International Journal of Electrical Energy, Vol. 3, No. 4, December 2015

Porcelain Insulator Maintenance Management for Smart Power Transformer

Rattanakorn Phadungthin and Juthathip Haema
College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand
Email: {rattanakorn.p, juthathip.h}@cit.kmutnb.ac.th

***Abstract*—Power transformer is one of expensive equipment in electrical power system. Porcelain insulators that are bushing and arrester are one of significant components of the transformer. Failures of the insulators are unacceptable due to catastrophic consequences to the transformer. Hence, this paper aims to present maintenance management of the transformer porcelain insulators by using electrical test results and visual inspection records with scoring and weighting techniques to evaluate their condition. Besides, statistical failures of main components are utilized for weighting number of bushing and arrester in order to calculate the percentage of entire porcelain insulators of power transformers. Loading transformers and tie-transformers are selected for the insulator condition assessment. Finally, condition based maintenance strategies of the porcelain insulators for smart power transformers are managed properly by following their obtained condition.**

***Index Terms*—smart power transformer, porcelain insulators, condition based maintenance, diagnostic techniques**

I. INTRODUCTION

Power transformer is one of the most important equipment in power system. Its function is to transfer the power from one voltage level to another required level. The transformer is very expensive and needs suitable maintenance task to all main components that are active part, insulating oil, on load tap changer, protective devices, tank, bushing, and arrester. As the bushing is the component that supports the incoming and outgoing electrical lines for the transformer, while the arrester is the component that protects the transformer itself from lightning disturbances, the bushing and the arrester are essential insulators of the transformer. In addition, they are one of main defective components of power transformer and sometimes lead to catastrophic damages to the power transformer. Appropriated diagnostic techniques are utilized to assess the condition of the bushing and the arrester in order to avoid their failures. A warning sign of their suspect condition is provided before the failures occur by means of using historical test results of the diagnosis with scoring and weighting techniques. The diagnostic techniques of the bushing and the arrester include electrical tests and visual inspection. Power transformer used in transmission system is mainly loading transformers in 115kV rating and tie-transformers in 230kV rating.

Therefore, this paper aims to present the failure statistics of bushing and arrester from the recorded data in the past 10 years. The condition of both components of the loading transformers and the tie-transformers is evaluated by using the electrical test results and visual inspection data with scoring and weighting techniques. Then their condition is represented by color indicator. The failure records are used to define weighting number of bushing and arrester for determining the percentage of entire porcelain insulators. Finally, the condition based maintenance of the considered porcelain insulators can be performed to accomplish the smart power transformer and to improve the reliability in the system.

II. BASIC KNOWLEDGE

A. Condition Based Maintenance

Traditionally, maintenance tasks focus on two broad categories, namely Corrective Maintenance (CM) and Preventive Maintenance (PM) [1]. The first, known as breakdown maintenance, is performed when failed components need to be restored. Due to high related cost of restoring the equipment to an operable condition under crisis situation, the latter maintenance task is introduced to avoid such a cost. The preventive maintenance or time base maintenance, so called TBM, is planned or routine maintenance that is performed on component based on a calendar schedule. As it might be too late for the maintenance, nowadays condition based maintenance is developed and preferred.

The condition based maintenance, so called CBM [2]-[5], is one of main maintenance strategies in a high voltage substation. It is performed in the electrical utilities for achieving reliability in the system. The CBM strategy is followed by the condition of concerned components [6]-[8]. Essential parameters such as diagnostic methods and available suitable data are considered for determining the condition with maximized accuracy. Advantages of the CBM are that the maintenance is done when required due to following the condition of the transformer. Then costs and manpower are saved or reduced. However, its disadvantages are that experienced experts and appropriate data are necessary.

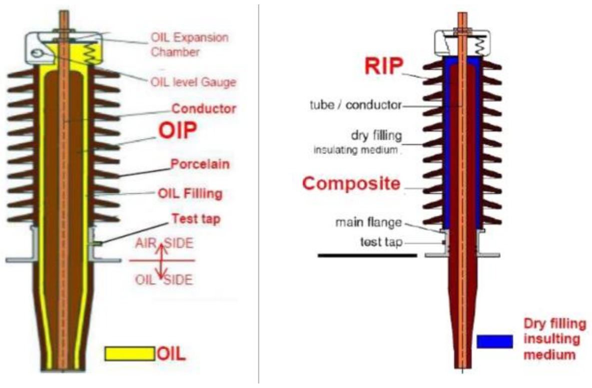
B. High Voltage Bushing

Manuscript received July 5, 2015; revised September 16, 2015.

doi: 10.18178/ijoee.3.4.219-224

Basically, a bushing is a device to insulate the incoming or outgoing conductor into or out of a grounded barrier, a transformer tank. It is so called condenser bushing which is characterized by a central conductor wound by insulating papers and conductive layers [9]-[13]. Its failure can affect very serious economic consequences. The gaps between main insulator and internal surface of porcelain are nowadays filled with oil and resin. Usually a high voltage bushing is made as a condenser type containing several layers of aluminum foil wounded around conductor and immersed in the oil inside the porcelain housing, so called oil immersed paper or OIP [14]. The benefits of the traditional type of bushing are low cost and heat dissipating, while the drawbacks are high maintenance cost, transportation, fire and explosion.

Due to main cause of bushing failure is oil leakage, resin impregnated paper or RIP is nowadays increasingly used. Furthermore, the RIP provides low maintenance cost, easy to transport, keep for storage, superior thermal and electrical performance even though the acquisition cost is high. The basic and modern types of the high voltage bushing [15] are shown in Fig. 1. The major difference between Resin Impregnated Paper (RIP) bushing technology and Oil Impregnated Paper (OIP) bushing is that the condenser cores in OIP technology are impregnated with transformer mineral oil while the impregnation in RIP technology is fulfilled via a curable epoxy resin to form a solid condenser core.



(a) OIP type (b) RIP type

Figure 1. Types of bushing.

Bushing diagnosis: To assess the condition of bushing, diagnostic methods applied in the condition evaluation are electrical tests and visual inspection. The electrical tests [16] and [17] are routine offline testing specified by manufacturers, whereas the visual inspection is an investigation with human senses such as eyes, noses and ears. Normally, the tests are done every 5 or 6 years, while the inspection is done every 2 or 4 weeks. The electrical tests due to available data to assess the condition of bushing are power factor and capacitance. The power factor is used for measuring dielectric losses or deterioration of bushing insulation, while the capacitance is used for determining bushing loss or measuring the integrity of bushing insulation. For the visual inspection, porcelain condition, porcelain cleanliness, oil leakage, oil level, and oil color are checked by operators in the utilities, as written in Table I.

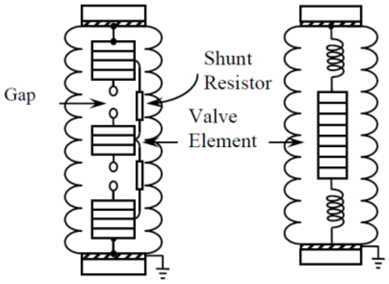
TABLE I. DIAGNOSIS OF BUSHING

Testing Type	Diagnostic Test
Electrical Test	• Power Factor • Capacitance
Visual Inspection	• Porcelain Condition • Porcelain Cleanliness • Oil Leakage • Oil Level • Oil Color

C. High Voltage Surge Arrster

Similar to the bushing in both appearance and construction, the arrester [18]-[22] is made from a porcelain shell to provide insulation and mechanical strength. A dielectric filler material such as oil, epoxy, or other materials is used to increase the dielectric strength. The arrester is a device that is used for protecting power transformer from overvoltage damage. To achieve maximum protection, arrester must be located very close to transformer bushings. The arrester with older design so called gap silicon carbide (SiC) is with a gap at which normal operating voltages cannot jump, while that with new design so called gapless Metal Oxide (MO) is a gapless that eliminates the high heat associated with arcing discharges [23]. Resistors of the conventional gap type are made of SiC, whereas those of the gapless type are made of MO.

The benefit of the gap type provides cheap price, but the drawback is moisture ingress. For the gapless arrester, the benefits are the best performance and reliability, and high heat elimination; but it is expensive one. Furthermore, a metal-oxide surge arrester using zinc-oxide blocks provides the best performance because surge voltage conduction starts and stops rapidly at an explicit voltage level, which improves system protection. Subsequently, failure is reduced due to no air gap contamination possibility. However, a small value of current always leaks at operating frequency. The two types of the arresters [24] are shown in Fig. 2.



(a) Gap type (b) Gapless type

Figure 2. Types of arrester.

Arrester diagnosis: Likewise, diagnoses of arrester condition assessment are electrical tests and visual inspection. The electrical tests due to available data include watt loss and insulation resistance. The watt loss can be very effective with repeating the test several times, while the insulation resistance is done on the arrester between the line connection and ground. Visual inspection for the arrester contains porcelain condition, porcelain cleanliness, grounding connector, and surge counter, as written in Table II.

TABLE II. DIAGNOSIS OF ARRESTER

Testing Type	Diagnostic Test
Electrical Test	• Watt Loss • Insulation Resistance
Visual Inspection	• Porcelain Condition • Porcelain Cleanliness • Grounding Connector • Surge counter

D. Scoring and Wegihting Techniques

The condition evaluation can be performed by using the historical test results with scoring and weighting techniques [25]. The scoring means that the condition is classified into various levels: good, moderate, and poor. The weighting means that the precision or the importance of each testing is ranked. The higher ranking number means higher importance. The condition evaluation represented by %CE can be calculated with the scoring and weighting techniques, as written in (1).

$$\%CE = \frac{\sum_{a=1}^{n}(S_a * W_a)}{\sum_{a=1}^{n}(S_{\max,a} * W_a)} * 100 \qquad (1)$$

where S_a means score of each diagnosis test; $S_{max,a}$ is maximum score; W_a is weighting number; and n is the number of diagnostic tests.

E. Maintenance Management with 4R Model

By applying the scoring and weighting techniques with the condition evaluation, maintenance recommendation can be set up with 3 different tasks for both individual insulators and entire porcelain insulators. The 4R model (routine, repair, refurbish and replace) with 3 separated condition levels (good, moderate and poor) is performed following the condition evaluation at which each testing (electrical tests and visual inspection) is divided into 3 scores with different weighting numbers that are defined by the experts who works in the electrical utilities.

Individual insulators: The 4R model of maintenance management of the bushing as written in Table III is that routine maintenance represented by green color is needed for the $\%CE_B$ with 0-39%, repair task represented by yellow color is for 40%-73%, and refurbish or replace task represented by red color is for 74%-100%. For the arrester condition assessment, routine maintenance represented by green color is needed for the $\%CE_A$ with 0-37, repair task represented by yellow color is for 38%-73%, and refurbish or replace task represented by red color is for 74%-100%, as written in Table IV. It is slightly different from the bushing maintenance levels because the testing and weighing numbers of each test are not the same. The refurbishment task means that the aging component will be reconditioned to achieve nearly new condition without buying the new one.

TABLE III. MAINTENANCE MANAGEMENT OF BUSHING

$\%CE_B$	Condition	Color Indicator	4R Model of Maintenance
0-39	Good	Green	Routine
40-73	Moderate	Yellow	Repair
74-100	Poor	Red	Refurbish/Replace

TABLE IV. MAINTENANCE MANAGEMENT OF ARRESTER

$\%CE_A$	Condition	Color Indicator	4R Model of Maintenance
0-37	Good	Green	Routine
38-73	Moderate	Yellow	Repair
74-100	Poor	Red	Refurbish/Replace

Entire insulators: After the condition of the individual insulators is reached, maintenance management of entire porcelain insulators for smart power transformer can be set up by using the percentage of the individual insulator conditions and their weighting number, as written in (2).

$$\%IC = \left[(\%CE_B) * (W_B)\right] + \left[(\%CE_A) * (W_A)\right] \qquad (2)$$

where $\%IC$ means the percentage of entire insulator condition; $\%CE_B$ means the bushing condition; $\%W_B$ is the percentage of weighting number of bushing; $\%CE_A$ means the arrester condition and $\%W_A$ is the percentage of weighting number of arrester.

Practically, the percentage of weighting number of the individual insulators can be fulfilled by several methods. One is an analysis of historical failure records of last 10 years. As the arresters of the tie transformers were not recorded for their failures during last 10 years, the weighting number will rely on the failure records of the components of the loading transformers, as illustrated in Table V with the calculated weighting number.

TABLE V. THE WEIGHTING NUMBER OF INDIVIDUAL INSULATORS

Individual Insulator	Weighting Number, %W
Bushing	85.65
Arrester	14.35

Consequently, the 4R model of maintenance management that is similar to the individual insulator maintenance is implemented and written in Table VI. Routine maintenance represented by green color is needed for the %IC with 0-39%, repair task represented by yellow color is for 40%-72%, and refurbish or replace task represented by red color is for 73%-100%.

TABLE VI. MAINTENANCE MANAGEMENT OF ENTIRE INSULATORS

%IC	Condition	Color Indicator	4R Model of Maintenance
0-39	Good	Green	Routine
40-72	Moderate	Yellow	Repair
73-100	Poor	Red	Refurbish/Replace

III. RESULTS AND ANALYSIS

A. Statistical Failure Result and Analysis

The scattering 58 failure events of 186 power transformers rating with 115/22kV are recorded in the past 10 years, while 28 failure records of 117 units are from 230/115kV power transformers. The failures of the transformer population are calculated as a percentage and illustrated in Fig. 3 and Fig. 4 for the 115/22kV transformers and the 230/115kV transformers, respectively.

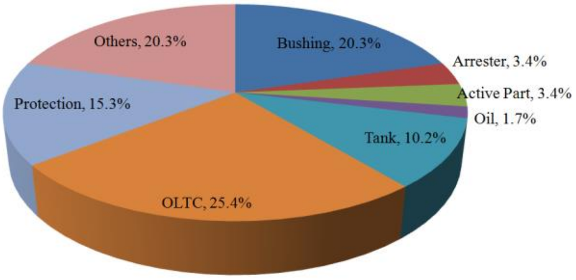


Figure 3. Failed components of 115/22kV power transformer.

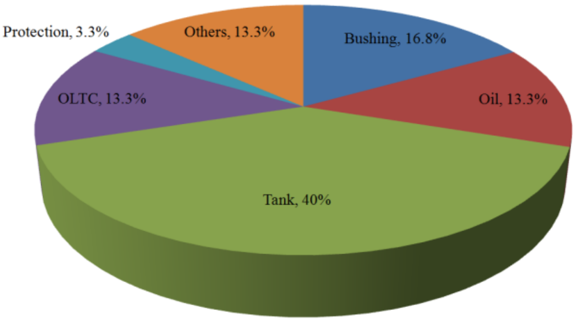


Figure 4. Failed components of 230/115kV power transformer.

The highest percentage of 115/22kV transformer failures is with OLTC (25.4%), while the lowest percentage is with insulating oil (1.7%). For the 230/115kV transformer, the highest failure percentage is with tank (40%), while the lowest percentage is with protection (3.3%). For the bushing, the failure occurred in 115/22kV transformers with 20.3%, whereas the failure occurred in 230/115kV transformers with 16.8%. When the arrester is concerned, the failure occurred in 115/22kV transformers with 3.4%, but no any failures occurred in 230/115kV transformers. As mentioned that the failure records of the loading transformers rating of 115/22kV is used for calculating the percentage of weighting number of bushing and arrester, 20.3% is the percentage of bushing failures, while 3.4% is the percentage of arrester failures. Subsequently, this ends up with 85.65% and 14.35% for the weighting numbers of the bushing and the arrester, respectively.

B. Condition Evaluation of Bushing

The test results and the visual inspection data of bushings of 115/22kV transformers (Tr1-Tr5) and 230/115kV transformers (Tr6-Tr10) are collected and summarized in Table VII and Table VIII, respectively. Note that "Norm" means normal; "G" means green; "Y" means yellow. The bushing condition, written as %CE_B, is also calculated in the Table.

TABLE VII. TEST RESULTS OF BUSHINGS OF LOADING TRANSFORMERS

Testing	Tr1	Tr2	Tr3	Tr4	Tr5
%Power Factor	0.61	0.57	0.52	0.73	0.64
%Capacitance	2.14	1.72	0.74	2.87	1.45
Porcelain Condition	Norm	Norm	Norm	Norm	Norm
Porcelain Cleanliness	Norm	Dirt	Norm	Dirt	Dirt
Oil Leakage	No	No	No	No	No
Oil Level	Norm	Norm	Norm	Norm	Norm
Oil Color	Norm	Norm	Dark Color	Dark Color	Norm
%CE_B	40.00	42.67	45.33	48.00	42.67
Color Indicator	Y	Y	Y	Y	Y

TABLE VIII. TEST RESULTS OF BUSHINGS OF TIE TRANSFORMERS

Testing	Tr6	Tr7	Tr8	Tr9	Tr10
%Power Factor	0.38	0.41	0.44	0.31	0.71
%Capacitance	0.98	1.13	1.49	2.26	2.53
Porcelain Condition	Norm	Norm	Norm	Norm	Norm
Porcelain Cleanliness	Norm	Dirt	Dirt	Norm	Norm
Oil Leakage	No	No	No	No	No
Oil Level	Norm	Norm	Norm	Norm	Norm
Oil Color	Dark Color	Norm	Dark Color	Norm	Norm
%CE_B	38.67	36.00	41.33	33.33	45.33
Color Indicator	G	G	Y	G	Y

The results show that the bushing condition of the loading transformers (Tr1-Tr5) and the tie-transformers (Tr8 and Tr10) is mainly in moderate as represented by yellow color indicators; but the transformers (Tr6, Tr7 and Tr9) are in good condition with green color indicator. Therefore, their recommended maintenance is routine task for the good condition transformers, while refurbishment such as cleaning their porcelain, and reconditioning their oil inside the porcelain should be managed for the others.

C. Condition Evaluation of Arrester

The test results and the visual inspection data of arresters of 115/22kV transformers (Tr1-Tr5) and 230/115kV transformers (Tr6-Tr10) are recorded and shown in Table IX and Table X, respectively.

Note that "Norm" means normal; "G" means green; "Y" means yellow. The arrester condition, written as %CE_A, is also calculated in the Table. The results show that the arresters of both the loading transformers and the tie-transformers are in good condition, represented by green color indicator. Hence, only routine maintenance task is needed for them.

TABLE IX. TEST RESULTS OF ARRESTERS OF LOADING TRANSFORMERS

Testing	Tr1	Tr2	Tr3	Tr4	Tr5
%Watt Loss	34.42	32.81	44.23	37.56	41.43
%Insulation Resistance	62.34	57.42	53.41	61.78	61.24
Porcelain Condition	Norm	Norm	Norm	Norm	Norm
Porcelain Cleanliness	Norm	Dirt	Norm	Norm	Dirt
Grounding Connector	Norm	Norm	Norm	Norm	Norm
Surge Counter	Norm	Norm	Norm	Norm	Norm
$\%CE_A$	33.33	36.00	33.33	33.33	36.00
Color Indicator	G	G	G	G	G

TABLE X. TEST RESULTS OF ARRESTERS OF TIE TRANSFORMERS

Testing	Tr6	Tr7	Tr8	Tr9	Tr10
%Watt Loss	43.87	40.72	38.31	36.93	41.94
%Insulation Resistance	58.92	64.67	63.83	64.52	59.81
Porcelain Condition	Norm	Norm	Norm	Norm	Norm
Porcelain Cleanliness	Norm	Norm	Norm	Dirt	Norm
Grounding Connector	Norm	Norm	Norm	Norm	Norm
Surge Counter	Norm	Norm	Norm	Norm	Norm
$\%CE_A$	33.33	33.33	33.33	36.00	33.33
Color Indicator	G	G	G	G	G

D. *Condition Evaluation of Porcelain Insulators*

As the weighting of bushing is 85.65% and arrester is 14.35%, the percentage of porcelain insulator condition can be calculated and written in Table XI for the loading transformers as well as in Table XII for the tie transformers.

TABLE XI. CONDITION EVALUATION OF PORCELAIN INSULATORS OF LOADING TRANSFORMERS

Item	Tr1	Tr2	Tr3	Tr4	Tr5
%BC	40.00	42.67	45.33	48.00	42.67
%AC	33.33	36.00	33.33	33.33	36.00
%IC	39.04	41.71	43.61	45.89	41.71
Color Indicator	G	Y	Y	Y	Y

TABLE XII. CONDITION EVALUATION OF PORCELAIN INSULATORS OF TIE TRANSFORMERS

Item	Tr6	Tr7	Tr8	Tr9	Tr10
%BC	38.67	36.00	41.33	33.33	45.33
%AC	33.33	33.33	33.33	36.00	33.33
%IC	37.90	35.62	40.18	33.71	43.61
Color Indicator	G	G	Y	G	Y

The results show that the porcelain insulators of only Tr1 of the loading transformers are in good condition represented by green color, whereas the others are in moderate condition with yellow indicator. For the tie transformers, the insulators of Tr6, Tr7, and Tr9 are in normal condition with green color indicator, while the others are in moderate condition with yellow color indicator. Therefore, the recommended maintenance of the transformer insulators with normal condition is routine maintenance, whereas the maintenance management of the others is repairing the defected components by inspecting the bushing and the arrester of those transformers.

IV. CONCLUSION

The percentage of defective components of the loading transformers and the tie-transformers is clarified. The porcelain insulator failure with the first transformer fleet is 23.7%, whereas that with the second transformer fleet is 16.8%. The porcelain insulators that are bushing and arrester of power transformer are analyzed by condition based maintenance in order to manage the proper maintenance for achieving smart power transformer with higher system reliability. The obtained condition is represented by color indicators: green for good, yellow for moderate, and red for poor. The 4R model maintenance tasks: routine maintenance for good condition, repairing for moderate condition, and refurbishment or replacement with a new component for poor condition are also given for a recommendation. The transformer insulator condition consists of two main evaluations at which scoring and weighting techniques are applied. The first evaluation is regarding the condition of individual insulator that is bushing or arrester. The recommended maintenance strategy is managed properly following their condition. The second evaluation concerns the entire insulator condition of power transformer. It is achieved by using the obtained individual insulator and the percentage of individual insulator weighting that is calculated by the percentage of statistical failures of last 10 years. Then the maintenance management of the power transformer porcelain insulator can be planned suitably.

The results from routine electrical tests and the data from visual inspection of power transformers rating 115/22kV and 230/115kV are gathered for the condition evaluation with the applied scoring and weighting techniques. Most bushings are in moderate condition represented by yellow indicator, repairing maintenance task is then recommended. All arresters are in good condition with green indicator, routine maintenance task is sufficient. Moreover, the condition of the entire porcelain insulators of the loading transformers is mostly moderate represented by yellow indicator, while that of the tie transformers is mostly good represented by green indicator. However, the porcelain insulators of the two tie transformers are in moderate condition represented by yellow indicator. The recommended maintenance of the insulators with good condition is routine maintenance, whereas that of the insulators with moderate condition is repairing task. The bushing and the arrester of the moderate condition transformer should be taken good care.

Consequently, the smart power transformer with the managed porcelain insulators improving system stability and reliability in the electrical utilities are accomplished. The proposed model of this research can be applied for other high voltage components in power system.

ACKNOWLEDGMENT

The authors gratefully acknowledge King Mongkut's University of Technology North Bangkok (KMUTNB) and the Power Transformer Maintenance Department at Electricity Generating Authority of Thailand (EGAT) for providing the data and supporting for this work.

REFERENCES

[1] A. H. C. Tsang, "Condition-Base maintenance: Tools and decision making," *Journal of Quality in Maintenance Engineering*, vol. 1, no. 3, pp. 3-17, 1995.

[2] X. Zhang and E. Gockenbach, "Asset-Management of transformers based on condition monitoring and standard diagnosis," *IEEE Electrical Insulation Magazine*, vol. 24, no. 4, pp. 26-40, 2008.

[3] J. Schneider, *et al.*, "Asset management techniques," *International Journal of Electrical Power & Energy Systems*, vol. 28, pp. 643-654, November 2006.

[4] J. Haema and R. Phadungthin, "Study and analysis condition assessment of power transformer OLTC by Duval triangle method via IT support," *The Journal of Industrial Technology*, vol. 9, no. 2, pp. 107-115, 2013.

[5] P. Wester and R. D. Damstra, "The impact of a condition based maintenance strategy on network system operations," presented at the CIGRE, Paris, France, 2000.

[6] G. Balzer, "Condition assessment and reliability centered maintenance of high voltage equipment," presented at the International Symposium on Electrical insulating Materials, Japan, June 5-9, 2005.

[7] M. Schwan, W. H. Wellssow, A. Schnettler, U. Zickler, M. Roth, and J. Schneider, "Risk-Based asset management for substations in distribution networks considering component reliability," presented at the CIGRE, Paris, France, 2006.

[8] M. Wang, A. J. Vandermaar, and K. D. Srivastava, "Review of condition assessment of power transformer in service," *IEEE Electrical Insulation Magazine*, vol. 18, no. 6, pp. 12-25, 2002.

[9] S. A. Bhumiwat, "Insulation condition assessment of transformer bushings by means of polarization/depolarization current analysis," presented at the IEEE International Symposium on Electrical Insulation, Indianapolis, Indiana, USA, September19-22, 2004.

[10] C. Ko and S. Zhang, "Improves transient hot-spot temperature calculation method of high voltage bushings," presented at the IEEE/PES Transmission and Distribution Conference and Exposition, Bogota, August13-15, 2008.

[11] N. Y. Utami, Y. Tamsir, A. Pharmatrisanti, H. Gumilang, B. Cahyono, and R. Siregar, "Evaluation condition of transformer based on infrared thermography results," presented at the 9th International Conference on Properties and Applications of Dielectric Materials, Harbin, China, July 19-23, 2009.

[12] B. K. Gupta, J. Densley, and A. Narang, "Condition assessment of oil-paper insulated bushings," presented at the IEEE Electrical Insulation Conference, Montreal, Quebec, Canada, 2009.

[13] C. Sumereder and A. Gumpinger, "Latest findings at transformer bushings condition evaluation by dielectric response methods," presented at the CIGRE, Australia, September 9-11, 2013.

[14] C. J. MacMillen, M. G. Comber, R. H. Hopkinson, and C. W. Schoendube, "The development of an oil-immersed surge arrester for distribution transformers," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, pp. 2481-2491, 2007.

[15] S. Keshwani and M. Mataray, "RIP (Resin Impregnated Paper) bushing for EHV class power transformer," *International Journal of P2P Network Trends and Technology*, vol. 6, pp. 27-29, March 2014.

[16] IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformer, IEEE Std. C57.12.00-2010.

[17] IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus-Part 1: Oil Filled Power Transformers, Regulators, and Reactors, IEEE Std. 62-1995.

[18] K. Mokhtari, M. Mirzaie, and M. Shahabi, "Leakage current analysis of polymer and porcelain housed metal oxide surge arresters in humid ambient condition," *Iranian Journal of Electrical & Electronic Engineering*, vol. 11, no. 1, pp. 79-86, March 2015.

[19] C. A. Chrisodoulou, M. V. Avgerinos, L. Ekonomou, I. F. Gonos, and I. A. Stathopulos, "Measurement of the resistive leakage current in surge arresters under artificial rain test and impulse voltage subjection," *The Institution of Engineering and Technology*, vol. 3, pp. 256-262, 2009.

[20] S. Y. Hong, G. Wang, H. F. Li, and J. J. Huan, "Study of metal oxide arresters health state evaluation based on fuzzy grey theory," presented at the IEEE Power Engineering and Automation Conference, Wuhan, China, September 18-20, 2012.

[21] G. R. S. Lira and E. G. Costa, "MOSA monitoring technique based on analysis of total leakage current," *IEEE Trans. on Power Delivery*, vol. 28, pp. 1057-1062, 2013.

[22] B. Richter, W. Schmidt, K. Kannus, K. Lahti, V. Hinrichsen, *et al.*, "Long term performance of polymer housed MO-surge arresters," presented at the CIGRE, Paris, France, 2004.

[23] R. E. Brown and B. G. Humphrey, "Asset management for transmission and distribution," *IEEE Power & Energy Magazine*, vol. 3, no. 3, pp. 39-45, June 2005.

[24] K. Hill, *Surge Arresters and Testing*, Doble Engineering Company, 2004.

[25] A. Naderian, S. Cress, R. Piercy, F. Wang, and J. Service, "An approach to determine the health index of power transformers," presented at the IEEE ISEI, Vancouver, June 9-12, 2008.

Rattanakorn Phadungthin was born in Sukhothai, Thailand. She received her B.Eng. from Chiang Mai University, Thailand in 1993, M.BF. from University of Technology, Sydney, Australia in 1997 as well as M.Sc. and Ph.D from the Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB) in 2005 and 2013, respectively. Her research interests include power transformer, asset management, condition based maintenance and maintenance strategy. Currently, she is a lecturer at Department of Electronic Engineering Technology, College of Industrial Technology (CIT), KMUTNB, Thailand. In addition, she is an Assistant Professor and a Deputy Dean for International and Special Affairs at CIT, KMUTNB.

Juthathip Haema was born in Tak, Thailand. She received her B.Eng. from King Mongkut's University of Technology North Bangkok (KMUTNB) in 2005 and M.Sc. from the Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB) in 2009. Her research interests include power transformer, condition based maintenance and power electronic. Currently, she is a lecturer at Department of Electrical Engineering Technology, College of Industrial Technology (CIT), KMUTNB, Thailand.