Using the Multi-Loop Method to Evaluate Generator Protection Elements

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Abstract

Stator winding interturn, interbranch, and series faults can result in large circulating currents in the faulted coils. Generator protection elements may not be sensitive enough to detect these fault conditions until the fault evolves into a phase-to-phase or phase-to-ground fault. Large machines have been severely damaged by delayed or failed protection system operation. Determining fault quantities for the various possible internal faults is not trivial and requires the aid of numerical models. Protection element models can then be used to determine the protection coverage provided by those elements. In this paper, we use the multi-loop method to obtain fault quantities and determine the sensitivity and coverage provided by various generator internal-fault protection algorithms. The multi-loop method is validated using test data from a scale-model machine in a lab.

1 Introduction

This paper is a summary of [1] and provides insight into the nature of generator internal faults and the sensitivity required from generator protection elements to detect such faults. An examination of the physical layout of a stator winding provides an indication of where faults are most likely to occur and the types of those faults. Most faults are phase-to-ground or phase-to-phase. Ground fault and differential schemes are relied on to rapidly identify and isolate these faults. In some windings, interturn or interbranch faults are possible. For instance, interturn faults are possible in windings that are constructed from multi-turn coils. Although the current through the winding can be relatively small, the current in the shorted turn can be several times nominal.

A series fault can result from a bar fracture (caused by high vibration, for example) or the failure of a welded or bolted connection. Often a portion of the winding conductor is vaporized before the insulation is breached [2]. Neither interturn nor series faults are detected by differential schemes because there is no difference in the currents at each end of the winding. While these faults are theoretically detectable by ground fault protection (for example, a neutral overvoltage element), it is often not possible to set the element sensitively enough to provide effective protection.

The first step in a fault survey is to examine the layout of the winding to identify possible failure locations. From this, the possible fault types and required type of protection can be determined. Ideally, by obtaining the fault currents and voltages for the potential fault points, the worst-case operating quantities can be determined. These can then be used to optimize the protection element settings.

For most internal-fault types, there are no good analytical methods for empirical calculation of fault currents and voltages. Research into numerical methods for internal-fault calculation extends back almost to the time when digital computers first became commercially available.

Park, Krause, and others have developed reference frame transformations that have generally become known as *dq0* models [3] [4]. These models assume a sinusoidal spatial distribution of the stator winding magnetomotive force (MMF), which greatly simplifies the development of machine models. These transformations are accurate for a fault at the generator terminals or external faults but, in their original formulations, cannot be applied for faults within the winding.

Several internal-fault calculation models have been described in [5]–[8]. The following observations can be made about these methods:

- Most methods replace the sinusoidal spatial distribution of the MMF with a winding function. The use of a winding function facilitates modeling of the harmonics corresponding to internal faults. Some generator protection functions use these harmonics.
- Most internal-fault models account for the nonuniform air gap found in salient-pole machines.
- Some internal-fault models seek to derive the model parameters from the operational parameters of the machine (X_d, X_q, X'_d, and so on). Others require more detailed information about the winding (pitch factor, distribution factor, and so on).
- Internal-fault models can be characterized in terms of the types of faults they can simulate (phase-to-ground, phase-to-phase, interturn, interbranch, and series).

In general, internal-fault models are more complex than the *dq0* models. However, once implemented and validated, internal-fault models provide valuable insights, as we will demonstrate.

2 Multi-loop method validation

The multi-loop method was developed and popularized by Gao [5]. It considers the geometry of the winding and allows each individual coil and branch of the winding to be modeled. The approach requires detailed winding information, but it allows all fault types to be modeled. The method allows branches to be grouped for the evaluation of split-phase or transverse differential protection schemes. The details and derivations of the method are available in [5].

We modeled the multi-loop method and compared our simulation results with measured data from a small 18 kVA, scale-model, solidly grounded, salient-pole generator with a motor as the prime mover, as shown in Fig. 1. The machine data are provided in the Appendix.

Fig. 1. 18 kVA, 6-pole machine used for multi-loop model.

The model was validated by verifying events with two types of loads, as well as both internal and external faults, by deactivating both the excitation and the governor controls. This section examines the behavior for the two loading conditions, one with an external phase-to-phase fault applied and the other with an internal interturn fault applied.

2.1 External fault

While the generator was loaded with a 6 A wye-grounded resistive load bank, a BC fault was applied. The comparison of the scale-model machine and the simulation responses in Fig. 2 shows that they are in close agreement.

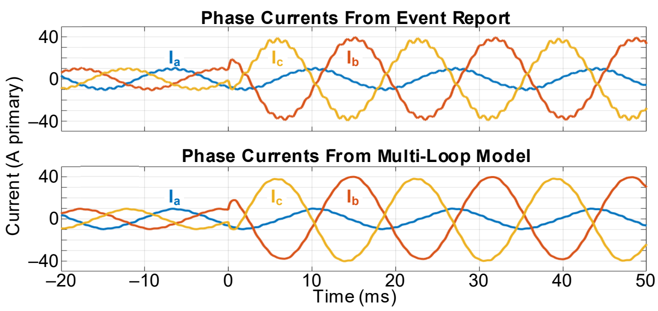

Fig. 2. Response comparison between the scale-model machine (top) and the simulation (bottom) for an external phase-to-phase fault.

2.2 Interturn fault

The generator was loaded by synchronizing it to an external power system. A turn-to-turn fault spanning five turns was applied on Phase A near the generator neutral terminal. A comparison of the phase currents from the scale-model machine and the simulation is shown in Fig. 3.

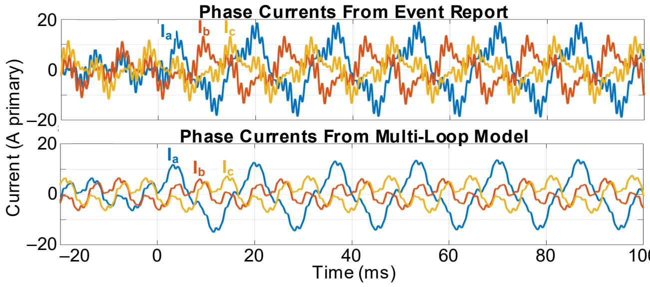

Fig. 3. Response comparison between the scale-model machine (top) and the simulation (bottom) for a five-turn interturn fault.

The significant higher-order harmonics in the event waveform of Fig. 3 that are not seen in the simulation are caused by slot harmonics that we did not model.

The measured circulating fault current for the five-turn fault was more than 7 pu (330 A) of the machine rated current, which demonstrates the severity of this condition. The fault current does not manifest itself in the phase currents and cannot be seen in Fig. 3, demonstrating the challenging sensitivity requirement for protection. Based on our lab test results, the five-turn fault generates a larger amount of circulating fault current than a one-turn (2.8 pu) or a ten-turn (4.5 pu) interturn fault (i.e., the behavior is nonlinear).

Protection schemes need to be designed with sufficient sensitivity to allow the reliable detection of these types of faults; otherwise, a fault can go undetected and cause considerable damage before it evolves into a phase-to-ground or phase-to-phase fault. If sensitive protection is not provided, local heating caused by the high fault current can present a fire hazard [9]. Machine damage due to internal faults can result in costly repairs and lost revenue caused by downtime in the order of $100 million, as seen from stator-winding failures from numerous large units [2].

3 Evaluation of generator protection elements

3.1 Machine fault survey

To evaluate the protection coverage provided to a machine by the protection elements, we performed a survey of the possible faults in the end-winding region and slots, as shown in Fig. 4, Fig. 5, and Fig. 6.

The benefit of the survey is that it only considers faults that are plausible and not those that are practically unlikely to occur because of the machine’s construction. The possible fault locations in the end-winding region, for instance, depend on the winding configuration, as shown in Fig. 4. We considered all shunt fault types that do not involve the ground: interturn, interbranch, and phase-to-phase.

Fig. 4. Possible fault points in the end-winding region for wave and lap winding configurations.

The possibility of a fault in the slot depends on the particulars of the winding. Stator windings are typically form-wound, multi-turn coils for smaller units and bars for larger units. If the slot is occupied by two single-turn bars, as shown in Fig. 5, only phase-to-ground faults are expected.

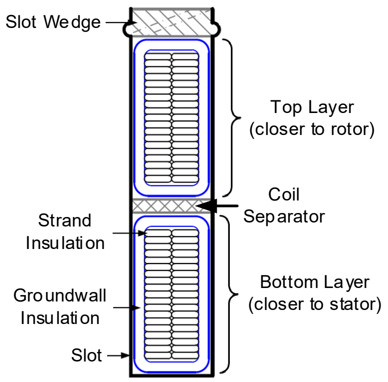

Fig. 5. Machine with Roebel bars on two layers separated by a Bakelite separator.

If the slot consists of coils or bars with multiple turns, the possibility of an interturn fault in the slot exists, as shown in Fig. 6.

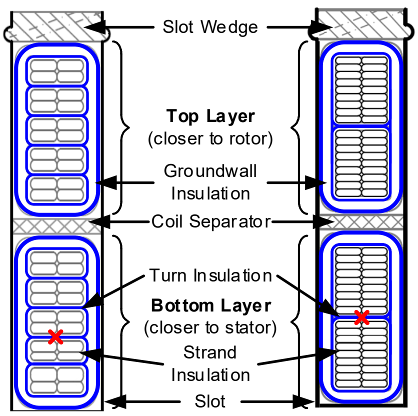

Fig. 6. Possible interturn fault locations in the slot for a machine with a form-wound multi-turn coil (left) or a two-turn Roebel bar (right).

The machine used in this study has a random-wound stator winding. This is typical for machines smaller than 1 MVA. The survey approach is the same as for a machine with form-wound coils. Based on the results of the internal fault survey, we found that there are 468 unique end-winding faults (450 phase-to-phase and 18 interturn). In the slot region, interturn faults can occur involving 1 to 10 turns.

In addition to the survey, we considered the possibility of a series fault in the form of a cracked or broken conductor [2]. Although such a condition is unlikely for our machine, we included this fault type to evaluate protection element sensitivity by comparing the minimum series-fault resistances that the elements detect.

3.2 Protection elements

This section discusses protection elements that are currently applied to detect stator phase faults and several other elements proposed in the literature. We did not include ground faults in the study because this fault type can be evaluated without a complex internal-fault model if the unit is high-impedance grounded.

The focus of this study was on determining protection sensitivity. Security is also an important protection consideration, but a security analysis does not require an internal-fault model. The pickup settings were chosen based on minimal instrument transformer and relay measurement errors and sensitive settings guidelines provided by manufacturers. Fig. 7 shows a single-line diagram of the machine under study, including the location of the current and voltage measurements used by the various protection functions.

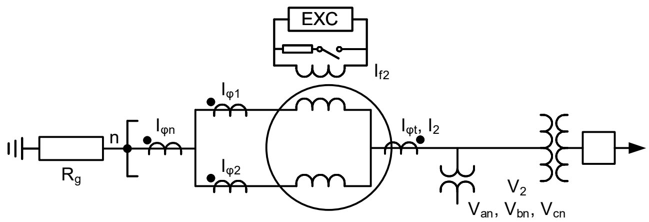

Fig. 7. Single-line diagram with instrument transformer signals used by protection functions.

3.2.1 Generator phase differential element

The generator phase differential element (87G) compares the phase currents at each end of the stator winding. We use the following equations to represent this element in the study.

$$87G_\phi = \left(I_{\phi DIF} > SLP \bullet I_{\phi RST}\right) \& \left(I_{\phi DIF} > PKP\right) \tag{1}$$

$$I_{\phi DIF} = \left|I_{\phi t} + I_{\phi n}\right| \tag{2}$$

$$I_{\phi RST} = \left|I_{\phi t}\right| + \left|I_{\phi n}\right| \tag{3}$$

$$SLP = 20\%;\ PKP_{MIN} = 10\% \tag{4}$$

3.2.2 Negative-sequence directional element

The negative-sequence directional element (32Q) uses negative-sequence quantities to identify an unbalance event and indicate whether it is internal to the generator. This element has been used for generator protection, as discussed in [10].

$$32QF = \left(Z_2 < Z_{2F}\right) \& \left(\left|V_2\right| > V_{2MIN}\right) \& \left(\left|I_2\right| > I_{2MIN}\right) \tag{5}$$

$$32QR = \left(Z_2 > Z_{2R}\right) \& \left(\left|V_2\right| > V_{2MIN}\right) \& \left(\left|I_2\right| > I_{2MIN}\right) \tag{6}$$

$$Z_2 = \frac{\mathrm{Re}\left(V_2 \bullet \left(I_2 \bullet e^{j\theta}\right)^*\right)}{\left|I_2\right|^2} \quad (7)$$

$$Z_{2F} = -0.3 \bullet Z_{2\_SYS};\ Z_{2R} = 0.3 \bullet Z_{2\_GEN} \quad (8)$$

$$V_{2MIN} = 1.0\%;\ I_{2MIN} = 2.0\%;\ \theta = 85° \quad (9)$$

We set the forward threshold to 30 percent of the strongest system negative-sequence impedance to allow a margin for nonhomogeneity corresponding to the angle difference between the system and generator negative-sequence impedances. We set the reverse threshold at 30 percent of the generator Z_2, which can be assumed to be 20 percent if this information is not available in the data sheet or via tests [11].

3.2.3 Unbalance overvoltage element

An unbalance overvoltage element (59GN) measures the phase-to-neutral voltage unbalance. Three PTs are each connected from the phase to the star point (neutral) of the machine via a high-voltage cable, and the PT secondary is connected via a broken-delta configuration [12].

$$59GN = \left|V_{an} + V_{bn} + V_{cn}\right| > PKP\left(\mathrm{Measured}\right) \quad (10)$$

$$PKP = 1.50\% \quad (11)$$

3.2.4 Split-phase overcurrent element

A split-phase overcurrent element (50SP) is applicable to machines with multiple branches, typically hydroelectric units. The standing circulating current in machines that is caused by manufacturing limitations rarely exceeds 0.5 percent for a well-balanced winding and is usually below 2 percent otherwise [9].

$$50SP = \left|I_{\phi 1} - I_{\phi 2}\right| > PKP \quad (12)$$

$$PKP = 3.0\% \quad (13)$$

3.2.5 Split-phase transverse differential element

A split-phase transverse differential element (87SP) uses the branch current magnitudes to provide a restraint to the split-phase current [10].

$$87SP_\phi \left(I_{\phi DIF} > SLP \bullet I_{\phi RST}\right) \& \left(I_{\phi DIF} > PKP\right) \quad (14)$$

$$I_{\phi DIF} = \left|I_{\phi 1} - I_{\phi 2}\right|;\ I_{\phi RST} = \left|I_{\phi 1}\right| + \left|I_{\phi 2}\right| \quad (15)$$

$$SLP = 20\%;\ PKP = 10\% \quad (16)$$

3.2.6 Stator field differential element

A stator field differential element (87SF) implements a differential between the second harmonic in the field current and the negative sequence in the terminal phase currents [13]. It uses N_{SF} as the transformation ratio corresponding to external unbalanced events and θ_C as the compensation angle.

$$87SF = \left(I_{DIF} > SLP \bullet I_{RST}\right) \& \left(\left|I_{f2}\right| > I_{f2MIN}\right) \& \left(\left|I_2\right| > I_{2MIN}\right) \quad (17)$$

$$I_{DIF} > \left|I_{2(60Hz)} + N_{SF} \bullet I_{f(60Hz)} \bullet e^{-j\theta c}\right| \quad (18)$$

$$I_{RST} > \left|I_{2(60Hz)}\right| + \left|N_{SF} \bullet I_{f(60Hz)} \bullet e^{-j\theta c}\right| \quad (19)$$

$$SLP = 20\%;\ I_{f/MIN} = 0.2\%;\ I_{2MIN} = 2.0\% \quad (20)$$

3.2.7 I_{f2} and P_{2t} element

The following method was proposed to detect internal asymmetric conditions using the second-harmonic field current as the operating quantity and the negative-sequence real power in the stator as the restraining quantity [14]. The following function uses a constant threshold for both the second-harmonic field current and the negative-sequence power:

$$67PF = \left(\left|I_{f2}\right| > I_{f2MIN}\right) \& \left(\mathrm{Re}\left(-V_2 \bullet I_2^*\right) > P_{2MIN}\right) \quad (21)$$

$$I_{f2MIN} = 0.2\%;\ P_{2MIN} = 0.05\% \quad (22)$$

Using P_2 makes this function less sensitive when the external system is more inductive (less resistive). An alternate would be to use Q_2, as follows:

$$67QF = \left(\left|I_{f2}\right| > I_{f2MIN}\right) \& \left(\mathrm{Im}\left(-V_2 \bullet I_2^*\right) > Q_{2MIN}\right) \quad (23)$$

$$I_{f2MIN} = 0.02\%;\ Q_{2MIN} = 0.05\% \quad (24)$$

This element effectively becomes a negative-sequence directional overcurrent element operating on the second-harmonic field current.

3.3 Protection performance with respect to survey

We used the internal-fault model validated in Section 2 for a fault study. We followed the fault survey procedure in Section 3.1 to identify the various fault types and locations for the study. The results in this section are for a model of the lab machine using the protection element settings from Section 3.2. For other machines, the performance of the elements is expected to vary depending on the machine, system, and load.

3.3.1 Phase-to-phase faults

The fault survey identified a total of 450 possible phase-to-phase fault locations. We applied faults at these locations and checked the protection operation. The results are shown in Table 1.

Element	Number of Faults Detected (higher is better)
87G	439
32Q	450
59GN	450
50SP	450
87SP	450
87SF	450
67QF	446

Table 1: Phase-to-phase fault results.

The results in Table 1 can be summarized as follows:

- 32Q, 59GN, 50SP, 87SP, and 87SF provide 100 percent coverage of the winding for this system when using the chosen sensitive settings.
- 67QF and 87G both detected most of the faults. Both elements are unable to detect some faults near the neutral because of their sensitivity limits.
- 87G, 50SP, and 87SP are the only functions that can reliably detect internal three-phase faults.

3.3.2 Interturn faults

We applied interturn faults and checked the protection operation. The number of shorted turns was varied from 1 to 10 to simulate interturn faults in the slot. The results are shown in Table 2.

Element	Number of Shorted Turns Detected (lower is better)
87G	NA
32Q	6
59GN	3
50SP	6*
87SP	10*
87SF	3
67QF	10

*Element gains or loses sensitivity depending on faulted branch because of steady-state asymmetry introduced by manufacturing tolerance.

Table 2: Slot interturn fault results.

Table 2 shows that none of the elements is sensitive enough to detect a single-turn fault for the given system.

The fault survey identified a total of 18 possible end-winding interturn fault locations. We applied faults at these locations and checked the protection operation. The results are shown in Table 3.

Element	Number of Faults Detected (higher is better)
87G	NA
32Q	18
59GN	18
50SP	18
87SP	6
87SF	18
67QF	18

Table 3: End-winding interturn fault results.

We summarize the sensitivity of the various elements to interturn faults as follows:

- 59GN and 87SF provide similar, high sensitivity. The sensitivity of all the instrument transformer and relay errors ($3V_0$, I_2, and I_{f2}) is three turns for this system.
- 32Q has slightly lower sensitivity because of the terminal PTs requiring slightly higher pickup supervision.
- 50SP and 87SP either gain or lose sensitivity depending on the faulted branch because there is a 0.4 percent steady-state circulating current.
- 67QF barely detects a ten-turn interturn fault; the sensitivity is limited by the resolution of the power calculation.
- 87G is unable to detect interturn faults.

3.3.3 Series faults

We inserted a resistance into one branch of the stator to simulate a series fault. The resistance was varied to check the protection operation. The results are shown in Table 4.

For reference, the machine X_d value is 3.6 ohms. Typically, the elements in consideration gain series-fault sensitivity with an increase in load current; the results presented correspond to our fully loaded machine model.

Element	Resistance Detected in Ohms (lower is better)
87G	NA
32Q	0.7
59GN	0.3
50SP	1
87SP	6
87SF	0.7
67QF	2

Table 4: Series fault results.

The results in Table 4 can be summarized as follows:

- 59GN can sensitively detect this condition.
- 32Q and 87SF are limited by the sensitivity of the negative-sequence current pickup. 87SF appears to behave similarly to 32Q but is polarized by I_{f2} instead of V_2.
- 50SP and 67QF are slightly less sensitive than the other elements because of slightly higher thresholds.
- 87SP sensitivity does not necessarily increase or decrease with load current. For heavy loads, the element has too much restraint; for light loads, the element does not see a sufficient operating signal. The overall sensitivity is lower than that of the other elements.
- 87G is unable to detect this condition.

While 59GN exhibits superior sensitivity for our system, it is frequently supervised by an element (such as 32Q), thereby incurring a sensitivity penalty. We did not consider an adaptive 50SP pickup that varies with slow seasonal variations to the standing circulating current; the change in pickup can be addressed by relay learning algorithms or operating procedures.

It is challenging to detect a single-turn fault. The protection element sensitivities we chose for evaluation were set as low as we considered reasonable. Good protection philosophy should consider adequate security margins in addition to sensitivity requirements based on a machine survey.

4 Conclusion

Conventional phase fault protection using generator phase differential elements can detect a large number of internal faults involving multiple phases, but it is unable to detect interturn, interbranch, and series faults. If protection for these fault types is needed, one of the other elements evaluated in this paper should be considered. We modeled internal asymmetric faults for a small generator using the multi-loop method and evaluated the sensitivity performance of various protection schemes.

Performing a survey of the stator winding is always a good idea to obtain a general idea of the protective requirements for the machine. Unlike some of the other approaches to machine modeling, the multi-loop method allows for a detailed protection scheme evaluation by modeling internal faults on any machine branch. However, a further evaluation of scheme performance with respect to security is required.

5 Appendix: Machine data

The relevant machine parameters are summarized in Table 5.

Parameter	Data
Rated power	17.5 kVA
Rated voltage	220 V
Rated current	46 A
Rated power factor	0.80
Nominal frequency	60 Hz
Rated speed	1,200 rpm
Number of pole pairs	3
No-load excitation current	3.14 A
Turns per stator coil	10
Coils per stator branch	9
Branches per stator phase	2
Number of stator slots	54
Stator pitch ratio	7/9

Table 5: Machine parameters.

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