Development and application of a diagnostic technology of electric devices by noticing higher harmonics of electric power source

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Abstract: A unique diagnostic technology for electric devices has been developed to detect anomaly and estimate the cause of failure of the device easily by analyzing the higher harmonics of electric source current. Higher harmonic diagnosis devices have been realized and improved to be served as the portable device for maintenance works of various electric equipment such as AC/DC motors, inverters, transformers, cables, *etc.*. The device has many favorable characters such as (i)capable of no direct contact test to the equipment on live state, (ii)not only the mechanical but also the electrical anomaly and deterioration can be diagnosed, (iii)capable of detecting incipient deterioration easily to prevent from developing to rare short, (iv)possible to apply for inverter, (v)possible to diagnose notwithstanding the capacity and voltage if the equipment is higher than 1 horse power, (vi) the weight of the device itself is as light as ca. 7 kg which includes battery power source, and (vii) easy to use even by non-experienced workers to handle and diagnose the equipment in real field. The merit of the device has been recognized in the domains of steel, electric power, chemical and automobile industries in Japan, Korea and China. For the appreciation and memory of the inventor of the device, late Hiroshi Koh, the principle and the product development of the higher harmonic diagnosis device are introduced in this paper, together with the prospect of further deployment by big data science and IoT (internet of things).

Keywords: higher harmonic diagnosis; no contact live diagnosis; simultaneous diagnosis of mechanical and electrical anomaly; principal component analysis

1 Introduction

Nowadays electric equipment prevails everywhere and becomes indispensable to every days' human life. If there happens any trouble in it, production line in factory stops, train and elevator does not run, supplies of electricity and water stops, and such problems will affect bad influence to industries and citizen life. In addition, fire and accident may happen. In order to prevent from such bad situation, it is important to examine the condition of electric equipment whether any anomaly, any degradation of parts regularly to maintain them.

On the other hand, the traditional way of the testing and maintenance of electrical equipment has been dependent on human work, where veteran engineers conduct on testing and maintenance by their experience and feeling when they sense some trouble they examine every part one by one to identify the cause of trouble. Therefore, they sometime overlook anomalies and degradation of parts in the place difficult to see and they need a lot of time and labor to do the maintenance work. There had been already specialized test devices developed for the maintenance workers. But their functions had been to find abnormal sound and vibration, and temperature change by sensors to know the occurrence of abnormality, and most of them had been low reliability because their performances depend on installation

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environment of the electric equipment.

One of the promising technologies to overcome the problems of testing and diagnosis of electric equipment is higher harmonics diagnosis device which will be introduced in this paper. This device has been realized by applying higher harmonic diagnosis technology which had been exploited by the life-long of effort of late Mr. Hiroshi Koh, a Korean born and living in Japan and the former president of A-TEC Co. In which follows, the author of this paper will explain first the principle and advantage of the higher harmonic diagnosis technology and then introduce the realization of it as diagnostic device and the used domains up to now and mention its future possibilities by applying data science and IoT.

2 What is higher harmonic diagnosis

2.1 Noticing higher harmonics for testing equipment

Higher harmonics are forms of wave which are integer multiples of basic wave (sinusoidal wave form). Higher harmonics diagnosis is a method of diagnosing electric equipment by analyzing the harmonics of electric current flow. The electric current flows through the electric equipment basically as the form of distorted wave which is the composite of basic wave and many higher harmonic wave. If the electric equipment is normal state, components of higher harmonics mixed in the distorted wave are not so large. But when some problem occurs in the equipment, specific orders of higher harmonics will appear in accordance with parts and module and their state to exhibit higher percentage in the distorted wave. Higher harmonics diagnosis method will diagnose the state of electric equipment by examining what kinds of higher harmonics and the percentage are included in the distorted wave.

The idea of utilizing higher harmonics for the diagnosis of electric equipment was first invented by Hiroshi Koh, former president of A-TEC Co., and a Korean native living in Japan. Until his invention, higher harmonics had been deemed as cumbersome matters because they will flow to other equipment through the connecting wires, generate unfavorable heat and vibration and cause failure of equipment and fire. Those problems of higher harmonics had been closed up in 70's when electric equipment had been rapidly prevailing in home and factories.

What inspired Hiroshi Koh to the idea of higher harmonics was when he had been engaged in the study of filter to suppress the generation of higher harmonics after he entered graduate school of engineering at Kyoto University in 1968. One day he observed experimental data which were strangely different from the past. And several days later, the experiment apparatus was failed at last. The point of his idea was that the reason of disturbed behavior of the apparatus by the generation of higher harmonics might be ascribed to the generation of special anomaly in the experimental equipment. That means, by inspecting the higher harmonics deeply we can predict the occurrence of failure in advance.

After him graduating from Graduate School of Engineering, Kyoto University in March 1972, he went back to Korea to work at Yionse University from November 1974 as the professor of electrical equipment. In 1979 he left Korea for Japan to enter Fujitec Co., one of the elevator makers, as the director of electronic parts development. At Fujitec, he noticed enormous cost for inspection and maintenance of elevators. If accident happens by machine failure, the trust of the company built up in many year will be dropped instantly. The inspection and maintenance service is indispensable for keeping safety. However it takes too many manpower and cost. If new device of diagnosing machine state rapidly and easily, it will surely improve the effectiveness of maintenance works with realizing large cost down.

2.2 Derivation contributing ratio table

In order to equip the diagnosis device with the universal applicability to many electrical equipment other than elevator, it is necessary to collect as many data as possible from many equipment. In 1981, Hiroshi Koh became independent from Fujitec and had continued his study as part time lecturer of Faculty of engineering, Doshisha University in Kyoto, and in July 1991, he opened Koh Engineering Office to start technical consultant. And in May 2002, he expanded Koh Engineering Office to establish A-TEC Co. to special degradation diagnosis of electric equipment. During those more than ten years from 1991 until 2002, he had collected as many as 37,200 data of various electric equipment.

By applying principal component analysis method of multivariate analysis for those equipment database, a sort of analysis table called “contribution ratio table” had been generated which will give the statistical relationship between the state of various anomaly and degradation of various parts and place, ratios of higher harmonics to form the distorted wave. The simplified examples of “contribution ratio table” are shown in Tables 1 and 2 for electric motor and inverter, respectively. Table 1 shows the statistical relationships between the four parts of anomalies in the main body of the motor and also the four parts of the anomaly in the load side and the contribution rate as the order of the higher harmonics in the current flow. Table 2 shows the similar relationship for the four anomaly parts of inverter.

Table 1 Deteriorated part and current harmonics of electric motor equipment

Electric motor equipment	Deteriorated parts of the equipment	Higher harmonics components in electric current			
		First principle component		Selected principle components	
		Order	Contribution rate (%)	Order (in decreasing order of score)	Cumulative contribution rate (%)
Main body of the motor	Rotary shaft and bearing, installation	2	55	2,4,3,5	86
	Insulation of stator winding between phases or to the ground	3	61	3,5,2,4	95
	Damage of bearing and housing	4	41	4,2,3,5	82
	Uneven air gaps (dirt adhesion, local overheat)	5	59	5,3,4,2	93
Motor load	Imbalance of rotary shaft	7	53	7,10,9,8,6	91

	and coupling				
	Damage of bearing, foreign matter adhesion	8	35	8,7,9,10,6	95
	Worn-out of rotary shaft and coupling paste	9	33	9,8,7,10,6	92
	Damage of wheel and belt system	10	30	10,7,8,9,6	93

Table 2 Deteriorated part and current harmonics of inverter equipment

Equipment	Deteriorated parts of inverter equipment	Higher harmonics components in electric current			
		First principle component		Selected principle components	
		Order	Contribution rate (%)	Order (in decreasing order of score)	Cumulative contribution rate (%)
Inverter	Smoothing capacitor	5	62	5,7	98
	Control board	11	21	11,17,13,25 ,19,23	96
	Electric power element	7	17	7,3,5,17,38 ,11,25,19 23,13,2,4, 6,8,9,10	99
	Drive board	38	89	38	89

Those tables called “contribution ratio table” summarize the tendencies of characteristic pattern to be observed in the fractions of various orders of higher harmonic to be compared with the normal state, when the abnormalities occur in various parts by the failure and degradation. Those statistical relationship in the contribution ratio table were reduced by principal component analysis method.

2.3 Analytical procedure for higher harmonic diagnosis method

On the basis of contribution ratio table, Hiroshi Koh developed higher harmonic diagnosis device by which the maintenance workers can test the electric equipment on the spot more simply, easily, safely and in shorter time than by other means. The following computing procedure is utilized in the developed diagnostic device.

(i)Using search coil, the leakage flux from the target equipment is measured for a fixed time to record the higher harmonics superimposed on power cable.

(ii)Repeat seen time recording and the exclude both the upper and lower limits of wave. The average wave form from the remaining five records is taken as the measured wave.

(iii)Execute FFT processing on the analog wave of the measured wave. Then calculate the content rate of higher harmonics from the second to the 40^{th}. The n-th content rate is defined as Hn.
(iv)For getting index value, the total distortion factor is calculated as the square root of sum of squares Hn from 2 to 40.
(v) The normalized content rate of each parts Cn is obtained by dividing the content rate of each parts of failure by total distortion factor. This relative index value is used for failure diagnosis.
(vi)Based on contribution ratio table, the control number of each parts is obtained by summing Hn times Cn from n=2 to 40.
(vii)Diagnosis of whether or not any anomaly occurrence and the degree of degradation is made by the degree of calculated control number of each parts.

To sum up, the estimation as to in which part is failed will be made by which orders of higher harmonics become large value and the degree of control number of each parts. In addition, degree of anomaly and degradation will be judged by seeing the degree of control number.

2.4 Function of higher harmonic diagnosis device as technical product and applicable equipment

In order to realize the higher harmonic diagnosis method as technical product of diagnosis device to the maintenance worker, the following functions were taken as design target:
(i)The computation time for the above procedures (1i) to (vii) in 2.3 should be executed in total 10 seconds with ca. 1 second of leakage flux measurement, ca. 9 seconds of FFT processing, failure diagnosis and display of the output.
(ii)The additional functions of storing the diagnosis result as well as print out should be finished in less than 1 minutes.

The first higher harmonics diagnosis device KS1001 to satisfy the above functions was produced in 2002, and the improved version of KS-3000A as shown in Fig.1 got the invention prize from Ministry of Education in 2005.

Fig.1 Higher harmonic diagnosis device KS-3000A.

The advantageous features of the higher harmonic diagnosis device can be summarized as the following seven points;
(i) capable of testing no direct contact to the equipment on live state,
(ii) not only the mechanical but also the electrical anomaly and deterioration can be diagnosed, (iii)capable of detecting incipient deterioration to discover easily and prevent rare short, (iv)possible to apply for inverter,
(v) possible to diagnose notwithstanding the capacity and voltage if the equipment is higher than 1 horse power,
(vi) easy to carry because the device body is compact with the weight is as light as ca. 7 kg which includes battery power source, and
(vii) easy to handle even by non-experienced workers to carry and diagnose the equipment in real work field.

By using this device, you can know not only whether or not anomaly and the degree of degradation but also what the failed parts, the cause of trouble and the countermeasures, simply by holding the pickup sensor of mike form up over power cable and switchyard. For example of motor equipment, you will get the detailed information such that whether serious abnormality in motor, and that the reason of abnormality is the failure of bearing which is needed to repair urgently. You can diagnose the state of parts even in a incipient stage of small crack by metal fatigue which cannot detect my eye inspection, and therefore you can clip a sign of trouble in an early stage. You can perform your maintenance work safely on the spot where the machine is working since you can examine the machine without contacting the sensor on the equipment.

3 Examples of higher harmonic diagnosis and the applicable equipment

3.1 Concrete examples of diagnosis

Two examples of practical application of the device will be explained for the anomaly diagnosis of pump motor.

3.1.1 Degradation of bearing on the opposite side of load (Case 1)

There are two bearings of pump motor shaft: load side and the opposite side. This bearing is the opposite side of load. Table 3 shows the base data for abnormal diagnosis of the bearing by the higher harmonic diagnosis. In Table 3, basic figure corresponds to the damage of bearing and housing as listed in Table1. On the other hand of basic figure, both normal and abnormal pumps are the data coming from the pump motor. The term PHTS in Table 3 means Pattern Total Harmonics Distortion, and it is given by the square root of the sum of the square of the contribution rate of n-th higher harmonics of the corresponding basic figure in Table 1. Whereas the contribution index in Table 3 is given by the ratio Hn/THD where Hn means the n-th order harmonic content, and THD is total harmonics distortion.

Table 3. Comparison of abnormal bearing of the pump with normal one (Case 1)

Basic figure	Order of harmonic	2^{nd}	3^{rd}	4^{th}	5^{th}	PTHD
	Contribution index	0.944	0.154	0.274	0.103	58.29
Normal bearing	Order of harmonic	2^{nd}	3^{rd}	4^{th}	5^{th}	THD
	Harmonics content ratio (%)	3.1	2.6	1.3	2.1	9.7
	Contribution index	0.32	0.269	0.13	0.216	-
Abnormal bearing	Harmonics content ratio (%)	2.7	1.4	1.1	2	4
	Contribution index	0.675	0.35	0.275	0.5	-

By using the data values of contribution index in Table 3, the three patterns of the rate of higher harmonics for basic figure, normal pump and abnormal pump, respectively are indicated in Fig.2. In this figure, black color indicates the pattern of basic figure, while blue and red colors are those of normal and abnormal pump. As you see that the pattern of abnormal pump resembles that of basic figure, the failure of pump is estimated as being caused by the degradation of bearing. As a matter of fact, ,wear of bearing ball as shown in Photo 1 and scratch on bearing case in Photo 2 were observed in the abnormal bearing.

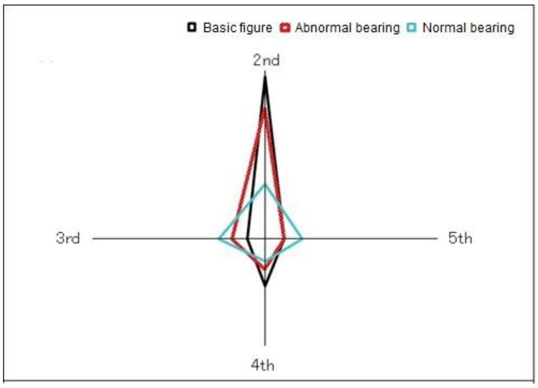

Fig.2 Comparison of higher mode pattern of motor.


Photo 1 Wear of ball bearing.


Photo 2 Scratch of bearing case.

3.1.2 Degradation of insulation of motor winding (Case 2)

Table 4 shows the base data for abnormal diagnosis of insulation degradation in motor winding by the higher harmonic diagnosis. In Table 4, basic figure corresponds to the insulation of stator winding as listed in Table1. On the other hand of basic figure, both normal and abnormal fan are the data coming from the pump motor.

By using the data values of contribution index in Table 4, the three patterns of the rate of higher harmonics for basic figure, normal fan and abnormal fan, respectively, are indicated in Fig.3. In this figure, black color indicates the pattern of basic figure, while blue and red colors are those of normal and abnormal fan motor. As you see that the pattern of abnormal fan resembles that of basic figure, the failure of fan is estimated to be caused by the degradation of insulation of the stator winding of the fun motor. In this case, insulation deterioration in stator winding as shown in Photo 3and interlayer short in Photo 4 were observed in the abnormal fan motor.

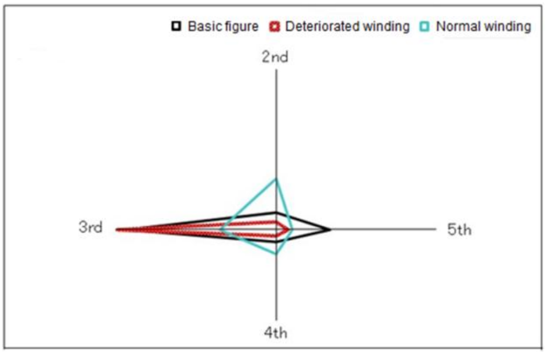

Fig.3 Comparison of higher mode pattern of fan.

As seen from Figs. 2 and 3 of the above two cases 1 and 2, higher harmonics contents are small in normal machine. On the other hand of normal one, the second harmonic content is especially large in case 1 while the third one significant in case2. Therefore by comparing the pattern of higher harmonics content with those of various abnormal causes in shown in Table 1, you can estimate the reason of abnormality with the degree of agreement between the both patterns. This is said to show the effectiveness of contribution ratio table which can be statistically derived by principal component analysis.

Table 4 Comparison of abnormally coil of fan with the normally one (Case 2)

Basic figure	Order of harmonic	2nd	3rd	4th	5th	PTHD
	Contribution index	0.107	0.933	0.076	0.336	65.41
Fan (Normal product)	Order of harmonic	2nd	3rd	4th	5th	THD
	Harmonic content ratio (%)	8.2	9	3.9	2.6	25.7
	Contribution index	0.319	0.351	0.152	0.101	-
Fan (Winding deterioration)	Harmonic content ratio (%)	9.8	206.3	7.8	15.7	207.7
	Contribution index	0.047	0.993	0.036	0.076	-

Photo 3 Insulation deterioration of coil winding.

Photo 4 Interlayer short of coil winding.

3.2 Expansion of applicable equipment and the oversea marketing

The author of this paper had made a prototype development of condition monitoring system HAMOS by applying higher harmonics diagnosis method by receiving subsidies from Ministry of economy, trade and industry in Japan in 2010, and since then by using the HAMOS he has accumulated field tests of diagnosing many kinds of electric equipment [(1)] . At present the HAMOS can be adapted not only to AC motors and inverters but also to DC motors, transformers, power condensers, generators, uninterruptible power supply, and even applicable to cable diagnosis of distribution line and power transmission line. The diagnosis accuracy of the HAMOS tested for various types of electric equipment is proved to be higher than 90 % on the basis of evaluating by principal components analysis[(1)].

In 2006, the author of this paper also tried to introduce the then improved version of the higher harmonic diagnosis device KS2000 to Japanese nuclear power companies. However, the proposal of the author had not been accepted in the nuclear power company. According to the maintenance staffs there, they update the equipment regularly with a fixed time span before the equipment exhibit symptoms of anomaly, and therefore the equipment are always trouble free as new facility. In fact, all the equipment working there on live the authors tested by KS2000 did not show any sign of troubles and degradation.

On the other of Japanese nuclear power industry which employs the maintenance policy of one-sided pursuit of high safety with the sacrifice of high cost, the higher harmonic diagnosis devices have been recognized and adopted in many process industries in East Asian countries such as steel making, electric power, chemical processes, automobile makers, *etc.*, where further efficiency with cost reduction has been requested for maintenance areas. In Japan, since there is no other effective ways of diagnosing inverters on live line, the higher harmonics diagnosis device has been paid attention in many public sectors. In public sectors, Ministry of land, infrastructure and transport and Water resources Agency recommended higher harmonic diagnosis technology for the maintenance of electric facilities in dams and water gates. (2) It is also considered for the remote monitoring system of wind power generation system. In China, its introduction has been in progress for bullet train and Oil well pumps. In Korea, its introduction has been progressing in steel making and automobile industries from the earlier days. Generally speaking, cost rise of maintenance and the inheritance of maintenance know-how is headache issue in any countries, and the higher harmonic diagnosis technology is expected as one of the promising ace card to overcome the issue.

4 Concluding remarks

To sum up, the higher harmonic diagnosis technology is a diagnostic method of electric equipment based on statistical data analysis method. It measures the content of higher harmonic in the electric current flowing though the failed equipment on one hand, and disassembling the failed equipment to validate the cause of anomaly on the other hand. Those database of higher harmonics content versus failed parts is utilized to reduce a sort of cause-effect co-relationship between the order pattern of higher harmonic component and the specific cause of failure of various parts. Since this diagnostic method depends on of experiential data statistics, it has both of merit and drawback methodologically. The drawback lies in that no theoretical explanation is given on why specific order pattern of higher harmonic appear when a certain failure or degradation occur in a specific parts.

On the other hand of such drawback, the merit of this method is that it will become possible to diagnose surely when a new cause-effect relationship will be found by accumulating much more data than at present status of no capability of diagnosis by the lack of enough database. However, this limit of scant database can be broken by a new wave of big data science and IoT (Internet of thing). (3) Hiroshi Koh had established higher harmonics diagnosis method by his life long effort of collecting data and analyzing the data for thirty years. However, it becomes possible to advance the higher harmonic diagnosis method drastically fast by using the present-day IoT and cloud computing with artificial intelligent (AI).

The higher harmonic diagnosis method has not yet been employed in nuclear industry in Japan, but it has been already recognized its worth and used in the other industries such as automobile industry which are exposed to international competition. Therefore it will be used in future in nuclear industries to improve maintenance works. The author of this paper would like to close the paper by expecting that the higher harmonic diagnosis device will be positively used in China and the other developing countries in Asia and Africa where nuclear power will expand rapidly in the coming twenty to thirty years.

Acknowledgments

This article is dedicated to Hiroshi Koh, former president of A-TEC Co., who passed away in November 14, 2016 with the age of 73. The author would like to convey his condolences and many thanks to his family members, especially his son Mamoru Koh, president of A-TEC Co, for offering many precious technical reports of his father's long year study on higher harmonic diagnosis method. Although not listed all of them in the references of this paper because all are all written in Japanese, the author could not have written this paper without those technical reports.

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