Available online at www.sciencedirect.com
SCIENCE DIRECT®
Electric Power Systems Research 69 (2004) 179–186
ELECTRIC POWER SYSTEMS RESEARCH
www.elsevier.com/locate/epsr

New generator incomplete differential protection based on wavelet transform

Tai NengLing [a,*], Ai Qian [a], Yin XiangGen [b], Chen DeShu [b]

[a] Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, PR China
[b] Department of Electrical Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, PR China

Received 17 April 2012; received in revised form 10 July 2012; accepted 21 August 2012

Abstract

This paper proposes a digital computer technique based on wavelet transform for generator incomplete differential protection scheme. Exploitation of the fault-generated high frequency currents, the new scheme can provide fault detection with high sensitivity and is also capable of discriminating between internal and external faults. The effectiveness of the proposed scheme was verified both in the experiment and in the field. The results show that the scheme can detect the generator fault with high sensitivity and selectivity during all operation conditions.

Keywords: Generator internal fault; Wavelet transform; Incomplete differential protection; High frequency current

1. Introduction

Stator winding faults of synchronous generator are considered serious problems because of the damage associated with high fault currents, mechanical damage and high cost of maintenance [1,2]. Differential protection is the most common type of method used to protect the stator of large synchronous machine. Three Gorges Hydropower Station will be one of the largest power stations in the world. Because the generators there have huge 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. Thus, the requirements need to be fulfilled are stringent for their generator protective systems. In order to develop the optimum protective equipment for the generators, great efforts had been done. Research results illustrated that the employed schemes including differential protection scheme, cut-phase transverse differential protection scheme and unit transverse differential protection scheme would have a blind zone [2]. For example for the short circuit happened between 81.25 (from neutral) and 89.58% in the first branch in phase A (termed as a1), the transient currents are very small, all schemes are unable to detect.

Most differential protection schemes in use today are either static relay or microcomputer-based types, which have a long history of providing reliable protection, and continue to be applied. These schemes generally rely on extracting fundamental frequency current signals to detect faults [3–6]. As a fault in a generator produces wideband signals and/or effective current waves, we can propose a new form of differential current relaying which exploits those high frequency signals. Much of those signals are outside the bandwidth of receptiblity of present generation of protection. As a recent technique, wavelet transform has been successfully used for developing new protection. In reference [6], it is employed for measurement of fault-generated high frequency signal in fault generator. In contrast to the traditional Fourier analysis that averages frequency features both in time and frequency domains, wavelets allow the decomposition of a signal into different levels of resolution (frequency octaves). This paper the first time presents on-line digital computer scheme with wavelet transform for incomplete differential protection of a synchronous generator based on the high frequency currents. The effectiveness of the scheme is verified both in experimental and field conditions.

The paper is organized as follows. Section 2 analyzes the principle of wavelet-based differential protection scheme,

* Corresponding author. Tel.: +86-21-54809165; fax: +86-21-62932394.
E-mail address: lifeiseasy@163.net (T. NengLing).

section 3 presents a general introduction of wavelet transform and the proposed incomplete differential scheme based on the high frequency currents, section 4 demonstrates and discusses the experimental and field test results, finally the conclusions are given in section 5.

2. Principle of wavelet-based incomplete differential protection

2.1. High frequency analysis of a fault generator

The steady-state and transient behaviour of large generators have been studied under a variety of representative fault conditions in references [1,2,7–10]. Based on the different mathematical models, simulation results have indicated that when an internal fault occurs on a stator winding, not only the airgap field harmonics are very strong, but also fractional harmonics are yielded, except for both odd and even harmonics. Harmonic analysis of the simulated results shows that the distortion of the currents is significant. For example the excitation current contains large second-order and fourth-order harmonics in addition to the dc current component. Similarly, the stator currents contain large third-order and fifth-order harmonics in addition to the fundamental current component. In reference [10], measured results have revealed that a salient synchronous machine with internal faults appears important harmonic current features. The generator has three branches per phase and 36 slots a branch. For example, when five slots is shorted, the third-, fifth- and seventh-order harmonics of the stator current are 14.99, 5.92 and 16.44%, respectively, of the fundamental current component. In summary, harmonic current components in both the stator and the rotor can be much larger under internal fault conditions than those under normal operation conditions. On normal conditions, there exists almost no harmonic component because of the generator symmetry. However, the phase windings are no longer intact under internal fault conditions, and both simulated and measured results have revealed that the harmonic current contained in the stator winding can be very significant. Therefore, attention should be paid to the effect of such harmonic current components caused by internal faults and the appropriate protection scheme can be provided on the basis of this principle.

2.2. Principle of wavelet-based differential protection

Conventional protection schemes generally rely on extracting voltage and current signals around the power system frequency to detect a fault. The wideband high frequency signals in a generator created by a fault are usually outside the bandwidth of most current transformers. Thus, almost no work has been reported in use of the high frequency for generator protection purpose.

A traditional differential protection schematic diagram for one phase of a generator stator is illustrated in Fig. 1. If

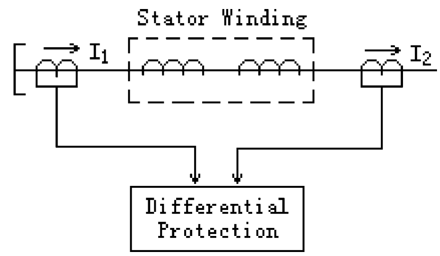


Fig. 1. Schematic diagram of traditional differential protection.

transformer mismatch are neglected, during normal operation and for external faults, the current, I_2, 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 and I_2. At the same time, the scheme can also be realized with only the sampling values of the current i_1 and i_2. Accomplished directly with the sampling values, the differential protection could achieve accuracy and high speed of fault detection. Different from the Fig. 1, the incomplete differential protection comprises the phase current at the terminal and corresponding partial branch current at the neutral as shown in Fig. 2. In Fig. 2, 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.

In this study, the fault-generated high frequency current signals are captured by a specially designed relay hardware/software, which is utilized to determine whether a fault is internal or external to the protected generator. Fig. 2 shows the basic arrangement of this technique. As shown, the current transformer is specially designed for the band of high frequency currents. Connected to the CT, the high frequency A/D module captures the signals I_A, I_B, I_C of the generator terminals, and I_{an}, I_{bn}, I_{cn} of the generator neutral, which are then first processed by the wavelet transform. With the wavelet analysis (listed below), the fundamental current component and the background noise are effectively removed. The currents are then represented to be the sampling currents with high frequency bands. The differential and average signals are derived as

$$i_d = |i_1 - i_2| \quad \text{and} \quad i_T = |i_1| + |i_2|$$

where i_1 is sampling current on generator terminals, i_2 is sampling current on generator neutral, i_d is differential current, i_T is average current.

The criterion to discriminate between internal and external faults is as below:

$$\begin{cases} i_d \geq i_{d0} \\ i_d \geq k i_T \end{cases} \tag{1}$$

For improving the reliability, the above equation should be calculated at least m times ($m \geq 16$) in one cycle repeatedly.

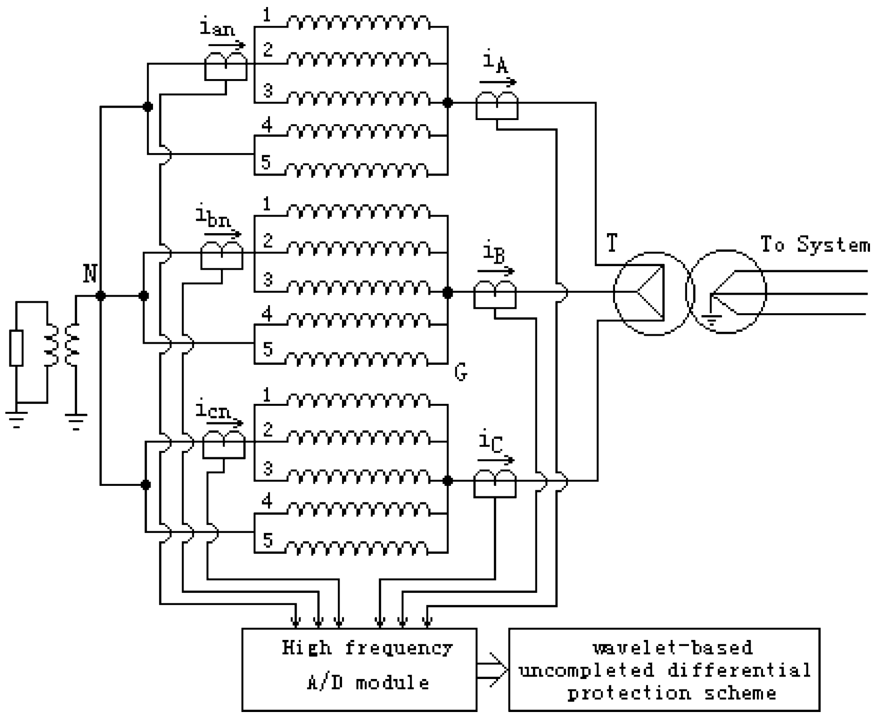


Fig. 2. Protection circuit of the wavelet-based incomplete differential protection scheme. (a1) Waveforms of the current I_A at the terminal; (a2) waveforms of the sum of current Ia_1, Ia_2 and Ia_3 at the neutral; (b1) the WT results of the current I_A at the terminal; (b2) the WT results of the sum of current Ia_1, Ia_2 and Ia_3 at the neutral; (c1) the differential current and average current for the traditional protection scheme; (c2) the high frequency differential current and average current for the proposed protection scheme.

Only if n ($n \geq 12$) times satisfied, the fault trip signal can be sent out.

3. Processing and coding the wavelet-transform coefficients

3.1. Wavelet analysis

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

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

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 [11]. 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 and fundamental current signals would be effectively removed in the reconstructed currents according to the algorithm described in reference [11]. Thus, the fault-generated transient high frequency currents could be obtained and be used in incomplete differential protection scheme.

3.2. Choice of analyzing wavelets

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 fundamental current component are effectively removed.

3.2.1. Selection of the wavelet filter

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 four 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 [11]. 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 five-order orthogonal wavelet is exploited after comparison. Furthermore, the standard deviation curves at different resolution levels are used.

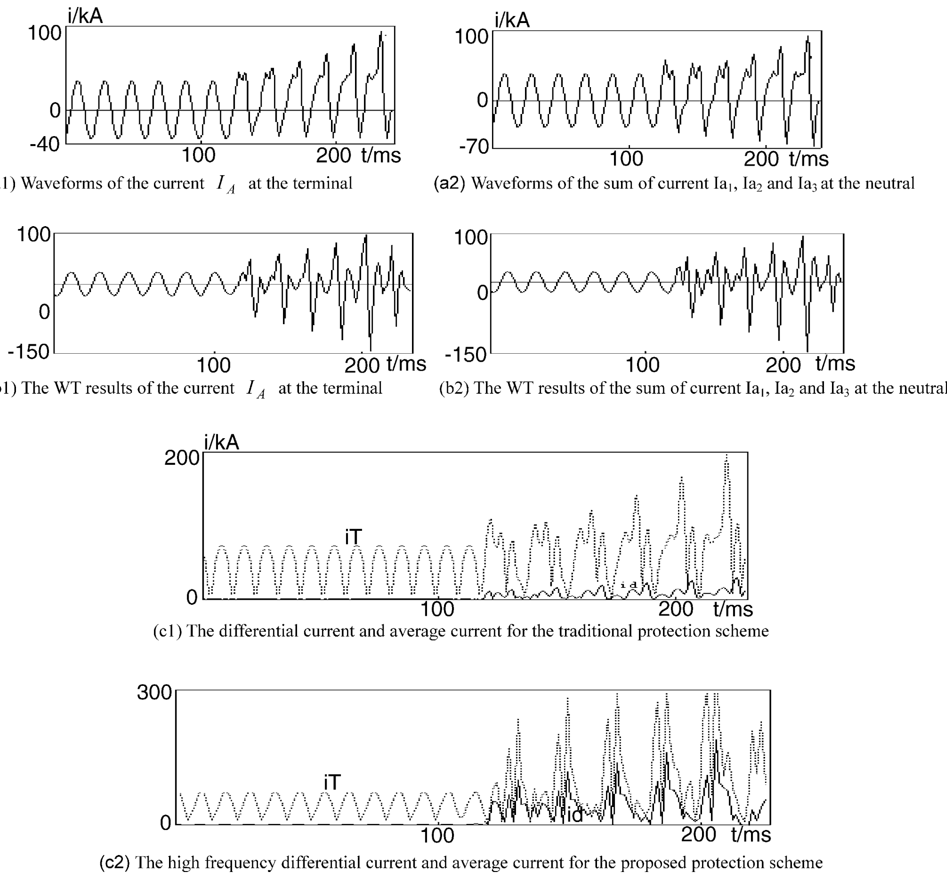
3.2.2. Signal processing

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 power system frequency 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 power system frequency component.

Then, the high frequency current could be obtained, which can be used in generator incomplete differential protection. 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. 3 is simulation result of a generator in three gorges hydropower station. Equivalent circuits for the fault currents of a generator are based on reference [1]. According to the reference, the currents are acquired considering various fault conditions. Fig. 3 shows the detection of the internal faults when a_1 86.81% shorted with a_1 84.03%, here a_1 indicates the first branch in phase A and the sampling rate is 12,000 Hz. There are 240 sample points in one fundamental cycle, which ensures the correct calculation of the high frequency currents. Fig. 3(a1) and (a2) refer respectively to the simulated waveforms of the stator phase current I_A at the terminal and the sum of current $\sum_{i=1}^{3} I_{ai}$ at the neutral of branch a_1, a_2 and a_3 in the same phase, which is made up of the incomplete differential protection. Their corresponding results of WT are shown as in Fig. 3(b1) and (b2). And Fig. 3(c1) and (c2) compares the differential and average waveforms between the traditional protection scheme and the proposed scheme. It can be seen from the figures that the average currents ensure the scheme's reliability on normal conditions. With the fault happening, the currents present the singularities and are resolved into fundamental and many harmonic components. In Fig. 3(c1), as fault currents are small in comparison with prefault load currents, differential current will be small in comparison with the average current. Therefore, the fault could not be detected. However, it is important to recognize that the differential current increases greatly in Fig. 3(c2) and the fault could be detected easily. The reason is that the new scheme is mainly based on the high frequency current component. As there exists no high frequency harmonic component on normal condition, the prefault load harmonic currents can be very small compared with the prefault load currents in the traditional scheme. When the fault happened, harmonic components of current under internal fault conditions are larger than those under normal conditions, thus differential current is larger in contrast with the average current. So the new scheme could ensure higher sensitivity. On the other hand, under some situations without fault (for example, switching), high frequency component 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 not operate on that condition.

In summarizing the analysis results obtained above, sufficient evidences can be provided to detect generator internal faults when applying the fault-generated high frequency current filtered with the wavelet analysis. So the high frequency current components can be used in differential protection scheme. The results listed below show that the new technique could detect the internal fault with high sensitivity and selectivity during all operation conditions.



(a1) Waveforms of the current I_A at the terminal

(a2) Waveforms of the sum of current Ia_1, Ia_2 and Ia_3 at the neutral

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

(b2) The WT results of the sum of current Ia_1, Ia_2 and Ia_3 at the neutral

(c1) The differential current and average current for the traditional protection scheme

(c2) The high frequency differential current and average current for the proposed protection scheme

Fig. 3. Transient response of A_1 $\alpha = 86.81\%$ shorted with A_1 $\alpha = 84.03\%$.

4. Experimental and field test results

According to the above, the new protection relay with the proposed scheme was developed. As Daubechies five-order orthonormal wavelet is easy to be realized in the real-time application, it is used in the scheme. To illustrate the efficiency of the new protection principle, it has been tested both in the experiment and the field situations. The protection relay was coupled to a commercial sequential-events recorder and installed in a model generator in Gehey Hydropower Station. The generator has the following characteristics:

- rated power: 125 MW with a power factor of 0.875;
- rated output voltage: 13.8 kV;
- rated speed: 96 rpm at 50 Hz;
- winding capacitance to ground per phase: 1.398 uf.

4.1. Relay hardware

The relay hardware, described in [6], is a multi-processor system comprising a master controller and one or more microprocessors (TMS320F206). One of typical relay hardware is shown in Fig. 4. The DSP card has been designed according to the low-cost principle but provides sufficient computing ability. And a watchdog has been fitted to the master microprocessor to check its operation. Outputs from relaying functions are automatically disconnected when the watchdog fails to provide the appropriate normal signal.The prototype contains:

- digital signal processor TMS320F206, 1 M bits of RAM, a 1 M bits of FLASH RAM for fault recording, and 16 K bytes of EEPROM for storing set values;
- voltage or current measuring circuits depending on the field requirements;
- input/output circuit comprising display, relay output signals, etc. . . ;
- a dual-port static SRAM (CY7C136) for port-to-port communication between DSP and MP80C51. Two ports are provided to permit independent access to any location in memory. It is the solution to applications requiring shared or buffered data in multiprocessor design;
- communication and managing system: a microprocessor 80C51 (MP80C51) for local user interface, LCD, communication unit and so on.

The device receives all of the signals both in normal operation and disturbances, stores all the incoming information such as settings, currents and voltages, recorded events and disturbances, and can print the information out or display them on LCD. For example, all the details of a short circuit can be shown, including its waveform and all

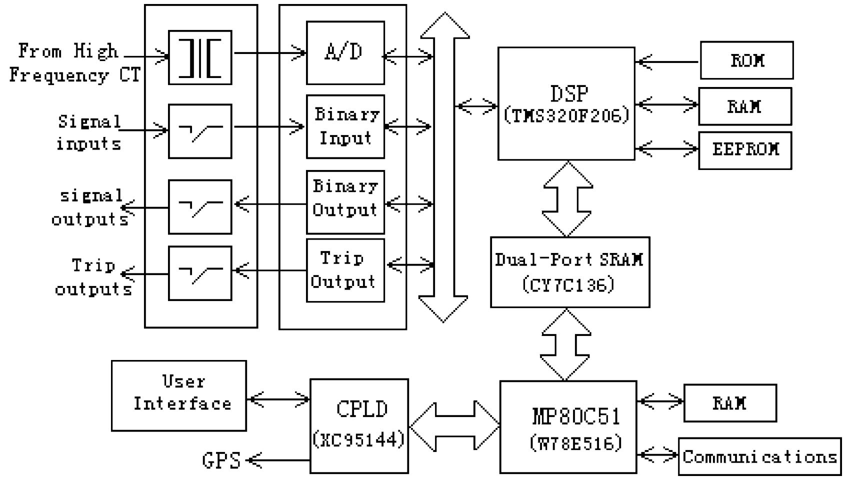


Fig. 4. Block diagram of one of typical relay hardware. (a1) Waveforms of the current I_A at the terminal; (a2) waveforms of the sum of current Ia_1, Ia_2 and Ia_3 at the neutral; (b1) the WT results of the current I_A at the terminal; (b2) the WT results of the sum of current Ia_1, Ia_2 and Ia_3 at the neutral; (c1) the differential current and average current for the traditional protection scheme; (c2) the high frequency differential current and average current for the proposed protection scheme.

the system parameters (current, voltage, frequency, power, etc.). This system can also be linked up to the supervisory station control system via communication such as fiber optic links. The protection functions always operate autonomously, or independently of the communication and managing system. For this reason, the managing system would provide only the fault event report and evaluation when certain protection operates. Any abnormality occurring in the communication and managing system has no possibility to disturb the protection function operation. Thus the operation and performance of the proposed scheme are determined only by the related hardware and software program.

According to the above hardware design, digital signal processing algorithms are used to obtain the high frequency currents and estimate the parameter setting required for the relay. Since the new scheme is based on differential principle and has few variables, the setting operation had been made as simple as possible.

An experimental prototype has been installed and tested, cooperated with the traditional protection scheme. Connection of the protection device is shown in Fig. 2. Where G is the generator, T is main transformer and N is neutral point. The generator is grounded through a distribution transformer T1 with a resistance loaded secondary. The scheme comprises the phase current at the terminals and the branch currents $I_{\phi 1}$, $I_{\phi 2}$, $I_{\phi 3}$ in corresponding phase. Here, ϕ respects phases A, B and C, respectively. It should be indicated that, the traditional differential and incomplete differential scheme are also verified on the generator for the performance comparison.

4.2. Experimental results

Many laboratory tests were conducted to validate the new scheme before the prototype is installed. The fault phase currents on the generator terminals and the branch current at the neutral were recorded as shown in Fig. 5(a1) and (a2), in which the fault point located at A_1 $\alpha = 81.25\%$ and A_1 $\alpha = 89.58\%$, and the comparison results of the fault data has been shown in Fig. 5(c1) and (c2), respectively. The corresponding WT results are shown in Fig. 5(b1) and (b2). In this case, the conventional protection schemes could not find the fault. However, the recording results indicate that the new scheme operates correctly as shown in Fig. 5. In Fig. 5(c2) there is a significant differential current i_d component, but it is so small that it surely cannot send out the trip signal in Fig. 5(c1). This is reasonable because when A_1 $\alpha = 81.25\%$ shorted with A_1 $\alpha = 89.58\%$, the generator symmetry is not seriously destroyed. So compared with the normal currents, the corresponding differential current appears not so much distinguished in Fig. 5(c1). However, due to existence of no high frequency harmonics component on normal condition, the differential current is larger than the average currents. So the new scheme could ensure higher sensitivity. At the same time, because of their periodical features, those fundamental frequency current components can be removed in the new scheme by software program easily, so they cannot affect the reliability of the new scheme. Experimental results under various situations show that the proposed method can keep high sensitivity without maloperation during all operation conditions.

It is important to indicate that oversensitivity will be a problem in the field, such as the maloperation. To overcome this disadvantage, some measures should be applied. First, for improving the reliability, the scheme should be evaluated at least 16 times in one cycle repeatedly, and only if above 12 times satisfied, the fault trip signal can be sent out. Second, the coefficients i_{d0} and k can be enlarged to reduce the sensitivity when it is needed in the field. At last, good hardware and software design could ensure the high reliability of the scheme.

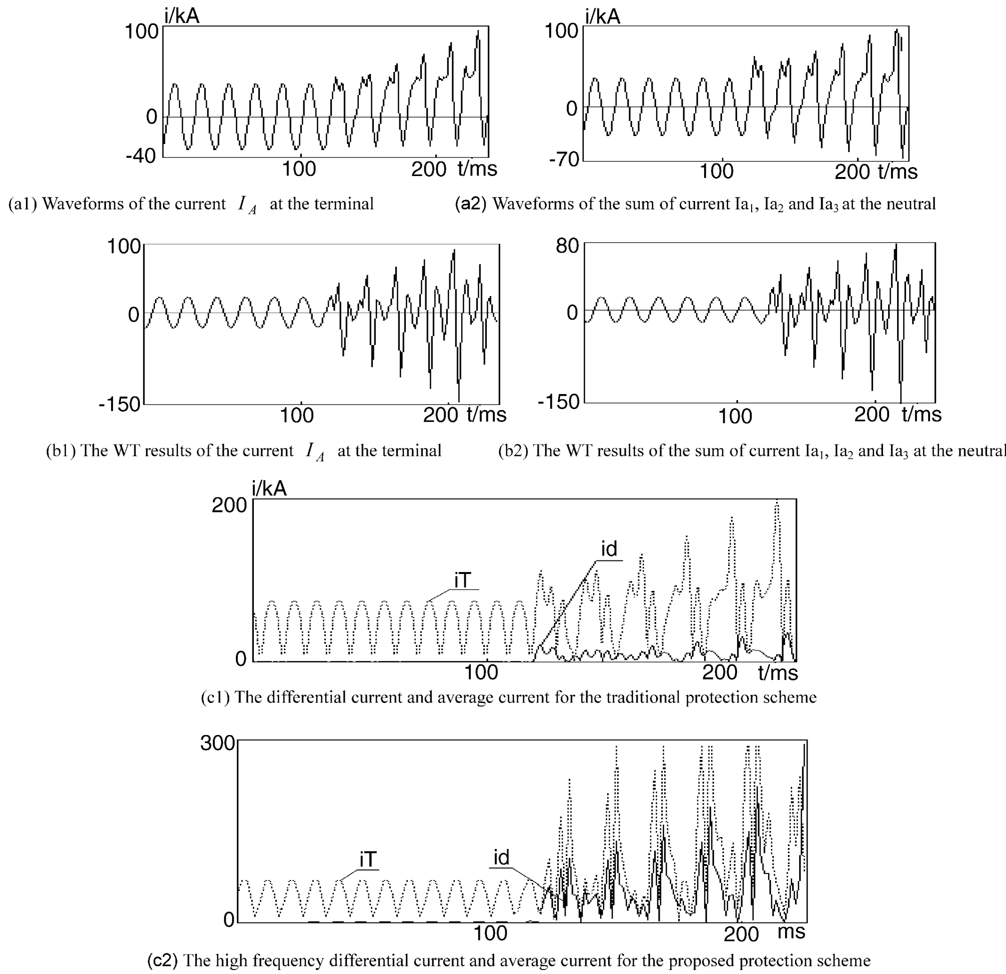


Fig. 5. Transient response of A_1 $\alpha = 81.25\%$ shorted with A_1 $\alpha = 89.58\%$.

4.3. *Field results*

On 16 August 2001, the protection relay was evaluated according to the simulated field condition. Since that time, the relay has operated flawlessly on various field conditions. Here, various field conditions include not only different internal faults but also field regulator malfunction under normal operations, power swings, and so on. During that period, three internal faults were found successfully. It is important to point out that one of the fault is single-phase-to-ground fault, and it is grounded with a 7.6 kΩ resistance. However, the conventional protection schemes cannot catch it. This situation is the same as we expected and indicates that the new scheme has high sensitivity and reliability.

5. Conclusions

The harmonic components caused by internal fault are very important for the generator internal fault detection. The paper proposes the use of the wavelet transform as a powerful tool for digital signals analysis. With the wavelet analysis, the fault current component around the power system frequency and the background noise are effectively removed. The currents are then represented to be the sampling currents with high frequency band, which contain important fault information. This feature demonstrates that the ability of the WT to discriminate the generator internal fault from the distorted signals.

Based on that technique presented above, a new generator internal fault protection scheme is developed and the practical implementation of the protection equipment is 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 during all operation conditions. It also reveals the feasibility of the scheme as a potential alternative in generator internal fault protection application.

Acknowledgements

The authors would like to express their thanks to the financial support given by the National Natural Science Foundation of China under contract number 50107007.

References

[1] X.H. Wang, Y.G. Sun, B. Quyang, et al., Transient behaviour of salient-pole synchronous machine with internal stator winding faults, IEE Proc. Electr. Power Appl. 149 (2) (2002) 143–151.

[2] X.H. Wang, W. Wang, S. Wang, Research on internal faults of generators and their protection schemes in Three Gorges Hydro Power Station, in: Proceedings of the IEEE Power Engineering Society 2000 Winter Meeting, Singapore, 23–27 January 2000.

[3] Z.Q. Bo, A new non-communication protection technique for transmission lines, IEEE Trans. Power Delivery 13 (4) (1998) 1073–1078.

[4] Working GroupJ11 of the Roatating Machinery Protection Subcommittee Power System Relaying Committee, Application of multifunction generator protection systems, IEEE Trans. on Power Delivery, vol. 14, no. 4, October 1999, pp. 1285–1293.

[5] P.J. Moore, A.T. Johns, Digital protection of power systems using digital techniques, Electrotechnology (October/November) (1990) 194–198.

[6] Tai Nengling, Hou Zhijian, Yin Xianggen, Chen Deshu, New Principle for 100% Stator Ground Fault Protection, IEEE Power Eng. Rev. (December) (2001) 56–58.

[7] T.s. Kulig, G.W. Buckley, D. Lambrecht, M. Lisese, A new approach to determine transient winding and damper currents in case of internal and external faults and abnormal operation. Part 3. Result, IEEE Trans. Energy Convers. 5 (1) (1990) 70–78.

[8] P.P. Reichmeder, D. Querrey, C.A. Gross, D. Novosel, S. Salon, Partioning of synchronous machine windings for internal fault analysis, IEEE Trans. Energy Convers. 15 (4) (2000) 372–375.

[9] P.P. Reichmeder, D. Querrey, C.A. Gross, D. Novosel, S. Salon, Internal faults in synchronous machines. Part I. The machine model, IEEE Trans. Energy Convers. 15 (4) (2000) 376–379.

[10] D. Jianyuan, D. Zhishan, Research on the stator windings faults of asynchronous generator and its diagnostic method, Proc. Chin. Soc. Elect. Eng. 19 (3) (1999) 36–42.

[11] S. Mallat, W.L. Hwang, Singularity detection and processing with wavelets, IEEE Trans. Inform. Theory 38 (2) (1992) 617–643.