IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received July 19, 2020, accepted August 17, 2020, date of publication August 24, 2020, date of current version September 30, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3018734

Research and Application of Generator Protection Based on Fiber Optical Current Transformer

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ABSTRACT This paper introduces the basic principle of fibre optical current transformer (FOCT), and explains the advantages of FOCT compared with electromagnetic current transformer (CT). FOCT can be wound around the primary conductor in any shape, has high harmonic accuracy and doesn't suffer from saturation, thus a good solution for generator relay protection. As a common electrical fault within large generators, the inter-turn short circuit in field windings (ISCFW) is likely to cause earth faults between the field winding and the rotor body and magnetization of the main shaft without timely intervention. Steady-state unbalanced currents of even orders and fractional orders related with pole pairs inside phase windings are required to monitor the ISCFW. The inter-turn fault of stator windings may rapidly develop into a phase to phase fault, which seriously threatens the safety of the unit. Split-phase transverse differential current reflects the steady-state current imbalance inside the stator winding. Nevertheless, for most steam turbine generators and some hydro turbine generators, it is unable to obtain phase-segregated transverse differential current due to impossibility of installing branch current transformer in the narrow space inside the generator. However, FOCT which uses fibre optic cable as a sensor is installable within limited space to measure the current of each group of winding branches of each phase. FOCT furthers phase-segregated transverse differential protection, partial differential protection and online monitoring of the ISCFW, thus optimizing the generators protection scheme. In addition, operating speed and sensitivity of generator differential protection are improved based on the reliable measurement from FOCT. The proposed scheme is verified by an application on a 300MW generator at a pump-storage power plant. This is the first attempt of applying FOCT to the relay protection of generator set, which provides reference for further development and application of FOCT in power plant.

INDEX TERMS Fibre optical current transformer (FOCT), phase-segregated transverse differential protection, stator winding inter-turn short circuit, rotor winding inter-turn short circuit.

I. INTRODUCTION

Stator winding inter-turn short circuit protection is essential for large generators. Phase-segregated transverse differential protection is an ideal scheme against the fault. Unfortunately, for most steam turbine generators and some hydro turbine generators, there is no room at the neutral point to install any conventional electromagnetic current transformer (CT) on each group of winding branches of each phase to facilitate phase-segregated transverse differential protection. To a steam turbine generator, only a dedicated voltage transformer (VT) for inter-turn short circuit protection can be installed and longitudinal zero sequence voltage protection can be applied against the fault. In some hydro turbine generators, only one dedicated CT for unit transverse differential protection can be installed at the connecting point between the neutral points of two groups of three phase winding branches. In some inter-turn fault cases, the sensitivity and operating time of unit transverse differential protection and longitudinal zero sequence voltage protection may not be satisfactory for clearing the fault quickly and preventing the generator from damage. For example, a generator of a hydropower plant in Zhejiang Province, China has been damaged after twice experiencing long-lasting stator winding inter-turn short circuit fault, although the unit transverse differential protection operated correctly.

The associate editor coordinating the review of this manuscript and approving it for publication was Malabika Basu.

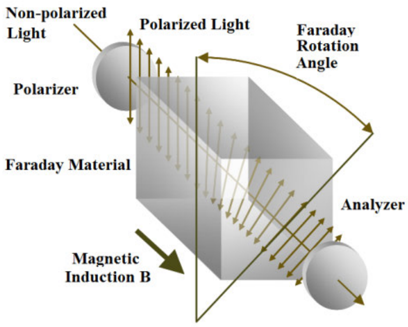

FIGURE 1. Sensing principle of FOCT.

As a common electrical fault of a large generator, the inter-turn short circuit in field windings (ISCFW) may lead to an earth fault between the field winding and the rotor body and magnetization of the main shaft without timely intrervention. Steady-state unbalanced currents of even orders and fractional orders related with pole pairs inside phase windings are applicable to monitor the ISCFW [1], [2]. Split-phase transverse differential current reflects the steady-state current imbalance inside the stator winding. Unfortunately, for most steam turbine generators and some hydro turbine generators, phase-segregated transverse differential current is unable to be obtained due to impossibility of installing branch current transformer in the narrow space inside the generator.

Fibre optical current transformer (FOCT) which uses the fibre optic cable as a sensor can be mounted on any shape of conductor in a limited space to measure the current of each group of winding branches of each phase, to optimize the protection scheme for a generator. FOCT has many applications in substations, especially in China. Alstom has applications of FOCT in Smart Substation and High Voltage Direct Current Transmission [3]. (NARI-Relays Electric Company) NREC has also successfully applied FOCT in underground cable fault discrimination etc. [4], [5]. But there is almost no application on generators in any power plant up to now. This paper provides an example of application on a generator.

II. BASIC PRINCIPLE AND CHARACTERISTICS OF FOCT

A. FIBRE OPTICAL CURRENT TRANSFORMER

Faraday magnetic optical effect is utilized by FOCT to measure current, as shown in Fig.1. Firstly, non-polarized light is linearly polarized by a polarizer. Secondly, the linearly polarized light passes through a magnetic optical material (fibre optic in this case) with its polarization direction being regulated by the magnetic field. The rotation angle of the polarized light (Faraday Optical rotation angle (φ)) is positively correlated with magnetic induction intensity. Finally, the Faraday Optical rotation angle is analyzed by an analyzer to calculate the magnetic field intensity and the current that generates the magnetic field [6]–[8].

When the optical fibre is closed around the conductor, the relationship between the Faraday Optical rotation angle

TABLE 1. Transient characteristic test of a FOCT (rated current 3kA).

	Operation	Symmetrical short-circuit current /kA	Peak current /kA	Maximum instantaneous error current /kA	Transient error /%
1	C-0.1s-O	46.8	131.6	1.0	1.5
2	0.5s				
3	C-0.1s-O	45.7	128.5	1.3	2.0

and current is described as:

$$\varphi = V \int_l H \cdot dl = V N_L I \tag{1}$$

where V is the Verdet constant of optical medium, l is the propagation distance of light in the optical medium, H is the magnetic induction intensity, N_L is the number of optical fibre loops and I is the electric current of the conductor.

B. CHARACTERISTICS OF FOCT

Reference [9] designed a space-saving sensor of FOCT, which is made of Spun Highly-birefringent fibre optic cable and can be wound around the primary conductor in any shape, thus a good solution for generator protection. The current measurement range of FOCT applied to generator protection shall be 8-10 times of rated current, and the maximum may exceed 300kA. According to different units, a suitable number of coils of optical fibre sensing ring can be designed to obtain good current measurement performance, and the volume of FOCT will not increase significantly. Moreover, FOCT is very suitable for generator protection because it has some obvious advantages compared with conventional CT.

References [10]–[12] analyse the cause and mechanism of CT saturation. Because the B-H magnetization curve of CT core is nonlinear, steady-state CT saturation can be caused by large steady-state symmetrical short current, and transient CT saturation can be caused by the decaying aperiodic component in short circuit current and/or by CT remanence. In case of short circuit fault of power equipment, the current increases rapidly, and the decaying DC component will be produced. When an electromagnetic CT saturates, the current waveform at its secondary side is distorted.

There is no saturation problem for a FOCT as there is no iron core. According to the transient characteristics test method of IEC 60044-8-2002 Part 8: electronic current transformer, the test results of a FOCT in Xi'an High Voltage Apparatus Research Institute are shown in table 1.

The test process shown in Table 1 is as follows: 'c-0.1s-o' is the first power on operation, i.e., ''close-0.1s-open''. A mixed current consisting of 46.8kA symmetrical current and about 80kA decaying DC component is given in 0.1s, and the decaying time constant is 100ms; After 0.5s shutdown, the second power on operation is carried out, and the specific process is the same with the first power on process. From the test results, FOCT has excellent transient characteristics, and the maximum transient error is about 2.0%. Therefore, FOCT applied to generator differential protection will obtain better protection performance.

TABLE 2. Measurement accuracy of harmonic current of FOCT.

Frequency /Hz	Applied current /A	Measurement result /A	Relative error /%	Phase deviation /μs
3Hz	1200	1202.6	0.2	160
10Hz	1200	1201.9	0.2	162
50Hz	1200	1202.4	0.2	170
100Hz	1200	1203.6	0.3	180
200Hz	1200	1202.4	0.2	200
300Hz	1200	1203.6	0.3	210

TABLE 3. Characteristics comparison of FOCT and electromagnetic CT.

Characteristics	Electromagnetic CT	FOCT
Size	Large	Small
Weight	Heavy	Light
Maximum measuring range	30 times rated current	50 times rated current
Accuracy level	5P20 / 5P30	5TPE
Dynamic and thermal stability composite error	<5%	<2%
Maximum error of peak instantaneous current in transient condition	<10%	<5%
Transient characteristics	Magnetic saturation	No saturation
Harmonic measurement	Near rated frequency	Measurable DC current, and measurement error of 50th harmonic is less than 3%
Operating temperature range	-40℃~70℃	-40℃~70℃

In addition, FOCT has better performance for much wider frequency range compared with the conventional electromagnetic CT. FOCT has good measurement performance for harmonic current. Table 2 shows the current measurement accuracy test result of a FOCT at various frequencies in Xi'an High Voltage Apparatus Research Institute.

FOCT can completely retain the DC and higher harmonic components in the current, which is conducive to the research and implementation of new protection principle based on harmonic component.

In summary, the characteristics comparison results of FOCT and electromagnetic CT are shown in Table 3.

FOCT also has some shortcomings, which should be overcome in practical applications. The temperature of the generator is high and the range of variation is large. The ambient temperature has an adverse effect on the measurement performance of FOCT. Reference [10] proposes that the Verdet constant of the sensing fibre and the quarter-wave plate error parameter are the main factors affecting temperature performance of FOCT. The solution is to adjust the quarter-wave plate parameters to compensate the influence of the Verdet constant of the sensing fibre. Reference [9] proposes that the digital dual close-loop demodulation scheme with four-state bias modulation and digital ramp feedback is adopted to enhance the dynamic range, measurement accuracy and long-term stability of FOCT. The measurement error of FOCT is less than 0.2% in temperature range of $-40°C \sim 70°C$ with these measures.

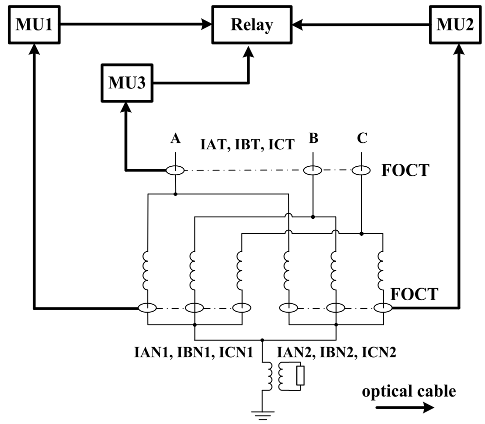

FIGURE 2. Generator protection scheme based on FOCT.

III. GENERATOR PROTECTION BASED ON FOCT

A. GENERATOR STATOR FAULT PROTECTION SCHEME BASED ON FOCT

A generator with two stator winding branches is shown in Fig.2. The FOCT sensor, which is a fibre optic cable, is wound around the conductor coming from each stator winding branch of each phase at the neutral point of the generator. The other parts of the FOCT, including the non-polarized light source, the polarizer and the analyzer, together with the signal processing circuit, are installed in the Merging Unit (MU). The MU processes the received signal, and sends the result (instantaneous value of current) to the generator protection relay via a fibre optic communication channel as per IEC 61850-9-2. After receiving the sampling data from different MU, the protection device uses an interpolation algorithm to process data synchronization according to the delay time of each measurement channel. The delay time of FOCT measurement channel is about 20us $\sim$ 500us, which has almost no influence on the protection performance. Additionally, FOCT can also be installed at the terminal of each phase.

Protective functions are realized based on the same current signals provided by FOCT. Details of the protective functions are presented in Table 4.

With the capability for a number of protective functions, the configuration of these functions is optimized based on quantitative calculation and analysis. The overall performance of generator protection, including the sensitivity against stator winding inter-turn short circuit fault and stator winding branch open circuit fault is improved.

B. GENERATOR ONLINE MONITORING OF THE ISCFW BASED ON FOCT

When turn to turn fault occurs in the rotor winding, the rotor magnetic potential is no longer symmetrical. Through the induction of the air gap magnetic field, the stator winding current will generate harmonic components related to the number of pole pairs, and this electrical performance is different from the harmonic characteristics of other faults. The

TABLE 4. Details of the protective functions.

Protective Functions	Current 1	Current 2
Phase differential protection	IAT	IAN1+IAN2
	IBT	IBN1+IBN2
	ICT	ICN1+ICN2
Partial differential protection	IAT	2*IAN1
	IBT	2*IBN1
	ICT	2*ICN1
	IAT	2*IAN2
	IBT	2*IBN2
	ICT	2*ICN2
Phase-segregated transverse differential protection	IAN1	IAN2
	IBN1	IBN2
	ICN1	ICN2
Unit transverse differential protection	IAN1+IBN1 +ICN1	0
	IAN2+IBN2 +ICN2	0

excitation potential induced by these harmonics is different in each branch of the same phase in the stator winding, so the circulating current between different branches is generated.

As shown in Figure 2, the currents of two stator winding branches are measured by FOCT, and then split-phase transverse differential current is achieved. With application of full-wave Fourier algorithm, RMS of $I_{sp.1/P}$, $I_{sp.2/P}$ ... (fractional/even harmonics) of split-phase transverse differential current is acquired [Here "P" refers to the number of pole pairs].

In the case of inter-turn short circuit fault, the eigenvalue increases due to fractional harmonics (e.g. 1/P, 2/P ...). On the contrary, in case of other faults or normal operation, the eigenvalue is much smaller (less than 0.1 p.u.). If the eigenvalue exceeds the corresponding threshold, the occurrence of an inter-turn short circuit fault is confirmed and online monitoring of the inter-turn short circuit fault is achieved.

The eigenvalue of the harmonics is calculated in this way:

$$I_{sp.Harm} = \sqrt{\sum_{\substack{k=1 \\ k \neq P, k \neq 3P}}^{\infty} I_{sp.k/P}^{2}} \tag{2}$$

where $I_{sp.Harm}$ is the eigenvalue of the harmonics, $I_{sp.k/P}$ is the RMS of corresponding fractional harmonic, k≠P and k≠3P. Since k≠P and k≠3P, the fundamental and 3rd harmonics are excluded from calculation of the eigenvalue.

In December 2011, a dynamic simulation experiment of this scheme was performed at Tsinghua University. The results indicate that the sensitivity of this scheme reaches 5% of the short-circuit turn ratio. Details of the experimental results are presented in Table 5.

In March 2012, this scheme was performed at Zhejiang Xin'an River Hydropower Plant, and then was put into operation at Yixing Pumped Storage Power Plant and Ertan Hydropower Plant. The waveform of transverse differential current in an alarm event of the field device is shown in Fig.3.

TABLE 5. Details of the dynamic simulation experimental results.

Operation Condition	Inter-turn short circuit ratio	Action of Protection
No-load operation	1.36%	no
	1.63%	no
	2.71%	yes
	6.91%	yes
	43.50%	yes
Grid-connected operation	1.36%	no
	2.71%	no
	5.56%	yes
	6.91%	yes

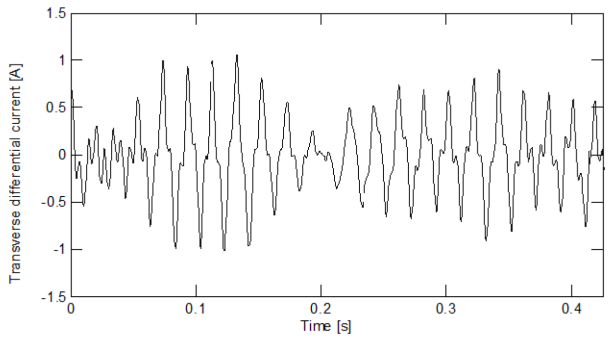

FIGURE 3. Transverse differential current in an alarm event of the field device.

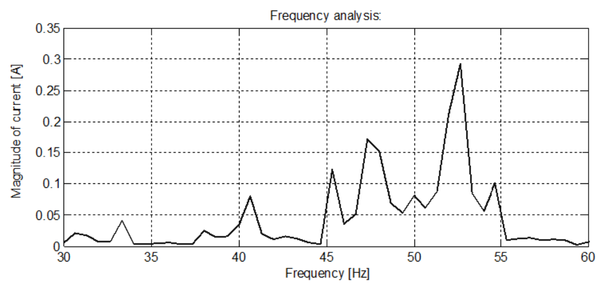

FIGURE 4. Frequency analysis of transverse differential current.

The amplitude of the transverse current changes periodically and contains many harmonic components. The spectrum analysis result of the current is shown in Fig.4. The higher frequency harmonic component is not shown in the figure because of low amplitude.

As seen in Fig.4, the main harmonic components are 54.8Hz, 52.4Hz, 47.6Hz, 45.2Hz and 40.5Hz, and which correspond to $\left(1+\frac{2}{p}\right)f_n$, $\left(1+\frac{1}{p}\right)f_n$, $\left(1-\frac{1}{p}\right)f_n$, $\left(1-\frac{2}{p}\right)f_n$ and $\left(1-\frac{4}{p}\right)f_n$. The number of pole pairs $p = 21$, and rated frequency $f_n = 50$Hz.

C. OPERATING TIME OF PHASE DIFFERENTIAL PROTECTION BASED ON FOCT

CT saturation affects the performance of differential protection to a large extent and can lead to misoperation or maloperation. The terminal current, neutral current and differential current waveforms of generator phase A based on

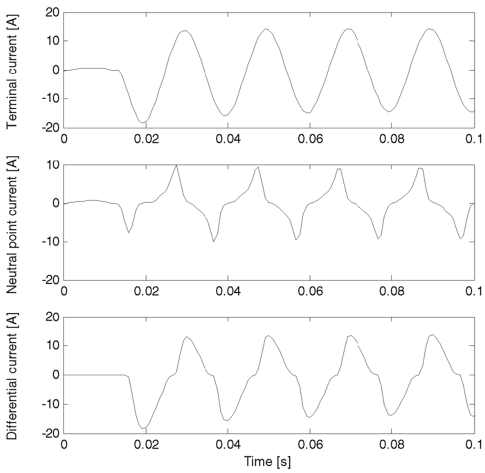

FIGURE 5. Generator current waveforms based on conventional CT for generator outside fault.

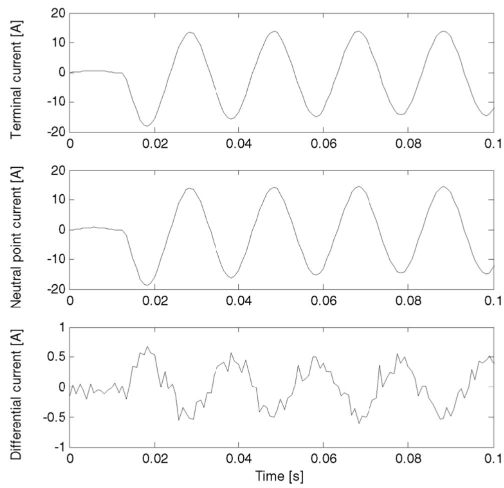

FIGURE 6. Generator current waveforms based on FOCT for generator outside fault.

a conventional CT for a generator outside fault is shown in Fig.5.

As seen from Fig.5, the false differential current is calculated due to the serious saturation of a conventional CT at the end of the machine. A common practice to avoid these consequences is to add CT saturation identification to the differential protection logic. Various methods are invented, one is based on the feature that the unsaturated period still exists in each cycle under CT saturation, another uses the time difference between the instant that the fault occurs and the instant that the CT starts to saturate [13]–[15]. CT saturation identification runs all of the time and in addition to differential protection action logic discrimination, the CT saturation detection module increases the logic complexity and prolongs the operating time of the differential protection by several milliseconds when an internal fault occurs.

On the contrary, there is no saturation problem for a FOCT as there is no iron core. Therefore, the measurement performance of FOCT is independent of waveform and magnitude of current. The terminal current, neutral current and differential current waveforms of generator phase A based on FOCT is shown in Fig.6 in the case of the same generator outside fault.

As seen from Fig.6, there is no waveform distortion caused by CT saturation at the generator terminal and neutral side current. The differential current, which only contains unbalanced current caused by CT measurement error on both sides, is too small to lead to misoperation of the differential protection.

CT saturation identification is disabled for a current differential protection device that connects to FOCT, thus the protection logic is simplified and the operating time is shortened by several milliseconds. A phase to phase fault inside a generator develops very quickly; shortening the protection operation time by even several milliseconds can prevent significant damage from occuring within the generator.

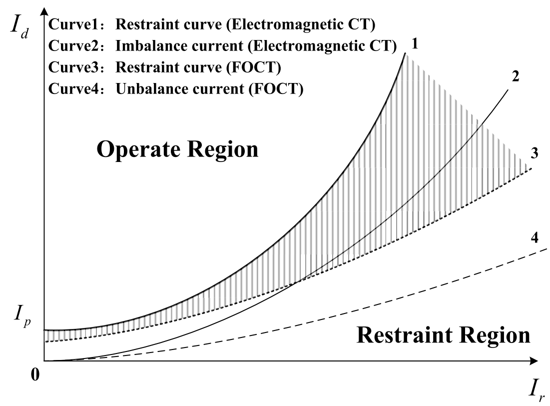

FIGURE 7. Unbalance current and restrained characteristic.

D. SENSITIVITY OF PHASE DIFFERENTIAL PROTECTION BASED ON FOCT

Load current or external fault current passes through current for differential protection, while differential imbalance current increases gradually with the increase of passing current for the factors of CT transformation characterized by: (1) ratio and angle error of individual protection class CT; (2) CT saturation caused by aperiodic component or by CT remanence; (3) mismatching in the types of CTs [16].

Percentage restraint characteristic is introduced in order to prevent unwanted operation caused by imbalance current [17], [18], (Fig.7). The start current for differential protection (Ip) is set to be larger than the maximum imbalance current when the generator runs at its rated capacity. Setting of the restraint slope is large enough to overcome the maximum imbalance current when external fault occurs. For differential protection based on FOCT, the above settings are reduced properly to get higher sensitivity. FOCT is of higher accuracy, has less likelihood of saturation and less imbalance current compared to a conventional electromagnetic CT.

As seen from Fig.7, the generator differential protection based on FOCT is set at a lower action threshold than that of an electromagnetic CT and the scope of action area is larger.

TABLE 6. Setting of complete longitudinal differential protection.

Differential protection based on	Starting value / pu	Initial ratio value	Maximum ratio value
Electromagnetic CT	0.2	0.05	0.5
FOCT	0.15	0.05	0.45

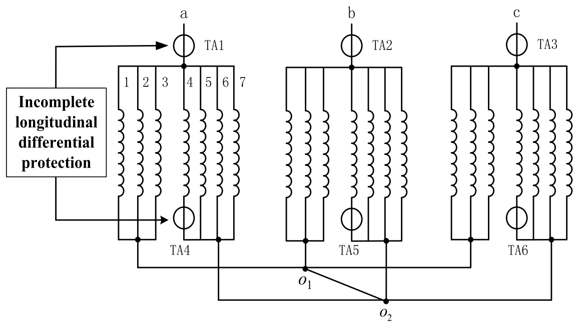

FIGURE 8. Optimized main protection scheme for Shenzhen pumped storage station generator-motor.

FIGURE 9. FOCT installed on the 4th branch.

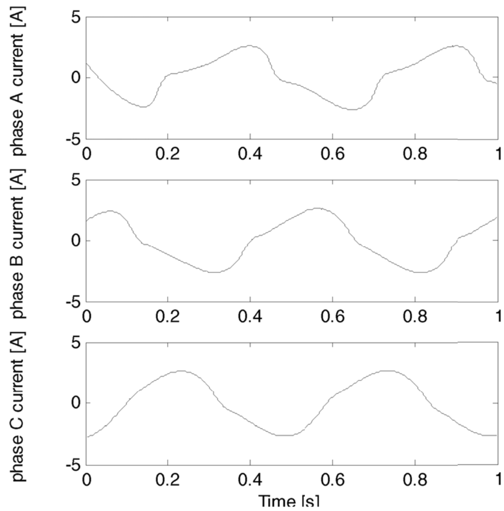

FIGURE 10. Conventional CT two times current during pump startup process at 4% rated speed.

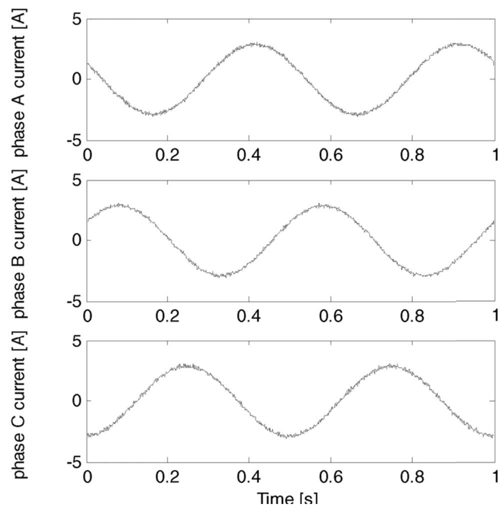

FIGURE 11. FOCT two times current during pump startup process at 4% rated speed.

The shaded part of the figure is the extra action area, so the operation sensitivity of the protection is higher. For example, the variable percentage restraint differential protection permits three main settings: the differential starting value, the initial ratio value and the maximum ratio value. Settings of complete longitudinal differential protection based on electromagnetic CT and FOCT is shown in table 6.

IV. FIELD APPLICATION AND MEASUREMENT PERFORMANCE ANALYSIS

The proposed scheme was implemented on a 300MW generator at Shenzhen Pump-storage Power Plant, Guangdong Province, China. There are seven stator winding branches for each phase which are separated into two groups. Electromagnetic CTs are installed on both branch groups. Although a variety of differential protection functions, including complete longitudinal differential protection and split phase transverse differential protection have been configured, there is still a protection dead zone such as stator inter-turn short circuit fault with small turns. To implement the proposed scheme, FOCTs were installed at the terminal side and the 4th branch on neutral side of generator, as shown in Fig.8. FOCT installed on the 4th branch is shown in Fig.9.

With the help of FOCT installed on stator winding branch, incomplete longitudinal differential protection was added to the existing differential protection to form a complete stator and rotor winding inter-turn short circuit fault protection scheme. The protection scheme can improve overall sensitivity and avoid protection dead zone for inter-turn faults.

Application of FOCT allows the generator protection to remain active and highly sensitive during startup or shutdown.

The waveforms of conventional CT and FOCT are shown in Fig.10 and Fig.11 respectively when the pump speed of the pumped storage unit rises to 4% of its rated speed (stator side electrical frequency 2 Hz).

From Fig.10 and Fig.11, it can be seen that at very low frequencies, a conventional CT has obvious distortion due to saturated secondary current, while FOCT is good in low-frequency transmission.

V. CONCLUSION

An FOCT sensor can be wound around a conductor in any shape in a narrow space. Additionally, FOCT's used within a generator stator winding branch at the neutral point allow measurement of the branch current and facilitate optimized generator protection. The use of FOCT's effectively improves the performance of current differential protection by way of decreased operating time and improved sensitivity through reduction of CT saturation caused by aperiodic components and bad low-frequency response by an electromagnetic CT.

FOCT's and their respective relays have been in successful operation in several power plants in China for some time. As a result, the number of FOCT's in operation in power plants is set to increase due to their highly accurate measurement capabilities [19], [20]. However, the stability of FOCT's over long time periods in harsh environments such as wide ranging temperatures, high and persistent vibration, and high electromagnetic radiation near the generator, etc. is yet to be validated in practice.

REFERENCES

[1] L. Hao, J. Wu, and Y. Zhou, "Theoretical analysis and calculation model of the electromagnetic torque of nonsalient-pole synchronous machines with interturn short circuit in field windings," *IEEE Trans. Energy Convers.*, vol. 30, no. 1, pp. 110–121, Mar. 2015.

[2] L. Hao, J. Wu, Y. Sun, X. Wang, Q. Zhang, and J. Chen, "A monitoring scheme for inter-turn short circuit of field windings in synchronous machines and its sensitivity analysis," *Autom. Electric Power Syst.*, vol. 37, no. 12, pp. 120–127, Dec. 2013, doi: 10.7500/AEPS201212225.

[3] A. H. Rose and J. N. Blake, "Free form factor optical current sensor for AC and DC commercial power applications," in *Proc. 18th Int. Conf. Opt. Fiber Sensors*, Cancun, Mexico, 2006, pp. 1–4, doi: 10.1364/OFS.2006.FB5.

[4] Y. Li, J. Shen, and X. Zhu, "Faulty zone discrimination method and realization for cable-overhead mixed lines in regional power grid," *JIANGSU Electr. Eng.*, vol. 33, no. 2, pp. 64–68, Jan. 2014.

[5] J. Zhao, L. Xu, and S. Luo, "A flexible optical current transformer for centralized cable fault identification applications," *Chinaese J. Electron Devices*, vol. 38, no. 1, pp. 32–36, Jan. 2015.

[6] G. Frosio and R. Dändliker, "Reciprocal reflection interferometer for a fiber-optic Faraday current sensor," *Appl. Opt.*, vol. 33, no. 25, pp. 6111–6122, Sep. 1994, doi: 10.1364/AO.33.006111.

[7] J. Blake, P. Tantaswadi, and R. T. de Carvalho, "In-line sagnac interferometer current sensor," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 116–121, 1996, doi: 10.1109/61.484007.

[8] K. Bohnert, P. Gabus, and J. Nehring, "Temperature and vibration insensitive fiber-optic current sensor," *J. Lightw. Tec.*, vol. 20, no. 2, pp. 267–275, Feb. 1, 2002, doi: 10.1109/50.983241.

[9] C. Yan, "FFOCT for generator protection," *Electr. Power Automat. Equip.*, vol. 37, no. 4, pp. 191–196, 2017.

[10] A. Chen, "Temperature performance optimization of FOCT," *Electr. Power Automat. Equip.*, vol. 31, no. 01, pp. 142–144, 2011.

[11] J. Yuan and H. Sheng, "The transient saturation of current transformer and its application calculation," *Relay*, vol. 20, no. 2, pp. 1–5, 2002.

[12] J. Chen, "Influence of the current transformer saturation on relay unit and its countermeasures in medium voltage power systems," *Automat. Electr. Power Syst.*, vol. 24, no. 6, pp. 54–56, 2000.

[13] M. Jing, "Cause analysis on the saturation of P class current transformers and its countermeasures," *Automat. Electr. Power Syst.*, vol. 21, pp. 94–97 and 109, Oct. 2007.

[14] Y. Zheng, Q. Shen, and L. Li, "Asynchronous method of TA saturation detection for relay protection," China Patent 02 138 487 8, May 21, 2003.

[15] X. Xu and B. He, "The measurement of dead angle during CT saturation in transformer differential protection," *Automat. Electr. Power Syst.*, vol. 22, no. 5, pp. 22–25, May 1998.

[16] Q. Shen, "Asynchronous method for the recognition of current transformer saturation and its application," *Automat. Electr. Power Syst.*, vol. 29, no. 16, pp. 84–86, Aug. 2005.

[17] W. Wang, *Principle and Application of Protection for Electric Main Equipment*, 2nd ed. Beijing, China: China Electric Power Press, 2002.

[18] J. He and C. Song, *Principle of Relay Protection of Power System*. Beijing, China: China Electric Power Press, 2010.

[19] L. Teng, "Optial current transducer and its application in protective relaying," *Power Syst. Technol.*, vol. 26, no. 1, pp. 31–33.42, 2002, doi: 10.13335/j.1000-3673.pst.2002.01.008.

[20] Q. Shang, R. Wang, and Y. Yang, "Application of optical current transducer in electricpower system," *J. North China Electr. Power Univ.*, vol. 28, no. 2, pp. 14–18, 2001.

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