CT Requirements for Generator Split-Phase Protection

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***Abstract*—The stator winding of a hydrogenerator is often made up of coils with multiple turns in the same slot. It is therefore possible for faults to develop between adjacent turns on the same phase (turn-to-turn faults). These faults cannot be detected by the stator differential protection because there is no difference between the neutral- and terminal-side currents. Split-phase protection, an overcurrent element responding to the difference between the currents in the winding parallel branches, is typically provided to detect these faults.**

Ideally, the split-phase element should be sensitive enough to detect a single shorted turn. Despite the fact that the current in this turn can be six to seven times the machine nominal current, the current seen by the split-phase protection can be quite small, in the order of one-twentieth of the generator full-load current. In addition, a spurious split-phase current can be measured due to current transformer (CT) errors, saturation during external faults in particular. Therefore, primary considerations in the application of split-phase protection are the method of measuring the difference in the currents between the parallel branches and the proper selection of the CT used for this purpose.

I. INTRODUCTION

We begin this paper with a review of stator winding construction, which provides an insight into how a turn-to-turn fault develops and how it is manifested as a circulating current. Next, we examine present practices used in split-phase protection and their relative performance in terms of sensitivity, security, and speed. This leads to a discussion of current transformers (CTs) as a source of split-phase current. Operating experience, settings guidelines, and CT selection criteria are covered next. The paper concludes with novel methods to improve the sensitivity, speed, and security of the split-phase element.

II. HYDROGENERATOR STATOR DESIGN

A. Understanding Construction of Stator Windings

Rated frequency is proportional to the number of poles and rotational speed of the generator. Generators with hydraulic turbines as prime movers are constructed with a larger number of poles because they operate with a relatively slower rotational speed. The number of stator slots in a hydrogenerator is, in turn, closely related to the number of poles of the machine. Furthermore, the number of winding parallel branches is determined by the number of stator slots [1]:

$$n_P = \frac{N_S T_C}{3T_{PH}} \tag{1}$$

where:

N_S is the number of stator slots.

T_C is the number of turns per coil (winding dependent).

T_{PH} is the number of turns per phase.

As a result, the low rotation speeds of hydraulic turbines encourage the designing of generators with parallel branch stator windings (n_P is proportional to N_S). The designers can manage the number of parallel branches with the number of turns per phase (n_P is inversely proportional to T_{PH}).

The turns per phase (T_{PH}) are determined early in the machine design based on the following relationship:

$$T_{PH} = \frac{k_1 k_2 V_{PH}}{4.44 f \varphi} \tag{2}$$

where:

k_1 is the pitch factor of the stator winding (>1.0).

k_2 is the spread factor of the stator winding (>1.0; for most designs, $k_1 \bullet k_2 \cong 1.1$).

V_{PH} is the rated phase-to-neutral voltage.

f is the nominal frequency.

φ is the flux (typical maximum flux density [B_M] in hydromachines is in the order of 0.6 to 0.7 T).

The number of the turns per coil (T_C) depends on the type of winding selected (n_P is proportional to T_C). Typically, a bar winding may only have one turn, whereas a coil winding consists of two or more turns.

Many factors influence the type of winding to be used, but in general, multiturn coil windings are used because they are more cost-efficient to manufacture (multiturn coils are wound by machine). The coils are wound such that adjacent turns have the smallest possible voltage difference between them. This allows the interturn insulation thickness to be minimized.

In the past, most large hydrogenerators in Europe and the United States used multiturn lap-connected coils. Machine designs originating in Russia used a single-turn, bar winding, wave-connected design. In large machines, it becomes difficult to insert each coil leg of a multiturn coil simultaneously into different slots. Roebel bar windings are manufactured in half-turn segments, making installation much easier on large machines. These single-turn designs have other advantages, as we will see later in this paper. Today, multiturn coils can be found on hydromachines with ratings of up to 150 MVA and 18 kV, with Roebel bar windings used for larger machines [2].

Once the number of stator slots, the type of winding, and the connection method have been determined in a given machine design, the distribution of the conductors in a given phase around the periphery of the stator must be decided. Typically, the designers can decide between a single-layer winding with varying coil pitch or a double-layer winding with varying coil pitch. The two types of windings with different pitch for a 24-slot machine are shown in Fig. 1.

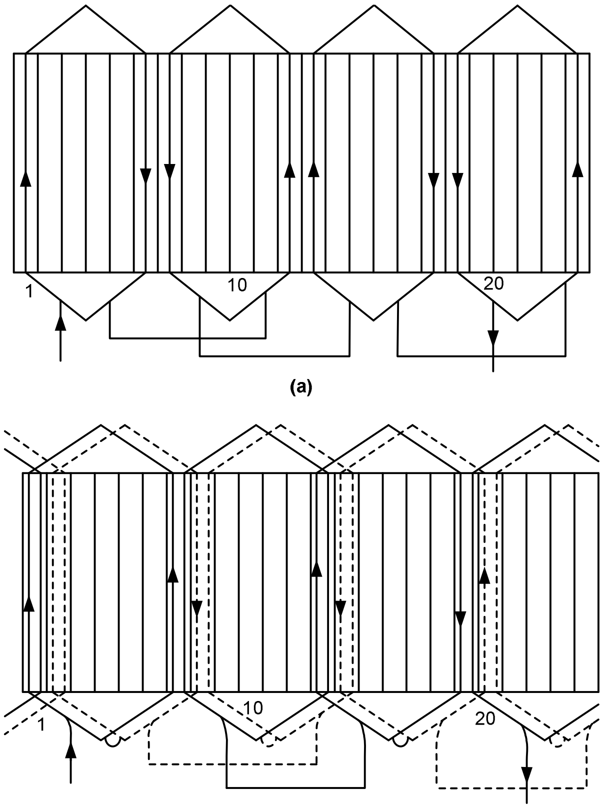

Fig. 1. Single-layer wave winding with a pitch of 0.83 (a). Double-layer wave winding with a pitch of 1 (b).

The material used to insulate the winding is dependent on the type of coils composing the winding and varies by manufacturer. Single-turn bars are typically wrapped with asbestos or glass insulated strand tape. The insulation for multiturn coil windings is composed of two parts: epoxy novalak mica paper tape for the slot portion and isopthalate varnished mica flake tape for the end winding.

Fig. 2 shows the conductor arrangement for two different windings. The slot width in a hydromachine will rarely exceed 1 inch (2.5 centimeters).

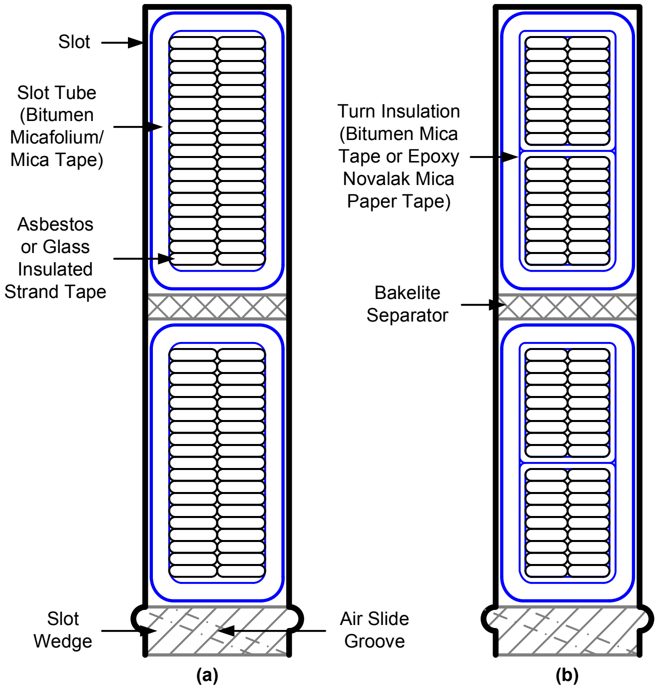

Fig. 2. Single-turn bar winding configuration (a). Two-turn coil winding configuration (b).

Fig. 3 shows slots of a typical hydrogenerator.

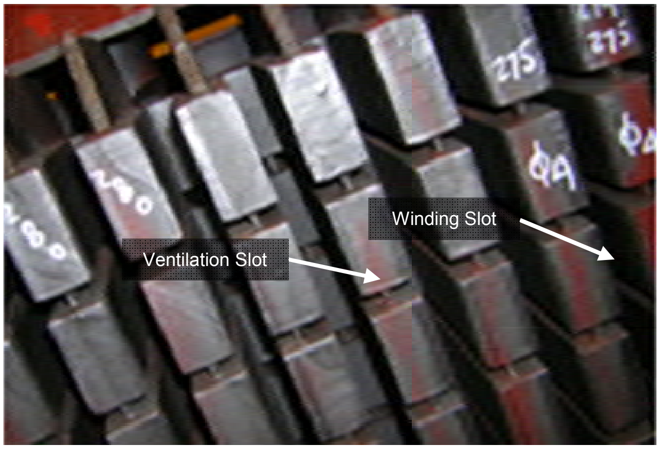

Fig. 3. Winding and ventilation slots of a typical hydrogenerator.

When examining Fig. 2a and considering the typical insulation used for this design, we notice that the two single bar winding coils are insulated from one another by a bakelite separator and an asbestos or glass stranded tape.

When examining Fig. 2b and considering the typical insulation used for this design, we notice that the separation between the two-turn coil windings is only bitumen mica tape. Through-fault conditions and variation in load result in the winding coils moving with respect to one another. This relative movement creates friction, which wears away the insulation between the windings over time. For the single-turn bar design, the friction is not an issue because the two single-turn bar windings are separated not only by their winding insulation material but also by a tough bakelite insulation material. The two-turn coil winding does not have this advantage, and over time, this movement between coils will result in a turn-to-turn fault.

Voltage surges present another failure mechanism. At power system frequencies, the voltage is distributed linearly throughout the winding. However, this desired situation is not the case during a fast front voltage surge where a much greater percentage of the surge appears across the first few turns.

An important point should be evident in the preceding discussion: when single-turn bar windings are used in a hydrogenerator, turn-to-turn faults are not a concern. For other designs, however, turn-to-turn faults must be considered as realistic failure modes of the protected machine.

B. Current Due to Turn-to-Turn Faults

Now, we examine the impact of turn-to-turn faults. Consider a winding with two parallel branches, and assume that there is one turn on one of the A-phase branches shorted, as shown in Fig. 4.

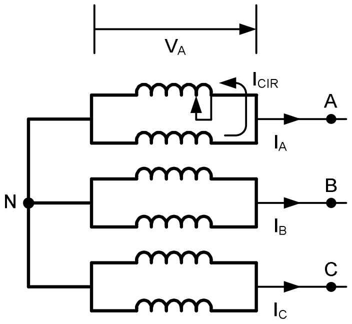

Fig. 4. Turn-to-turn fault in a two-winding machine.

If we examine the A-phase winding, we realize that the differences between the two windings result in a circulating current.

The current that circulates because of a shorted turn is primarily dependent on two factors.

First, the shorted turn reduces the voltage in the branch by an amount proportional to the line-to-neutral voltage divided by the total number of turns in the branch. This voltage difference drives a current, which circulates through the parallel branches. The net magnetomotive force adds to zero around the circuit, and consequently, the associated flux does not cross the air gap. This current is therefore limited only by the leakage reactance.

Second, an added flux is produced by the current flowing in the shorted turn. If we assume rated current is flowing at the generator and think about the shorted winding behavior as an autotransformer, then the current in the shorted turn can be estimated as the product of the nominal current and the total number of turns making up the circuit (ampere-turn balance). This large current couples strongly with another coil in the same slot. Depending on the configuration of the winding, this coil may be part of the same phase or a different phase. If it is a part of the same phase, then the induced current acts to reduce the current produced by the voltage difference (the first factor mentioned previously).

Fig. 5 shows a simplified equivalent circuit for calculating the circulating current based on the previous observations. Not surprisingly, this circuit resembles the case of two transformers in parallel but on different taps.

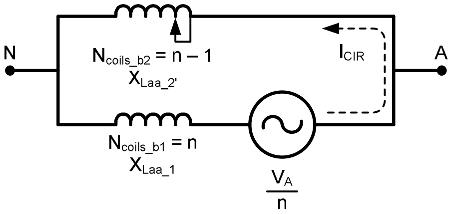

Fig. 5. Simplified equivalent circuit for a turn-to-turn fault in a machine.

The equivalent circuit contains the driving force and the limiting impedance, allowing us to approximate the circulating currents as follows:

$$I_{CIR} = \frac{k\frac{V_A}{n}}{X_{Laa1} + X_{Laa2'}} \tag{3}$$

where:

$\frac{V_A}{n}$ is the voltage per turn.

n is the number of turns.

k is the number of shorted turns.

X_{Laa1} is the leakage reactance of Branch 1.

$X_{Laa2'}$ is the leakage reactance of Branch 2.

For windings with two parallel branches, the leakage reactance for the unfaulted branch (X_{Laa1}) will be twice the value provided in the machine data sheet. However, determining the leakage reactance of the faulted winding ($X_{Laa2'}$) may be difficult, as explained previously.

While it is adequate to consider Fig. 5 and the associated (3) for the understanding of the circulating current, there are difficulties in applying the equation in practical situations and limits to its accuracy. The *IEEE Tutorial on the Protection of Synchronous Generators* [3] lists a typical value for the circulating current due to a shorted turn of 4 percent of the generator full-load current. Whenever possible, the generator manufacturer should be consulted for an accurate value.

C. Variability in the Circulating Current

Fig. 6 is a vector diagram illustrating the difference between the winding currents for a turn-to-turn fault. Analyzing the vector diagram, we can conclude that detecting a turn-to-turn fault should not be too complex because there is a difference between the currents in both magnitude and angle. This implies that a protection scheme operating on the difference between the branch (W1 and W2) currents is well-suited for detecting these types of faults.

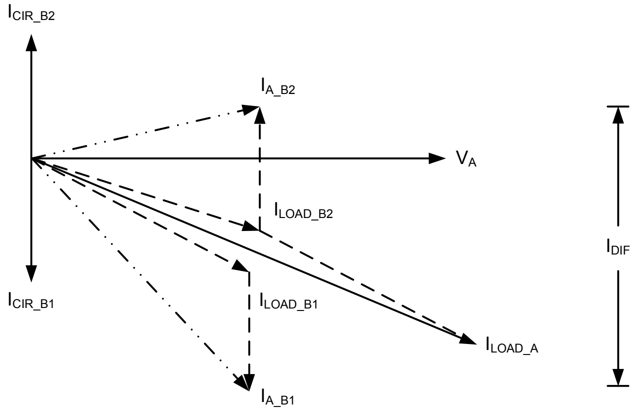

Fig. 6. Phase diagram showing the relationship between the terminal voltage, load current, and circulating current for a turn-to-turn fault in a machine.

An important observation that can be made from Fig. 6 is that the difference current (I_{DIF}) during a turn-to-turn fault is dependent on the circulating current and the load current.

The circulating current (I_{CIR}) is determined by the number of turns that are short-circuited and the volts-per-turn value of the machine. Because neither of these two factors changes during a turn-to-turn fault, the circulating current does not depend on the machine load.

The load current (I_{LOAD}) is dependent on two factors:

- The active power load connected to the machine.
- The percentage excitation (or in other terms, the power factor) of the machine.

Both these factors change during the normal operation of the machine, which implies that the differential current varies as the power factor and active power supplied by the machine vary.

It is easy to understand why the load current varies proportionally with the variation of the active load, but understanding why the excitation of the machine affects the load current is less intuitive. To explain this, we consider the equation for the voltage at the A-phase terminals of the machine:

$$V_{A\_TERM} = -r_s I_A - \frac{d\lambda_A}{dt} \qquad (4)$$

where:

$d\lambda_A$ is a flux linkage of the A-phase.

Typically for a machine, the resistance of the stator winding (r_s) is much lower than the inductance of the winding, and as such, we can ignore it for all practical purposes. Therefore, the terminal voltage of the machine can be approximated by a simplified equation:

$$V_{A\_TERM} = -\frac{d\lambda_A}{dt} \qquad (5)$$

The terminal voltage of the machine is held constant by the voltage of the power system. This implies that the flux linkage of the machine is constant. The flux linkage of the machine is determined by the following:

$$\lambda_A = L_{AA} I_A + L_{AB} I_B + L_{AC} I_C + L_{AF} I_{F\_DC} \qquad (6)$$

where:

L_{AA} is the self-inductance of the A-phase winding.

L_{AB} is the mutual inductance between the A- and B-phase windings.

L_{AC} is the mutual inductance between the A- and C-phase windings.

L_{AF} is the mutual inductance between the A-phase and field windings.

The first three terms of (6) are responsible for what is known as armature reaction. Assume that the machine is connected to a power system and is not exporting any real power and the field current (I_{F_DC}) is such that it fully supports the flux linkage of the machine required to maintain the terminal voltage of the machine. This means that the phase currents (I_A, I_B, and I_C) are zero. If we now wish to export reactive power (VARs) from the machine, we simply increase the field current, thereby increasing the flux linkage between the field and A-phase windings. Because the total A-phase flux linkage has to remain constant, the flux linkage created by the mutual coupling and self-coupling of the armature windings has to be such that it opposes the increase of flux linkage created by the field winding. In other words, changes in the field current required to change the reactive power result in changes in the stator current and, consequently, in the differential current.

Similarly, if we wish to import reactive power, we decrease the field current, thereby decreasing the flux linkage between the field and A-phase windings, resulting in the flux linkage of the mutual windings and self-windings having to enforce the flux linkage of the field winding.

Fig. 7 illustrates the three scenarios described above.

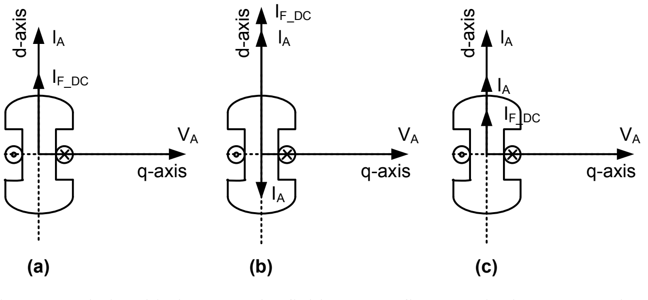

Fig. 7. Relationship between the field current, flux, terminal current, and terminal voltage for a nominally excited machine (a), underexcited machine (b), and overexcited machine (c).

Now that we understand how both power and power factor affect the load current of the machine, we see how they influence the abilities of a device that measures the difference current between two branches on the same winding. Fig. 8 shows the differential current for a machine with a turn-to-turn fault under lightly loaded conditions (Fig. 8a) and heavily loaded conditions (Fig. 8b).

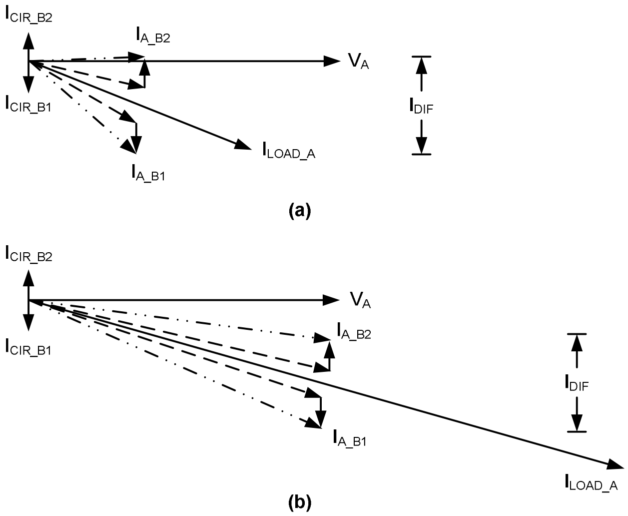

Fig. 8. Phasor diagram showing the relationship between the circulating current, load current, and difference current under lightly loaded conditions (a) and heavily loaded conditions (b).

From Fig. 8, we can see that when the machine is lightly loaded, the differential current is pronounced because it is mostly related to the constant circulating current. However, when the machine is heavily loaded, the load current tends to mask, or bury, the circulating current, resulting in the less pronounced differential current.

Other phenomena that produce natural variations in the circulating current are reviewed in Section V.

In all discussions so far, we have assumed that the winding branches are identical and that they have the same inductance. In practice, however, this is not the case because of manufacturing tolerances, such as differences in the construction of each of the branches and variations in the air gap. These differences between the parallel branches result in a natural (standing) circulating current occurring between the branches without any turn-to-turn faults. These differences also result in a transient circulating current during external fault conditions, as explained in Section IX.

D. Operation of Hydrogenerators With Bypassed Coils

Should a stator fault develop in a hydrogenerator, the protection system will trip the machine offline. It may be desirable to put the machine quickly back into service. Therefore, a temporary repair can be performed. This typically involves cutting out and bypassing the faulted coil. The faulted coil is left open-circuited, and the machine is placed back into service.

The asymmetry introduced into the winding by this repair can have a significant impact on the machine operation. Unbalanced currents cause heating of the rotor. Unbalanced mechanical forces produce vibrations and can cause the rotor to rub the stator [4]. As a result, the loading on the machine will likely need to be reduced during bypassed coil operation. In some cases, healthy coils in other branches are also bypassed in order to make the stator more symmetrical and limit the level of unbalance.

In addition, the bypassed coil can have a significant impact on the quiescent value of the circulating current (see Fig. 9).

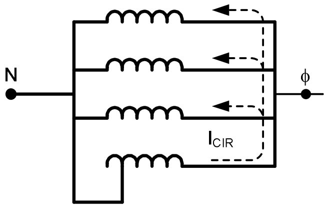

Fig. 9. Winding with a bypassed coil (one phase shown).

The magnitude of the current that circulates because of the bypassed coil differs depending on the winding configuration (alternate pole versus adjacent pole) and on the winding pitch [5]. There can also be a significant coupling with the other two phases of the winding [6]. As a result, the circulating current can be elevated in each phase to varying degrees.

The level of the circulating current can also exhibit a strong correlation with generator loading with a significant difference in the circulating current (up to 25 percent) observed between no-load and full-load conditions [7].

The increased value and variation in the circulating current impact the settings of the split-phase protection. Section V addresses this issue in more detail.

III. STATOR SHORT-CIRCUIT PROTECTION

Traditionally, each phase of a hydromachine stator winding is constructed of two, four, or eight parallel branches with each branch having several coils and each coil having a number of turns, as described in Section II. The significance of these design styles is two-fold:

- Turn-to-turn faults are possible in such configurations.
- An additional means of detecting stator faults is now possible by effectively comparing currents from the parallel branches—split-phase protection.

The stator winding may be protected by either a dedicated (independent) differential element and a split-phase protection element or a single protection scheme that is a combination of these two elements. Fig. 10 illustrates how these schemes are typically applied.

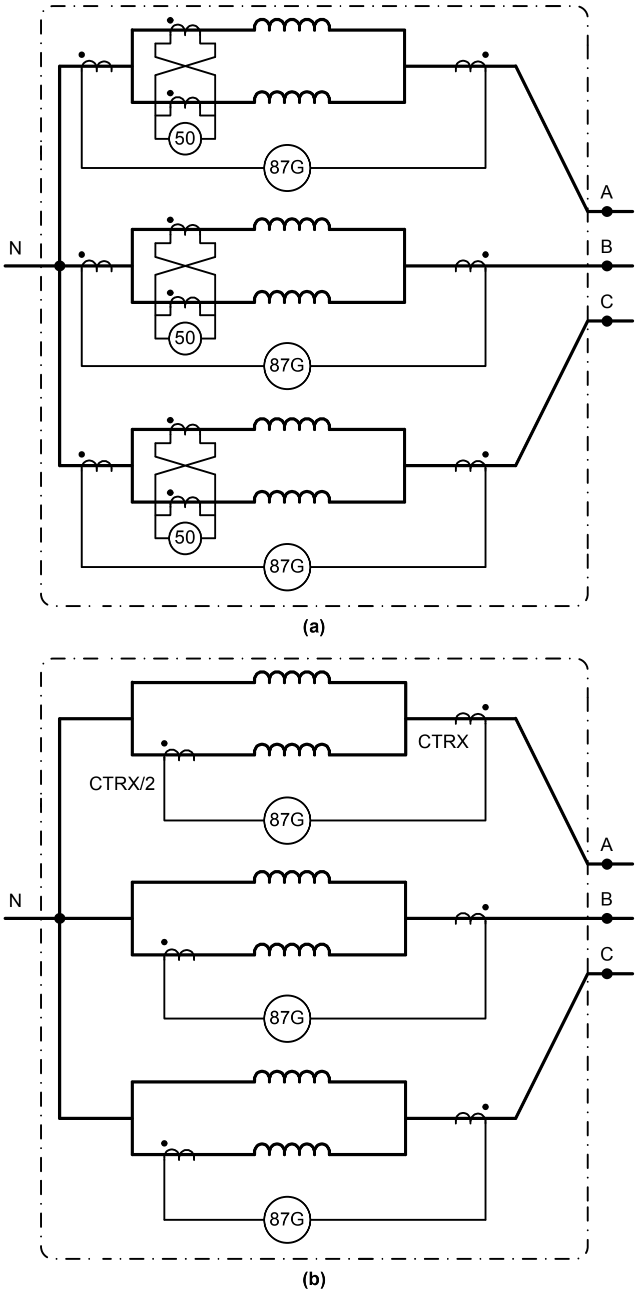

Fig. 10. Protection scheme with dedicated stator phase-winding differential and split-phase protection elements (a). A single protection scheme combining stator phase-winding differential and split-phase protection (b).

If we examine the protection arrangement shown in Fig. 10a, differential protection (87G) is selected to protect the stator against phase faults but not against turn-to-turn faults. The stator phase-winding differential protection responds to the difference between the currents at the terminal and neutral sides of the stator phase (even if a phase is composed of multiple branches). During a turn-to-turn fault, the load current entering the phase with the faulted winding is still equal to the load current exiting the phase with the faulted winding. Therefore, 87G remains balanced and does not respond to the turn-to-turn fault. For detecting turn-to-turn faults, the machine is additionally equipped with a split-phase overcurrent-based protection element (Fig. 10a and Fig. 11).

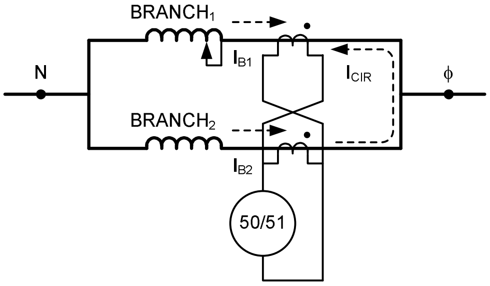

Fig. 11. Circulating current between two branches of the phase winding caused by a turn-to-turn fault.

An alternative solution is to devise a differential element that spans the entire winding and assumes the known split of the current between the parallel branches. Should this split be upset by the turn-to-turn fault and the resulting circulating current, the element responds. This approach (Fig. 10b) compares the branch current with an equal share of the total current, and as a result, it becomes unbalanced during a turn-to-turn fault, allowing detection of turn-to-turn and (at least in theory, subject to sensitivity limitations) phase and ground faults.

In the past, when generator protection was composed of discrete relays, the protection engineer might have had to choose between split-phase and differential protection. Invariably, split-phase protection was chosen because in addition to stator turn-to-turn faults, the split-phase scheme can detect stator phase and ground faults and even turn-to-turn faults in the rotor circuit [5]. Notably, several modern microprocessor-based relays provide either stator differential or split-phase protection, but not both.

A. Split-Phase Overcurrent Protection

In the most commonly applied type of split-phase protection, the currents from the parallel branches are measured as two quantities, each representing approximately half of the total current, as shown in Fig. 11. The split-phase current, representing the difference between the two groups, is derived either from two differentially connected CTs or from a single- or dual-window, core-balance CT. The impacts of the choice of CT source are detailed in Section IV.

The split-phase current is applied to an overcurrent element. Both instantaneous and inverse-time elements may be applied. Because this method operates only from the split-phase current, it may be thought of as a low-impedance, differentially connected element. It has no inherent restraint mechanisms. Optimal setting of this element is the focus of Section V.

B. Combination of Split-Phase and Stator Phase-Winding Differential Elements

In the combined split-phase and differential scheme shown in Fig. 10b, one CT (sometimes referred to as the split-phase CT) measures half of the total current and the other measures the total winding current. The ratio of the split-phase CT is half of the ratio of the phase CT. As a result, with no circulating current, the output of the two CTs adds to zero.

The currents from the two CTs are typically applied to a percentage differential element. This provides a restraint mechanism to secure the element under external faults and other conditions that lead to measurement errors.

However, we examine if this linear percentage differential element is sensitive enough to detect a turn-to-turn fault. The operating and restraint currents are determined as follows:

$$I_{OPERATE} = \left| I_{PHASE} + I_{WINDING} \right| \tag{7}$$

$$I_{RESTRAINT} = \frac{1}{2}\left(\left| I_{PHASE} \right| + \left| I_{WINDING} \right| \right) \tag{8}$$

We consider a machine with two parallel branches and capable of producing 4,000 A at full load. The split-phase CT is selected to be 2000/5. We assume a single turn-to-turn fault in this machine will produce a circulating current of approximately 80 A or 0.2 A secondary (4 percent of full-load current).

Using (7) and (8) and 5 A secondary as 1 pu, a differential protection element would derive the following operate and restraint currents:

$$\begin{aligned} I_{OPERATE} &= 0.04 \\ I_{RESTRAINT} &= 1.02 \end{aligned} \tag{9}$$

If we plot this on the percentage differential plane (Fig. 12), assuming a minimum pickup of 0.1 pu and a slope of 25 percent (typical for a generator relay), we can see that from a differential protection point of view, it plots solidly into the restraint region.

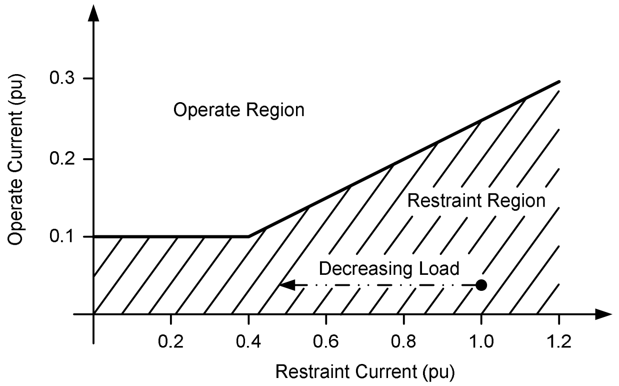

Fig. 12. Percentage differential characteristic with a turn-to-turn fault in the blocking region.

The example illustrates that the combined protection, based on a linear percentage differential element, would also fail to detect a single turn-to-turn fault. This scheme has a much lower sensitivity to turn-to-turn faults than the dedicated split-phase protection scheme does. What is more noteworthy about this scheme is that as the load current of the machine increases, the sensitivity of this scheme to detect turn-to-turn faults decreases.

Evidently, this scheme offers better security than other approaches (by using the restraint produced from both the load and external fault currents). However, we will see in Section IX that there are approaches to security that do not sacrifice sensitivity.

C. Negative-Sequence Differential

A lesser-known method that may be used for detecting turn-to-turn faults is the negative-sequence differential element. The protection scheme requires measuring the negative-sequence current entering and exiting the winding. The scheme can be realized as shown in Fig. 13.

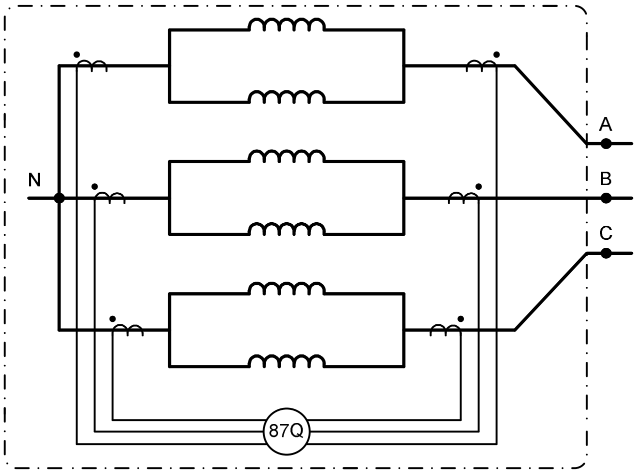

Fig. 13. Negative-sequence protection scheme that can be applied to detect turn-to-turn faults.

This scheme can provide good sensitivity in detecting a turn-to-turn fault, but it has to overcome the same issues as the split-phase protection schemes mentioned previously (standing unbalance due to differences in the windings and CT errors).

The difference between the negative-sequence differential scheme and the traditional split-phase scheme is that instead of only having to deal with the errors of two CTs and two windings, this scheme has to deal with the errors of six CTs and differences between six windings.

Section VIII discusses ways to reduce the impact of the standing unbalance on this and other schemes. Section IX presents methods whereby this scheme, as well as the others discussed in this section, can be secured during external faults.

IV. MEASUREMENT METHODS FOR SPLIT-PHASE PROTECTION

Three methods for measuring the split-phase current are in common use. These include the following:

- Separate differentially connected CTs.
- Single-window, core-balance CT.
- Dual-window, core-balance CT.

This section reviews basic characteristics of each of these measurement techniques, pointing to their advantages and limitations. Section VII introduces a new measurement method.

A. Separate Differentially Connected CTs

With reference to Fig. 14, two CTs are connected in parallel in a differential fashion, so the current in the sensing path (split-phase overcurrent relay) is a difference of the two secondary currents.

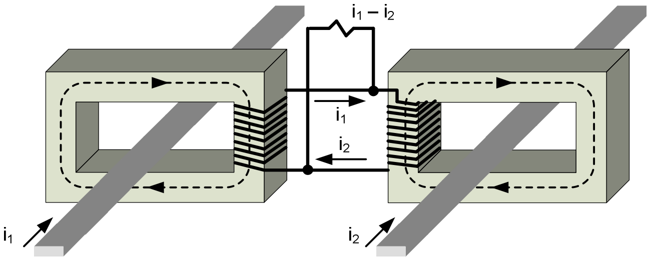

Fig. 14. Differentially connected CTs for split-phase measurement.

For small machines, the two CTs can be included in a single assembly with just the differential secondary terminals brought out. For larger machines, the two CTs may be installed as separate assemblies.

This application has an advantage of keeping the primary conductors straight and in parallel.

However, each secondary winding must be rated for carrying half of the full-load current. As a result, the ratio (number of secondary turns) cannot be too low or else the secondary current in each winding will be high. This limits the sensitivity of this measurement method.

Also, the accuracy is limited by differences in the magnetizing characteristics of the two cores. Each CT has its own ratio error, reflecting its own tolerances in the magnetic and winding materials. As a result, the secondary currents may be slightly different, even if the primary currents are perfectly equal. This difference appears as a spurious split-phase current, limiting accuracy. Placing the two CTs in one assembly encourages CT manufacturers to match the magnetizing characteristics of the two cores for better accuracy.

This method can be used in two ways. In one alternative, the sensing device is connected to the paralleled secondary windings (Fig. 14). In another alternative, a sensing device can measure both secondary currents individually and derive the difference internally.

The latter method can have less accuracy because the measurement errors (linearity) of the sensing device for the two inputs can cause extra errors. These errors can further increase the spurious values in the internally derived difference between the two currents.

The former method avoids this challenge and allows matching the input range of the sensing device to the expected signal level of the circulating current. Typically, a sensitive input is used to interface with the circulating current that is many times lower than the full-load current in each of the primary conductors.

B. Single-Window, Core-Balance CT

With reference to Fig. 15, a single-window, single-secondary CT is used to sense the split-phase current. The two primary conductors are passed through the window in such a way that their directionality is inverted, creating opposite fluxes in the CT core and therefore allowing the common flux to cancel. As a result, the secondary winding couples only to the split-phase current.

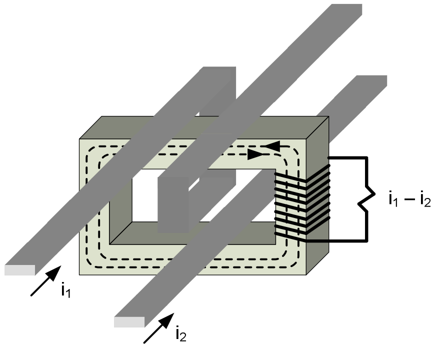

Fig. 15. Single-window, core-balance CT.

This solution can use a low ratio (small number of secondary turns) to account for the low level of the split-phase current that is transformed into the secondary winding. This improves sensitivity and accuracy.

However, this method faces the challenge of having to route one of the primary conductors through the CT window in such a way that it produces the flux in the opposite direction (i_1 current in Fig. 15). This requirement limits the applicability of this method to smaller machines.

C. Dual-Window, Core-Balance CT

To overcome the mechanical disadvantages of a single-window CT, a dual-window CT can be used, as depicted in Fig. 16.

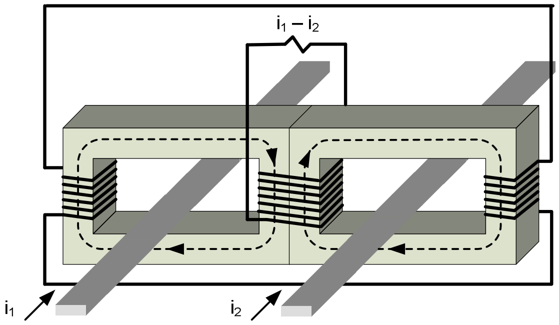

Fig. 16. Dual-window, core-balance CT.

In this method, the two primary conductors are parallel, but they pass through two windows of a single CT core. The sensing winding is placed on the middle limb so that the two common fluxes cancel and the winding couples only the difference between the two primary currents (i.e., the split-phase signal). Often, a buckle winding is added to the outer limbs of the core to prevent the reactance from being somewhat high due to the secondary winding not being fully distributed around the core perimeter.

This type of CT is provided as a single assembly and offers good sensitivity and accuracy combined with relative simplicity of installation. However, the lack of a fully distributed winding makes this CT prone to errors due to external flux.

D. Proximity Errors

As explained previously, split-phase protection requires measuring a relatively small difference (a few percent) between two relatively large currents.

When using two differentially connected CTs, the differences in the two magnetizing currents appear as measurement errors, as explained in Section IV, Subsection A.

Also, when using the core-balance measurement methods (single or dual window), there is a possibility of extra errors caused by proximity effects. The geometry of the core, the primary conductors, and their mutual physical positions are not perfectly symmetrical. This is particularly true when the cores are relatively small, the primary conductors are not centered, the core is oddly shaped, the primary conductors change direction soon after exiting the CT window, or other phase conductors are in close proximity to the outside edge of the CT window [8].

The presence of the magnetic core considerably reduces the impact of these factors by having the flux concentrated and guided by the core, but small differences can still occur and be projected as measurement errors, particularly in the sensitive split-phase measurements.

Placing specially selected extra compensating coils on the core is a known practice to deal with proximity errors [8].

V. SETTINGS GUIDELINES AND OPERATING EXPERIENCE WITH SPLIT-PHASE PROTECTION

A. Protection Scheme and Trip Functions

The most commonly used scheme to detect turn-to-turn faults is the application of three individual overcurrent relays, one per phase, connected to the secondary circuit of the differentially connected CTs on the stator windings, as shown in Fig. 11. An overcurrent relay dedicated to each phase is required so that the relays can be independently set based on the magnitude of the standing circulating currents in each phase. Where a multifunction relay is applied, it is important that the integrated split-phase element allow independent, per-phase settings.

The split-phase relay operates to trip the generator breaker and initiate generator shutdown. Both instantaneous and time-overcurrent elements can be applied, as explained later in Section V.

The split-phase protection should initiate a complete shutdown process of the generator and lock itself out. This lockout feature is essential as a precautionary measure in order to not bring the generator back into service prematurely without proper inspection, because turn-to-turn faults are permanent in nature.

In addition, the split-phase protection initiates a deluge operation, because turn-to-turn faults can cause a fire due to overheating. The deluge system will trigger to spray water only if both the split-phase protection and the heat activating device operate simultaneously. It will also close louvers to starve oxygen in the generator chamber.

B. Selecting Split-Phase Overcurrent Element Settings

Ideally, no circulating currents should flow in the parallel windings of a generator stator under normal load conditions. However, as explained in Section III, due to many factors related to the winding reactance and air gap (manufacturing tolerances, ambient temperature variations, terminal voltage and load variations, and so on), there will be a finite amount of circulating current flowing in the parallel windings.

Therefore, the split-phase settings must be established based on the magnitude of standing split-phase current. This normal unbalance can also vary during the life of a generator and may not be known when the machine is initially placed in service. The settings should therefore be established after proper measurement of the circulating currents in the generator and periodically checked for security.

1) Baseline of the Standing Split-Phase Current

The existence of the circulating currents in the winding may present protection engineers with a degree of difficulty in determining proper settings. The task becomes further complicated with unequal magnitudes of the currents in all three phases.

In order to address those issues, field measurements of the currents should be conducted periodically and compared with those of the existing split-phase settings. This is because normal circulating currents continuously fluctuate, including during seasonal changes. If the magnitude of the circulating currents found from the measurements has increased significantly over time, the relay settings should be revised accordingly. Measurement of the highest split-phase current is usually found at the maximum operating voltage and current but can also occur for an unloaded machine under high voltage.

A preferred way to carry out the measurements is to take monthly readings over a reasonably long period, such as 16 months, followed by spot checks taken approximately every 6 months in the succeeding years. It is recommended to place the 6-month checks at the points when the established split-phase current reaches its minimum and maximum over its repetitive cycle. The recording is to be taken with a multimeter that is calibrated to accuracy. Preferably, the same meter should be used throughout the measuring period. Fig. 17 shows a graph of typical split-phase current fluctuation over a period of 16 months.

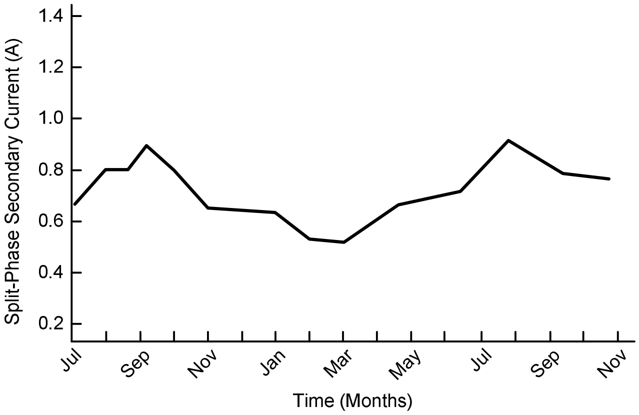

Fig. 17. Typical seasonal variation of split-phase standing current on a hydrounit.

2) *General Settings Considerations*

Ideally, the split-phase overcurrent element is set to detect a single shorted turn.

From the sensitivity point of view, the generator manufacturer should be consulted to provide data on the value of the minimum split-phase current for a single shorted turn (typically about 4 percent of the generator full-load current).

From the security point of view, a three-phase fault test can be conducted at reduced voltage to determine the maximum standing split-phase current under external fault conditions. The split-phase current under the normal voltage can be determined through linear extrapolation to full-load voltage. This technique is useful to assess the transient split-phase current that originates from within the machine because of differences in the branch reactances. However, this technique will likely not uncover the spurious current due to CT errors because the CTs may not saturate during the reduced-voltage short-circuit test.

The standing split-phase currents that exist in all three phases under normal load conditions should be reasonably close to each other, unless the machine operates with a bypassed coil. In this case, the same minimum pickup setting can be applied for all three phases, based on the highest measured split-phase currents.

If, however, one of the split-phase currents is unusually high compared with the other two phases, individual phase settings should be considered.

Typically, this is the case when temporary repairs take place. After a stator coil failure, the operation staff is under pressure to bring the generator back into service with its failed coil removed or bypassed. Running the machine with one less coil will cause further voltage unbalance between the parallel windings, leading to an additional increase of the circulating currents. This will also have a further adverse effect upon the split-phase protection settings, further decreasing the sensitivity of the protection. Therefore, it is recommended that the impact of a coil removal on the generator, as well as the protection settings, be carefully weighed. Often, the pickup setting must be increased significantly on the phase that includes the bypassed coil.

3) *Split-Phase Time-Overcurrent Element Settings*

The pickup level should be selected to account for the maximum standing split-phase current, with margin. Guidelines for establishing the maximum standing split-phase current were provided previously in this section. Because the split-phase currents can change over time, a margin of 50 percent is typically applied (the pickup is 150 percent of the maximum standing current) in order to ensure the element is secure until the next inspection of the standing split-phase current.

Selection of the time setting should be based on ensuring stability during external faults. The time delay of 0.5 second at twice the pickup is considered sufficient to effectively time-coordinate with close-in external faults that can cause spurious split-phase current readings due to CT errors and differences in branch reactances. For example, the IEEE Moderately Inverse (U1) Curve, as shown in Fig. 18, is chosen with the time dial set to 0.65 to achieve the aforementioned desired time-delay setting of 0.5 second.

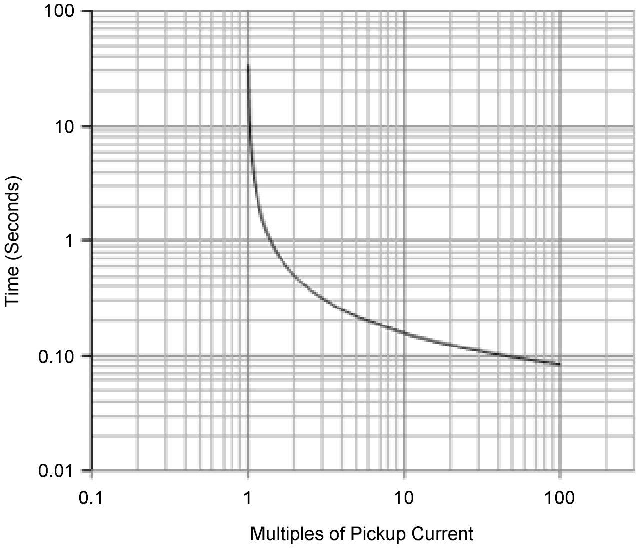

Fig. 18. IEEE moderately inverse-time characteristic applied to a split-phase time-overcurrent element.

Some close-in, three-phase external faults can be severe enough that an unwanted split-phase protection operation can occur. In cases where these faults are not cleared before the split-phase protection times out, the setting can be increased to three to four times the standing split-phase current to avoid such misoperation.

Some split-phase elements can also be vulnerable to the presence of inrush currents during a dead bus synchronization, where a transformer is suddenly energized by closing a generator synchronizing breaker.

If a microprocessor-based relay is installed for protection, it is a good practice to select filtered magnitude as the operating signal (not the true rms [root-mean-square]) in order to reduce the impact of harmonics and dc offset present in the inrush and external fault currents. Also, a momentary application of a different settings group with the higher timing can be implemented to avoid a misoperation when energizing the unit transformer.

4) *Split-Phase Instantaneous Overcurrent Element Settings*

Without the advantage of waiting through the external fault current, the pickup setting for the instantaneous split-phase element should be based on the highest possible value of the split-phase current. This transiently highest value occurs in conjunction with the subtransient external fault current, which, in turn, may reach up to several times the full-load current.

The resulting split-phase currents for this external fault under the worst conditions can transiently reach a value of five to seven times the standing split-phase current. According to one practice, the pickup setting can be selected as seven times the highest standing split-phase current.

When set that high, the instantaneous split-phase element will likely not detect a single-turn fault. It will instantaneously detect faults that include several turns and will provide backup protection to the generator differential protection.

VI. CT SELECTION RULES

This section is focused on the selection criteria for split-phase protection with differentially connected CTs, as shown in Fig. 19.

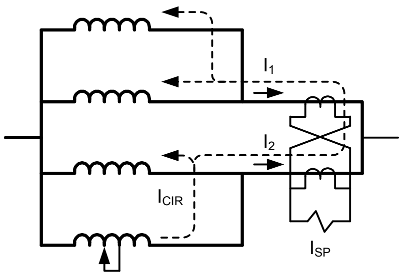

Fig. 19. Split-phase protection application for machines with four branches in parallel—relationship between the split-phase current and the circulating current.

We assume a split-phase protection application with the parameters shown in Table I and illustrate the process for CT selection using this example.

TABLE I
EXAMPLE SYSTEM PARAMETERS

Nominal power	65 MVA
Nominal voltage	13.8 kV
System X/R	30
Subtransient reactance	0.38 pu
Leakage reactance	0.15 pu
Number of parallel circuits	4
Number of coils	33
Turns per coil	4
Split-phase element minimum pickup	0.25 A secondary

A. *CT Ratio*

The nominal generator current is calculated at 2,719 A. Because there are four parallel branches, the impedance of each branch (Z_{BRANCH}) may be approximated as four times the leakage reactance, or 1.758 Ω primary. The impedance of a single turn (Z_{TURN}) is 1.758 Ω/(4 • 33), or 13 mΩ primary. The voltage across a single turn is as follows:

$$\begin{aligned} V_{TURN} &= \frac{\text{Nominal ph-n Voltage}}{\text{Number of Coils} \bullet \text{Turns Per Coil}} \\ &= \frac{13.8\ \text{kV}}{\sqrt{3} \bullet 4 \bullet 33} = 60.4\ \text{V} \end{aligned} \tag{10}$$

The circulating current (I_{CIR}) that flows because of a single shorted turn can be approximated as the following:

$$\begin{aligned} I_{CIR} &= \frac{V_{TURN}}{Z_{BRANCH} - Z_{TURN} + \dfrac{Z_{BRANCH}}{\text{Number of Circuits} - 1}} \\ &= \frac{60.4\ \text{V}}{1.758\ \Omega - 0.013\ \Omega + \dfrac{1.758\ \Omega}{4-1}} = 25.912\ \text{A primary} \end{aligned} \tag{11}$$

The split-phase current will be as follows:

$$\begin{aligned} I_{SP} &= \frac{\text{Number of Branches} \bullet I_{CIR}}{\text{Number of Branches} - 1} \\ &= \frac{4 \bullet 25.912\ \text{A}}{3} = 34.519\ \text{A primary} \end{aligned} \tag{12}$$

Each CT sees half of the nominal rated current under load conditions. Therefore, a CT with a ratio of 1500/5 would produce a split-phase current of the following:

$$34.519\ \text{A} \bullet \frac{5}{1500} = 0.115\ \text{A secondary} \tag{13}$$

This is less than the minimum pickup of the split-phase element. Choosing a CT with a nonstandard secondary rating of 15 would allow the element to detect a single shorted turn.

B. *CT Class*

The CT connection is at risk for an external, close-in phase-to-phase or three-phase fault. The generator contribution is limited by Xd", and the system X/R ratio will be large. Consequently, the general rules for differential CT selection should be applied, including the following:

- Use a CT with a fully distributed secondary winding, and connect to the full winding ratio.
- Select CTs with matching characteristics (i.e., the same manufacturer, excitation curve, and internal resistance).
- Select CTs with the highest practical knee-point voltage. The required voltage for saturation-free operation is given by the following:

$$V_k > (1 + X/R) \bullet I_S \bullet Z_S \tag{14}$$

where:

I_S is the secondary current for a three-phase fault.

Z_S is the one-way lead resistance up to the parallel connection (not including the return path) plus the CT internal resistance.

Returning to the example, a three-phase fault just outside the differential zone would produce a fault current of 7,156 A primary. Each CT would see 71.5 A. Assuming a CT internal resistance of 0.1 Ω and a lead resistance of 0.1 Ω, then the knee-point voltage required for saturation-free operation is as follows:

$$V_k > \left(1 + 30\right) \bullet 71.5\ \text{A} \bullet 0.2\ \Omega = 443\ \text{V} \tag{15}$$

If saturation cannot be avoided, then it must be dealt with using the methods described in Section IX.

VII. NEW MEASUREMENT METHOD FOR SPLIT-PHASE PROTECTION

A. The Measurement Principle

The task is to measure small differences between two currents (i_1 and i_2). It is therefore convenient to represent the two currents with common (COM) and unbalance (UNB) components, as follows:

$$i_1 = i_{COM} + i_{UNB} \tag{16}$$

$$i_2 = i_{COM} - i_{UNB} \tag{17}$$

In other words, the two components are the following:

$$i_{COM} = \frac{1}{2}\left(i_1 + i_2\right) \tag{18}$$

$$i_{UNB} = \frac{1}{2}\left(i_1 - i_2\right) \tag{19}$$

The unbalance component (19) is simply half of the split-phase current and therefore is of interest for split-phase protection.

Referring to the example in Section VI, the above currents under load conditions and a single-turn fault would be as follows: i_1 = 1,366.33 A primary, i_2 = 1,352.67 A primary, i_{COM} = 1,359.50 A primary, and i_{UNB} = 6.825 A primary.

For simplicity, we continue using the term "split-phase current" instead of the unbalance current and rewrite (16) and (17) as follows:

$$i_1 = i_{COM} + 0.5 \bullet i_{SP} \tag{20}$$

$$i_2 = i_{COM} - 0.5 \bullet i_{SP} \tag{21}$$

The new measurement method stems from the idea to force the common and split-phase currents into separate secondary windings, each having a different ratio adequate for the level of the common and unbalance currents.

With reference to Fig. 20, two CTs are used. The primary conductors are placed in parallel through each of the windings with the advantages of easy installation and the possibility of having the two CTs as independent assemblies.

The two primary currents are represented by the common and split-phase components. These components induce the common and split-phase fluxes in the two cores.

Each CT is equipped with two secondary windings having N_{COM} and N_{SP} number of turns, respectively.

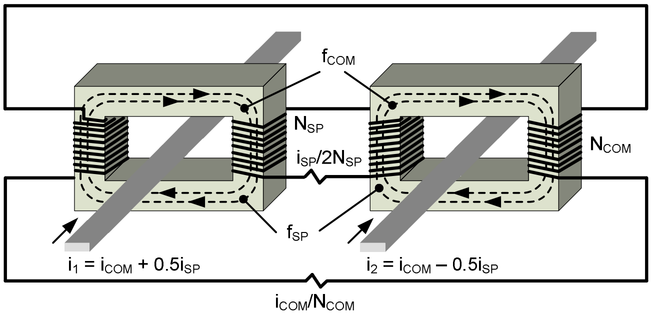

Fig. 20. Dual-ratio CT connection.

The common windings (N_{COM} turns) are connected in such a way that they only couple with the common flux, and therefore, only the common current can flow in the N_{COM} circuit. Because of the way the two windings are connected, it is impossible for any split-phase current to flow in this circuit. The N_{COM} connection is simply open-circuited for the split-phase current.

The split-phase windings (N_{SP} turns) are connected in such a way that they only couple with the split-phase flux, and therefore, only the split-phase current can flow in the N_{SP} circuit. Because of the way the two windings are connected, it is impossible for any common current to flow in this circuit. The N_{SP} connection is simply open-circuited for the common current.

If the N_{COM} circuit were the sole connection in the scheme of Fig. 20, the scheme would be technically deficient by not allowing the path for the split-phase current and flux.

Similarly, if the N_{SP} circuit were the sole connection in the scheme of Fig. 20, the scheme would be technically deficient by not allowing the path for the common current and flux.

As a system, however, the two circuits constitute a technically valid connection, forcing the large common component to couple into the high-ratio N_{COM} loop and the small split-phase component to couple into the low-ratio N_{SP} loop.

As a result, the two currents of interest are measured with adequate ratios, sensitivities, and signal ranges.

We refer again to the example of Section VI and assume N_{COM} = 300 (1500/5). If so, the common secondary current reads 1359.5/(300) = 4.532 A secondary. This current can be used for metering or short-circuit protection functions. Assume further that N_{SP} = 20. If so, the split-phase secondary current during a single-turn fault reads 13.65 A primary/(2 • 20) = 0.341 A secondary. This is well within the sensitivity and settings range of the split-phase protection element assumed in the example of Section VI.

The common loop can supply a device that requires measuring the common current component or can just be short-circuited to facilitate the split-phase current measurement with a low ratio for sensitivity.

The split-phase component loop can supply a sensitive input device that requires measuring the split-phase current component.

A single device can measure both the common and split-phase components, with two inputs having adequate input ranges. Such a device can respond to each of the components individually and, subsequently, derive the original conductor currents using (20) and (21).

B. Advantages

The new method has the following advantages:

- The same CT assembly can be used to measure the common and split-phase current components. Effectively, this scheme is a dual-output, dual-ratio CT.
- The split-phase current is measured with a low ratio, accounting for the low level of the signal. This allows the reduction of sensitivity requirements for the relay inputs.
- Mechanical mounting is simple, with the primary conductors in parallel and an option to use two separate assemblies for each of the conductors.
- The CT can be manufactured with a fully distributed winding, significantly reducing proximity effects.
- The accuracy of the measurement is comparable with the differentially connected CT method.

VIII. ADDRESSING THE INHERENT UNBALANCE BETWEEN PARALLEL WINDING BRANCHES

As mentioned in Section II, limitations in stator manufacturing and temporary repairs result in a non-zero value of the split-phase current. This standing current (inherent unbalance) is known to vary in many machines. This variation correlates with changes in terminal voltage and loading of the machine. The correlation with loading is particularly strong in machines operated with bypassed coils [7]. Certain machines also display seasonal or daily split-phase current variations, which evidently are temperature related.

The consequence of these variations is that field measurements must be carried out over an extended period of time in order to determine a secure pickup setting and these measurements need to be rechecked on a regular basis, as explained in Section V.

Section VI illustrated the small change in split-phase current due to a single shorted turn. Consequently, applying higher settings required for machines that experience large current variation can result in significantly desensitized protection.

In a microprocessor-based relay implementation, it is possible to track this variation and remove it from the operating signal, thereby restoring the sensitivity of the element. Fig. 21 presents one such algorithm.

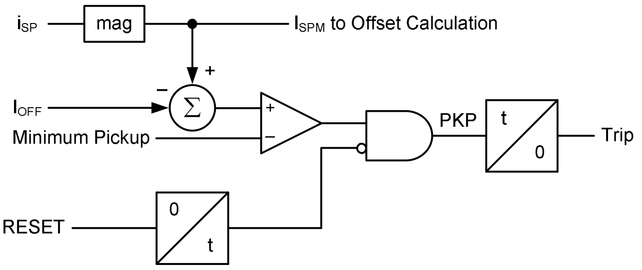

Fig. 21. Adaptive split-phase overcurrent element.

The offset value (I_{OFF}) is calculated as follows:

- A weighted average is carried out using the current value of I_{SPM} and the previous value of I_{OFF}. Fig. 22 shows a simplified flow chart for this operation.
- However, if the RESET input is asserted, then I_{OFF} takes the value of the split-phase current magnitude (I_{SPM}), effectively resetting the offset calculations. This is necessary for events for which a known change in the split-phase current occurs, such as when the generator breaker opens.
- Furthermore, if PKP asserts, then I_{OFF} is not updated. This is to prevent the algorithm from adapting to the change in split-phase current due to a fault before the trip timer has a chance to time out.

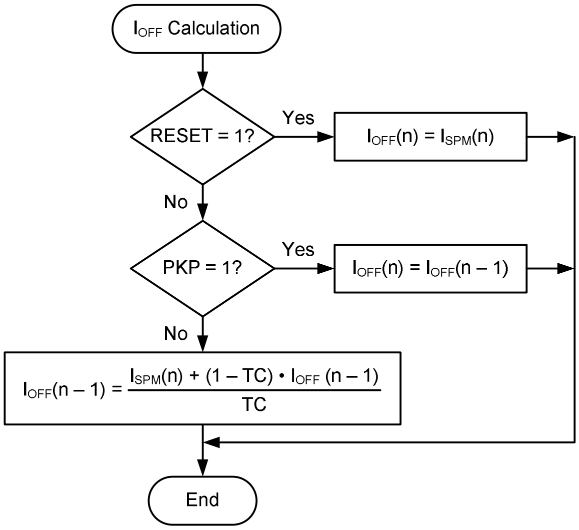

Fig. 22. Offset calculations for the algorithm of Fig. 21.

The variable TC is a time constant, which determines how quickly the offset calculation tracks the split-phase current (a relay calibration setting or a user setting). Fig. 23 illustrates how the offset calculation responds to an arbitrary step change in the split-phase current.

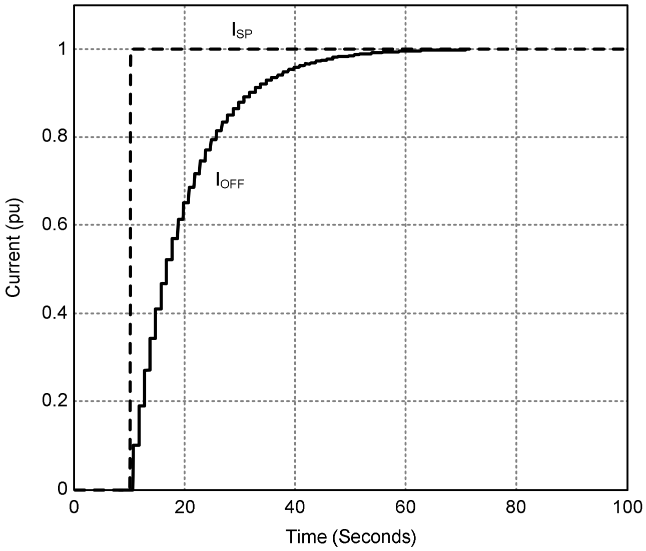

Fig. 23. Offset calculation response to a step change in the split-phase current (TC = 10 seconds).

The presented algorithm tracks the magnitude of the split-phase current. An alternative approach is to track the phasor (complex) value of the split-phase current. The approach would benefit from the ability to detect changes in angle, as well as magnitude. However, the phasor approach could be exposed to false operation for a step change in angle due to a change in system frequency because an error in frequency tracking produces a rotating phasor. Because the impedances of the stator circuit are homogeneous, magnitude tracking is considered just as effective and potentially more secure.

A potential weakness to the approach lies in the possibility of a fault that produces a change in current that is less than the selected pickup setting. In this case, the algorithm would adapt to the fault current and remove it from the operating signal. As a consequence, the pickup must be set to less than that expected for a single shorted turn. The element should also operate in parallel with a conventional (nonadaptive) split-phase overcurrent element. The conventional element operates for multiturn faults and acts as a backup to the adaptive function.

IX. SECURING SPLIT-PHASE PROTECTION

A. *Security of Split-Phase Protection Elements*

In all the discussion regarding split-phase protection so far, we see that all the schemes have to deal with the same issue of a natural standing split-phase current resulting from the differences in the stator windings and the different performances of the CTs in the scheme under normal operating conditions. During an external fault, an additional transient difference current is produced. This transient current is due to the following two phenomena.

First, a circulating current transient is produced in the primary circuit. The magnitude is dependent on the incidence angle of the external fault and on the characteristics of the damper winding. In machines without a damper winding, this current can be two to three times larger than the quiescent split-phase current and can take up to 30 cycles to decay.

Second, if differentially connected CTs are used to measure the split-phase current, then a difference in the CT characteristics during the fault, including CT saturation, will result in a spurious split-phase current.

Protection engineers select the primary current rating of CTs used in split-phase protection schemes based on the full-load current rating of the winding, typically 25 times higher than the circulating current produced during a turn-to-turn fault (see Section VI). By doing this, they trade sensitivity for security during external faults. However, due to the long decay of the dc current produced during an external fault, the CTs may end up saturating. Both CTs will not saturate to the exact same degree, and as a result, a difference current occurs (Fig. 24) and may result in inadvertent operation of the scheme. In applications for machines with low-impedance damper windings and differentially connected CTs, protection engineers delay the operation of the split-phase protection element, typically by up to 30 cycles, in order to prevent misoperation.

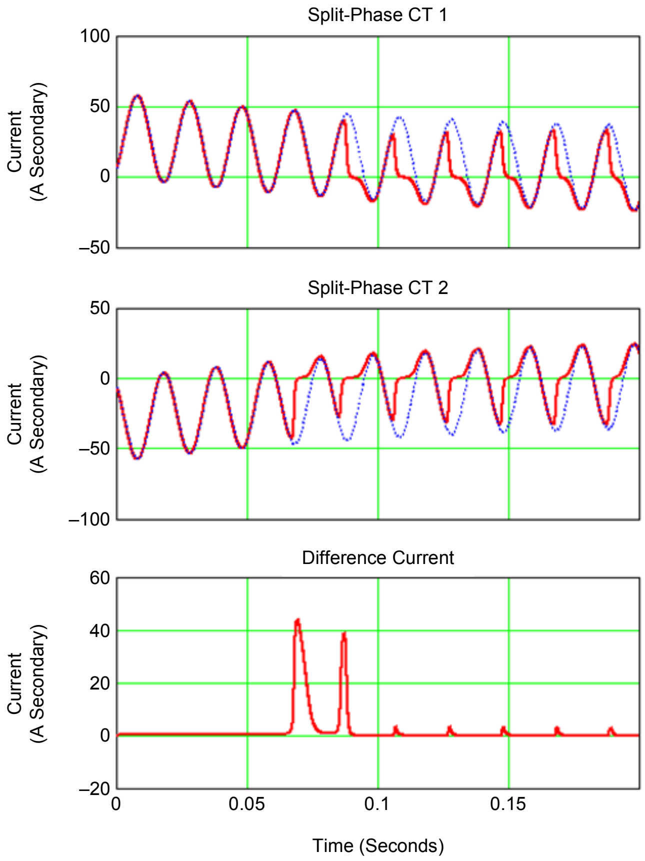

Fig. 24. Unequal saturation of the CTs in a split-phase protection scheme resulting in a fictitious differential current.

By delaying the element by up to 30 cycles, the scheme is secured from inadvertently operating during external faults, but at the same time, the protection is delayed by 30 cycles for a genuine turn-to-turn fault. In the next subsection, we discuss a new innovative method using external fault detection logic that secures this type of protection scheme during external faults without the need of an additional time delay.

B. *External Faults and the Role of AC and DC External Fault Detection*

Several microprocessor-based relays have been developed that make use of an external fault detector to provide additional security for a differential element during external faults. Because the split-phase element is also at risk under the same circumstances, it makes sense to employ the same logic to secure the split-phase element. In a multifunction generator relay, the logic can be shared by both functions.

External fault detectors employed within differential relays often are designed to detect two types of CT saturation:

- High-magnitude external faults, which can cause saturation due to the large ac component of the current.
- Low-magnitude external faults in which a decaying dc component with a long time constant is responsible for CT saturation.

During a heavy external fault, the CTs are initially expected to provide at least a half cycle of saturation-free operation. The ac path therefore looks for a step increase in the restraining current (I_{RST}) that is not accompanied by a corresponding increase in the differential current (I_{DIF}). Fig. 25 shows the simplified logic diagram of the ac external fault detection logic.

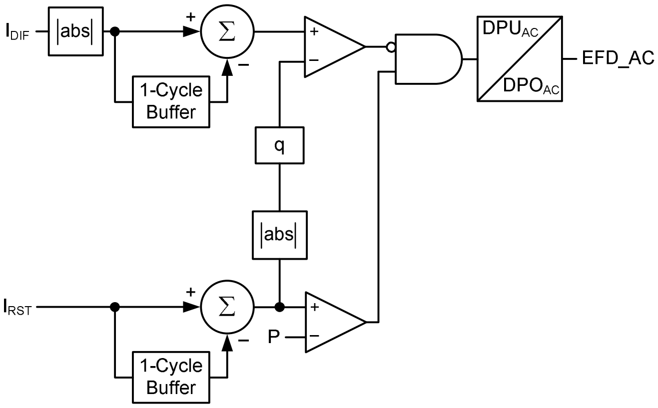

Fig. 25. AC external fault detection logic.

For detecting low-magnitude external faults that have long-decay dc signal content, the dc path compares the fundamental frequency current magnitude (I_{AC_MAG}) with the dc component current magnitude (I_{DC_MAG}), as shown in Fig. 26. A significant dc component is declared if the dc component is greater than a certain portion of the CT nominal rating or the ac component at the time. An external fault is declared if the current contains a significant dc component, if the differential current (I_{DIF}) is low compared with the restraint current (I_{RST}), and if this situation persists for several cycles.

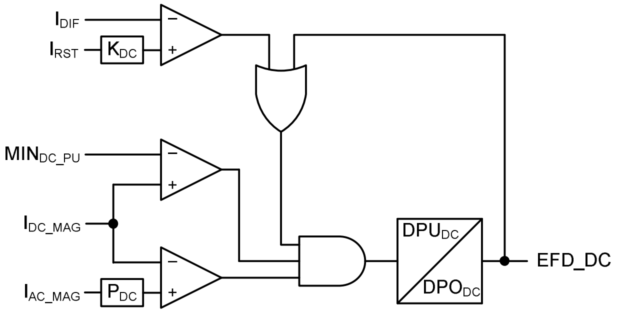

Fig. 26. DC external fault detection logic.

The outputs from the ac and dc external fault detection logic are connected together with an OR gate to provide one external fault detection element. The external fault detector has significant advantages compared with a simple delay because it allows instantaneous operation for internal faults and relieves the protection engineer of the task of determining an optimal delay setting. It addresses the problem of spurious split-phase currents that arise from the response of the machine or from the performance of the CTs.

C. Open CT Detection

So far, we have discussed methods of increasing the sensitivity of turn-to-turn protection elements and securing them during external fault conditions. However, how do we secure these schemes from misoperating when a CT is either inadvertently open- or short-circuited? The answer to this question lies in what type of protection scheme is employed to provide the turn-to-turn protection.

If a standalone split-phase protection scheme (comprised of two differentially connected CTs with one of these CTs open-circuited) is used, the scheme would be subjected to the load current of the winding (in A secondary). By simply using the information provided by these two CTs, there is no way to distinguish if this is due to a genuine internal fault or if there is trouble associated with one of the CTs in the scheme. If a microprocessor-based relay is used in implementing the scheme, it is likely that the differential protection scheme will also be realized in this relay. If this is the case, part of the ac external fault detection logic could be used to secure the split-phase protection element, as shown in Fig. 27.

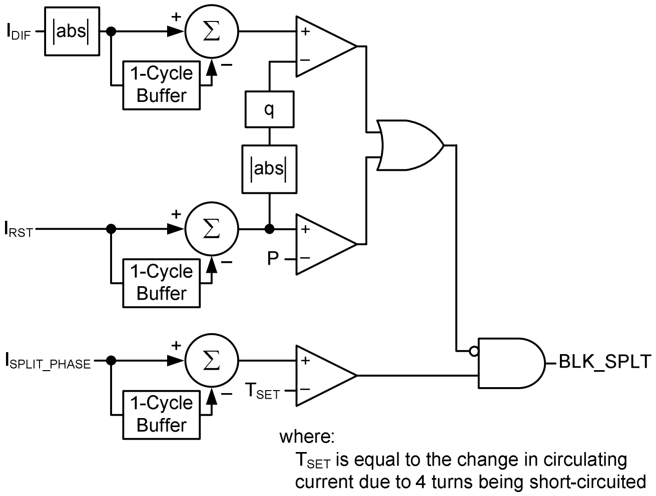

Fig. 27. Security logic for preventing inadvertent operation of the split-phase protection element due to an open-circuited CT.

Note that if the machine is lightly loaded and one of the CTs in this scheme is open-circuited, it will not be possible to detect this condition; similarly, if one of the CTs is short-circuited, this will also not be detected.

If turn-to-turn protection is realized by using the combined differential and split-phase protection scheme or the negative-sequence differential scheme, then detecting an open- or short-circuited CT is possible. The open-circuited CT logic is performed on a per-phase basis and functions as follows. The logic calculates both the restraint and difference currents. A troubled CT condition is declared if the increase in the differential current is equal to the decrease in the restraint current.

Adaptive split-phase protection that removes the standing split-phase current from the operating signal is more sensitive (Section VII). When supervised with the external fault detection logic and open CT detection logic (Section VIII), the split-phase protection elements are also more secure. In this way, better performance is achieved by relying on time delay or elevated pickup thresholds, without extensive engineering effort for the calculation of settings.

X. CONCLUSION

Turn-to-turn faults are possible in stator windings with coils made up of multiple turns in the same slot. Undetected, these faults can cause considerable damage before evolving into phase or ground faults. It is desirable to detect these faults and trip the machine in the typical short-circuit protection time frame (fraction of a second).

Split-phase protection takes advantage of the parallel configuration of hydromachine windings to detect turn-to-turn faults, as well as other fault types. However, achieving adequate sensitivity without jeopardizing security is a challenge. This is mainly due to the normal practice of using differentially connected CTs to measure the split-phase current.

In this paper, we present the underlying principles of split-phase protection, review methods for split-phase current measurement, and identify potential measurement errors. The paper identifies the mechanisms that produce transient split-phase currents during external faults.

We review existing methods of split-phase protection and offer settings guidelines and rules for CT selection.

We describe a novel method for the measurement of split-phase current. The method promises to provide the improved sensitivity of a core-balance CT and, at the same time, the ease of installation of differentially connected CTs.

The paper presents a new method for addressing the inherent unbalance in the stator currents, which results in a standing split-phase current without the need to desensitize the split-phase element or risk misoperation on external faults.

The paper reviews methods to secure split-phase protection during external faults and describes an improved method to provide security without sacrificing operation speed or sensitivity for internal faults. Future work is envisioned to implement these methods into a microprocessor-based relay and to carry out field trials.

XI. REFERENCES

[1] J. H. Walker, *Large Synchronous Machines: Design, Manufacture, and Operation*. Oxford University Press, 1981.

[2] Voith Hydro, "Micalastic® Insulation for High Voltage Hydro Generators," 2009. Available: http://www.voithhydro.com.

[3] *IEEE Tutorial on the Protection of Synchronous Generators*, 1995.

[4] J. DeHaan, "Electrical Unbalance Assessment of a Hydroelectric Generator With Bypassed Stator Coils," proceedings of the IEEE International Conference on Electric Machines and Drives, Seattle, WA, May 1999.

[5] H. R. Sills and J. L. McKeever, "Characteristics of Split-Phase Currents as a Source of Generator Protection," *Transactions of the American Institute of Electrical Engineers, Part III: Power Apparatus and Systems*, vol. 72, no. 2, pp. 1005–1016, January 1953.

[6] R. G. Rhudy, H. D. Snively, and J. C. White, "Performance of Synchronous Machines Operating With Unbalanced Armature Windings," *IEEE Transactions on Energy Conversion*, vol. 3, no. 2, pp. 391–397, June 1988.

[7] D. Finney, B. Kasztenny, M. McClure, and G. Brunello, "Self-Adaptive Generator Protection Methods," proceedings of the IET 9th International Conference on Developments in Power System Protection, Glasgow, United Kingdom, March 2008.

[8] K. W. Jones, "Addressing Window Type Transformer Proximity Errors," proceedings of the 59th Annual Conference for Protective Relay Engineers, College Station, TX, April 2006.

XII. BIOGRAPHIES

Sungsoo Kim received his BASc in electrical engineering from the University of Toronto, Canada, in 1985. Since joining Ontario Power Generation in 1986, Sungsoo has worked exclusively in power system protection and control engineering. His experience includes protection designs, operations support, project management, and support. Sungsoo is currently the manager of the protection and technical compliance section in the hydroengineering division. He is active in many working groups within the Power System Relaying Committee (PSRC), a member of IEEE, a Canadian representative in the NERC System Protection and Control Subcommittee (SPCS), and a registered professional engineer in the province of Ontario.

Dale Finney received his bachelor's degree from Lakehead University and his master's degree from the University of Toronto, both in electrical engineering. He began his career with Ontario Hydro, where he worked as a protection and control engineer. Currently, Dale is employed as a senior power engineer with Schweitzer Engineering Laboratories, Inc. His areas of interest include generator protection, line protection, and substation automation. He is a holder of several patents and has authored more than a dozen papers in the area of power system protection. He is a member of the main committee of the IEEE PSRC, a member of the rotating machinery subcommittee, and a registered professional engineer in the province of Ontario.

Normann Fischer received a Higher Diploma in Technology, with honors, from Witwatersrand Technikon, Johannesburg in 1988, a BSEE, with honors, from the University of Cape Town in 1993, and an MSEE from the University of Idaho in 2005. He joined Eskom as a protection technician in 1984 and was a senior design engineer in the Eskom protection design department for three years. He then joined IST Energy as a senior design engineer in 1996. In 1999, he joined Schweitzer Engineering Laboratories, Inc. as a power engineer in the research and development division. Normann was a registered professional engineer in South Africa and a member of the South Africa Institute of Electrical Engineers. He is currently a member of IEEE and ASEE.

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