UNIVERSITI PUTRA MALAYSIA

TRANSFORMER ASSET MANAGEMENT BASED ON MARKOV PREDICTION MODEL UTILIZING HEALTH INDEX

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FK 2019 85

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

August 2019

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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August 2019

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Transformers are considered among the important assets in a power system network, failures of which could lead to costly consequences. The degradation of transformers is a complex phenomenon that can be affected by multivariable factors. Accurate estimation of condition and life expectancy is quite difficult to be achieved due to complexity of aging mechanisms in transformers. Commonly, the prediction of transformer lifetime for asset management strategies is attained based on the probability of failure or failure hazard rate from the failure recorded data. However, the failure data is very limited and may not be available for the young population of transformers. Nowadays, the majority of utilities have implemented Condition Based Maintenance (CBM) as part of the asset management scheme. Under CBM, a single quantitative assessment known as Health Index (HI) is usually formulated to provide the overall condition of the transformers. Typically, HI is used to determine the present condition state of transformers and there is a potential to utilize HI for future states predictions. Due to the limitation of long-term records and also scattering data of HI, common mathematical approaches such as regression, trend line fitting, and extrapolation techniques are not suitable to determine the condition of transformers due to the overreliance on the data, which may affect the reliability of the predictions.

This research presents a study on the application of stochastic probabilistic method known as the Markov Prediction Model (MPM) to estimate the future transformer condition states based on the transformer population HI. The prediction model was designed based on the MPM method that utilized two transition probabilities derivation techniques known as maximum likelihood (frequency of transition) and nonlinear least-squares minimization. The models were developed based on the utility oil condition monitoring data consisted of dissolved gases, oil quality and furanic compounds. Based on the computed HI, 120 transformers were arranged according to the corresponding states and the

consecutive year, and the transition probabilities were determined based on the frequency of transition approach. The maintenance costs were estimated based on future-state distribution probabilities according to the developed MPM and the proposed maintenance policy model. In the second MPM model, the HI for 3195 oil samples ranging between 1 to 25 years of age was computed and the transition probabilities were obtained based on a nonlinear least-squares minimization technique. Further, the future performance condition curve of the transformers was determined based on the Markov chain algorithm. A statistical analysis was carried out to test the performance of MPM on the HI data. In addition, the impact of pre-determined maintenance repair rates on the HI data for transformers asset management strategies were performed through a sensitivity study using the updated MPM. Finally, the changes of the HI state distribution of the transformer population and the performance condition curve were discussed.

The analysis on the relationship between the predicted and actual computed numbers of transformers using the MPM with the frequency of transition technique reveals that all transformer states are still within the 95% prediction interval. There is a 90% probability that the transformer population will reach ‘very poor’ state after 76 years and 69 years based on the transformer transition states for the year 2013/2014 and 2012/2013 respectively. Furthermore, the total maintenance cost based on the probability-state distribution increases gradually from Ringgit Malaysia (RM) 5.94 million to RM 39.09 million based on the transformer transition states for the year 2013/2014 and RM 37.56 million for the year 2012/2013 within the 20-year prediction interval. On the other hand, MPM with nonlinear least-squares minimization technique indicates that the method can be used to predict the future transformers condition states. The chi-squared goodness-of-fit analysis reveals the predicted HI for the transformer population obtained based on MPM concurs with the average computed HI along the years and the average error is 3.59%. Based on the case study, it is shown that the pre-determined maintenance repair rates can improve the HI state distribution and performance condition curve. The 30% pre-determined maintenance repair rate gives the highest enhancement and it is the most effective for the transformer population at ‘poor’ state.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGURUSAN ASET BAGI PENGUBAH BERDASARKAN MODEL RAMALAN MARKOV MENGGUNAKAN INDEKS KESIHATAN

Oleh

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Pengubah merupakan salah satu aset penting dalam rangkaian sistem kuasa, dimana kegagalan alat ini boleh menyebabkan kerugian yang besar. Degradasi pengubah adalah satu proses kompleks dan ia dipengaruhi oleh pelbagai faktor. Ketepatan untuk menganggar kondisi dan jangka hayat pengubah sukar dicapai kerana mekanisma degradasinya yang kompleks. Lazimnya, teknik ramalan jangka hayat dilaksanakan dengan menggunakan kebarangkalian atau kadar kerosakan yang diperolehi daripada data kerosakan yang direkodkan bagi tujuan strategi pengurusan asset. Walau bagaimanapun, data kerosakan pengubah adalah terhad dan kebiasaannya tidak tersedia untuk populasi pengubah yang baru. Pada masa kini, majoriti utiliti telah melaksanakan Peyelenggaraan Berdasarkan Kondisi (CBM) sebagai sebahagian daripada skim pengurusan aset. Dibawah CBM, penilaian kuantitatif yang dikenali sebagai Indek Kesihatan (HI) telah dirumuskan untuk mewakili kondisi keseluruhan pengubah. Secara amnya, HI digunakan untuk menentukan kondisi semasa pengubah, walau bagaimanapun terdapat potensi untuk menggunakan HI bagi tujuan ramalan penilaian kondisi masa depan. Oleh kerana kekurangan data direkodkan untuk jangka panjang serta taburan HI data yang berselerak, teknik matematik seperti regresi, garis arah, dan teknik ekstrapolasi tidak begitu sesuai untuk menganggar kondisi pengubah kerana ia bergantung pada jumlah data yang mungkin menjejaskan kebolehpercayaan ramalan.

Kajian ini membentangkan penggunaan kaedah probabilistik stokastik yang dikenali sebagai Model Ramalan Markov (MPM) untuk meramal kondisi pengubah dengan menggunakan data populasi HI. Model MPM ini dibangunkan berdasarkan kepada dua teknik terbitan kebarangkalian peralihan yang dikenali sebagai kebarangkalian maksimum (kekerapan peralihan) dan pengoptimuman tidak linear. Model ini dibangunkan menggunakan data pemantauan kondisi minyak pengubah yang dibekalkan oleh pihak utiliti. Ia terdiri daripada gas

terlarut, kualiti minyak dan sebatian furanik. Berdasarkan HI yang dikira, 120 pengubah disusun mengikut kondisi semasa dan tahun secara berturutan, dan kemudiannya kebarangkalian peralihan ditentukan berdasarkan pendekatan kekerapan peralihan. Seterusnya, kos penyelenggaraan juga dianggarkan berdasarkan taburan kebarangkalian populasi daripada MPM mengikut model skim penyelenggaraan yang dicadangkan. Bagi model MPM yang kedua, HI bagi 3195 sampel minyak pengubah berumur diantara 1 hingga 25 tahun dihitung dan kebarangkalian peralihan diperolehi berdasarkan teknik pengoptimuman tak linear. Seterusnya, keluk prestasi kondisi masa depan bagi pengubah ditentukan dengan menggunakan algoritma rantaian Markov. Analisa statistik dijalankan bagi menguji prestasi MPM yang dibangunkan dengan menggunakan data HI. Di samping itu, kesan daripada pengenalan kadar pembaikan dari penyelenggaraan terhadap HI juga dikaji bagi tujuan pengurusan aset pengubah. Ia dilakukan melalui kajian kepekaan dengan mengemaskini MPM yang dibangunkan. Akhir sekali, taburan kebarangkalian populasi pengubah dan keluk prestasi pengubah dibincangkan.

Analisa perbandingan antara bilangan pengubah yang sebenar dan ramalan MPM berdasarkan teknik kekerapan peralihan mendapati semua kumpulan kondisi pengubah masih berada dalam jalur ramalan 95%. Selain itu, terdapat 90% kebarangkalian bahawa populasi pengubah akan mencapai keadaan 'tidak baik' selepas 76 tahun berdasarkan kondisi peralihan alat ubah tahun 2013/2014, manakala 69 tahun pula berdasarkan kondisi peralihan alat ubah tahun 2012/2013. Selain itu, jumlah kos penyelenggaraan berdasarkan taburan kebarangkalian populasi meningkat secara beransur-ansur dalam selang masa 20 tahun. Ia meningkat dari Ringgit Malaysia (RM) 5.94 juta kepada RM 39.09 juta berdasarkan kondisi peralihan pengubah untuk tahun 2013/2014 dan RM 37.56 juta untuk tahun 2012/2013. Seterusnya, pembangunan MPM berdasarkan teknik pengoptimuman tidak linear menunjukkan bahawa ia boleh digunakan untuk meramalkan kondisi HI pengubah masa depan. Analisa chi-squared goodness-of-fit mendapati purata ralat antara HI rujukan dan ramalan MPM adalah 3.59%. Hasil kajian kes juga menunjukkan bahawa kadar pembaikan dari penyelenggaraan yang telah diperkenalkan dapat membantu meningkatkan taburan populasi dan prestasi keadaan HI pengubah. Pengenalan kadar pembaikan dari penyelenggaraan sebanyak 30% kepada MPM memberikan peningkatan yang paling tinggi dan juga paling berkesan untuk penambahbaikan taburan populasi pengubah yang berada pada kondisi 'kurang baik'.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Beneficent and the Most Merciful for the blessing of giving me opportunity, strength and patience to complete my PhD study.

First and foremost, I would like to express sincere gratitude and appreciation to Universiti Putra Malaysia (UPM) especially to my supervisor Associate Professor Dr. Norhafiz Azis for all his guidance, motivations and endless helps during the study. I wish to thank also all members of Supervisory Committee; Professor Ir. Mohd Zainal Abidin Ab. Kadir, Associate Professor Dr. Jasronita Jasni and Dr. Mohd Hendra Hairi for their valuable assistance and comments in completing this research. Many thanks to Ministry of Education (MOE) and Universiti Teknikal Malaysia Melaka (UTeM) for the opportunity and financial support given.

I would also like to thank my family for their continuous support, sacrifices and prayers. Especially to my parents Yahaya bin Sahob and Jamilah binti Hj. Sahat; my lovely wife, Ismadiana binti Ismail; my four gorgeous kids, Emir Luqman, Mawar Alisa, Umar Khalif and Melur Nadra.

Last but not least, special thanks to my colleagues and friends for their help and advice throughout this journey.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

2ACF	2-Acetylfuran
2FAL	2-Furaldehyde
2FOL	2-Furfurol
5H2F	Hydroxymethyl
5M2F	5-Methyl-2-Furaldehyde
ACBDV	AC Breakdown Voltage
BDV	Breakdown Voltage
C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6	Ethane
CA	Condition Assessment
CBM	Condition Based Maintenance
CH_4	Methane
CI	Critical Index
CIGRE	International Council on Large Electric Systems
CM	Corrective Maintenance
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DGA	Dissolved Gas Analysis
DGF	Dissolved Gases Factor
EHR	Equipment Health Rating
FA	Furfural Analysis
FMECA	Failure Mode Effect and Criticality Analysis
H_2	Hydrogen
HI	Health Index
$HI_{(Ave.)}$	HI Average
$HI_{(Prob.)}$	HI Probability Plot
IEEE	Institute of Electrical and Electronics Engineers
IFT	Interfacial Tension
LS	Least Square
MLE	Maximum Likelihood Estimator
MM	Markov Model
MPM	Markov Prediction Model
MTTF	Mean Time to Failure
OEM	Original Engineering Manufacturers
OQA	Oil Quality Analysis
OQF	Oil Quality Factor
PPM	Part per Million
r^2	r-squared
RI	Risk Index
RM	Ringgit Malaysia
RUL	Remaining Useful Life
TBM	Time Based Maintenance
TCI	Transformer Health Index
TDCG	Total Dissolved Combustible Gas
TNB	Tenaga Nasional Berhad
USD	United State Dollar

CHAPTER 1

INTRODUCTION

1.1 Background

Transformers are among the important assets in a power system network, failures of which could lead to costly consequences. Nowadays, transformer asset management is becoming a crucial aspect in the power system network planning due to the increase in electrical demand and the attentive focus in cost-effective business model among the electrical utility providers. A proper maintenance plan helps utility providers to strategize the asset management of the equipment. According to [1], [2], the degradation of transformers is a complex phenomenon that can be affected by multiple factors. Among the factors causing failures of transformers include design issues, unusual loadings, abnormal events, electrical faults and advanced degradation of insulations.

In recent years, the majority of utility companies have implemented Condition Based Maintenance (CBM) as part of condition based management to closely monitor the condition and manage their transformer fleets. Through this approach, the management strategy of the asset can be improved and the cost can be reduced as compared to the previous Time Based Management (TBM) [3]. CBM uses the overall condition monitoring data from the transformers and provides information on the possible actions that can be carried out by the utility companies [4]. Engagement of CBM is in line with the progression of diagnostic and condition monitoring techniques. Under CBM, a single quantitative assessment known as Health Index (HI) is commonly formulated to provide the overall condition of transformers. Typically, HI comprises of multiple input parameters such as oil condition monitoring data, loadings, design, location, and electrical/mechanical integrities [5]. HI provides a comprehensive condition assessment of transformers compared to single assessment methods such as Dissolved Gases Analysis (DGA), Total Dissolved Combustible Gas (TDCG), oil quality analysis, furanic analysis, thermal analysis and other analyses which mainly focuses on the identification of faults or estimation of transformer lifetime [6]. HI has been widely adopted by many electrical utilities around the world due to the simplicity, easy to understand and straightforward approach of this method.

Conventionally, HI is used to determine the current condition states of the transformers. However, there is a potential to utilize HI to predict the transformer future condition states. Currently, the common mathematical approaches such as regression, fitting, and extrapolation techniques are not suitable due to the scattering nature of HI and limited data in the database affecting the data reliability and inaccurate predictions [7]. Moreover, there are still few studies carried out to model the future condition of transformers using HI data. For example, studies such as those in [8]-[10] are mainly focused on the utilization of the HI to determine the current condition of transformers and its impact on the power system network.

The stochastic method known as the Markov Model (MM) is one of the prediction method that is capable to determine the future states of the transformers based on the HI using a probability decision process where future decisions on maintenance schemes depend on the actual assets performances. MM is widely implemented to model the performance and deterioration of different types of equipment. For instance, in civil engineering, MM is applied to model the degradation of bridge deck and elements [11], pavements [12], water piping components [13], and steel hydraulic structures [14]. MM is also utilized in [15], [16] for electrical equipment such as modeling the condition of switchgear and identification of transformer faults. The model develops in this study will be known as the Markov Prediction Model (MPM).

1.2 Problem statement

The transformer future condition states are an important indication for asset manager to plan their maintenance, repair and replacement activities. Recently, many electrical utilities adopted HI as condition assessment for their transformers [8]-[10], [17]-[20]. HI is formulated using the scoring system based on standards, guidelines and expert judgements. Thus, a valuable quantitative evidence about the overall condition of the transformers can be determined by considering multiple inputs from the established condition monitoring techniques. However, there are several issues with the available predictive approaches and the utilization of HI methods to estimate future condition states for asset management. These issues include:

- HI is commonly used to assess the current condition states of transformers [21], [22]. The valuable information obtained through HI is not utilized to predict the future condition states of the transformers although HI is commonly adopted by many utilities. It is due to the scattering nature of HI data especially for transformer population. Moreover, the statistical techniques such as regression, fitting analysis, trend forecasting and extrapolation are not consistent and not reliable to model future performance and deterioration of the HI. These techniques are quite sensitive to the latest input data and not a probabilistic orientation process [7].

- Ideally, comprehensive recorded historical population data is required to predict and model the future condition states of transformers [3]. However, a long-term recorded condition monitoring data are always limited, especially for young population of transformers. Besides, the condition monitoring information for each transformer is also incomplete due to poor database systems. Thus, the application of prediction method faces difficulties since the models rely heavily on data such as regression, trend lines fitting analysis, and other similar techniques [7]. Further, the models will also suffer due to the lack of left censored data.

Therefore, an accurate prediction approach that depend on long-term condition monitoring data may not be feasible.

- Some utilities introduce additional factor in order to prioritize the asset management activities such as maintenance, repair or replacement [23], [24]. The factor is conjoined with the HI to indicate the risk of the transformers. The factor known as Critical Index (CI) or Risk Index (RI) is used to define the criticality of transformers' condition state in the power network system. In some cases, the factor is used to predict the probability of failure for the transformers. The index is computed based on the failure data, failure records, 'sister' failure history, risks and consequences of the transformer to the power system networks [23]. Unfortunately, the failure data are normally limited and unavailable. Thus, many of the utilities face this common problem in order to plan their asset management strategies. This failure data issue is also shared by other similar projection analysis such as failure hazard rate, Weibull, and Mean Time to Failure (MTTF) [25]-[27].

Unfortunately, there are still lack of studies conducted to address these issues and to explore a new approach for transformers asset management using the existing HI method. Therefore, this study provides a novel approach to the utilization of HI information to predict the future condition states for the transformers and exploits the benefits of HI to strategizes asset management activities.

1.3 Research aim and objectives

The aim of this research study is to develop an innovative approach by using MPM to predict the future condition states of transformers for asset management activities. The approach is developed based on the HI information obtained from the transformer condition monitoring population data. In order to achieve the aim of this research, the detailed objectives are as follows:

1. To develop and evaluate the MPM based on HI by utilizing frequency of transition approach for future state probabilities and maintenance cost study.
2. To develop and analyze the MPM based on HI using nonlinear least-squares minimization technique for future state distribution and performance condition curve.
3. To investigate the effect of pre-determined maintenance repair rate through updated MPM for transformers asset management strategies.

1.4 Scope of work

The research study focuses on the utilization of HI to predict future states condition of transformers using Markov chain model for asset management decision. Thus, the study is conducted based on the following sets of limitations:

- The model is developed using utility oil samples data of 33/11 kV distribution transformers. The HI is calculated based on the analysis of the three major oil sample groups which are Dissolved Gas Analysis (DGA), Oil Quality Analysis (OQA) and Furfural Analysis (FA). The parameters used are hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), carbon monoxide (CO), carbon dioxide (CO_2), moisture, AC dielectric breakdown voltage (ACBDV), acidity, interfacial tension, color, 2-furaldehyde (2FAL). The utility HI algorithm obtained in the literature is updated according to the available parameters in the oil samples data.

- The development of MPM utilizing HI values only consider the transformer normal deterioration process which is irreversible and the scattered nature of the HI data. The transition probabilities computation techniques are based on the behavior and nature of the accessible HI data.

- The maintenance cost of the study is estimated based on the average costs obtained from the Original Engineering Manufacturers (OEM). However, assumption is made using the repair policy that is commonly used in the previous study on the pre-determined maintenance repair rate for improved MPM.

- Since there is no prediction model that fully utilize the HI data so far, the comparison and validation of the MPM results are based on the computed actual HI obtained from the condition monitoring data. The results will also be supported using appropriate statistical analyses.

1.5 Contribution of the research

Figure 1.1 illustrated the contributions in graphical form. The details of the contributions of this research study are as follows:

- The use of stochastic approach to predict and estimate future condition states of transformers from condition monitoring data is developed. The approach is based on the Markov chain algorithm with the utilization of HI data. MPM is also developed as a prediction model using the current utility condition states assessment i.e. HI. MPM is a dynamic model that can be updated using the transition probability once more data is available.

- MPM is designed based on maximum likelihood and nonlinear least-squares minimization techniques. Both of these techniques do not rely on failure data to derive the transition probabilities. These techniques also do not require long term data and can be performed with only specific minimum recorded data. Thus, this approach has the advantage to reduce the dependency on large HI data.

- The MPM developed is not only able to predict future condition states of transformer population, but is capable to estimate the future maintenance costs for that population. The MPM is also capable to demonstrate the distribution of transformer population in each condition states and HI performance condition curve. In addition, the updated MPM allows the effect of rehabilitation of transformers to be simulated with pre-determined maintenance repair rate. Consequently, the MPM assists the utility to plan and optimize the investments that support sustainable transformer asset management.

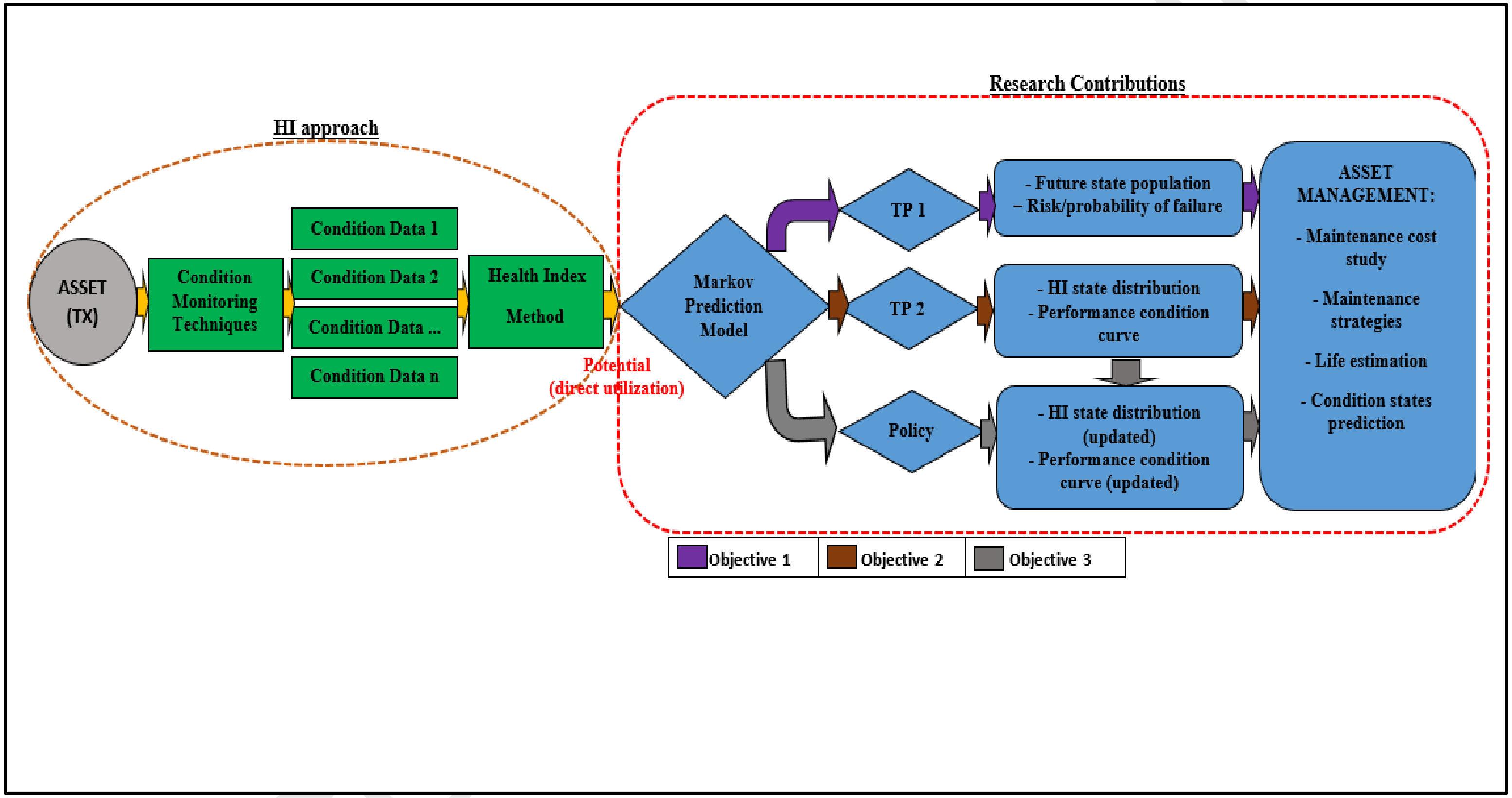

Figure 1.1: Graphical illustration of research contributions

1.6 Thesis outline

The thesis consists of five chapters, which cover the introduction, the literature review, the methodology, the results and discussion and also the conclusions and recommendations for possible future works.

Chapter 1 describes the introduction of this research along with the problem statement, research aim and objectives, scope of work, limitation and contributions of the research study.

Chapter 2 discusses the various aspects on the aging and stressed transformers. Next, the approaches on predicting and managing the transformer fleets are summarized. In addition, the methods used by utilities to assess the transformer condition states known as Health Index (HI) are explained. Finally, the potential of Markov chain model as prediction approach that utilize condition monitoring data is discussed.

Chapter 3 presents the procedures used to develop the MPM. First, the process involved to model the MPM that starts from obtaining the condition monitoring data up to the HI calculation, predicting the future condition states, estimating the maintenance cost and determining the maintenance effects of the pre-determined repair rates. Next, this chapter also explains the concepts for both transition probabilities techniques used in the development of MPM. Finally, the chapter describes the application of the transformer's asset management strategies through the updated MPM.

In Chapter 4, discussion about the outcomes of the research study is presented. First, the chapter details the prediction results of the future condition states of transformers based on frequency of transition and nonlinear least-squares minimization techniques. Next, the chapter presents the comparison analyses between the computed and the predicted future condition states of transformers data. Further, the robustness of the MPM results are explained using the statistical analyses. Last but not least, this chapter also discusses the various possible strategies the asset manager can be consider to manage the asset.

Finally, Chapter 5 summarizes and concludes the research study. The recommendations for the possible future works on MPM using HI transformer population data are proposed at the end of this chapter.

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LIST OF PUBLICATIONS

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