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Generator Protection with a New Static Negative-Sequence Relay

GENERATOR PROTECTION WITH A NEW STATIC NEGATIVE SEQUENCE RELAY

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ABSTRACT

This paper describes the development of a new static negative sequence relay for generator protection. This relay has a broader range of settings and greater sensitivity to provide protection for modern large generators as well as units in unattended stations, such as remote-controlled hydro and gas turbine peaking plants. An example is given of its application, in light of newly proposed ANSI standards.

INTRODUCTION

Since negative phase sequence overcurrent relays were first introduced some 20 years ago,1 this type of protection has become standard for the majority of generators. Such relays were developed in response to the recognition that the negative sequence current components of unbalanced faults could cause dangerous overheating in critical parts of the generator rotor and that therefore a practical device for protecting the generator was a relay which directly measured this quantity causing the problem. Its function was and is to protect the machine in the event line relays or circuit breakers fail to perform as expected. Industry standards were established defining unbalanced fault capabilities of generators in terms of the rotor heating criteria I_2^2t, which at that time was 30 for cylindrical rotor generators and 40 for salient pole generators. These standards have been periodically reviewed and revised to maintain a balance between the needs of the system2 and the capabilities which can economically be provided in the larger turbine generators.3 The most recent proposal for standards revision by the ANSI C50. 1 Subcommittee on Synchronous Machines specifies I_2^2t capabilities of the larger turbine generators allow as 5. In addition, this standards proposal defines for the first time the continuous negative sequence current, I_2, capability of generators.

Along with the strides in system relaying, which have led to a reduction in generator requirements for system faults, there has in recent years been widespread adoption of "independent pole switching"5 for improving transient stability. Additional possibilities are thus introduced for the "open conductor" type of unbalances. Such unbalances will in general result in much lower negative sequence current levels than are present with faults.

There has therefore grown a pressing need for negative sequence relays having a wider range of I_2^2t setting capability than heretofore required and a furthering need for increased pickup sensitivity to provide I_2^2t protection at the lower levels of negative sequence currents approaching the continuous negative sequence current capability of the generator.

Another significant change which has occurred in the generation pattern of today's systems is the addition of many remote-controlled pumped storage hydro units and gas turbine peaking plants having little or no operator surveillance. Despite the higher I_2^2t capabilities inherent in hydro generators and in the smaller ratings of turbine-generators the unattended nature of these type plants require that they be as completely self-protecting as possible, thus increasing the need for a negative sequence relay sensitive to all levels of negative sequence current damaging to the machine.

The type SGC relay described in this paper was developed to meet these new needs. Through use of static elements it does this with better accuracy over the pickup range than is possible with the electromagnetic types.

A useful adjunct to the basic alarm and protection functions is a visual indication of the "ambient" negative sequence current flow, such as may result from unbalanced loading.

SYSTEM UNBALANCE CONDITIONS

Generator negative phase sequence currents can result from any unbalance condition on the system including untransposed lines, single phase loads, unbalanced type line faults and open conductors. The "background" negative sequence current produced by untransposed lines and load unbalances for machines tied into the transmission network usually does not exceed 2 or 3 percent well within the continuous 12 capabilities of the generator.

The conditions for which negative sequence relay protection becomes important are primarily those of unbalanced faults or "open conductor," which can either be an open line conductor or misoperation of one or more poles of a breaker. Fig. 1 illustrates the relative severity of these disturbances in terms of I_2 , which is proportional to the rate of generator rotor heating, and indicates that the line-line fault is the most severe from this standpoint. The "open conductor" cases are the least severe but perhaps are the most insidious in that they may more easily escape detection. An open phase condition caused by a broken conductor will usually be accompanied by a fault with prompt clearing times. An open phase resulting from misoperation of one pole of a circuit breaker requires other means than the normal line fault relaying to detect. The magnitude of negative sequence current accompanying this condition depends greatly on the system line configuration as shown by the simplified example of Fig. 2; thus the desirability of a negative sequence relay having a wide range of sensitivity.

The I_2^2t duties accompanying various faults and contingency situations are analyzed in reference 2. In general the most adverse transmission fault situation including a "stuck breaker" condition resulted in an I_2^2t duty of 1.5 representing a margin of approximately 3 to 1 over the minimum machine rated I_2^2t capabilities presently envisioned in the standards.

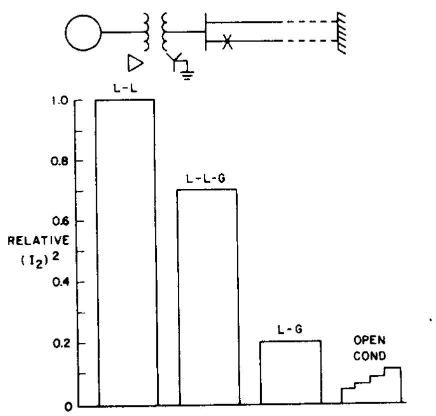


Fig. 1. Relative negative sequence duties for system unbalance conditions.

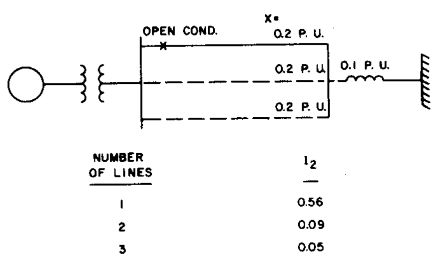


Fig. 2.

001,101,0101, negative sequence

MACHINE CAPABILITY

In the way of introductory review, in large turbine generators with solid steel rotor forgings, losses due to negative phase sequence stator current appear primarily at the surface of the rotor.3 The negative phase sequence stator current generates double frequency currents in the surface of the rotor, the slot wedges, and, to a smaller degree, the field winding. The current distribution at the surface of the rotor corresponds to the current distribution in the rotor of a squirrel-cage induction motor. That is, the currents flow axially over the length of the rotor and close circurnferentially at the ends, with the same number of poles as in the stator winding.

The need to accommodate unbalanced stator currents has a significant influence on the design and operation of turbine generators. Requirements for unbalanced fault capability expressed in terms of the rotor heating criterion IA, were first introduced in industry standards in 1955.6 Directly cooled generators were introduced in the 1950's and experience in their design and operation led to review of requirements and capabilities and the establishment of revised standards in 1965.7,8

Exerpts from the 1965 standards are shown in Table I below. The standards require that the machine shall be capable of withstanding, without injury, unbalanced short circuits at its terminals of 30-seconds duration or less, provided the machine phase currents under fault conditions are such that the negative phase sequence current (I2), expressed in terms of per unit stator current, at rated WA, and the duration of the fault in seconds (t), are limited to values which give an integrated product (I_2^2t) equal to or less than the values shown in Table 1.

TABLE I

ANSI Requirements (1965) for Unbalanced Faults on Synchronous Machines

Types of Synchronous Machine	Permissible I_2^2t
Salient pole generator	40
Synchronous condenser	30
Cylindrical rotor generators	
indirectly cooled	30
Directly cooled	10

In Table 1, indirectly cooled generators are those in which the heat generated within the principle portion of the windings must flow through the major ground insulation before reaching the cooling medium. In directly cooled generators, in which higher power densities have been achieved, the coolant flows in close contact with the conductors so that the heat generated within the principle portion of the windings reaches the cooling medium without flowing through the major ground insulation.

Additional experience has been accumulated in the ensuing years, which have also seen a continuation in the growth of the largest unit ratings being placed in service. Progress made in the design of large turbine generators has again suggested a review of power system needs and generator capabilities for unbalanced faults, and a proposal for standards revision for directly cooled generators has been made by the ANSI C50.1 Subcommittee on Synchronous Machines. This proposal has the form of a relationship between generator I_2^2t capability and generator kVA rating, Fig. 3.

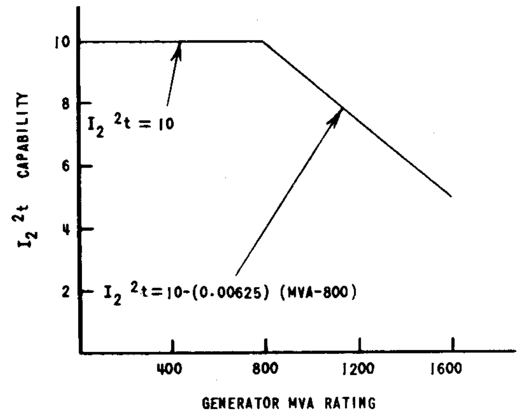


Fig. 3. Proposed revised standard for unbalanced fault capability, 12't, for directly cooled generators as a function of *generator rating.*

In addition to the I_2^2t requirements for system faults shown in Fig. 3, the new standards proposal also requires that the generator shall be capable of withstanding the thermal effect of unbalanced faults at the machine terminals, including the decaying effects of:

(1) field current, where protection is provided by causing field current reduction, such as with an exciter field breaker or equivalent.

(2) de component of the stator current.

This latter requirement stipulates, in essence, that the generator will be self-protecting relative to the thermal effects of unbalanced faults at the machine terminals.

Two new areas are also covered by the new standards proposal. First, combustion gas turbine driven generators (indirectly air cooled rated 10,000 kVA and above) are covered by a new section, ANSI C50.14, and are required to meet the appropriate I_2^2t capability shown in Table 1. Second, new material has been added covering generator continuous unbalanced current capability, which is based on an IEEE committee report4. Continuous unbalanced current capabilitv is shown in Table 11.

THE TYPE SGC RELAY

Relay Performance Required for Machine Protection

Power losses in synchronous machines due to negative sequence currents appear as rotor heating, with the exception of a small armature loss. The temperature rise caused by this energy input to the rotor is proportional to

$$K = I_2^2t$$

where 12 2t is the rotor heating criterion as described in the preceding - section and K is a constant for the machine as shown in Table 1. The time to trip should closely follow the equation $t = K/I_2^2$ over the range of time for which this is valid.

At the request of the ANSI C-50.1 Subcommittee the IEEE Power System Relaying Committee was asked in late 1971 to develop specifications for negative se

TABLE II

Continuous Unbalanced Current Capability

A generator shall he :apahle of withstanding, without injury, the effects of a continuous current unbalance corresponding to a negative phase sequence current of the values listed below, providing rated Kva is not exceeded. and the maximum current does not exceed 105 percent of rated in any phase. Negative phase sequence current is expressed in percent of rated stator current

Type of Generator	Permissible 12 (percent)
Salient Pole	
With connected amortisseur windings	10
With non connected amortisseur windings Continuous performance with nonconnected amortisseur windings is not readily predictable. Therefore, for anticipated unbalanced conditions, machines with connected amortisseur windings Should be specified.	–
Cylindrical Rotor	
Indirectly cooled	10
Directly cooled -- to 960 mva	8
96 I to 1200 mv a	

These values also express the negative phase sequence current capability at reduced generator kVA capabilities in percent of the stator current corresponding **to the reduced capability.**

quence relays to provide generator protection. The following four general specifications were provided by a working group of that committee:

"1. There will be two functions with separate outputs
   (a) Tripping
   (b) Alarm

"2. The tripping unit will be adjustable in the range of $I_2^2t = K$ (where K is in the range of 2 - 40). Time limit of operation set at 250 sec.

"3 The tripping unit will have a negative sequence current pickup that is adjustable in the range of about 0.1 to 0.4 per unit of rated generator positive sequence current on a secondary basis. Application requirements may require this setting to be related to the K setting of item 3 above.

"4. The alarm unit will have an adjustable pickup in the range of 0.03 to 0.20 per unit of rated generator positive sequence current on a secondary basis. It will include an inherent time delay to avoid nuisance alarms on transient conditions."

In addition to these general requirements there are a number of other design criteria which must be considered. A negative sequence current segregating network is fundamental to this type of relay, and is also the most critical since errors here are magnified by the nonlinear action of the inverse time-overcurrent function. Accordingly, the effects of temperature and frequency changes should be held to a minimum. Transient response should provide accurate performance immune from false operation. The input impedance must be low to minimize loading on the current transformers, which normally supply several relays in series.

Continuous rating of the network must at least match the generator continuous capability. Conservatively, short term overcurrents in the region of 20 per unit were taken as an upper limit (system fault contribution based on a five percent transformer). This current will contain substantial offset.

Table 11 reflects the fact that below a certain level of negative sequence current, a thermal balance exists and enough heat is dissipated from the rotor to prevent damage. A level detector, or "pick-up" circuit, which controls integration in the tripping function is therefore required, and should be adjustable over a suitable range.

If a machine has been subjected to an unbalanced current condition, which is removed prior to tripping, a subsequent unbalanced condition occurring before the machine rotor has recovered to normal temperature will necessitate a shorter operating time than indicated by the $I_2^2t = K$ equation. Thus, the reset rate of the integrator should approximate rotor cooling rates.

A simple method of setting K should be provided, as this constant varies greatly with the type of machine. In addition a separate signalling output is desirable as an alarm feature, in order to warn an operator of a potentially dangerous situation. Consequently, the alarm level detector should be more sensitive than that for the tripp. ing function, and a time delay to avoid nuisance alarms on transient conditions should be included.

Operating Principles

A functional block diagram of the relay is shown in Fig. 4. Following is a brief description of the more important characteristics.

The negative sequence network accepts the generator line currents as inputs and produces a single phase voltage proportional to the negative sequence component of the input. By employing transactors and wire-wound resistors, it is possible to reject positive and zero sequence current components while maintaining good long-term and temperature stability.

The Current Transformer Tap Selector is adjusted to match the current transformer full load secondary current. In effect this calibrates the relay to the same per unit base as the generator. This is immediately followed by a Bandpass Filter with a center frequency of 60 hertz which is included to reject any harmonics which are present.

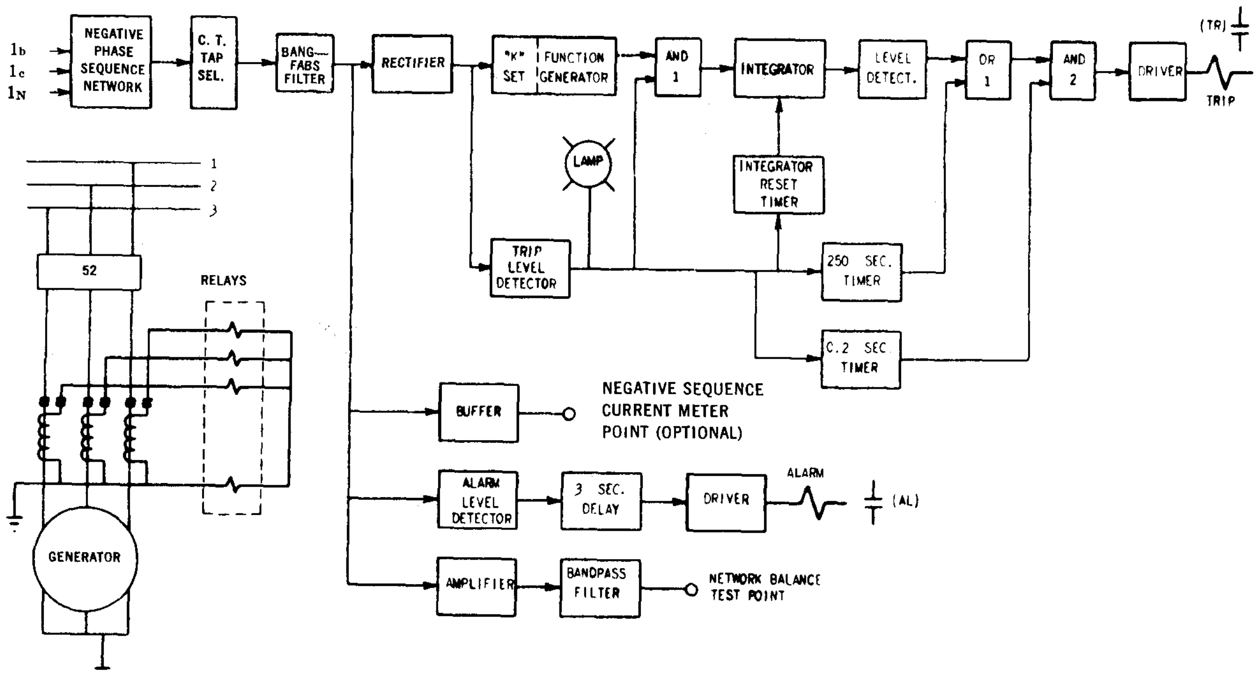
The Function Generator is a non-linear circuit which squares a portion of the incoming signal as determined by adjustment of the "K set" potentiometer. In the presence of unbalanced currents the integrator is enabled by the trip level detector, and this will result in tripping action if the unbalance is not removed. When the trip level detector is picked up it also lights a solid state lamp, indicating to the operator or tester, that integration is taking place.

There are two auxiliary timing features controlled by the trip level detector. The first of these is a security feature which is included to ensure that tripping cannot occur for at least 0.2 seconds after pickup. The second timer provides a time limit on the integration resulting in tripping in no more than 250 seconds after pickup of the trip level detector.

One optional feature is an external meter which may be remotely located and is calibrated directly in per unit value negative sequence current. This is valuable in the determination of the severity of unbalance immediately after the alarm sounds.

Relay Characteristics

Controls available for relay setting are listed in Table Ill. The C.T. tap selection is in increments of 0.2 amps, so the maximum mismatch is less than 4%. However, this may be compensated for by using the other controls, all of which are continuously variable.



FUNCTIONAL BLOCK DIAGRAM OF SGC

Fig. 4.

TABLE III

Range of Relay Adjustment

	Range		
Adjustment	Min.	Max.	Units
C.T. Tap Selector	3	5	Amps
Alarm Pick-Up	3	20	Percent 12
Trip Pick-Up K Set	9	40	Percent 12
	2	40	Seconds

The integrator reset rate is linear and can best be described as Reset time in seconds = (2.5 seconds) (percent of I_2^2t setting accumulated)

Thus a machine with a K of 10 which had accumulated an I_2^2t of 5 would, on removal of the fault, cause the integrator to reset to zero after a time of 125 seconds.

TYPICAL APPLICATION

An example of the application of the SGC relay for protection of a large generator representative of present day nuclear plants is shown in Fig. 5 (a) and 5 (b). Per the proposed ANSI standards, the continuous 12 capability for this rating is 5% and the short time I_2^2t capability is 5.6. The SGC tripping characteristic should be set sufficiently below 5.6 to provide some margin for the additional rotor heating duty which would occur after the SGC relay tripped. This additional I_2^2t duty would be quite small if the generator main circuit breakers opened successfully to clear the fault. On the other hand if this did not occur (presumably because of a circuit breaker failure) then the I_2^2t duty would become significant.

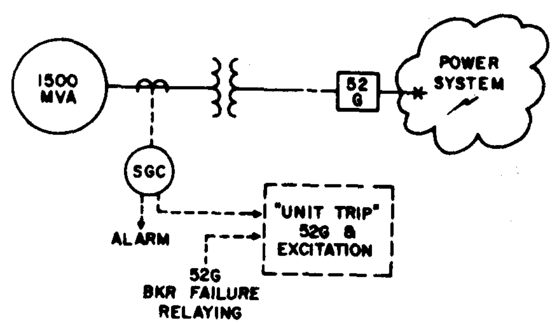


Fig. 5a. Schematic arrangement of SGC example.

For the machine in this example the most severe transmission line fault, consisting of L-L fault just off the generator high voltage bus, would result in a maximum negative sequence current flow in the generator of about 1.5 per unit. Consider that such a fault was detected by protective relaying but that because of a circuit breaker failure, the fault persisted for about 0.25 second before it was finally cleared by back-up relaying and circuit breakers. During the time the fault was on the system it produced an I_2^2t in the generator of (1.5)2 (0.25) = 0.6. For this application therefore any K setting from the minimum pickup setting of the relay, which is 2.0, to slightly under the I_2^2t rating of the machine, say 5.0, would both coordinate with the line relays and protect the machine. Slightly higher values of 12 (about 2.0) would apply to the same fault at a fossil plant because of the typically lower reactances of the 2-pole generators than those of the 4-pole generators of the nuclear plants.

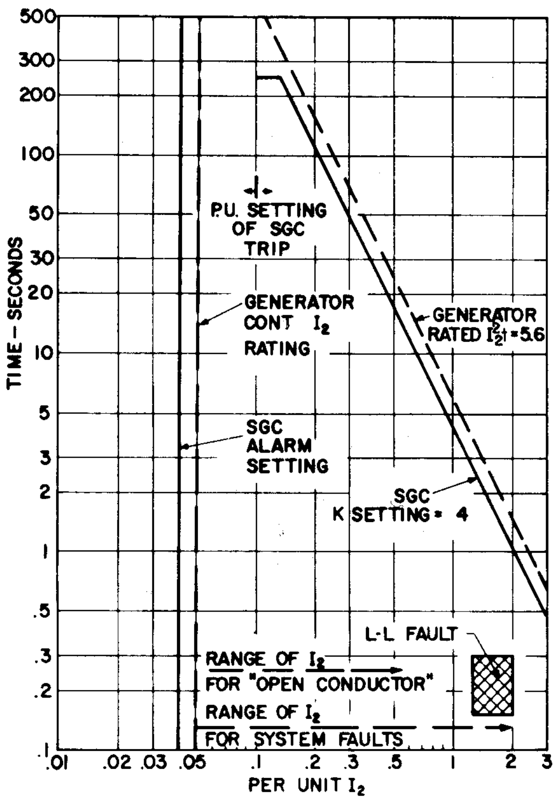


Fig. 5b. Example of SGC application

Cross hatched area shows typical range of generator duty for L-L fault near HV bus. cleared in backup times.

If the fault under consideration has been on a line adjacent to the generator (with a ring bus or breaker and a half scheme) and the circuit breaker between the generator and the faulted line had failed to operate, then the back-up relaying and circuit breakers could not isolate the generator from the fault. However, the breaker failure relaying in such configurations should be arranged to immediately trip the generator field breaker or initiate other means of excitation reduction, as shown in Fig. 5(a). Under such conditions, the rotor heating resulting from the continued flow of negative sequence current would continue until the field excitation decayed. The duty associated with the I_2 fault decrement for this situation will still be less than that of the L-L fault at the generator terminals (discussed under the section on Machine Capability) which the generator is required by the new proposed standards to be capable of withstanding.

While Fig. 5(b) indicates a K setting of 4.0, which provides a large margin against undesired tripping, the actual setting employed will depend on the philosophy of the individual user. If for example he wished to consider multiple contingencies such as the case in which not only his generator breaker but also his breaker failure relaying failed to function, a lower K setting would be required.

Similarly, the pick-up setting for the trip element will vary depending on the degree of responsibility the utility wishes to place in the hands of the operator. The minimum pick up of the SGC tripping unit is about 9% negative sequence current. In the example of Fig. 5, a 10% setting was assumed as probably the lowest which utilities would wish to use for direct tripping of units of this size. On the other hand the alarm unit setting would be placed just above the normal unbalance of the system, such that any change from this would be detected. The direct reading I_2 meter would then provide a valuable accessory for judging the seriousness of the change in the system.

If additional protection is desired for values of negative sequence current below the 9% sensitivity of the trip unit, it could be obtained by setting the alarm unit with a pickup that is slightly higher than the continuous capability of the (5% in this case). The output of the alarm unit would then be used to give an alarm immediately and to start an external long time timer which could be connected to trip the unit off the system.

Conclusion

The progress which has occurred over the years along two parallel paths the increased ratings of turbine generators, and the improvements in system protection have led to the most recent standards on generator I_2^2t capabilities, and provided the means to continue to meet the requirements of the power system. This in itself has necessitated improvements in the sensitivity and range of protection over that previously considered adequate. In addition, however, there has been an increasing number of unattended, remote-operated plant such as peaking gas turbine plants and pumped hydro units where these is a need for these to be as selfprotecting as possible.

The SGC relay described in this paper is a completely static relay which has been designed to provide protection for these larger generator ratings now appearing and also to provide improved protection for the smaller ratings, particularly for the remote-operated units such as hydro and gas turbine plants where protection over a wide range of I_2 is desirable.

The SGC relay could be considered as a replacement for existing electromagnetic relays where a greater sensitivity is desired.

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TRANSACTIONS PAPER

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