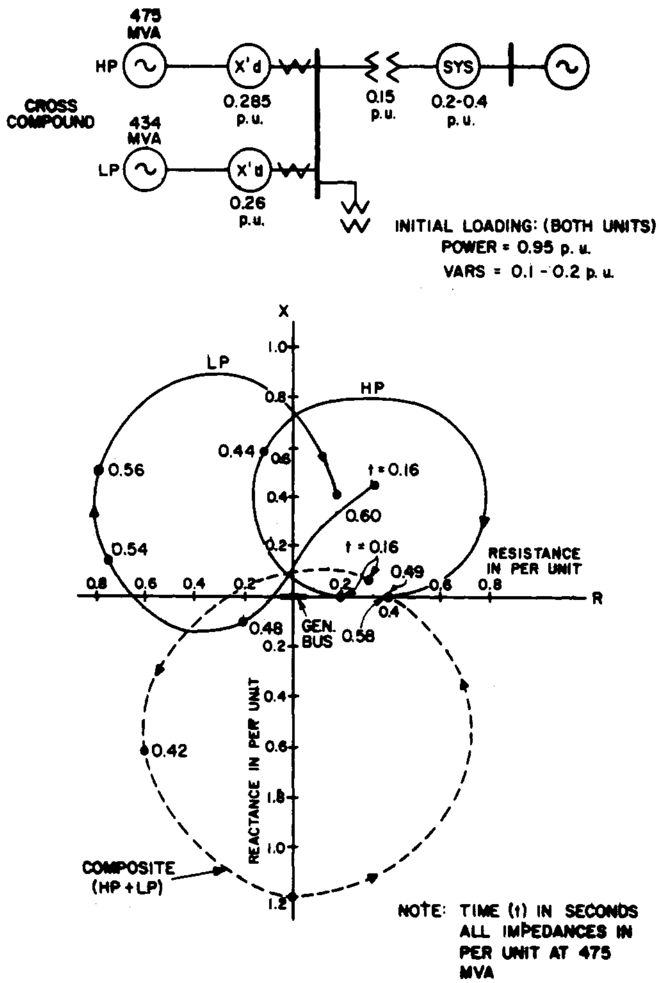


Fig. 4 Loss of Synchronism Characteristic - Cross Compound Unit

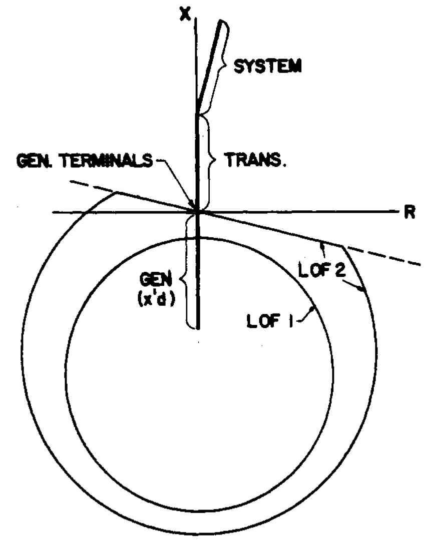


Fig. 5 Typical Loss-of-Field Relay Characteristic

IV. RELAYS FOR OUT-OF-STEP TRIPPING OF GENERATORS

General

The basic schemes that are available to the relay engineer to detect locally the generator out-of-step condition are essentially the same as those utilized to detect this condition at transmission line terminals. The methods, as discussed here, are applied to obtain a tripping function.

Loss-Of-Field Relaying

Although loss-of-field relaying is applied primarily to protect a generator for a loss-of-field condition, the conventional distance relays used to detect such a loss may provide a measure of generator out-of-step protection. The typical setting characteristics of two different relays commonly used for loss-of-excitation relay protection are shown in Figure 5. It is apparent that tripping of the generator can only occur for out of step conditions that appear electrically in the generator, i.e., swing characteristics that pass electrically thru the generator step-up transformer would not be sensed by these relays. It should be noted that because of the time delay in the protection scheme, tripping will occur only for swings that dwell within the characteristics for a sufficient period of time.

Mho Element Scheme

The mho element scheme is the simplest method of detecting an out-of-step condition that appears electrically in a generator or the step-up transformer. The concept as illustrated in the R-X diagram of Figure 6 requires the use of an impedance element sensing current and voltage at the high-side terminals of the unit transformer, and reaching electrically into the local generator. If for a loss of synchronism, the swing impedance characteristic should enter the circle, immediate tripping will occur. Without any supervision this scheme may well result in tripping for recoverable swings unless the setting sensitivity is restricted to detecting swings in excess of 120°.

The 120° criterion is the typical maximum angular separation of machines in a power system which is likely to occur without loss of synchronism. The scheme has the added disadvantage that tripping can occur when the angle approaches 180° . This subjects the circuit breaker to a maximum recovery voltage during interruption.

It should be noted that the mho circle element is sometimes applied to sense current and voltage at the terminals of the generator and be directionally oriented to look through the transformer into the system. With some reverse offset, electrically into the generator, the relay can be set to provide a characteristic similar to that shown in Figure 6. However, to prevent misoperation for faults or swings appearing beyond the high side terminals of the transformer either the reach must be set short of these terminals or tripping must be time delayed. This may nullify the use of the scheme.

An example of the mho circle scheme applied at the high side terminals of a generator step-up transformer in a typical system is shown in Figure 7. The setting objective is to provide relay operation for any out-of-step characteristic that passes electrically through the generator or step-up transformer and which cannot be sensed by a loss-of-excitation relay. The angle of swing (δ), in the sample in Figure 7 is

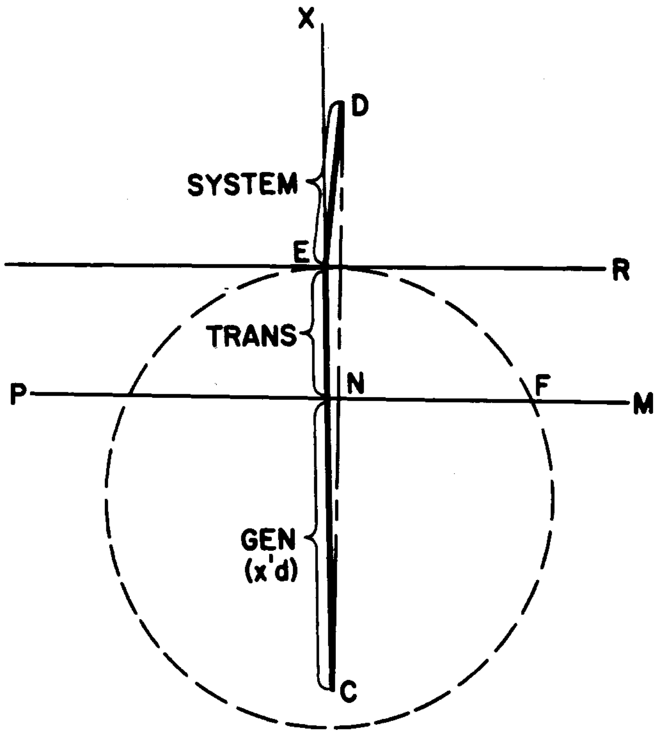


Fig. 6 Mho Circle Scheme

approximately 112° at the point where the swing impedance characteristic comes into the mho circle characteristic. At this angle of swing, recovery may be possible for some system disturbances. This dictates that the setting sensitivity must be carefully studied to insure that operation of the mho element will not occur for stable swings. As the mho circle is made smaller in size, however, it is apparent that tripping will occur at a less favorable angle to effect interruption of the swing current. The rate of angular change also becomes more critical for out-of-step sensing.

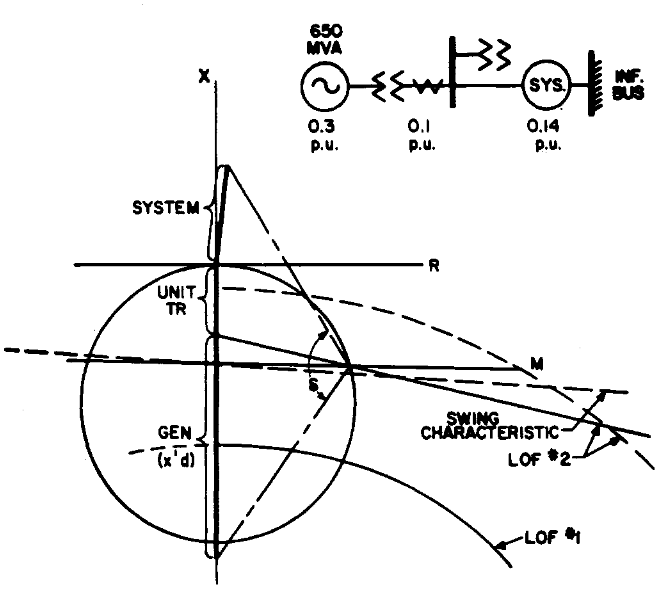


Fig. 7 Application of Mho Circle Scheme

Also note in Figure 7 that LOF #1 Relay would not operate and that LOF #2 Relay would trip, only if the swing impedance characteristic remains within the relay characteristic for the time delay inherent in the scheme.

To minimize the probability of false tripping of a generator for a loss-of-potential condition, some users may prefer to install an overcurrent fault detector in series trip logic with the mho relay. This application necessitates careful system swing studies to insure that fast operation of the over-current element will occur for nonrecoverable swings.

Single Blinder Scheme

The sensing elements of this scheme consist of two impedance elements, usually referred to as blinders, and a supervisory relay. The characteristics are shown in Figure 8 with the dashed circle representing the supervisory function. To restrict operation to swings appearing in the generator or transformer and to prevent operation for recoverable swings that pass through both blinder elements, the relay must be supervised by a mho element. This supervision also precludes tripping for the oscillatory reactive flow that predominates after synchronizing of a generator before load pickup. The blinder units have opposite polarity such that an impedance value falling between the A and B characteristics as at N will cause both units to pick up. The angle of the blinder units can be adjusted so that the characteristics can be made parallel to the equivalent system impedance represented by line DC.

Control logic is provided to aid in detecting the out-of-step condition. The differentiation between an internal fault and an out-of-step condition is made in the scheme by sensing the origin of the swing and whether there is a change from the +R to the -R region on the R-X plot. This variation corresponds to the actual real power reversal that occurs during an out-of-step condition but usually not for the fault period, i.e., from a few cycles before to a few cycles after the fault.

For the example in Figure 8, when a loss of synchronism occurs, the swing impedance having progressed to H will first cause the mho element to pick up and will also cause the A blinder unit to pick up if it is not already picked up due to load. As the swing progresses, it will cross the B unit characteristic at F and the B unit will pickup. Finally the swing impedance will cross the A unit characteristic at G, for example, and the A unit will drop out. If this sequence is followed, the breaker trip circuits will be completed when the impedance is at point G, or following reset of the supervisory unit, depending on the particular scheme being used. The reach setting of the blinder unit controls the impedance NF and NG and thus for a given system condition controls the angle, such as DFC. Since this is a measure of the angle between the source voltages, tripping can be controlled to effect circuit breaker opening when the angle is less than a particular value, such as 90°. This limits the voltage appearing across the opening breaker poles to a more favorable value for arc interruption.

It should be noted in Figure 8 that the scheme can initiate tripping for swings passing through lines terminating at the high voltage terminals of the transformer. A line distance relay will detect a swing as soon as it enters its characteristic while the blinder scheme will not provide tripping until the swing has left the supervising mho circle. This will allow line relays to clear on instability where these relays are not blocked by out-of-step detection schemes.

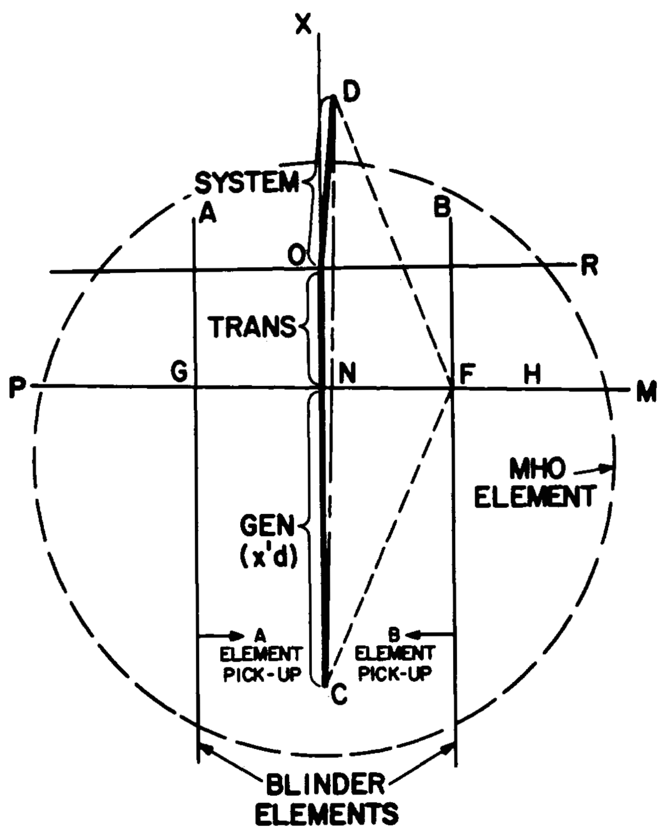


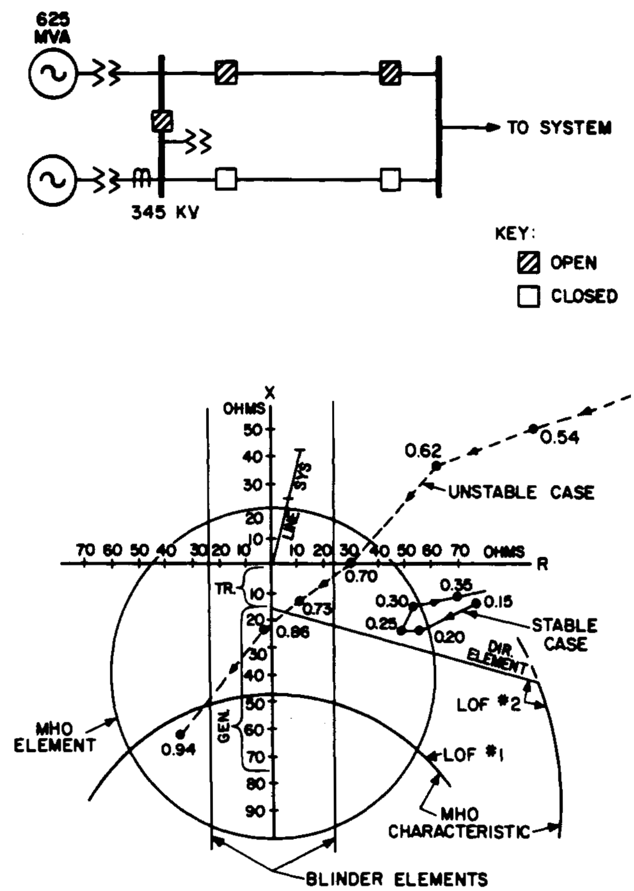
Fig. 8 Blinder Scheme

The advantages of the blinder relay scheme, as compared to the mho element scheme, for generator protection can be seen by studying the setting examples in Figures 7 and 9. As the diameter of the mho circle indicated in Figure 7 is increased to provide greater sensitivity for out-of-step swings in the generator, it is possible for tripping to occur for the recoverable swing indicated in Figure 9. With the addition of the blinder elements, however, tripping would not occur. For the out-of-step condition shown in this figure, it is clear that the scheme will provide not only tripping of the generator, but will effect interruption at a favorable swing angle. The general application of this scheme to generators, however, requires a careful study of the mho element setting to prevent tripping for swings that cross both blinder elements and fool the inherent logic of the scheme.

Double Lens or Double Blinder Schemes

The double lens and double blinder systems perform in a manner similar to the systems previously described. The supervisory mho element is included in the double blinder system to obtain the same security features covered in the discussion on the single blinder scheme. Referring to Figures 10 and 11, the outer element operates when the swing impedance enters its characteristics, as at F. Note that in the double blinder scheme the mho element will pick-up before the outer blinder element. If now the swing impedance remains between the outer and inner element characteristics for longer than a pre-set time, it is recognized as an out-of-step condition in the logic circuitry. When the swing impedance now enters the inner element characteristics, a portion of the logic circuitry is sealed in after a short time delay. Then as the swing impedance leaves the inner element characteristic, its traverse time must exceed a pre-set time before it reaches the outer characteristic. Tripping does not occur until the swing impedance passes out of the outer characteristic, or for the double blinder scheme until the reset of the supervisory mho element depending on the particular logic being used. This is to provide for the case where sequential clearing of a fault inadvertently sets up the first two steps of logic in the scheme. In the case of a fault, the inner and outer elements reset practically simultaneously and no incorrect tripping results.

Again, the swing angle DFC is controlled by the settings to limit the voltage across the opening poles of the breaker. Once the swing has been detected and the impedance has entered the inner characteristic, the swing can now leave the inner and outer characteristics in either direction and tripping will take place. Therefore, the setting of the inner element must be such that it will respond only to swings from which the system cannot recover. This restriction does not apply to the single blinder scheme because the logic requires that the apparent ohms enter the inner area from one direction and exit toward the opposite. The single blinder scheme may for this reason be a better choice for the protection of a generator than either the mho scheme, the double blinder scheme, or the concentric circle scheme.



NOTE:

1. ALL IMPEDANCES IN OHMS AS VIEWED FROM 345 KV BUS.
2. ALL TIME VALUES INDICATED ON SWING CHARACTERISTICS ARE IN SECONDS.

Fig. 9 Example of Blinder Scheme for a Stable and an Unstable Case

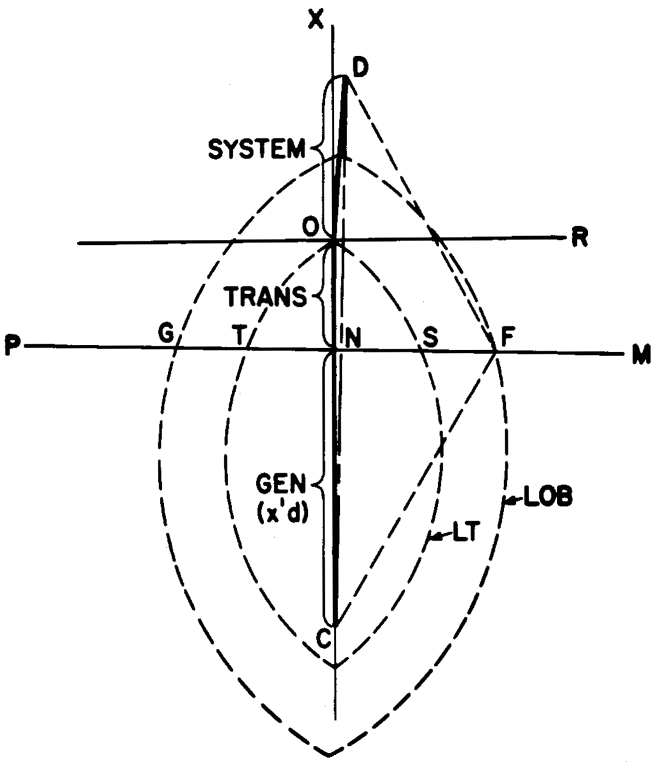


Fig. 10 Double Lens Scheme

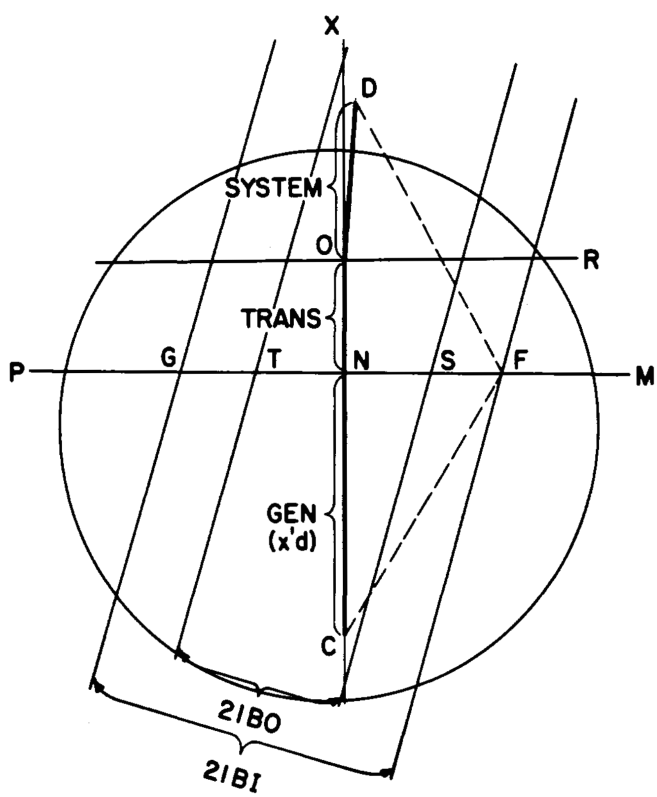


Fig. 11 Double Blinder Scheme

Concentric Circle Scheme

The concentric circle scheme uses two distance units and operates essentially the same as the double lens scheme.

When this method is employed, particular care must be exercised to insure that the inner sensing element responds only to non-recoverable swings. This requirement may well necessitate the use of the double lens or the double blinder scheme when both a fault tripping function as well as out-of-step protection are desired, i.e., those schemes are characteristically equipped to provide fault sensitivity more easily with minimum response to swing conditions.

Triple Lens Scheme

This out-of-step tripping scheme uses a relay consisting of three lens units: an outer, a middle, and an inner lens, which have a common maximum reach at the greatest sensitivity angle. This scheme is functionally more secure than the other schemes since it uses four steps in the out-of-step tripping sequence in order to discriminate between the out-of-step condition and recoverable power swings and faults. To obtain such reliability, the logic circuitry is inherently more sophisticated than with the other systems.

V. GENERATOR OUT-OF-STEP PROTECTION PRACTICES

In 1970 a survey was conducted by the Working Group to determine what out-of-step protection was being applied by relay engineers to detect such a condition at the unit location. To aid in this study, a letter of inquiry was sent to all members of the Power System Relay Committee. In 1973 a follow-up letter was sent to all who responded to the survey to aid in clarifying current protection practices.

The replies to this survey are summarized in Table I. The types of protection in use or authorized can be classified as a form of mho or blinder (or in combination) scheme. Some place dependence on the loss-of-field relaying with an ohmic sensing element for out-of-step detection.

A number of companies are employing the simple mho element scheme to provide both high-speed out-of-step protection and a measure of back-up protection for transformer faults. As generally applied, a mho element sensing current and voltage on the high side of the unit transformer is directionally oriented to electrically look into and through the unit transformer. The reach of the relay is set to obtain overlap with the impedance or mho element, with which these companies obtain loss-of-excitation protection. The reach is limited to preclude pick-up during recoverable system swings. This achieves the objective of electrically bridging the gap between the phase relays of the lines terminating on the high side bus with the unit transformer and the ohmic characteristic of the loss-of-excitation relay.

Several forms of the blinder scheme are in use by a number of companies. Most of these feature mho supervision of the blinder units and are applied to function only as out-of-step trip protection.

A majority of the companies that replied to this inquiry are using conventional loss-of-field relaying to protect for both loss-of-excitation and loss-of-synchronism conditions. Several users indicated their loss-of-field relays are set so as not to operate for recoverable swings. A number of the reporting companies were among those experiencing loss-of-field relay operations for out-of-step conditions that developed during the course of the Northeast Power Failure of 1965.

It is also of interest to note that a number of companies switch a generator electrically from the system, but do not shut it down completely for an out-of-step condition.

Several companies indicated a preference for manual control to be exercised by operators for a loss of synchronism condition. One company stated that out-of-step protection is not used because loss of excitation protection and automatic speed and voltage control are applied to generators in their system to minimize the probability of incurring the out-of-step condition.

TABLE I

Summary of Replies to 1970 and 1973 Letters of Inquiry

A. Number of companies responding to letter of inquiry. 25

B. Number of companies not employing out-of-step protection for generators (other than loss-of-field). 9

C. Number of companies that apply various impedance relay schemes for the protection of generators:

Type of Scheme

Mho Element		Blinder		Loss-of-Field	
E	P	E	P	E	P
8	3	8	4	13	-

Note: E-existing; P-planned

Remarks:

1. Number of companies employing out-of-step protection for generators (other than loss-of-field)

   Blinder relay only 1
   Mho relay only 2
   Blinder relay with overcurrent supervision. 2
   Blinder relay with mho element supervision. 3

2. Four of the reporting companies use mho ele-schemes primarily as fault protection -- out-of-step protection for the generator is incidental. Three of the four companies use no intentional time delay in the scheme.

VI. CONCLUSIONS

Although the 1970 opinion survey conducted by the Working Group indicates light interest in local out-of-step protection for generators, some relay engineers apparently regard this zone of coverage as vital to system protection.

The pertinent points to be considered in the application of out-of-step relaying to a generator can be summarized from this study as follows:

1. There are some out-of-step characteristics that will pass electrically thru a generator or its associated step-up transformer. This tends to occur when a generator pulls out of synchronism in a relatively tight system. Such a characteristic will also exist due to a low excitation level on a generator.

2. The out-of-step characterisitics can be most simply sensed by relay schemes with a mho type of distance element oriented to look electrically into the generator and its associated step-up transformer.

   It is recommended that no intentional time delay be used in the schemes other than that required to logically sense the out-of-step conditon. Otherwise, the swing may go thru the distance characteristic before tripping can occur. The mho element can be connected to sense current and voltage quantities on either the high voltage side or the machine side of the transformer. The setting should not reach into the high voltage transmission system to avoid tripping for system faults and swing conditions that should be detected by other relay systems.

3. The simple mho circle scheme provides both out-of step protection and fast back-up relaying for multiphase lead faults on the generator and transformer. It has the disadvantage of circuit interruption at an unfavorable angle of swing, and is subject to tripping for recoverable swings. The more sophisticated schemes such as the blinder and lens types minimize the probability of tripping for recoverable swings and permit controlled switching of the generator at a preferred angle of swing. The conventional loss-of-field relay provides limited out-of-step protection because the associated time delay may preclude tripping for swings passing thru its characteristics.

4. It should be emphasized that the data presented in Section II - LOSS OF SYNCHRONISM CHARACTERISTICS are the results of generalized studies that do not consider the effects of all combinations of generator designs, voltage regulator characteristics, system parameters or the interaction effect of other generators. These effects can only be completely determined by the study of a generator connected to a specific system. It is strongly recommended that the user determine the actual loss-of-synchronism impedance loci for each generator considering the overall effects of the system before selecting a protection scheme. These loss-of-synchronism characteristics can readily be obtained with a high degree of accuracy using available computer programs.

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Discussion

F. H. Birch (Central Electricity Generating Board, Leeds, England); After four years study of this subject a CIGRE Working Group, of which I have been Convenor, has completed a report which will be published in ELECTRA early in 1977. The report reaches the following main conclusions.

If out-of-step operation occurs with the electrical centre passing through the transmission system, out-of-step blocking and out-of-step tripping relays can be used to prevent undesired tripping of lines and sectionalise the system into self-sustained islands. However, as system designs differ considerably, studies are necessary in each case in order to determine optimum relaying strategy. Generators should not be tripped, except where the local load (including the power station auxiliaries) is insufficient to allow the generators to operate satisfactorily after the transmission connections have been broken. In this case the load would be secured by maintaining the transmission connections and tripping the generators.

If, on the contrary, the electrical centre is liable to pass through one or more large generators or their step-up transformers, there is a growing opinion in Europe in favour of the addition of out-of-step protection, capable of disconnecting the affected units without delay. Such protection would be justified for the reasons stated by the authors and also because there is the risk of losing the auxiliaries before automatic re-synchronising takes place. Furthermore, fast removal from the system of a large generator running out of step avoids the risk of loss of auxiliaries to other generators which remain in step and minimises disturbance to other system loads. Out-of-step protection of large pumped-storage units is definitely recommended, because these are particularly prone to fall out of step when operating underexcited in the pumping mode.

A fast three pole overcurrent relay is a simple and effective means for protecting a generator against damage during very severe out-of-step conditions, such as may occur after slow clearance of a nearby three-phase fault. A relay set to operate when the current in all three phases exceeds, for example, 85% of the a.c. subtransient value for a three phase short-circuit at the stator terminals, would be stable with H.V. faults beyond the step-up transformer and under the more likely out-of-step conditions associated with low system infeeds through long transmission lines.

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Joseph A. Imhof, Chairman: The authors wish to thank Mr. Birch for his summary of the conclusions reached in the report of his CIGRE Working Group on out-of-step relaying for generators.

Although the authors did not address such problems as the need for sectionalizing a system into self-sustaining islands or the tripping of generators for a case of partial load rejection, they are in agreement with the CIGRE Working Group that in-depth studies are necessary to determine the optimum relaying strategy.

Our Working Group concurs with Mr. Birch's comments concerning fast tripping of generators to minimize the risk of losing auxiliary systems for a loss-of-synchronism condition. This philosophy of relatively fast tripping to maintain the auxiliary power systems can also be extended for out-of-step characteristics that appear electrically in the transmission lines connected to the station bus. This approach obviously necessitates more sophisticated sensing schemes that inhibit line tripping via the line relays and permit generator tripping via the generator out-of-step relays.

The use of a fast three-pole overcurrent relay to detect an out-of-step condition is certainly a simple and effective means of protecting a modern generator. However, to effectively discriminate between a three phase fault close to the station high voltage bus and a severe out-of-step condition it appears that this application would be limited to systems that are electrically very potent. The statement by Mr. Birch that such a relay would be stable for high voltage faults in a relatively long-line system environment tends to invalidate the application, i.e., in obtaining security for system faults, relay sensitivity for a loss-of-synchronism condition is unduly compromised. Perhaps the relay scheme as visioned by Mr. Birch is somewhat more sophisticated than his remarks seem to indicate.

Manuscript received April 11, 1977.

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