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Phaselet Algorithm Based Differential Protection for Large Generator

***Abstract**. This paper presents a new differential protection scheme for large generator based on phaselet algorithm. The harmonic components caused by the internal fault are very important for the generator internal fault detection. With the wavelet analysis, the background noise and the high harmonic information are effectively removed. The currents are then represented to be the sampling currents, which contain important fault information. Analysis shows that the harmonic components can be enlarged after phaselet algorithm, and it also enables the efficient phasor computation of over sample windows that are not restricted to an integer multiple of a half cycle. For the severe internal fault, the criterion based on phaselet 1 and 2 have good speed performance. Simulation results demonstrate that the new scheme is successful in detecting the generator internal fault. It has higher sensitivity, and selectivity and quick speediness*

Streszczenie.** W artykule opisano nową strukturę ochrony różnicowej dla dużych generatorów, opartą na algorytmie fazowym. Zastosowana analiza falkowa, pozwala na eliminację wysokich harmonicznych i szumu w tle, w pomiarach prądu. Oczyszczone próbki pomiarowe zawierają informacje dotyczące awarii, służące do ich wykrywania. Analiza wykazała, że składowe harmoniczne mogą zostać powiększone, dzięki algorytmowi fazowemu. Dodatkowo uskutecznia on obliczanie fazora w oknach próbkowania, nie ograniczonych do całkowitej wielokrotności połowy cyklu. Badania symulacyjne potwierdziły skuteczność metody, w wykrywaniu awarii wewnętrznych. **(Algorytm Phaselet w ochronie różnicowej dużych generatorów).

Keywords: generator internal fault, phaselet, wavelet transform, split-phase transverse differential protection.
Słowa kluczowe: awaria wewnętrzna generator, transfromata falkowa, ochrona różnicowa dzielonych uzwojeń

Introduction

Large modern power systems have very large synchronous generators with rating of 600MW and above. In China, there are 14 generators with rating of above 900MW in operation. Because the generators have large size and great cost, the various faults such as the internal faults may cause serious result to machine owing to severe mechanical and heat damage. So the requirements need to be fulfilled are stringent for generator protective systems [1-2]. For example, for the severe internal fault, the quicker trip signal is the better choice.

Differential protection is the most common type of method used to protect the stator of large synchronous machine. In order to develop the optimum protective equipment for the generators, great efforts had been done. Research results illustrated that the employed schemes for large generator including differential protection scheme, cut-phase transverse differential protection scheme and unit transverse differential protection scheme, have a long history of providing reliable protection, and continue to be applied. However, continuing rapid improvements in signal process and digital computer technology have prompted a re-evaluation of those protective devices [3-7]. For instance, as most of them apply the Full-cycle Fourier in current computation, the trip signal must be over 20ms. The differential protection, as one of the most important main protections, it should not only has reliable selectivity and sensitivity, but also has good speediness. In the current differential protection, in order to improve the speediness, people often apply the half-cycle Fourier filter to calculate the differential current. So the differential algorithm responds to the internal faults in about half-a-cycle.

In contrast to the traditional Fourier analysis the signal features in an integer multiple of a half cycle, phaselets are partial sums in the computation for fitting a sine function to measured samples [3]. Each slave computes phaselets for each phase current and transmits phaselet information to the master for conversion into phasors. Phaselets enable the efficient computation of phasors over sample windows that are not restricted to an integer multiple of a half cycle at the power system frequency. Determining the fundamental power system frequency component of current data samples by minimizing the sum of the squares of the errors gives rise to the first frequency component of the Discrete Fourier Transform (DFT). By this way, a much better signal characterization and a more reliable discrimination can be obtained. So it is ideal technique for studying transient signals. In this paper phaselet algorithm was proposed as a new approach to detect the internal fault in the generator.

Principle of phaselet algorithm based differential protection

In the case of a data window that is a multiple of a half cycle, the phaselet computation is simply sine and cosine weighted sums of the data samples. In the case if a window that is not a multiple of a half-cycle, there is an additional correction that results from the sine and cosine functions not being orthogonal over such a window. The computation can be expressed as a two by two matrix multiplication of the sine and cosine weighted sums.

$$R_e\,a_p = \sum_{k=p\bullet q-q+1}^{p\bullet q} X_k \bullet \cos\frac{2k\pi}{N} \tag{1}$$

$$I_m\,a_p = \sum_{k=p\bullet q-q+1}^{p\bullet q} -X_k \bullet \sin\frac{2k\pi}{N} \tag{2}$$

where: P – the phaselet index, it is also the number of phaselets per cycle, $R_e\,a_p$ 、 $I_m\,a_p$ – real and imaginary components of the pth phaselet, respectively, N – the number of samples per cycle, k – the kth sample of the mimic output.

The computation of phaselets and sum of squares is basically a consolidation process. The phaselet sums are converted into stationary phasors by multiplying a precomputed matrix.

Suppose the sample points in one fundamental cycle are 96, which ensures the correct calculation of the high frequency currents. Then there are 24 points in a phaselet and 4 phaselets in a cycle. As the amplitude-frequency characteristic is a good criterion for the performance of the algorithm. It is applied to compute the filter performance of the phaselet.

Let:

$$|H| = \frac{\sqrt{(U_{\mathrm{Im}1}^2 + U_{\mathrm{Re}1}^2)}}{U_n} \tag{3}$$

where: $U_{\mathrm{Im}1}$ – the imaginary part of the fundamental frequency component， $U_{\mathrm{Re}1}$ – the real part of the fundamental frequency component， U_n – the amplitude value of the nth harmonic signal.

Considering that phaselet 1 and 2 have short time in the computation, and it will be used in this paper. Table.1 give the simulation results with different incipient angle for the different frequency component.

Table.1 The amplitude-frequency characteristic analysis of the phaselet 1 and 2

algorithm	Incipient angle	The 2nd harmonic componen t	The3rd harmonic component	The 4th harmonic component
phaselet 1	0°	74%	91%	103%
	30°	84%	132%	96%
	60°	113%	133%	64%
	90°	129%	111%	37%
phaselet 2	0°	84%	0%	33%
	30°	78%	0%	31%
	60°	58%	0%	21%
	90°	42%	0%	9%

Table.1 shows that phaselet 2 can remove the multiple components of the third harmonic completedly. However, its filter performance for the even harmonics is not so good, and it always changed with the fault incipient angle. For phaselet 1, the filter performance for all of the harmonics presents bad, under some conditions the harmonic components are even enlarged. It is resonable considering that the fore part half-cycle wave is mirror image with the back part half-cycle wave of the odd harmonics, but the fore part half-cycle wave is completely same with the back part half-cycle wave of the even harmonics.

At present, the steady-state performance and transient behavior of large generators have been studied under a variety of representative fault conditions in references [1-2]. Both simulated and measured results have revealed this fact, when an internal fault happens, there will be some harmonic currents and present as transient components. For example, there are some space harmonics in the air-gap magnetic field and strong time harmonics current in each winding because of electromagnetic coupling with the internal fault. They have much more fault information than the steady components because they are caused usually by the fault. But there exists almost no harmonic component because of the generator symmetry on normal conditions [4-7]. In reference [8], measured results have revealed that a salient synchronous machine with internal faults appears important harmonic current features. The generator has 3 branches per phase and 36 slots a branch. When 5 slots is shorted, the third-order, fifth-order and seventh-order harmonics of the stator current are 14.99%, 5.92% and 16.44%, respectively, of the fundamental current component. These currents bear a relationship to the severity of the fault. Therefore, the harmonic current components will not be always limitation to the protection scheme. Phaselet is an ideal technique to study transient signals in a cycle. In this paper it is proposed as a new approach to detect the internal fault in the generator.

A traditional differential protection schematic diagram for one phase of a generator stator is illustrated in Fig.1. If transformer mismatch are neglected, during normal operation and for external faults, the current, I_1, entering the winding is equal to the current, I_2, , leaving the winding. In practical case the differential current, which is proportional to the vector difference of I_1 and I_2 would be small. And a restraining current (average current) could make the scheme operate correctly on different conditions, which is proportional to the vector sum of the currents I_1,.

The differential protection cannot detect the interturn short circuit and the circuit of two branches in the same phase. But it can protect the short circuit between different phases very effectively. The split-phase transverse differential protection and the incomplete protection is useful to all internal short circuit faults.

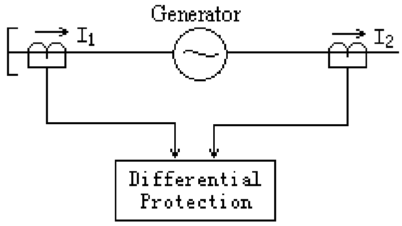


Fig.1 Schematic diagram of traditional differential protection

Different from the Fig.1, the split-phase transverse differential protection scheme and the incomplete differential protection scheme are listed in fig.2 and fig.3, respectively. For the discussion of the performance of new scheme, a large generator in Three gorges Power Station is taken as example. And the generator is directly connected to step-up transformer and grounded thro ugh a distribution transformer with a resistance-loaded secondary. The generator has 40 poles, 5 branches per phase and 36 slots a branch. Fig.2 shows the basic arrangement of the new technique. Connected to the CT, the A/D module captures the signals i_{a1}, i_{b1} and i_{c1} of the left branches, and i_{a2}, i_{b2} and i_{c2} of the right branches, which are then first processed by the wavelet transform. The absolute value of the sample received is stored in memory location. With the wavelet analysis (listed below), the the high harmonic information and the background noise are effectively removed. The currents are then represented to be phaselets in this paper.

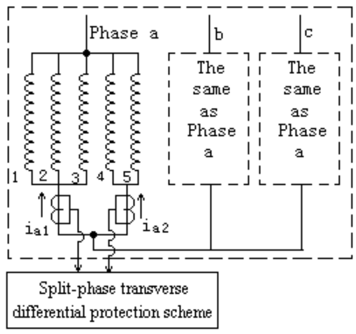


Fig.2 Protection circuit of the phaselet-based split-phase transverse differential protection scheme

The incomplete differential protection comprises the phase currents I_A , I_B , I_C at the terminal and corresponding partial branch currents at the neutral as shown in Fig.3. In Fig.3, the partial branch currents I_{an}, I_{bn} and I_{cn} are comprised by the currents in branch 1, 2 and 3 of the corresponding phase. The differential protection, as one of the most important main protections, it should not only has reliable selectivity and sensitivity, but also has good speediness.

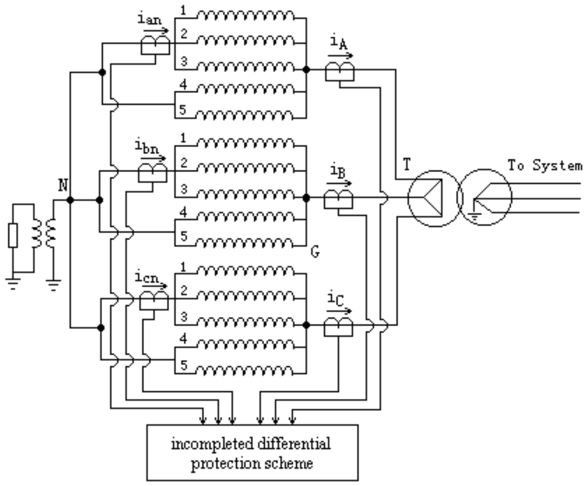


Fig.3 Protection circuit of the phaselet-based incompleted differential protection scheme

In this paper, in order to improve the speediness, we apply the phaselet algorithm to calculate the differential and average current. So the differential algorithm responds to the internal faults is less than half-cycle, which meets our design criteria. The differential and average signals are derived as:

$i_d = | i_1 - i_2 |$ and $i_T = | i_1 | + | i_2 |$

where : i_d – differential current, i_T – average current.

The criterion is separated in three stages:

i) The criterion based on phaselet 1 to discriminate between internal and external faults is as below:

$$\begin{cases} i_d \geq i_{d0.1} \\ i_d \geq k\, i_{T.1} \end{cases} \tag{4}$$

ii) The criterion based on phaselet 2:

$$\begin{cases} i_d \geq i_{d0.2} \\ i_d \geq k\, i_{T.2} \end{cases} \tag{5}$$

iii) Full-cycle phaselet based current protection:

$$\begin{cases} i_d \geq i_{d0.3} \\ i_d \geq k\, i_{T.3} \end{cases} \tag{6}$$

For improving the reliability, there are $i_{d0.1} > i_{d0.2} > i_{d0.3}$ and $i_{T.1} > i_{T.2} > i_{t.3}\ \Delta I_0$. Only if n (n≥3) times satisfied, the fault trip signal can be sent out.

Signal Processing with Wavelet-transform

In wavelet analysis, any continuous function f with finite energy can be expanded to its wavelet series:

$$f_J(x) = \sum_{k=0}^{2^{J\min}-1} c_k^{J_{\min}} \phi_{J_{\min,k}}(x) + \sum_{j=J_{\min}}^{J-1} \sum_{k=0}^{2^j-1} d_k^j \psi_{j,k}(x) \tag{7}$$

Dilated by 2^j and translated by k, $\varphi_{j,k}(x)$ and $\psi_{j,k}(x)$ are generated respectively from scaling function $\varphi(x)$ and mother wavelet $\psi(x)$. The coefficient c_k^j represents the smooth information of original signal, while the coefficient d_k^j represents the detail information. According to that, a given signal can be decomposed into its detailed and smoothed versions with Multiresolution analysis (MRA). They have two important properties: one is the localization property in time domain; the other is the partitioning of the signal energy at different frequency bands.

As wavelets allow the decomposition of a signal into different levels of resolution (frequency octaves), a new filter can be designed based on wavelet with different masking parameters in different resolution bands.

At the same time, it is proven that the noise can be detected from the wavelet transform modulus maxima with special characteristics [9-10]. Thus we also can develop a denoising algorithm based on wavelet to remove the noise, which the protection scheme is not needed.

After the corresponding scales and modulus maxima masking, the noise fluctuations would be effectively removed in the reconstructed currents according to the algorithm described in reference [9-10]. Thus the useful information could be obtained and be used in the differential protection scheme.

The Wavelet Transform scheme developed in this paper is composed of two stages: First, select the wavelet filter and transform the measured current into its wavelet representation. Secondly, perform signal processing on the transformed current, by which the noise and the high frequency current component are effectively removed.

By adopting the multiresolution analysis decomposition algorithm, implementation of the wavelet transform was done. It was found that one way of improving the performance of the scheme is to select a proper wavelet filter. The quality of a wavelet-based signal representation depends heavily on the choice of the analyzing wavelets. There are two criteria for the selection of the mother wavelet in generator protection. At first, the shape and the mathematical expression of the wavelet must be selected correctly so that the physical interpretation of wavelet coefficients is easy. Secondly, the chosen wavelet must allow a fast computation of wavelet coefficients.

Because different fault signals have different optimal filters, it is critical to select the right wavelet filter. Instead of trying to compute the optimal wavelet coefficients for a given current, the wavelet scheme tries to find the “best” (rather than optimal) wavelet filter from a reservoir of available filters. The best filter is identified using the filter selection module. The filter selection module tries out each of the available filter on the current by processing only the first level detailed subcurrent of the MRA decomposition for each of the filters. The first level subcurrent is then quantized in a crude but systematic manner. More specifically, experiments have shown that a quantization step size of 4 in current decomposition gives a reliable measure of the information representation given by a specific wavelet filter. The filter selection module then selects the specific wavelet filter that yielded the smallest number of non-zero wavelet coefficients. That filter has a quick computation speed for the particular current.

The choice of filters used by the filter selection module is restricted to include only the short Daubechies filters, mainly because of their easiness of implementation and their good performance. Actually, different wavelet basis functions have been proposed and selected in reference [10]. Each has its feasibility depending on the application requirement. However, investigated in the laboratory with a long time, the Daubechies wavelets have been proven to be very efficient in signal analysis. Daubechies wavelet filters longer than 12 taps are not used since it was found that these longer filters did not perform better than the shorter ones. And in the proposed scheme, the Daubechies 5-order orthogonal wavelet is exploited after comparison. Furthermore, the standard deviation curves at different resolution levels are used.

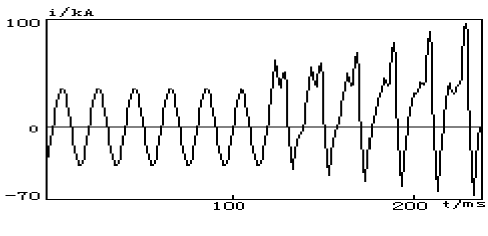
As mentioned above, a current signal is decomposed into different levels of resolution, and different frequency components are projected into those different levels. Thus only incorporating the masking parameter with the corresponding level, the nouseful component could be effectively removed. At the same time, by selecting the wavelet transform modulus maxima that correspond to the noise, denoising algorithm can also be developed. Because the reconstruction process is essentially based on iteratively adding the detailed components to the scaled-up subcurrent, it is crucial that subcurrent in different levels preserved perfectly in order to allow very high reconstructed current quality, except the levels which contain the noise component. Then, the fundamental frequency and some harmonic current components could be used in generator differential protection.

Simulation Results

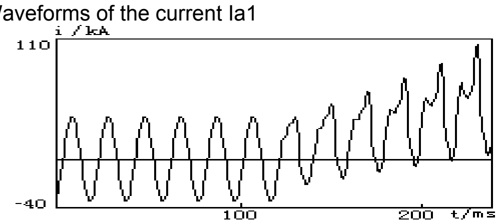
Until protection device is actually implemented in the field, simulation tests, which can only approximate the true operating conditions, must be employed to evaluate the relay performance. The operation of the protection scheme was tested with various types of simulated faults by using the model generator. The mathematical models described in references [1-2] can be used effectively to calculate the currents of the large generators under fault conditions. The calculation results can be directly suitable for engineering or experimental application. The generator has 40 poles, 5 branches per phase and 36 slots a branch. The winding capacitance to ground per phase is c_G =1.81 μF , the inductance and the resistance of a turn are L=0.000064H and r=0.000213Ω, the grounding impedance of the generator (including the grounding transformer) referred to the generator side Z=601.5+j30Ω.

Lots of faults were conducted, including those light faults that the traditional protection scheme could not detect:

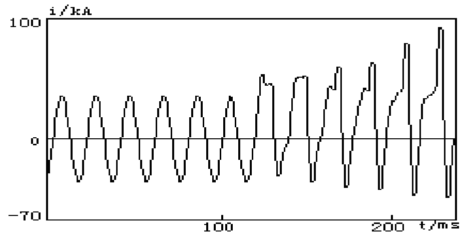
i) internal single phase to ground fault with 20 kΩ resistance;
ii) internal single phase faults with 2.8 percent of the stator winding is shorted;
iii) internal two phase faults with 2.8 percent of the stator winding is shorted;
iv) different external faults.



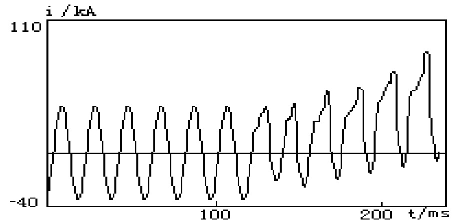
(a1) Waveforms of the current Ia1



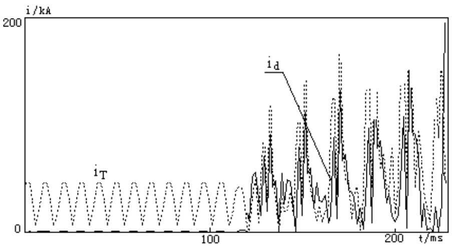
(a2) Waveforms of the current Ia2



(b1) The WT results of the sum of current Ia1

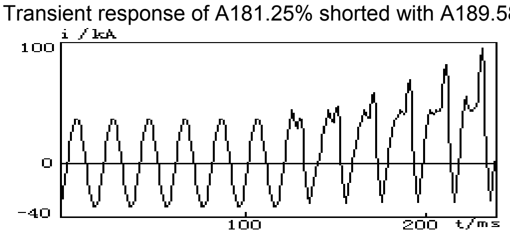


(b2) The WT results of the sum of current Ia2

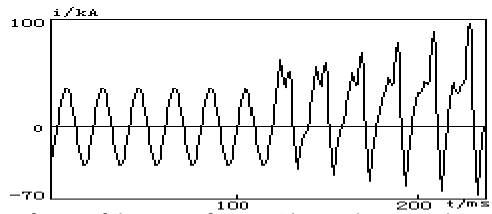


(c) The differential current and average current for the split-phase transverse differential protection

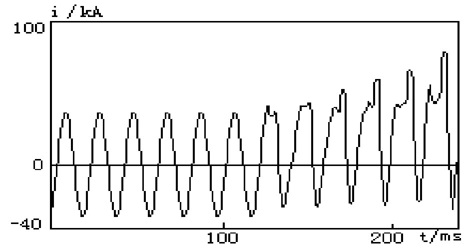
Fig.4 Transient response of A181.25% shorted with A189.58%



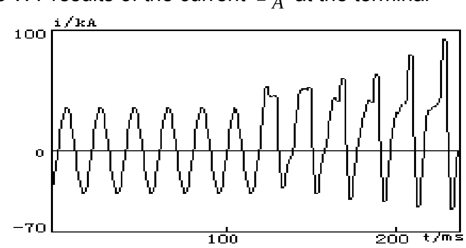
(a1) Waveforms of the current I_A at the terminal



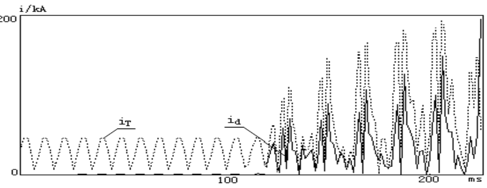
(a2) Waveforms of the sum of current Ian at the neutral



(b1) The WT results of the current I_A at the terminal



(b2) The WT results of the sum of current Ian at the neutral



(c) The differential current and average current for the incompleted differential protection

Fig.5 Transient response of A1 α =81.25% shorted with A1 α =89.58%

Suppose α is the ratio between the number of turns from the neutral to the fault point and the total number of turns in series for one phase. Fig.4 is result of the above generator. It shows the detection of the internal fault when A1 81.25% shorted with A1 89.58%, here A1 indicates the first branch in phase A, and the sampling rate is 4800Hz. There are 96 sample points in one fundamental cycle. Fig.4.a1 and Fig.4.a2 refer respectively to the waveforms of the stator branch current I_{a1} and I_{a2} in phase A as shown in Fig.2. Their corresponding results of WT are shown as in Fig.4.b1, b2. In this case, the conventional protection schemes could not find the fault. Fig.4.c compares the differential and average waveforms of the split-phase transverse differential protection. When the fault happens, the currents will present the singularities and are resolved into fundamental and some harmonic components. In Fig.4.c, it is important to recognize that the differential current increases and the fault could be detected. The reason is that the new scheme is mainly based on the both some harmonic current components and the fundamental frequency current. As there exists no harmonic component on normal condition, the prefault load harmonic currents can be very small compared with the prefault load currents. When the fault happened, harmonic current components under internal fault conditions are larger than those under normal conditions because they are enlarged by phaselet, thus differential current is large when it is compared with the average current. So the new scheme would have higher sensitivity. On the other hand, under some situations without fault (for example, switching), high frequency components are present. But it could not affect the correct operation of the scheme. Because the differential current is small, and the restraining current could ensure the scheme operate correctly.

The fault phase currents on the generator terminals I_A and the branch current I_{an} at the neutral as shown in Fig.3 are listed in Fig.5.a1 and a2. The corresponding WT results are shown in Fig.5.b1, b2. Based on the same reasons, the new scheme could ensure higher sensitivity. Experimental results under various situations show that the proposed method can keep high sensitivity without maloperation during different conditions. For the severe internal fault, the criterion based on phaselet 1 and 2 could detect it in less than half-a-cycle time.

Conclusions

The harmonic components caused by the internal fault are very important for the generator internal fault detection. Phaselets enable the efficient computation of phasors over sample windows that are not restricted to an integer multiple of a half cycle at the power system frequency. In this paper phaselet algorithm was proposed as a new approach to detect the generator internal fault. At the same time, wavelet theory provides a new tool for the signal processing. Using the properties of the multiresolution analysis and the features in the decomposed waveform, one will have the ability to extract important information from the distorted signals. With the wavelet analysis, the background noise is effectively removed. The currents are then represented to be the sampling currents, which contain important fault information. Analysis shows that the harmonic components can be enlarged after phaselet algorithm. The paper proposes the use of the phaselet as a powerful tool for fault currents analysis.

Based on that technique presented above, a new generator internal fault protection scheme is developed and the simulation results are also demonstrated. From the test results, this paper shows that the proposed approach is successful in detecting the generator internal fault, and could have high sensitivity and selectivity. For the severe internal fault, the criterion based on phaselet 1 and 2 can send the trip signal quickly. It also reveals the feasibility of the scheme as a potential alternative in generator internal fault protection application.

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