Non-intrusive inductively coupled method for condition monitoring of electrical systems

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NON-INTRUSIVE INDUCTIVELY COUPLED METHOD FOR CONDITION MONITORING OF ELECTRICAL SYSTEMS

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Abstract

Off-line frequency response analysis method is widely adopted as a diagnostic technique for critical electrical system, for examples, winding deformation in transformer and stator' winding defects in induction motor. Usually, frequency response analysis detects abnormality of an electrical system by comparing its measured impedance's frequency response with that of healthy one, which is new or has undergone a major overhaul. Off-line frequency response analysis requires shutdown of the system to be tested and therefore it lacks the real-time condition monitoring feature when the system is powered up and operates in its usual operating condition. Several on-line frequency response analysis methods have been reported but additional design and circuitries are necessary to facilitate excitation of signal and to measure the response. All these require some forms of direct electrical contacts to the system under test when it is powered by high-voltage, which can be a safety concern for personnel who handles the instrument on-site. Also, any additional circuitry to establish the electrical contact has a direct impact on the frequency response of the system under test, which can affect the accuracy of the diagnostic. This thesis proposes an on-line frequency response analysis technique that adopts a fully inductive coupling approach so that there is no direct electrical contact with the system under test, which eliminates the safety hazards. Also, the implementation is relatively easy and the installation can be done without switching off the power supply to the system. In addition, the calibration of the proposed method is relatively straightforward. Both the injecting and receiving probes can be calibrated off-line and therefore regular re-calibration of the probes without interrupting the operation of the monitored electrical system is possible, as opposed to other on-line methods that may require the monitored

electrical system be switched off. The proposed method has relatively wide bandwidth that can be tailored to specific electrical system for best results. The theory behind the proposed method is described and the method validated experimentally. Using a transformer and an induction motor as system under test, on-line condition monitoring for early detection of defects is demonstrated.

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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AC	Alternating Current
AI	Artificial Intelligence
ANN	Artificial Neural Network
ASLE	Absolute Logarithmic Error
CCC	Cross Correlation Coefficient
CM	Condition Monitoring
CUT	Component Under Test
DC	Direct Current
DGA	Dissolved Gas Analysis
EUT	Equipment Under Test
FRA	Frequency Response Analysis
HV	High Voltage
LV	Low Voltage
LVI	Low Voltage Impulse
MCSA	Motor Current Signature Analysis
NICS	Noninvasive Capacitor Sensor
PD	Partial Discharge
PDA	Partial Discharge Analysis
PUL	Per Unit Length
RMS	Root Mean Square
RMSE	Root Mean Square Error
SCI	Short Circuit Impedance
SFRA	Sweep Frequency Response Analysis
SNR	Signal to Noise Ratio
SUT	System Under Test
TF	Transfer Function
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio

Chapter 1 Introduction

1.1 Background

Condition monitoring (CM) of a mission-critical electrical system is important for both its reliability enhancement and life-span extension. Some of the incipient faults within an electrical system can be detected during scheduled maintenance but some may not be detected and can deteriorate further, causing complete system failure before the next maintenance. Hence, accessibility of real-time information on the characteristic of an electrical system to ensure its reliable operation with minimum down-time is necessary so as to minimize the economic impact due to destructive failure. On-line CM acquires real-time parameters that are linked to an electrical system's operating condition for detection of early signs of defects to avoid catastrophic damage [1]–[8]. A typical CM system consists of sensing, data acquisition and fault diagnosis sub-systems, which can be deployed round the clock [3], [9].

Mission-critical electrical infrastructures, such as generators, transformers and motors usually operate round the clock and those are capital intensive assets [2]. Therefore, their reliability is vital to the overall electrical power distribution network [3]. Several commonly adopted CM techniques for an electrical system are partial discharge (PD), frequency response analysis (FRA), thermal analysis, dissolved gas analysis (DGA) and vibration [1], [10]–[21]. The FRA of the impedance of a transformer is a well-established diagnostic technique [22], [23] for diagnosing the winding displacement and deformation. Any deformation of a transformer's winding changes its inductance and capacitance, and such deviation

will be reflected in the measured frequency response of the winding's impedance [24], [25]. An off-line method was first reported in 1970s as a diagnostic technique for transformer's defects [26]. By injecting a signal into the transformer winding and measuring the resultant signal through varying frequency, the transfer function allows frequency response of the transformer impedance to be extracted. Defects of a three-phase transformer can be detected by comparing the impedance frequency response of each phase of the winding of the transformer-under-monitored with respect to the measured impedance frequency response of the same winding of the same transformer during the factory test. Due to manufacturing tolerances, slight differences may exist between identical transformers [25], [27] and special attention is needed for the signature profile of the reference transformer. Off-line FRA can only be carried out when the electrical system is shut down for periodic maintenance. Any defect that occurs between the window periods of the scheduled maintenance can develop into a serious defect and causes unexpected damage to the system. There are several methods reported for on-line FRA but they require additional circuitries for excitation signal and resultant response. The additional circuitries has direct impact on the frequency response of the system under test and may affect the diagnosis accuracy [23]. Also, some forms of direct electrical contacts to the high-voltage power supply are necessary, which can pose safety hazards to personnel who uses the test instrument on-site. These on-line methods usually adopt capacitive coupling approach, either using an external capacitor [28] or capacitive bushing tap [29]–[34]. Due to high dielectric and thermal stress, premature bushing failures can happen, which incurs unnecessary downtime for the system under test [35].

1.2 Motivation and Objective

Due to the shortcomings of the earlier mentioned on-line FRA techniques for CM purpose, the motivation of this thesis is to develop a fully inductively coupled on-line FRA method without direct electrical contact to the system under test so that real-time CM for early detection of defects becomes possible.

The objectives of the thesis are as follows:

- Based on an inductive coupling approach, to develop an on-line FRA technique to extract frequency response of any electrical system without interrupting its normal operation;
- Theoretical analysis and experimental validation of the proposed method based on cascaded $ABCD$ two-port network;
- Demonstration of defects detection capability on a transformer and an induction motor; and
- Deployment of suitable statistical indicators to enhance defect detection capability.

1.3 Thesis Overview

This thesis will be organized as follows:

Chapter 1 introduces the background, motivation and objective of the thesis.

Chapter 2 provides a comprehensive literature review on condition monitoring for electrical systems.

Chapter 3 describes the theoretical background behind the proposed inductively coupled method and validates it experimentally.

Chapter 4 demonstrates the defect detection capability of the proposed method on a custom-made transformer and an induction motor with emulated defects.

Chapter 5 discusses the enhancement of defect detection capability of the proposed method using suitable statistical indicators.

Chapter 6 concludes the thesis with potential future work.

Chapter 2 Literature Review of Condition Monitoring of Electrical Systems

2.1 Introduction

Detecting incipient faults of an electrical system can be done through condition monitoring (CM) by extracting its characteristic and analyzing it. With CM properly implemented, the characteristic of the system can be monitored continuously so that early signs of defects can be detected. Nowadays, implementation of CM can be done more effectively on an electrical system due to rapid development of transducers, data acquisition methods and signal processing techniques. For on-line CM, several key factors have to be considered, such as sensor's sensitivity, installation cost, ease of implementation and reliability. Electrical systems such as battery chargers, generators, transformers, motors and circuit breakers are critical sub-systems of power generation and distribution [2], as their functioning is vital to the availability and reliability of the electrical power supplies to households and industry [3]. To narrow down the coverage of literature review, CM of transformers and induction motors will be the main focus in this chapter.

2.2 Review of Condition Monitoring of Transformers

2.2.1 Common Defects

A transformer can operate under numerous stresses, such as thermal, electrical, mechanical and environmental. Thermal ageing results from eddy current losses and resistive loss of the coil, which causes chemical reactions that lead to degradation of the insulation of the transformer and reduces its life span. The degree of acceleration of the insulation failures depends on temperature, water and oxygen

contents. Besides deterioration of insulation, thermo-mechanical effect also leads to winding deformation. In addition, short circuit current in the transformer also creates high electrodynamic forces and contributes to winding deformation. During the winding deformation process, it worsens the degradation of insulation due to the mechanical expansion and contraction. According to statistics, winding deformation is one of the most common failures in the transformer [36]. Winding deformation might occur during operation, external short circuit, lightning and heavy explosion of combustible gas in transformer oil. A transformer may still be capable for normal operation if there is a slight winding deformation. However, if it is not detected early, the capability of insulation against high electrical stress will be consecutively decreased and results in irreversible damage to the transformer. Two major root causes of winding deformation are discussed as follows.

2.2.1.1 Short Circuit Current

The most common transformer failure is due to short circuit current, which creates strong electromagnetic force on the winding. In general, such forces can be categorized into radial, axial and combined forces that cause radial, axial or angular winding deformation or insulation breakdown. Also, loosened clamping structures due to ageing of insulation reduces the ability to withstand the electromagnetic force. Fig. 2-1 shows various possible forms of winding deformation [23].

Fig. 2-1. Causes of various winding deformations

The radial forces produced by the axial leakage field act outwards on the outer winding tending to stretch the winding conductors and it can cause hoop stress. On the other hand, the radial forces lead inner winding to experience radial compressive stress. Therefore, tensile strength of outer winding is important to withstand against hoop stress. The radial force between two windings can be calculated by [29]:

$$F_{radial} = \Pi d \left(\frac{\sqrt{2} \mu_0 NI}{2h} \right) \sqrt{2} NI \quad (2.1)$$

where h is the winding height, d is the average winding diameter, NI is the winding's ampere-turns in RMS and μ_o is the vacuum permeability.

Free buckling and forced buckling due to radial forces are most common types of deformation as shown in Fig. 2-2 [29].

Fig. 2-2. (a) Forced buckling (b) Free buckling (2D view) (c) Free buckling (3D view)

Asymmetrical windings are always in danger since radial magnetic flux of short circuit current generates axial forces which lead to tilting or bending of winding. Also, small winding displacement during transportation has also worsened the deformation due to axial force during short circuit. Fig. 2-3 and Fig. 2-4 show tilting and bending of winding due to forces, respectively [23], [24].

Fig. 2-3. (a) Before tilting (b) After tilting

Fig. 2-4. (a) Bending (side view) (b) Bending (close view)

2.2.1.2 Transportation

Transformers must be handled with care during transportation to minimize winding displacement and deformation. In industry, there are four main transport modes, by truck, train, sea and air. Some prior preparation is necessary to minimize the vibration of the transformer. Before filling the transformer oil on-site, transformer tank is filled with dry air or nitrogen to avoid chemical reaction on the insulation and absorbing moisture during transportation. Also, transformer bushings are dismantled from the tank for ease of transportation and the gas is pressurized to ensure its pressure is higher than the outside pressure. All the mechanical forces should be carefully identified and taken into calculation during loading, transportation and unloading of the transformer.

2.2.2 Common Diagnostic Techniques

There is no single diagnostic method that can detect and identify all the defects of a transformer due to its complex structure and various factors that affect the ageing process. Hence, there are different diagnostic techniques reported in literature [10], [14]–[20] and each of them has its own merits. In general, these techniques can be classified into chemical, electrical, thermal/optical and mechanical, as illustrated in Fig. 2-5 to Fig. 2-8, respectively.

Fig. 2-5. Chemical based diagnostic methods

Fig. 2-6. Thermal and optical based diagnostic methods

Fig. 2-7. Mechanical based diagnostic methods

Fig. 2-8. Electrical based diagnostic methods

These diagnostic techniques have led to four main types of commonly used condition analyses, namely dissolved gas analysis (DGA), thermal analysis, partial discharge analysis (PDA) and FRA. Each of them will be briefly introduced.

2.2.2.1 Dissolved Gas Analysis

High power transformers are immersed in oil, which serves as insulation and thermal transfer medium. Transformer insulation is usually made of hydrocarbon oil and paper, which degrades with time and produces gases. However, chemical decomposition of the insulation accelerates when there is localized overheating, arcing and partial discharges, and dissolve gases such as carbon monoxide (CO), acetylene (C₂H₂), carbon dioxide (CO₂), ethane (C₂H₆), methane (CH₄), ethylene (C₂H₄) and hydrogen (H₂) are generated. An incipient fault can be detected early through analyzing the above-mentioned gases so that unexpected failure can be avoided. Dissolved gas analysis (DGA) is commonly used as an on-line diagnostic method to analyze transformer's insulating oil and to diagnose potential incipient faults without shutting down of the transformer. IEC 60599 [37] and IEEE C57.104 [38] provide guidelines to perform DGA accurately. According to these standards,

Roger's gas ratio and the Dornenburg techniques provide well-established guidelines to classify transformer faults. Gas generation rate and dissolved gas percentage in insulation oil of the transformers are analyzed. Furthermore, each gas generation is a function of temperature and it can be used as an indicator to predict and identify a potential fault. However, low dissolved gas content can affect the calculation of gas ratio and may lead to inaccuracy and uncertainty of the results. Although DGA has been well established, it is not a complete solution to identify all defects or faults in the transformer, as not all the gases in the insulation oil can be correlated to a defect or fault accurately and vice versa. In addition, measurements from different transformers provide very diverse DGA results, which make the fault diagnosis inconclusive. To enhance the diagnostic capability of incipient faults of in-service transformers, computational techniques such as artificial neural network (ANN) and fuzzy logic have been employed in [39]–[44].

2.2.2.2 Thermal Analysis

The condition of insulation directly affects the transformer's life span and thermal ageing is mostly responsible for degradation of insulation [45]–[54]. Temperature rises due to power dissipation in the conductor and magnetic core daily cyclic overloading above the ratings creates temperature stress which accelerates ageing of the insulation. Lack of efficient cooling during transformer operation can add to further overheating. Therefore, transformer rating should be selected according to its intended loading and cooling capacity to minimize thermal stress. On the other hand, degraded insulation can lead to increase in water content that affects the voltage withstand capability and subsequent electrical breakdown. Hence, the rate of ageing insulation due to thermal stress is proportional to the water content. One of the most challenging issues in thermal analysis is the accuracy of the thermal

model in identifying temperature hot-spot within the transformer. IEC 60354 [55] and IEEE C57.91 [56] guidelines provide the necessary steps for the calculation of hot-spot temperatures and localization of hot-spots. With empirical thermal equations, the calculated temperatures for different loading conditions can be predicted. In most cases, the outcome of these calculations is rather conservative due to several simplifying assumptions in the equations. Moreover, parameters of empirical equations can vary with time or not readily available to develop an accurate thermal model for each transformer. Also, ambient and cooling temperatures are not included in the conventional calculation which limits the transformer's thermal model for predicting temperatures under different loading conditions. In conclusion, the challenge is to develop an accurate thermal model that resembles the operating condition of the transformer.

2.2.2.3 Partial Discharge Analysis

Insulation breakdown is responsible for serious failures of transformers. An early sign of insulation failure is partial discharge (PD). According to IEC 60270 [57], PD occurs when electric field exceeds the threshold of the insulation. If PD is identified in early stage of the failure, a complete breakdown due to insulation ageing can be avoided. Manufacturing defects such as voids or air filled fractures are the root causes of PD activity. Therefore, PD analysis [58]–[70] is a useful tool to detect local inhomogenities (PD sources) in the insulation. It has been used in past decades as a non-destructive diagnostic tool for transformers, cables and electrical machines. PD results in electromagnetic and acoustic waves, which can be measured with electromagnetic and acoustic sensors. Acoustic sensors are usually placed in the enclosure of the transformer. They are simple to implement but have poor sensitivity and it is difficult to detect the wave speed due complex transformer

structure. Electrical based PD sensing techniques have better sensitivity but localization of PD source can be challenging since the electromagnetic wave can be affected by other ambient signal and noise. In addition, the complex structure of the transformer disturbs the PD wave propagation and affect the accuracy of the final result. Conventional signal analysis techniques are not suitable for PD signal analysis due to special characteristic of PD signal and new techniques have been proposed such as phase resolved, intensity spectra and time resolved techniques. However, the most challenging part is to localize the PD source if PD signal is detected.

2.2.3 Winding Deformation Analysis

The earlier mentioned techniques are mainly focus on the insulation ageing of the transformer but not winding deformations due to mechanical stress. Conventionally, off-line diagnostic methods such as short circuit impedance (SCI) and transfer function (TF) have been developed to detect transformer winding deformation. Basically, these methods detect changes in winding inductance and capacitance due to winding deformation.

2.2.3.1 Short Circuit Impedance Measurement

Short circuit impedance (SCI) measurement is carried out with the transformer's secondary winding short circuited. The cable used to short circuit the secondary has a direct influence on SCI measurement results and hence, its length must be shortened as much as possible and its cross-sectional area must be at least 30% larger than that of transformer winding to minimize measurement error. During factory test, SCI is measured and recorded as part of the quality control process. According to IEC 60076-5 [71], winding deformation can be detected if the

measured SCI of the transformer deviates from the factory value by $\pm 1\%$. As SCI can only be measured off-line, it does not have the real-time on-line condition monitoring capability.

2.2.3.2 Transfer Function Measurement

The transfer function of an electrical system characterizes its unique behavior and feature. It can be measured either in time-domain or frequency-domain for a well-defined input signal. Low voltage impulse (LVI) technique is most popular in time-domain measurement, while FRA is usually applied in frequency-domain analysis. Sweep FRA (SFRA) has become popular as a most suitable non-intrusive technique in transformer winding deformation diagnostic due to its high sensitivity, reliability, simplicity and reproducibility [30]. There are several guidelines available in IEEE PC57.149 [72] and IEC 60076-18 [73] for SFRA measurement and analysis. An off-line FRA method was first reported in 1970s as a diagnostic technique for transformer's winding deformation [26] and since then, it has been widely adopted as a popular diagnostic technique. By injecting a sinusoidal signal into the transformer winding and measuring the resultant signal through varying frequency, the transfer function allows FRA of the transformer impedance be extracted. The frequency-dependent transfer function of the transformer under test is given by:

$$TF_{(f)} = \frac{U_{out(f)}}{V_{in(f)}} \quad (2.2)$$

where $V_{in(f)}$ and $U_{out(f)}$ are frequency-dependent input voltage and output current (or voltage), respectively. Due to the relatively large parasitic capacitance of the transformer winding, the resonant frequencies of the transformers, are quite low and hence FRA measurement is usually carried out below 2 MHz [23], [74]–[76].

Defects of a three-phase transformer can be detected by comparing the impedance frequency response of each phase of the winding of the transformer-under-monitored with respect to the measured impedance frequency response of the same winding of the same transformer during the factory test. Any winding movement and deformation in a transformer changes its inductance and capacitance and such deviation will be reflected in the measured frequency response of the transformer's impedance [24], [25]. If the frequency response is not available during the factory test, identically constructed transformer or inter-phase comparison can be used as a benchmark for the diagnosis. Due to manufacturing tolerances, slight differences may exist between identical transformers [25], [27] and special attention is needed for the signature profile of the reference transformer. Also, most utility companies have their own database which contains historical SFRA measurement to compare with future measurements. Due to off-line nature of FRA, it does not allow real-time CM of a transformer under its powered up operating condition. Moreover, off-line FRA requires shutting down of the power supply system, which can only be performed during scheduled maintenance. FRA is a comparative method where new resonance, shift in resonance frequency or any deviation in the frequency response is an indication of winding deformation. There is considerable industrial interest to develop defect classification technique for identification of various defects accurately. A wide range of techniques such as winding models [77] and analysis of frequency response data have been developed to interpret winding defects but the accuracy is very much dependent on the details of the transformer model.

2.2.3.3 On-line Frequency Response Analysis

To allow on-line FRA of a transformer under its powered up operating condition, a few techniques have been developed by injecting and receiving signals through either an external capacitor [28] or capacitive bushing tap [30], [31]–[34], as illustrated in Fig. 2-9(a) and Fig. 2-9(b), respectively.

Fig. 2-9. On-line FRA measurement setups (a) Using external capacitors (b) Using capacitive bushing tap

One of these techniques injects and receives signal for FRA through capacitive bushing tap [31]. Another technique injects a nanosecond pulse signal with a protection circuit to the transformer winding through capacitive bushing tap with its response extracted from another bushing tap [34]. These on-line FRA techniques based on bushing taps very much dependent on the bushing characteristic, which has a direct impact on the frequency response of the transformer and some vital information related to transformer winding defects might be missed out [78]. The ageing of bushing capacitors requires regular replacements, which can incur unnecessary downtime for the transformer. Another technique based on capacitive and inductive couplings, uses noninvasive capacitor sensor (NICS) installed on the porcelain surface of the bushing to inject signal into the transformer winding [30]. Then, a Rogowski coil is installed between neutral and the ground for detecting the

response. However, it requires very careful design of protection circuit and high pass filters to isolate the measurement instrument from high voltage power supply. Also, ageing of the bushing capacitance or external isolation capacitance can influence the accuracy of winding frequency response and regular re-calibration of the setup is needed [35]. Also, additional circuitries for injecting and receiving signals require some forms of electrical contacts to the high-voltage transformer, which can pose safety hazards to personnel who performs the measurement on-site.

2.3 Review of Induction Motor Defects and Diagnosis

2.3.1 Stator Winding Defects

Advanced fault diagnostic technique is necessary to maintain characteristic of the electrical machines within nominal operating conditions. Any incipient fault that is not detected early can result in unexpected machine downtime and incurred heavy economic losses. For example, motor downtime in an offshore oil refinery plant can translate into a cost of US\$25,000/hour [79]. An electrical machine operates under different stresses, such as long-term thermal aging, thermal overload, contamination, mechanical vibrations and voltage transients caused by adjustable-speed drives, can lead to mechanical and electrical failures [80]. Failures in an induction motor can be further classified into bearing, stator and rotor related failures. Stator winding defects have been reported as major causes of failures in induction motors [81]. Thermal sources such as copper and eddy current losses create non-uniformed temperature distribution in the motor. If temperature overloading continues, it accelerates chemical reactions of the insulation material and reduces the insulation quality. As a result, inter-turn short circuit occurred between two adjacent windings and if not detected early, it can lead more serious

short circuits such as winding to ground and phase to phase [82]. If these defects are not rectified, they may develop further to localized hot spots due to high short circuit current and rapidly spread to other windings, causing irreversible damage of the motor. Therefore, to minimize the thermal and electrical stress on the insulation, factors such as loading, weight, starting cycle, inertia and torque curve should be considered carefully during project phase [83]. Winding defects due to electrical stress can be categorized into voltage spikes, tracking and corona. Eventually, insulation deteriorate due to electrical stress and inter-turn short circuit is the early stage of insulation failure. Hence, it is important to detect early signs of inter-turn short circuit in the motor so that timely remedial measures can take place to avoid catastrophic outage [80], [84]–[87].

2.3.2 Induction Motor Diagnosis Techniques

2.3.2.1 Inter-turn Short Diagnosis

Detection of inter-turn short has drawn special attention since it is an early stage of insulation break down. It has been shown that the extracted harmonics spectrum of stator current reveals winding faults of induction motor and each fault linked with specific harmonic component in the stator current. Therefore, motor current signature analysis (MCSA) can be used to identify inter-turn short without disturbing the motor operation. Inter-turn short can be detected by frequencies around the fundamental sidebands of the supply frequency which is given by:

$$f_{st} = f_s \left[\frac{n}{p} (1 - s) \pm k \right] \quad (2.3)$$

where f_s is the power supply frequency; $n = 1, 2$; $k = 1, 3, 5$; p is the number of pole pairs and s is the per-unit slip.

Only specific pairs of n and k are useful to identify inter-turn short due to voltage unbalances and other asymmetries components in the spectrum [88]. Nevertheless, these techniques faced some difficulties since other faults, such as supply voltage unbalances, saturation of magnetic material, design and constructive asymmetries, rotor slot harmonic and sensor asymmetries also contribute harmonic components in the current spectrum of a healthy motor, which is new or has been repaired recently, making interpretation of inter-turn short a challenging task [89]. In addition, signal to noise ratio (SNR) of these techniques degrades, especially inverter-fed motors generate harmonics into the motor current and contaminates the fault spectra [90]. Loading of the motor also affects the accuracy, as harmonic spectrum is dynamically changing according to speed or torque of the machine and fully known motor parameters are required to identify fault precisely. In general, MCSA is useful to detect rotor faults, bearing issues and unaligned shaft but it is not good enough to identify inter-turn winding short due to insulation fault [91].

Search coil technique has also been reported as a useful on-line approach to detect radial or circumferential magnetic flux component [92]. It is less than size of rotor tooth width so that it can be fixed in the air gap of the stator [9]. A large coil wound concentrically around the shaft of the machine to extract axial flux leakage to detect inter-turn fault based on asymmetries of spectra is also reported [93]. These techniques require special designed sensors to be placed inside or outside the machine but are not well received by the industry, as the placements of the sensors can influence the results significantly and there is no established guideline for the use of these techniques [94].

The inter-turn short circuit generates a negative-sequence component of the motor current and it can be used to identify such fault. However, it requires compensation

for unbalanced supply voltage and intrinsic asymmetry of the motor, which may not be practical to implement [95].

Finite element analysis (FEA) is being widely used to investigate and analyze faults using magnetic flux distribution and structural health of induction machines [96]. For examples, influence of broken bar fault to the electromagnetic characteristics is analyzed using FEA [97], [98]. Also, it is applied to estimate the magnitude of fault specific frequency components for different eccentricities at full load condition [99] and to analyze the effect of radial flux density in the air gap under steady-state and phase-to-phase short circuit fault conditions of an induction motor [100]. However, FEA cannot be applied directly for on-line condition monitoring due to time consuming effort in solving coupled non-linear differential equations. To enhance decision making process to identify faults, artificial intelligence (AI) can be deployed but AI techniques require huge historical data for comprehensive training before a reliable diagnosis can be achieved.

2.3.2.2 Stator Insulation Diagnosis

Monitoring of stator insulation is highly desirable to identify signs of degradation of insulation. Poor insulation emits transitory and low-energy electrical discharges which radiate electromagnetic and acoustic waves. Therefore, off-line PD analysis is the only capable technique to evaluate internal insulation. However, the guides for off-line PD such as IEEE 1434 [101] and IEC 60034-27 [102] recommend test voltage that is significantly higher than the rated voltage of the motor [103]. The test voltage from the PD testers can degrade the insulation of low or medium voltage motors, which reduces the machine's life span [104], [105]. Again, PD analysis is highly susceptible to electromagnetic interference of power system and identification of PD signal is extremely challenging. In addition, PD analysis

depends on many other factors such as supply voltage, humidity, temperature, load of the machine, test instrument and measurement procedure. Therefore, these factors can affect repeatability of PD measurements.

2.3.3 On-line Frequency Response Analysis

Similar to transformers, FRA is able to detect changes in the stator winding due to inter-turn short. By injecting a signal into the stator winding and measuring the resultant signal through varying frequency, the frequency response of the winding's impedance can be extracted. Any defects associated with the stator's winding can be identified by comparing its impedance frequency response with that of the new induction motor. One technique injects a signal into the stator winding through series inductor and capacitor as shown in Fig. 2-10 and measures the resultant signal through a magnetic probe in the vicinity of the stator [106].

Fig. 2-10. (a) Signal coupling box (b) Measurement setup

The change in the phase lag between the injected signal and the measured magnetic flux can be used as an indicator for defect detection. This on-line technique depends on the characteristics of series inductor, capacitor and wiring connections. Also off-line machine winding equivalent circuit parameters are required in this technique to choose coupling box elements. Another technique based on voltage and current sensors is proposed in [107]. It injects high frequency signal through a power line communication device and receives the signal through voltage and current sensors to extract the frequency response of the impedance. Another similar technique is proposed in by using an impedance meter to extract frequency response [108]. However, all these on-line FRA techniques require careful design of protection circuit to isolate the measuring system from the high voltage power supply, and the protection circuit also constraints the bandwidth for the injecting signal and hence, their implementation is complicated and not widely used [109].

2.4 Summary

The defect diagnostic methods for transformers and motors, such as thermal analysis, DGA and PDA have been reviewed with their merits and limitations. Based on literature review, transformer winding displacement and deformation can only be diagnosed accurately using off-line FRA. Similarly, the same applied to

inter-turn short of stator winding in an induction motor. Nowadays, on-line condition monitoring techniques are important to minimize the downtime of critical electrical systems. Conventional on-line FRA based on capacitive coupling is more complicated to implement on-site, as it requires extra protection circuit. In addition, the ageing of capacitive coupling device has strong influence on the equipment's frequency response and it has limited bandwidth for wide applications. Therefore, techniques, which based on capacitive coupling are not well received by the industries. Hence, a simple and yet reliable on-line FRA method based on fully inductively coupled technique is the main motivation of this thesis.

Chapter 3 Inductively Coupled In-Circuit Impedance Measurement

3.1 Inductive Coupling Probes

Inductive coupling probes or current probes have been widely used for current measurements for metering or diagnostic purposes [110], [111]. There are two types of current probes, one for direct current (DC) measurement and another for alternating current (AC) measurement. The DC current probes are based on the Hall's effect and the AC current probes are based on the magnetic induction [112]. For the AC current probes, they can be used for inducing an AC signal into an electrical cable or receiving an AC signal from an electrical cable. The current probes can be clamped onto the cable without any direct electrical contact and therefore have little impact to the electrical system. There are various types of current probes available commercially with different bandwidth, current rating and aperture size, as shown in Fig. 3-1.

Fig. 3-1. Current probes (a) Low current rating and wide bandwidth (b) High
current rating and narrow bandwidth

The operating principle of current probes is similar to that of a transformer, where the primary winding is the current carrying conductor being clamped and the secondary winding is n-turn copper wire wound on a magnetic core. Its equivalent circuit model is shown in Fig. 3-2 [112].

Fig. 3-2. Current probe equivalent circuit (a) Basic circuit (b) Comprehensive circuit with parasitic elements

A current probe clamped onto a current carrying conductor is shown in Fig. 3-2(a) as a one-turn primary winding with n-turn secondary winding. The secondary winding is terminated with a burden resistor R . For a more comprehensive equivalent circuit shown in Fig. 3-2(b), parasitic components have to be considered, such as primary and secondary stray capacitances C_p and C_s . The magnetic core can be modeled as a magnetizing inductance L_m in parallel with a core loss resistance R_c . R_s and L_l represent the secondary winding resistance and leakage inductance, respectively. L_R is the equivalent series inductance of the burden resistor. Usually, the transfer impedance of current probe is required to convert the measured secondary voltage V_R to the primary conductor current. For in-circuit impedance

measurement, an injecting current probe (for example, Solar 9217-1N) and a receiving current probe (for example, Solar 9207-1) are necessary, as shown in Fig. 3-3(a) and Fig. 3-3(b), respectively. The transfer impedances of these current probes can be determined using a circular cross-section transmission-link calibration fixture (for example, Solar 9125-1) as shown in Fig. 3-3(c).

(a)

(b)

(c)

Fig. 3-3. (a) Injecting current probe (b) Receiving current probe (c) Calibration fixture for measurement of transfer impedance

The current probe can be clamped onto the inner conductor of the fixture and the outer conductor serves as the low impedance reference ground for the vector network analyzer (VNA), as illustrated in Fig. 3-4. One end of the fixture is connected to VNA's port 1 and the other end of the fixture is terminated with a 50 Ω .

Fig. 3-4. Measurement setup to extract the transfer impedance of the current probe

The transfer impedance of the current probe is defined as:

$$Z_T = \frac{V_2^-}{i_1} \quad (3.1)$$

where V_2^- is reflected voltage wave of the current probe and i_1 is the current flowing through the 50 Ω termination and it can be determined by:

$$i_1 = \frac{V_1^-}{50} = \frac{V_1^+(1+S_{11})}{50} \quad (3.2)$$

By substituting (3.2) into (3.1), the transfer impedance can be expressed in terms of S-parameters as follows:

$$Z_T = \frac{50V_2^-}{V_1^+(1+S_{11})} = \frac{50S_{21}}{1+S_{11}} \quad (3.3)$$

where S_{11} and S_{21} are the input port voltage reflection coefficient and the forward voltage gain, respectively. Through the above-mentioned measurement setup, the transfer impedance versus frequency for the injecting probe and the receiving probe

can be determined, as plotted in Fig. 3-5(a) and Fig. 3-5(b), respectively. As expected, the transfer impedance of the receiving probe is lower than that of the injecting probe.

Fig. 3-5. Transfer impedance of (a) Injecting probe (b) Receiving probe

3.2 Two-port Network Analysis

$ABCD$ or chain parameters of a two-port network are briefly introduced here as it will be adopted for the analysis of in-circuit impedance extraction based on

inductively coupling approach. Two-port $ABCD$ network is chosen as it can be easily cascaded for circuit analysis. As the measurements obtained from VNA are in terms of S-parameters, the conversion from S-parameters to $ABCD$ parameters will also be explained here for the benefit of readers. The scattering parameters or S-parameters are measured in the forms of incident, reflected and transmitted waves of a two-port network. However, the impedance or admittance of the two-port network deals with voltage and current.

Fig. 3-6. Two-port network expressed in terms of S-parameters

Fig. 3-6 shows a typical two-port network, where V_1^+ and V_1^- are amplitudes of the incident and reflected voltage waves at the port 1, respectively. The relationship of these waves can be expressed as S-parameters:

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} \quad (3.4)$$

where S_{11} , S_{12} , S_{21} and S_{22} are input port voltage reflection coefficient, reverse voltage gain, forward voltage gain, and output port voltage reflection coefficient, respectively. Two-port network can also be represented in terms $ABCD$ parameters, as illustrated in Fig. 3-7(a). The input and output voltages and currents as related as follows;

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (3.5)$$

(a)

(b)

Fig. 3-7. (a) Single two-port $ABCD$ network (b) Cascaded two-port $ABCD$ network

If there two two-port networks, as defined by $ABCD$ matrices shown in Fig. 3-7(b), where the respective networks are represented by (3.6) and (3.7), respectively:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (3.6)$$

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} V_3 \\ I_3 \end{bmatrix} \quad (3.7)$$

By substituting (3.7) into (3.6) gives:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} V_3 \\ I_3 \end{bmatrix} \quad (3.8)$$

It shows that the product of the two $ABCD$ matrices will give the $ABCD$ matrix of overall cascaded network. Table 3-1 shows the two-port $ABCD$ networks of a few commonly used circuits.

Table 3-1. *ABCD* parameters of commonly used networks

Series impedance model	Transmission line model
$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos \beta l & jZ_0 \sin \beta l \\ jY_0 \sin \beta l & \cos \beta l \end{bmatrix}$

If the two-port network measurement is done using VNA, the *ABCD* parameters can be obtained by converting *S*-parameters to *ABCD* parameters as follows [113]:

$$A = \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{2S_{21}} \quad (3.9)$$

$$B = Z_0 \frac{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}} \quad (3.10)$$

$$C = \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2Z_0 S_{21}} \quad (3.11)$$

$$D = \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}{2S_{21}} \quad (3.12)$$

where Z_0 is the characteristic impedance of the VNA.

3.3 In-Circuit Impedance Extraction with Inductive Coupling Probes

Fig. 3-8 shows the basic measurement setup to extract the in-circuit impedance using the proposed inductive coupling method. The high voltage AC power supply is represented by the source voltage V_S and the source impedance Z_S . The electrical system powered by the AC power supply has an impedance denoted as Z_E . To extract the in-circuit impedance, the measurement requires a VNA and two clamp-

on type current probes. Port 1 of the VNA induces a signal into the circuit through the injecting probe and port 2 of the VNA tracks the same signal via the receiving probe. The measurement setup in Fig. 3-8 can be modeled by an equivalent circuit formed by three two-port networks, N_{IP} , N_X and N_{RP} , as illustrated in Fig. 3-9. N_{IP} , N_X and N_{RP} are two-port networks of the injecting probe, unknown in-circuit impedance to be measured and the receiving probe, respectively. The unknown in-circuit impedance to be measured, Z_X is the resultant series impedance of Z_S , Z_W , and Z_E , where Z_W is the impedance of the wiring connection between $a-b$ and $a'-b'$.

Fig. 3-8. Basic setup for in-circuit impedance measurement

Fig. 3-9. Equivalent two-port networks model of the measurement setup shown

in Fig. 3-8

Usually, Z_S and Z_W are relatively small and Z_X is dominated by Z_E . The resultant $ABCD$ two-port network N_T seen by VNA's ports 1 and 2 is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_T = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{IP} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_X \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{RP} \quad (3.13)$$

where $\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{IP}$, $\begin{bmatrix} A & B \\ C & D \end{bmatrix}_X$ and $\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{RP}$ are two-port $ABCD$ networks of the injecting probe, in-circuit impedance to be monitored and the receiving probe, respectively. By defining voltage and current relations of two-port network of impedance to be monitored, $ABCD$ parameters of N_X are defined as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_X = \begin{bmatrix} \left. \frac{V_{x1}}{V_{x2}} \right|_{I_{x2}=0} & \left. \frac{V_{x1}}{I_{x2}} \right|_{V_{x2}=0} \\ \left. \frac{I_{x1}}{V_{x2}} \right|_{I_{x2}=0} & \left. \frac{I_{x1}}{I_{x2}} \right|_{V_{x2}=0} \end{bmatrix}_X \quad (3.14)$$

where V_{x1} , I_{x1} , V_{x2} and I_{x2} are input voltage and current of port 1 of N_X , and output voltage and current of port 2 of N_X , respectively, as indicated in Fig. 3-9.

By definition, A , B , C and D are open-circuit voltage transfer ratio, short-circuit transfer impedance, open-circuit transfer admittance and short-circuit current transfer ratio, respectively. The in-circuit impedance Z_X can be determined by solving parameter B in $\begin{bmatrix} A & B \\ C & D \end{bmatrix}_X$. By solving parameter B in N_X , Z_X can be extracted as follows:

$$Z_X = B_X = \frac{A_{RP}(D_{IP}B_T - B_{IP}D_T) - B_{RP}(A_TD_{IP} - C_TB_{IP})}{(A_{IP}D_{IP} - C_{IP}B_{IP})(A_{RP}D_{RP} - C_{RP}B_{RP})} \quad (3.15)$$

Before Z_X can be determined, the two-port networks of the two inductive coupling probes must be first characterized, which will be discussed in details in following section.

3.4 Characterization of the Current Probes

The $ABCD$ parameters of an ideal current probe is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1/n & 0 \\ 0 & n \end{bmatrix} \quad (3.16)$$

where n is number of turns of secondary winding wound on the magnetic core. In reality, all current probes are non-ideal due to leakage inductance, core loss and inter-winding capacitance. Therefore, the actual $ABCD$ parameters of a current probe have to be carefully characterized in the frequency range of interest so that Z_X can be determined accurately.

The injecting and receiving probes to be used for proposed setup will be characterized using a circular cross-section transmission-link calibration fixture. To ensure accuracy and repeatability, the voltage standing wave ratio (VSWR) of the calibration fixture should be less than 1.2 so that the most of the input signal is transferred to the output load with minimum reflection [114]. Fig. 3-10 shows the VSWR measurement setup. VNA's port 1 is connected to one of port of the calibration fixture with the other port terminated with $50\ \Omega$. The measured VSWR versus frequency of the calibration fixture is plotted in Fig. 3-11 and highest VSWR is 1.04 at 10 MHz, which is much less than the required 1.2.

Fig. 3-10. VSWR measurement setup for the calibration fixture

Fig. 3-11. Measured VSWR versus frequency (100 kHz to 10 MHz) for the calibration fixture

To characterize the current probe, the probe is clamped onto the inner conductor of the calibration fixture and the outer conductor serves as the common ground reference for the VNA. One end of the fixture is connected to the VNA port and the other end of the fixture is terminated with a short. For the receiving probe, VNA's port 1 induce a signal to the test fixture and the resultant current in the inner conductor induces a signal at the probe's output and measured by VNA port 2, as shown in Fig. 3-12(a). For the injecting probe, the connections to ports 1 and 2 are interchanged, as illustrated in Fig. 3-12(b). The equivalent circuits are derived based on the circuit model of the current probe shown in Fig. 3-2(b). Once the two-port S-parameters of the receiving and injecting probes are measured, they will be converted to the respective $ABCD$ parameters of N_{IP} and N_{RP} , as plotted in Fig. 3-13(a) and Fig. 3-13(b), respectively.

Fig. 3-12. Characterization of current probe (a) Receiving probe (b) Injecting probe

(a)

(b)

Fig. 3-13. Measured $ABCD$ parameters of (a) Receiving probe (b) Injecting probe

To provide an insight of the extracted $ABCD$ parameters of injecting and receiving probes, experiment setup shown in Fig. 3-12 are analyzed in terms of its equivalent circuit model, where Z_P , Z_M and Z_S are the impedances of the primary's core loss, magnetization and secondary winding, respectively. The resultant two-port $ABCD$ network seen by VNA's ports 1 and 2 is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_P \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1/Z_M & 1 \end{bmatrix} \begin{bmatrix} n & 0 \\ 0 & 1/n \end{bmatrix} \begin{bmatrix} 1 & Z_P \\ 0 & 1 \end{bmatrix} \quad (3.17)$$

By further manipulation of (3.17), it can be expressed as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} n \left(1 + Z_P/Z_M \right) & nZ_S \left(1 + Z_P/Z_M \right) + Z_P/n \\ n/Z_M & nZ_S/Z_M + 1/n \end{bmatrix} \quad (3.18)$$

$n < 1$ for the receiving probe shown in Fig. 3-12(a), as the primary has only one turn, which is the inner conductor of the calibration fixture. By observing the measured $ABCD$ parameters in Fig. 3-13(a), Parameter A in (3-18) is dominated by n and Z_P , which is inductive in nature with an inductance of 32 nH. Z_P in parameter B is negligible and therefore it is dominated by nZ_S , which is also inductive in nature with an inductance of 1.6 μ H. Parameters C and D are dominated by n and they are nearly constant and frequency invariant. For the measured $ABCD$ parameters of the injecting probe shown in Fig. 3-12(b), $n > 1$ and $Z_P \gg Z_M$. Parameter A is dominated by n and hence it is nearly constant with frequency. Since Z_S is negligible for injecting probe, parameter B is dominated by Z_P/n and is inductive nature with an inductance of 175 nH. Z_M and the parasitic capacitance causes a resonant in parameter C , as clearly observed in Fig. 3-13(b). According to (3.18), the injecting probe with smaller parameter C is expected to induce higher voltage at the secondary of the probe. Since Z_S is negligible for the injecting probe, parameter D is dominated by $1/n$ and is nearly constant with frequency.

3.5 Validation of Extracted Impedance

For validation of the proposed inductive coupling method in impedance extraction, a known component-under-test (CUT) is treated as an “unknown impedance” Z_{CUT} . For validation purpose, several known passive components of different values are chosen as Z_{CUT} . To reduce the influence of the inductance due to the wiring connection to the CUT , it is shortened to its minimum possible length.

Fig. 3-14. Measurement setup for experimental validation

The injecting and receiving probes are clamped onto the circuit loop and connected to ports 1 and 2 of the VNA, respectively; as shown in Fig. 3-14. The two-port $ABCD$ parameters of N_T are measured with the setup and N_X is obtained using (3.13) with the characterized $ABCD$ parameters of the two probes. The impedance Z_X , which is the resultant impedance of the wire loop and Z_{CUT} , can be extracted from parameter B of N_X as described in (3.15). Similarly, the wire loop impedance can also be extracted using the proposed method by replacing the CUT with a short. The impedance of the wire loop (Z_{WIRE}) can be de-embedded from Z_X to extract Z_{CUT} as follows:

$$Z_{CUT} = Z_X - Z_{WIRE} \quad (3.19)$$

A $33 \, \Omega$ ($\pm 5\%$) resistor is chosen as the CUT and Z_X and Z_{CUT} are extracted and plotted in Fig. 3-15. For comparison purpose, the loop impedance is also plotted. Based on the measured impedance, the wire loop has an inductance of 386 nH. For CUT with low impedance, the loop inductance has a significant impact on the accuracy of the extracted impedance at high frequency and have to be de-embedded. Fig. 3-15 shows that by de-embedding the loop's inductive reactance from Z_X , Z_{CUT} can be extracted with very good accuracy.

Fig. 3-15. Extracted CUT's impedance with and without de-embedded wire loop impedance

Therefore, the loop impedance will be de-embedded from the subsequent measurements for different CUT. Fig. 3-16 shows that the measured impedance of the three resistors (100 Ω , 1 k Ω and 10 k Ω) with the proposed inductive coupling method. The results agree well with the impedance measured directly using an impedance analyzer. Hence, it shows that the proposed method provides a good measurement dynamic range from 100 Ω to 10 k Ω , which is good enough for most practical situations. Similarly, the impedances of selected capacitors (0.01 μF , 0.1 μF and 2.2 μF) and inductors (47 μH , 470 μH and 1 mH) are also measured using the proposed method and the results are shown in Fig. 3-17 and Fig. 3-18, respectively. Again, good agreements are observed and the self-resonant frequencies of the capacitors and inductors are also agreed with the measurements from the impedance analyzer (Agilent 4294A).

(a)

(b)

Fig. 3-16. Comparison of extracted impedance of resistors using proposed two-probe method (TP) and impedance analyzer (IA) (a) Magnitude (b) Phase

(a)

(b)

Fig. 3-17. Comparison of extracted impedance of capacitors using the proposed two-probe method (TP) and the impedance analyzer (IA) (a) Magnitude (b) Phase

(a)

(b)

Fig. 3-18. Comparison of extracted impedance of inductors using the proposed two-probe method (TP) and the impedance analyzer (IA) (a) Magnitude (b) Phase

(a)

(b)

Fig. 3-19. Extracted impedance of the RLC circuit using the proposed method (TP) and the impedance analyzer (IA) (a) Magnitude (b) Phase

As most electrical systems such as transformers or motors exhibit either series or parallel resonant behaviors with frequency, second part of the validation is to extract impedance of series and parallel *RLC* circuits using the proposed method. Two circuits with known R , L and C values are used to emulate these behaviors. For series *RLC* circuit: $R = 1\ \Omega$, $L = 1\ \mu\text{H}$ and $C = 33\ \text{nF}$; and for parallel *RLC* circuit: $R = 1\ \text{k}\Omega$, $L = 1\ \mu\text{H}$ and $C = 33\ \text{nF}$. Fig. 3-19 shows the extracted impedance responses up to 10 MHz using the proposed method for the series and parallel *RLC* circuits. The impedance responses are in good agreement with the direct measurement using an impedance analyzer (Agilent 4294A).

3.6 Summary

This chapter has proposed a fully inductively coupled on-line FRA method to overcome the shortcomings of on-line condition monitoring based on capacitive coupling techniques described Chapter 2. The theory behind the proposed method is described. Using two inductive coupling probes and a VNA, the frequency response of in-circuit impedance of a powered up electrical system can be extracted with the help of two-port *ABCD* parameters analysis. De-embedding of the impedance of the wire connection can be easily done to enhance the measurement accuracy. Furthermore, the setup is relatively easy to be implemented compared to other proposed methods, as it does not have direct electrical contact with the high voltage power supply and hence, no shut down of power system is needed. This makes the method an attractive alternative for on-line condition monitoring purpose.

Chapter 4 On-Line Frequency Response Analysis of Electrical Equipment

4.1 On-Line Frequency Response Analysis of Transformer

4.1.1 Experiment Setup and Equivalent Circuit Model

Transformers are parts of the critical infrastructures in power delivery systems. Any early signs of defects, if not detected early, will cause power failures to thousands of households. Hence, real-time condition monitoring is essential to serve as detection of these early signs. This chapter focuses on how the proposed method described in Chapter 3 can be used to monitor the impedance frequency response of a transformer in real-time under its actual operating condition. For demonstration purpose, a 2:1 step-down 1.5 kW transformer is chosen as the transformer under test. The on-line monitoring setup is shown in Fig. 4-1(a). For analysis of results in the subsequent section, Fig. 4-1(b) shows equivalent circuit of the measurement setup with the transformer [115]–[118]. The primary winding of the transformer ($b-b'$) is connected to 230 V/50 Hz power mains ($a-a'$). Both the injecting and receiving inductive coupling probes are clamped onto the cable connecting between the power mains and the primary winding of the transformer. For a non-ideal transformer, there are hysteresis and eddy current losses in the core, and the total loss is modeled as a core loss resistance R_c . L_m represents the magnetizing inductance of the transformer. L_s and L_p are secondary and primary windings' inductances, respectively; whereas R_s and R_p are secondary and primary windings' resistances. The primary to secondary turn ratio of the transformer is denoted as n . C_p , C_s and C_T are parasitic capacitances of primary winding, seconding winding and

between windings, respectively. These capacitances usually show their effects at higher frequencies [115]. These capacitances (C_p , C_s and C_T) are indicated in Fig. 4-1(b). Fig. 4-1(c) shows the equivalent circuit of Fig. 4-1(b) referred to the primary of the transformer. Hence, the parasitic capacitances referred to primary are given by:

$$C_{T'} = \frac{C_T}{n} \quad (4.1)$$

$$C_{P'} = C_P + C_T \left(\frac{n-1}{n} \right) \quad (4.2)$$

$$C_{S'} = \frac{C_S}{n^2} + C_T \left(\frac{1-n}{n^2} \right) \quad (4.3)$$

(a)

(b)

Fig. 4-1. On-line monitoring setup for in-circuit impedance extraction of primary impedance of the transformer (a) Setup (b) Equivalent circuit (c) Equivalent circuit referred to the primary

The aforementioned parameters of the 1.5 kW transformer are extracted off-line using an impedance analyzer (Agilent 4294A). The core loss resistance and magnetizing inductance can be extracted with the measured primary impedance by keeping the secondary open-circuited. At low frequencies, the primary impedance is dominated by inductive reactance when the secondary is open-circuited. Then, the calculated total primary equivalent inductance using measured primary impedance is equal to $L_P + L_m$. Since the leakage inductance is much smaller than magnetizing inductance, primary inductance is equal to magnetizing inductance which can be determined using following equation.

$$L = \frac{|Z|}{2\pi f} \quad (4.4)$$

The core loss resistance is not constant over the frequency range due to nonlinear characteristic of the magnetic core [119] and usually is obtained using curve fitting method. The leakage inductance and winding resistance can be determined from measured primary impedance with the secondary short-circuited. When secondary

is short-circuited, measured primary impedance is dominated by leakage inductance and winding resistance. Therefore, the leakage inductance can be calculated from (4.4) at low frequency, using measured primary impedance and it is equal to $L_p + n^2 L_s$. The primary impedance at very low frequency is dominated by winding resistance and measured resistance at low frequency is equal to $R_p + n^2 R_s$. Similarly, secondary inductance can be calculated using measured secondary impedance when primary is short circuited. Once it is found, secondary capacitance can be calculated from (4.5) at resonant frequency. Table 4-1 shows extracted transformer equivalent circuit parameters.

$$\omega = \frac{1}{\sqrt{LC}} \quad (4.5)$$

Table 4-1. Transformer equivalent circuit parameters

Parameter	Description	Value
C_p	Primary capacitance	219 pF
C_s	Secondary capacitance	304 pF
C_w	Winding to winding capacitance	258 pF
R_c	Core loss	25 k Ω
L_m	Magnetizing inductance	58 mH
$R_p + n^2 R_s$	Total winding resistance referred to primary	272 Ω
$L_p + n^2 L_s$	Total leakage inductance referred to primary	1.08 mH

To validate the extracted equivalent circuit parameters of the transformer, a 150 Ω resistive load is connected as secondary load (Z_L) in Fig. 4-1(a). Then primary impedance is measured using the impedance analyzer and compared with the

simulated primary impedance based on the equivalent circuit model with the same load. Fig. 4-2 shows the comparison and close agreement is observed.

Fig. 4-2. Measured and simulated primary impedance of the transformer with 150 Ω resistive load

Parasitic capacitances and winding inductance of the transformer is expected to deviate from its norms if the winding is deformed or displaced. To illustrate their impacts on the primary impedance frequency response, simulations with the transformer terminated at 150 Ω secondary load are performed with variation of primary winding capacitance and inductance from their respective healthy values of 219 pF and 1.08 mH, respectively. The simulated primary impedance frequency responses with these capacitance and inductance variations are shown in Fig. 4-3(a) and Fig. 4-3(b), respectively. They show that any slight change of these parameters due to deformation of winding can be detected through the FRA.

(a)

(b)

Fig. 4-3. Primary impedance frequency response (a) varying capacitance (b) varying inductance

4.1.2 In-Circuit Impedance Measurement of Transformer

To show the ability to extract the in-circuit impedance of the transformer under varying operating conditions, the primary impedance of the transformer is extracted under two loading conditions, with $Z_L = 150 \, \Omega$ and $Z_L = 270 \, \Omega$. The in-circuit impedance that consists of the transformer's primary impedance and the power source impedance Z_s will be monitored and measured using the proposed method. Before connecting the transformer to AC mains, Z_s can be extracted by adding a bypass capacitor across $a-a'$, which serves as an AC short across the transformer's primary. To know the exact impedance of the bypass capacitor, it is measured off-line with an impedance analyzer. Then, the bypass capacitor is connected across $a-a'$ and the resultant impedance of the source and the bypass capacitor is measured on-line. By doing so, the impedance of the bypass capacitor can be de-embedded from the measured in-circuit impedance to extract Z_s . Based on the extracted Z_s versus frequency shown in Fig. 4-4, it is inductive in nature and has an inductance of $1.8 \, \mu\text{H}$.

Fig. 4-4. Impedance frequency response of the power source impedance (Z_s)

Once Z_s is known, the bypass capacitor is removed and the transformer will be connected according to Fig. 4-1(a), where the on-line impedance to be monitored is the resultant impedance of the source, the wiring and the transformer's primary. Similarly, the wiring can be measured off-line. Once the source and wiring impedances are de-embedded, the primary impedance of the transformer can be determined. Fig. 4-5 shows the primary impedance of the transformer under two loading conditions (150 Ω and 270 Ω). Fig. 4-5 indicates that higher load resistance results in higher primary impedance at low frequency. As frequency increases, a parallel resonance happens due to the winding inductance and parasitic capacitance. The extracted primary impedance versus frequency under the two operating conditions has shown that the proposed on-line impedance monitoring has the ability to detect the impedance profile variation unique to a specific operating condition. It is obvious that the source impedance is negligible as compared to the primary impedance of the transformer and therefore the on-line impedance measured is dominated by the transformer primary impedance.

(a)

(b)

Fig. 4-5. On-line in-circuit primary impedance frequency response with $Z_L = 150 \, \Omega$ and $Z_L = 270 \, \Omega$ (a) Magnitude (b) Phase

For ease of analysis, the equivalent circuit referred to primary as shown in Fig. 4-1(c) is simplified to that shown in Fig. 4-6. The leakage inductances of primary and secondary windings are very small compared to the magnetization inductance and therefore neglected. Also, the inter-winding capacitance (C_T) is negligible too because the voltage drop across leakage inductances are insignificant [120]. Hence, the overall parasitic capacitance can be represented by a shunt capacitance C_e across the transformer primary, as shown in Fig. 4-6. The load resistance in series with winding resistance referred to primary side is represented by R_e . Also, the resultant leakage inductance due to L_p and $n^2 L_S$ is denoted as L_e .

Fig. 4-6. Simplified equivalent circuit of transformer referred to primary

Total impedance looking into $b-b'$ in Fig. 4-6 is given by:

$$Z_{b-b'} = R_P + Z_{par} \quad (4.6)$$

where Z_{par} is the parallel impedance of $1/j\omega C_e$, R_c , $j\omega L_m$ and $(R_e + j\omega L_l)$. The parallel impedance $R_c/j\omega L_m$ is much larger than $R_e + j\omega L_l$ for the both $Z_L = 150 \Omega$ and 270Ω . Therefore, $R_e + j\omega L_l$ dominates the measured impedance and results in the difference shown in Fig. 4-5(a). Hence, Z_{par} can be simplified as follows:

$$Z_{par} \approx \frac{(R_e + j\omega L_l) \left(\frac{1}{j\omega C_e} \right)}{R_e + j\omega L_l + \frac{1}{j\omega C_e}} \quad (4.7)$$

The parallel resonance occurs at $\omega_o = \frac{1}{\sqrt{L_l C_e}}$ and $|Z_{par}|$ will be:

$$|Z_{par}| = \sqrt{\left(\frac{L_l}{C_e R_e} \right)^2 + \frac{L_l}{C_e}} \quad (4.8)$$

Equation (4.8) reveals the impedance magnitude at resonance decreases with increasing load resistance, i.e. the parallel resonant impedance with $Z_L = 270 \Omega$ is lower than that with $Z_L = 150 \Omega$, as observed in Fig. 4-5(a), because of higher R_e .

Also, higher load resistance results in smaller leakage inductance, which leads to

higher resonant frequency, as $\omega_o = \frac{1}{\sqrt{L_l C_e}}$.

4.1.3 On-line Detection of Defects

To demonstrate the ability of the proposed method for on-line monitoring of impedance frequency response of the transformer as a tool of defect detection, a customized 1.5 kW step-down transformer as shown in Fig. 4-7 is designed and fabricated as the equipment under test (EUT). Extra 1, 2 and 3 turns in both primary and secondary windings are wound and these extra turns can be short-circuited externally to emulate defects within the transformer, as illustrated in Fig. 4-8.

Fig. 4-7. Fabricated transformer as EUT for on-line monitoring

Fig. 4-8. Turn-to-turn short in the primary (a) 1-turn shorted (b) 2-turn shorted (c) 3-turn shorted

A $100\ \Omega$ resistor (Z_L) is connected to the secondary of the transformer as a nominal load, as shown in Fig. 4-9. The primary terminals of the transformer ($d-d'$) are connected to 230 V / 50 Hz power supply ($c-c'$) through power cables. The injecting and receiving inductive coupling probes are clamped onto the power cable connecting between the power supply and primary of the transformer to extract the impedance response looking into $d-d'$. The frequency response of the primary's impedance will be extracted to monitor any deviation of the impedance of the transformer from its norms.

Fig. 4-9. Experimental setup for on-line frequency response measurement for inter-turn short circuit detection

Fig. 4-10(a) and Fig. 4-10(b) show the measured impedance responses looking into $d-d'$ with the inter-turn shorts of primary and secondary windings, respectively. The measurement frequency range is from 100 kHz to 2 MHz. Both the measured impedance responses show that the deviation of impedance due to inter-turn short can be detected. The impedance deviation is due to the changes of the transformer's winding inductance and capacitance from its normal condition. As both the primary and secondary windings are wound on the same core and according to Lenz's law, shorted turns in the primary or secondary winding do influence the magnetizing inductance, where it decreases with higher number of shorted turns. Inter-winding capacitance remains constant for both cases. The shorted turns in the primary and secondary winding reduces the overall parasitic primary winding capacitance. Fig. 4-10(a) shows that shorted turns in the primary winding have a more visible influence on the primary's impedance. As expected, the influence of shorted turns in the secondary winding is less visible, as shown in Fig. 4-10(b). A resonance around 250 kHz due to the winding inductance and parasitic capacitance is clearly observed. Below 250 kHz, the impedance is dominated by the transformer primary inductance, as well as the reflected inductance and load impedance from secondary to primary. With more turns shorted in the primary winding, the primary inductance reduces and the reflected secondary inductance is also reduced due to lower turn ratio. This inductance reduction is observed below 250 kHz in terms of inductive reactance. On the other hand, below 250 kHz, the inductive reactance increases with more shorted turns in the secondary winding, which is also well observed in Fig. 4-10(b). Above 250 kHz, the transformer's primary impedance is dominated by the parasitic capacitance of the winding.

(a)

(b)

Fig. 4-10. On-line impedance frequency response at $d-d'$ with shorted turns in the
(a) primary winding (b) secondary windings

With the emulated turn to turn short circuit in the primary and secondary windings, the frequency response from the primary impedance of the transformer has demonstrated its ability to detect changes of the transformer's internal parameters such as inductance and capacitance due to winding deformations, such as radial and axial movement of the windings, which is likely to affect the winding capacitance.

Before the on-line measurement, the two-port networks of the two inductive coupling probes are characterized off-line separately. Then the proposed method is applied through a two-step process. For the first step, the on-line two-port S -parameters are measured with the VNA through the inductive coupling probes. For the second step, the impedance of a system-under-test (SUT) is extracted based on the measured on-line two-port S -parameters from the first step. These two steps are rather straightforward without interrupting the SUT. For the results presented in this thesis, there is a total of 101 frequency points for the full frequency range, which takes less than 10 seconds using a VNA (Bode 100, 10Hz-40MHz) interfaced with a personal computer (Toshiba Portege R930, CPU 2.9GHz, RAM 8GB). To shorten the data processing time, one can select a few frequency points based on the characteristic of the SUT, instead of a full sweep across the whole frequency range.

In reality, defects deteriorate gradually over a period of time [24], [82] and the on-line FRA measurement monitors the winding's frequency response continuously, and thus is able to distinguish the gradual change of FRA spectrum due to the defects. Therefore, measurement data collected in the range of a few seconds is adequate to identify the potential fault before it deteriorates further. Also, specific diagnostic algorithm can be adopted for post-processing of data for decision-making, so that incipient faults can be detected early before they worsen to irreversible damage to the SUT.

4.1.4 Effect of Temperature on On-Line Frequency Response Analysis

Deviation of frequency response can be influenced by several factors such as temperature, humidity and contamination etc. [121] because the parameters of the EUT might be altered due to any of the above-mentioned factors and reflected in its impedance frequency response. Of all these factors, temperature and moisture content are the most significant amongst all. Therefore, temperature influence on the FRA will be investigated. A temperature chamber shown in Fig. 4-11 is used to vary the ambient temperature of the transformer. The experiment setup for on-line impedance measurement is similar to Fig. 4-9. Similarly, the $100\ \Omega$ resistor (Z_L) is placed outside the chamber and connected to secondary of the transformer through the temperature chamber feedthrough panel. The primary terminals of the transformer ($d-d'$) are connected to 230V / 50Hz power supply ($c-c'$) through wires via the temperature chamber feedthrough panel. The impedance frequency response of the transformer is measured and extracted at two temperatures, $30\ ^\circ\text{C}$ and $75\ ^\circ\text{C}$, as shown in Fig. 4-12.

Fig. 4-11. Temperature chamber

Fig. 4-12. Extracted impedance frequency response of the transformer at 30 °C and 75 °C

Above the resonant frequency, it is clearly observed that the equivalent capacitance of the transformer decreases with rising temperature. This is expected, as the permittivity of winding insulation made of enamels, decreases with higher temperature [122]. However, influence of the inductance is rather insignificant. By comparing the deviation graphically will be challenging to distinguish the temperature influence on the impedance, as the change is hardly noticeable. Similarly, impedance frequency response of the transformer with emulated inter-turn short in the primary is also measured for 30 °C and 40 °C, as shown in Fig. 4-13(a) and Fig. 4-13(b), respectively. The same is emulated at the secondary for 30 °C and 40 °C, as shown in Fig. 4-14(a) and Fig. 4-14(b), respectively. In both situations, the change in the equivalent inductance of the transformer is clearly observed due to the emulated inter-turn short.

Fig. 4-13. Extracted frequency response when inter-turn short at primary and the temperature (a) 30 °C (b) 40 °C

(a)

(b)

Fig. 4-14. Extracted frequency response when inter-turn short at secondary and the temperature (a) 30 °C (b) 40 °C

4.1.5 On-Site Measurement

To show the ability of the proposed method for on-line FRA outside laboratory, with the permission of the university's facility management department, one of the distribution transformers in a substation is chosen for on-site measurement. The selected 22 kV / 415 V step-down transformer is rated at 2500 kVA. Due to safety concerns, it is not allowed to clamp the inductive coupling probes on the 22 kV primary side of the transformer. Therefore, only the impedance frequency responses of the three-phase secondary feeders are measured and extracted. The injecting and receiving probes are clamped onto each of the three-phase feeders, as shown in Fig. 4-15 and Fig. 4-16.

Fig. 4-15. Transformer room electrical layout and location of the measurements point

Fig. 4-16. (a) Measurement setup behind switchboards (b) Clamped inductive coupling probes on three-phase feeder

To protect the measurement instruments from transients and surges, the two inductive probes are connected to the VNA through surge arrester, as shown in Fig. 4-17.

Fig. 4-17. Measurement setup with protection circuit

Fig. 4-18 shows the extracted impedance frequency response from 1 kHz to 6 MHz of each of the three phases. In general, all the three phases exhibit similar frequency response due to balanced loading conditions. As the transformer is powered up and connected to all the loads, it is not allowed to emulate any defect, as what has been carried out in the laboratory. Nevertheless, the measurement results presented have shown that the proposed method can be deployed on-site for practical applications.

Fig. 4-18. Extracted frequency response for each phase of feeder

4.2 On-line FRA of Single Phase Induction Motor

4.2.1 Experiment Setup and Equivalent Circuit Model

Stator winding insulation failures can cause intern-turn short, phase-to-phase short and winding grounded to motor frame through the slot, as shown in Fig. 4-19 [88]. The insulation degradation can be caused by contaminants, abrasion, vibration or voltage surge, as discussed in Chapter 2.

Fig. 4-19. Typical stator winding defects due to insulation failures

Fig. 4-20. Insulation damage that leads to defects in the stator windings in a three-phase induction motors. (a) Inter-turn short in the same phase. (b) Winding short. (c) Wining to stator short at the end of the stator slot. (d) Inter-winding short. (e) Lead to lead short. (f) Phase to phase short [123]

Some of the typical defects due to insulation failures in the stator winding are shown in Fig. 4-20. A single-phase 4-pole 120 W induction motor is chosen for on-line FRA and the laboratory experimental setup is shown in Fig. 4-21. It is powered by 230V / 50Hz AC power mains and both the injecting and receiving probes are clamped onto one of the wires between the power mains and the induction motor. A selected portion of the stator winding is artificially shorted to emulate inter-turn short and inter-coil short, as illustrated in Fig. 4-22.

Fig. 4-21. Experimental setup of on-line FRA of induction motor

Fig. 4-22. Emulated inter-turn and inter-coil shorts in the stator winding

4.2.2 Frequency Response of the Motor Impedance

The extracted impedance versus frequency looks into d-d' in Fig. 4-21, using the proposed method is plotted in Fig. 4-23. The measured frequency range is from 10 kHz to 1 MHz. A parallel resonance around 46 kHz is clearly observed due to the stator winding's inductance and parasitic capacitance. With reference to a stator winding of a new motor, deviation of the impedance frequency response can be seen when the inter-turn and inter-coil shorts in the stator winding are emulated. Shorted turns decrease the total number of turns of the stator's winding and reduce its inductive reactance, which is clearly observed. Similarly, the inter-coil short has significantly reduced the stator winding inductance, as observed in the frequency response. Based on FRA using the proposed method, it has shown its ability to detect deviation in the induction motor's electrical parameters, such as inductance and capacitance, due to defects within the stator winding while motor is in its usual operating condition.

Fig. 4-23. On-line impedance frequency response of the induction motor without and with emulated defects

4.3 On-line FRA of 3-Phase Induction Motor

4.3.1 Experiment Setup and Equivalent Circuit Model

The proposed method is extended for a 3-phase 4-pole star-connected 1 HP motor. For the experiment setup, the motor is powered by a 3-phase supply as shown in Fig. 4-24(a) and both injecting and receiving inductive probes are clamped onto the phase-A of the 3-phase cable. Fig. 4-24(b) illustrates the wiring connection of Fig. 4-24(a). The equivalent circuit model of each phase with respect to neutral ($A-N$, $B-N$ or $C-N$) is shown in Fig. 4-24(c) [124], [125], where R_l , R_2 , R_c , R_{sf} and R_{sw} are stator resistance, rotor resistance, core-loss resistance, stator-copper resistance at the anti-resonance frequency, and loss-equivalent resistance at the first resonance, respectively. L_l , L_2 , L_m and nL_l are stator-leakage inductance, rotor-leakage inductance, magnetizing inductance, and fraction of total stator L_l attributed to the first few turns of the first slot, respectively. The effective winding-to-neutral stray capacitance of the first slot and inter-turn winding capacitance are shown as C_{sf} and C_{sw} , respectively. One or more of the above mentioned parameters will deviate if there are faults in the stator and will be reflected in the frequency response of the motor. To demonstrate the ability of the proposed method to detect such faults, an inter-turn short circuit will be emulated and discussed in the next section.

Fig. 4-24. (a) Experimental setup for on-line FRA of 3-phase induction motor (b)

Wiring connection (c) Equivalent circuit per phase

4.3.2 Inter-turn Fault Diagnosis of 3-phase Motor

The stator winding consists of a bundle of insulated copper wires and the insulation of these wires can fail due to various reasons as discussed in Chapter 2. If the motor continues to operate with the degraded insulation, it can lead to irreversible damage to the motor subsequently. Therefore, it is important to detect early sign of inter-turn short within the stator winding so that the necessary preventive measures can be taken. To emulate such fault, two nearby turns within the stator winding in a specific stator slot is intentionally shorted, as shown in Fig. 4-25(a). Due to the inter-turn short, the effective number of turns in the winding of phase-A is reduced, as illustrated in Fig. 4-25(b) [126]. As a result, electrical parameters such as L_m , L_1 , L_2 , R_1 , R_{sw} and C_{sf} are expected to deviate from their norms.

Fig. 4-25. Emulated stator winding inter-turn short (a) Actual view (b) Circuit illustration

Since the inductance is directly proportional to the number of turns, L_m has reduced due to the inter-turn short. Similarly, for L_1 and L_2 too. The motor without the emulated inter-turn short will be used as a benchmark for comparison. Its in-circuit impedance frequency response from 10 kHz to 1 MHz for each phase is measured and extracted, as plotted in Fig. 4-26. As expected, the stator winding is inductive in nature but when frequency increases, the inter-winding capacitance causes a parallel resonance at around 36 kHz. Fig. 4-27, Fig. 4-28 and Fig. 4-29 show the extracted impedance frequency responses of phases A, B and C, respectively. As the inter-turn short is only emulated in phase-A, as illustrated in Fig. 4-25(b), its impedance frequency response has clearly revealed the deviation from its norms. On the other hand, impedance frequency responses of phases B and C remain unaffected, as shown in Fig. 4-28 and Fig. 4-29, respectively. The effective impedance extracted from phase A is in fact the impedance of phase A in series with those of phases B and C in parallel. The measurement results show that only the fault occurred in the respective phase is more visible in its frequency response. Therefore, the proposed method allows the identification of the defect in the respective phase.

Fig. 4-26. Impedance frequency response of the motor without emulated inter-turn short

Fig. 4-27. Impedance frequency response of phase A with the emulated inter-turn short

Fig. 4-28. Impedance frequency response of phase B with the emulated inter-turn short

Fig. 4-29. Impedance frequency response of phase C with the emulated inter-turn short

4.3.3 Repeatability of Frequency Response Extraction of Motor

In view of the need to monitor the condition of the motor in real-time, repeatability of on-line measurement is important to rule out unnecessary false alarm. To show the repeatability of the proposed method, frequency response of phase A is monitored over three days for the setup shown in Fig. 4-24(a). Fig. 4-30 shows the extracted impedance frequency responses at 9 am, 12 pm and 3 pm for three consecutive days, where the frequency responses are rather similar over the three days, a good indication for repeatability of the real-time condition monitoring data. When an inter-turn short happens, the deviation in the impedance frequency response is clearly observed.

Fig. 4-30. Extracted impedance frequency responses for a period of three days

4.3.4 Temperature Influence on On-line Frequency Response

Ambient temperature is one of the factors to be considered for on-line FRA. The impedance frequency response of phase A is extracted for a range of temperatures,

from 40°C to 80°C at 10°C intervals. The cable length $x = 1$ m, as shown in Fig. 4-24(a). The extracted impedance frequency responses are plotted in Fig. 4-31 and the impedance frequency response with inter-turn short is also plotted for comparison purpose. The ambient temperature has negligible impact on the impedance frequency response. Again, when the inter-turn short happens, the change in impedance frequency response is easily detected.

Fig. 4-31. Extracted impedance frequency response under varying ambient temperature

4.3.5 Cable Length Influence on On-line Frequency Response

To investigate the possible influence of cable length on the on-line FRA, the cable length, indicated as “ x ” in Fig. 4-24(a), increases from 1 m to 3 m. The impedance frequency responses for the two different cable lengths are plotted in Fig. 4-32. The resonant frequency shifts downwards when the cable length increases from 1 m to 3 m. It is expected, as longer cable length introduces additional inductance, which

leads to lower resonant frequency. It is also observed that the inter-turn short can be detected regardless of the cable length.

Fig. 4-32. Extracted impedance frequency responses for varying cable length

To analyze the extracted impedance frequency response, the per-unit-length (PUL) distributed equivalent circuit model for each phase of the 3-phase power cable is shown in Fig. 4-33 [127].

Fig. 4-33. PUL equivalent circuit model of the power cable for each phase

R_a and L_a are PUL wire resistance and inductance, respectively; and R_d and C_w are PUL dielectric loss and capacitance between wires, respectively. When the cable length increase from 1m to 3m, higher inductance and capacitance are expected,

which shifts the resonant frequency downwards. Therefore, during on-line FRA, the specific installation and power cable between the power mains and the motor will be taken as reference for monitoring the impedance deviation for defects detection purpose.

4.4 Summary

Using an in-house designed and fabricated transformer with emulated defects, the proposed method described in Chapter 3 has shown its capability to extract and detect the impedance variation due to the emulated defects in section 4.1. For actual implementation on-site for high voltage power transformers, the proposed method with proper protection measures has also shown its ability to extract the impedance response of an active transformer in a substation.

Using single-phase and 3-phase induction motors as systems under test, the defect detection capability of the proposed on-line FRA method has been demonstrated in section 4.2 and 4.3. Using the inter-turn short as an emulated defect, the proposed method has detected the deviation of impedance frequency response from that of a new induction motor. The repeatability of the proposed method has also been demonstrated to verify the reliability of the measured data. The influence of ambient temperature on the impedance frequency response is found to be negligible. However, the electrical installation of the motor, such as the length of the power cable does have an impact on the measurement data. Therefore, the impedance frequency response of the motor with specific length of cable must be taken into account to serve as the reference for subsequent on-line FRA analysis for defect detection.

The operating bandwidths of the inductive coupling probes can be tailored according to the electrical system's frequency response to achieve best defect detection performance. As demonstrated in this Chapter, different frequency ranges can be selected according to the transformer and induction motor's impedance responses. Due to the relatively large winding capacitance and inductance of the transformer winding, the resonant frequencies of the transformers are usually low and hence FRA measurement below 2 MHz are adequate for most transformers [23], [74]–[76]. For an example, a 400-MVA step-up transformer has a frequency bandwidth of 100 Hz to 1 MHz [23],[29]. On the other hand, FRA of induction motors are usually carried out from 10 kHz to 10 MHz due to relatively lower winding capacitance and inductance [128]-[129]. Therefore, the only modification is the right choice of probes without a complete change of the condition monitoring measurement instruments.

Chapter 5 Enhancement of Defect Detection Capability

5.1 Statistical Indicators for On-line FRA

In the previous chapter, the proposed on-line impedance extraction method has shown its ability to detect the emulated defects of a transformer and motors when those are connected to the power supply and operated under its normal operating condition. To enhance the detection sensitivity, advanced analytical methods such as machine learning, can be applied to convert the frequency response data to useful defect indication, especially for very small deviation in the frequency response data. As an example, the defects in the secondary winding are less visible, as shown in Fig. 4-10(b). One can deploy some statistical indicating tools to enhance the detection of this small impedance deviation by computing the amount of agreement or disagreement between two frequency responses [130]. Statistical methods such as root mean square error (RMSE), cross correlation coefficient (CCC), absolute logarithmic error (ASLE) are most suitable to provide better indication of the variation of measured parameter relative to its norm.

Let's consider measured impedance of the transformer without and with emulated defect as two functions $A(f)$ and $B(f)$, respectively. RMSE of $A(f)$ and $B(f)$, can be computed as follows [18]:

$$RMSE_{(A,B)} = \sqrt{\frac{\sum_{i=1}^N [A(i) - B(i)]^2}{N-1}} \quad (5.1)$$

where $A(i)$ and $B(i)$ are the i^{th} values of measured impedance of the transformer without and with emulated defect at a specific frequency, respectively; where N is

the total number of sampled impedance values. RMSE indicates variation of $A(f)$ with respect to $B(f)$. RMSE shows a low value when $A(f)$ and $B(f)$ are very close. On the other hand, high value of RMSE indicates that the two data sets are spread widely. Literature shows that the meaningful information scattered around the valley or lower values in a magnitude response is often underestimated with RMSE. CCC is another technique that can be adopted to compare the similarity of two data sets and it is computed as follows:

$$CCC_{(A,B)} = \frac{\sum_{i=1}^N A(i)B(i)}{\sqrt{\sum_{i=1}^N [A(i)]^2 \sum_{i=1}^N [B(i)]^2}} \quad (5.2)$$

CCC is considered inadequate for the comparison of frequency responses, which may include the patterns similar in shape but different in magnitude. It tends to over-estimate the generation, elimination and deviation in existing resonant frequencies. Therefore, fully log-scaled comparison ASLE has been proposed in [27] as an improved statistical technique to provides more equitable indication compared to RMSE and CCC. Mathematical expression of ASLE is given by following equation.

$$ASLE_{(A,B)} = \frac{\sum_{i=1}^N |20 \log_{10} A(i) - 20 \log_{10} B(i)|}{N} \quad (5.3)$$

In next sections above indicators are calculated and analyzed to enhance the defect detection capability of transformer and motor using on-line FRA.

5.2 Transformer Defect Detection Using Statistical Indicators

Impedance near the resonant frequency can vary significantly and affect the repeatability of the indicators. Therefore, for the study described here, the sample

size $N = 801$, sampled values $N = 1$ to 17 are below resonance and sampled values $N = 18$ to 801 are above resonance. Using the measured impedance frequency responses in Fig. 4-10(a) and Fig. 4-10(b), the computed RMSE is plotted in Fig. 5-1.

Fig. 5-1. Computed RMSE for inter-turn short at the primary and secondary windings

Based on the literature reviews, a deviation $> 1\%$ from its base value will translate to $RMSE > 1$, which is indicated as the critical level of RMSE, as shown in dash line in Fig. 5-1. RMSE has demonstrated its ability to provide alert of either 1, 2 or 3 turns short in both primary and secondary windings but it tends to be over sensitive for the inter-turn short in the primary below resonant frequency. Also small frequency shift of the resonance in impedance frequency responses has a strong influence in the RMSE indicator [27].

Fig. 5-2 shows calculated CCC and critical region of CCC is defined with $CCC < 0.9998$. It shows that the calculated CCC only alerted 2 or 3 turns short in the

primary winding above the resonant frequency but failed to alert for other cases, which clearly reveals its inadequacy to provide good indicator for defects that associated with small impedance change.

Fig. 5-2. Computed CCC for inter-turn at the primary and secondary windings

In fact, CCC approaches 0 if the impedance's frequency responses are very different and approaches 1 if the impedance's frequency responses are of similar trend. For example, considering a particular condition of $A(i) = cB(i)$ at some frequencies where c is a constant coefficient, CCC tends to approach 1 if c is large. It may mislead the final decision and therefore not a good choice to differentiate impedance's frequency responses with similar trend.

Finally, ASLE is calculated and plotted in Fig. 5-3. Its critical region is defined as $ASLE > 0.3$, as indicated in Fig. 5-3. ASLE has shown its superiority over the earlier two techniques in providing alert of either 1, 2 or 3 turns short in both primary and secondary windings.

Fig. 5-3. Computed ASLE for inter-turn short at the primary and secondary windings

For ASLE, equidistant logarithmic vertical and horizontal axis of the impedance frequency responses overcomes the issues faced by CCC and RMSE. Therefore, it is most suitable for detection of impedance frequency response's variation of an EUT. Hence, it is important to select the proper statistical indicator to enhance defect detection capability in on-line monitoring [132].

To evaluate the temperature influence on the defect detection which is discussed in section 4.1.4, ASLEs of Fig. 4-13 and Fig. 4-14 are computed and plotted in Fig. 5-4(a) and Fig. 5-4(b), respectively. At 30 °C, ASLE is above the critical limit and increases with severity of the defect, i.e. more number shorted turns. At 40 °C, ASLE is less than that of 30 °C but it is still able to detect the defect clearly.

The proposed method is ideal for electrical systems where their capacitance and inductance are influence by potential defects. Therefore, electrical systems such as transformers and induction machines are most suitable for the proposed method.

Other sensors, such as voltage, current, vibration and temperature sensors can be deployed to capture additional parameters and integrate with the proposed method to develop a comprehensive on-line condition monitoring system, of course at higher costs.

(a)

(b)

Fig. 5-4. Computed ASLE for inter-turn short at (a) Primary (b) Secondary under different temperatures

5.3 Induction Motor Defect Detection Using Statistical Indicators

On-line FRA of induction motors are discussed in section 4.2 and 4.3. CCC, RMSE and ASLE statistical analyses can be adopted for enhancement of identifying stator winding's defects and computed indicators are shown in Table 5-1. All three indicators clearly show their ability to provide good indication of stator winding's defects. To find the most suitable statistical indicator for defect detection purpose, deviation caused by the defect in terms of percentage is calculated as follows:

$$\text{Deviation}(\%) = \frac{|\text{Critical Limit} - \text{Calculated Value}|}{\text{Critical Limit}} \times 100 \quad (5.4)$$

Table 5-1. Critical limits and calculated values of statistical indicators

Statistical Indicator	Critical Limit	Inter-turn Short		Inter-coil short	
		Calculated Value	% Deviation	Calculated Value	% Deviation
CCC	< 0.9998	0.9968	0.3	0.8563	14
RMSE	> 1.0	553	55200	2812	281100
ASLE	> 0.4	0.53	33	1.38	245

From Table 5-1, it can be seen that the deviation of CCC for the emulated inter-turn short is only 0.3%, which indicates its poor sensitivity in the detection of minor defect in the stator winding. On the other hand, deviation of RMSE is so significant for the inter-turn short, which tends to be over-sensitive for minor defect and may lead to high false alarm rate. Again, the fully log-scaled ASLE provides reasonable deviation as well as good discrimination between minor (inter-turn short) and major (inter-coil short) defects, which fits well for condition monitoring with the purpose of defect detection and differentiation.

Chapter 6 Conclusion and Future Work

6.1 Conclusion

On-line condition monitoring of a critical electrical infrastructure for early signs of defects is important for preventive maintenance purposes, which is not achievable using the conventional off-line measurement techniques. This thesis proposes an on-line FRA technique based on a fully inductively coupled approach, where there is no direct electrical contact with high voltage electrical system is needed.

With the system to be monitored remains connected with the high voltage power supply under its usual operating condition, the proposed method has the ability to extract the impedance frequency response of the system for specific frequency range of interest. It can be easily installed on-site without the need of shutting down the power and only requires a one-time calibration process. Hence, it overcomes the shortcomings of other existing on-line FRA methods, such as capacitive coupling, where extra design effort is needed to provide the necessary electrical isolation to the on-line measurement instruments. Therefore, the proposed method eliminates the electrical safety hazards and service interruption during the implementation process.

The proposed method is first validated using known passive components as unknown impedance to be measured. Subsequently, it is applied to transformers and induction motors for on-line FRA. Through emulated defects, the ability of the proposed method for defect detection is demonstrated experimentally. For example, the frequency response of an operational transformer is extracted for an on-line condition monitoring purpose.

The implementations of on-line condition monitoring systems are usually more expensive as compared to off-line condition monitoring systems. However, the merits outweigh the cost, especially if there is an irreversible damage to the critical electrical systems. Comparing to existing on-line condition monitoring systems based on capacitive coupling method, the proposed inductive coupling method does not require additional protection circuit and therefore simple and cost effective. The clamp-on type inductive coupling probes and VNA with embedded computer are commonly available instruments in the market. As there is no direct electrical contact to the electrical systems to be monitored, the proposed measurement setup can be easily installed on-site without modification of the electrical systems. With the move towards a smarter grid, on-line condition monitoring becomes a necessity, especially for critical electrical infrastructures such as transformers and induction motor-driven machines, as demonstrated in the thesis. Also, the operating bandwidth of the on-line measurement system and the number of frequency points can be easily tailored to a specific electrical system based on its frequency characteristic with frequency.

To enhance the defect detection capability for slight impedance deviation, various statistical diagnostic indicators have also been explored and studied. By combining the proposed on-line FRA method with a suitable diagnostic indicator, detection of very slight deviation of impedance response is feasible.

6.2 Future Work

With the successful development and demonstration of the hardware design of the proposed inductively coupled on-line FRA method, the following future work is worth exploring:

- On-site implementation of the proposed method on an electrical system for long-term data collection to predict the life-span of the system under test;
- Study the mean-time-between failures (MTBF) before and after the implementation of the proposed method in condition monitoring; and
- Feasibility study of machine learning model to differentiate various types of defects for fault diagnostic.

Author's Publications

Journal Publications

1. Kangrong Li, Kye Yak See and Sooriya Bandara Rathnayaka, “Impact analysis of conducted emission measurement without LISN”, *IEEE Trans. Electromagnetic Compatibility*, vol. 58, no. 3, pp. 776–783, June 2016.
2. Sooriya Bandara Rathnayaka, Kye Yak See and Kangrong Li, “On-line impedance monitoring of transformer based on inductive coupling approach”, *IEEE Trans on Dielectrics and Electrical Insulation*, vol. 24, no. 2, pp. 1273-1279, April 2017.
3. Sooriya Bandara Rathnayaka, Kye Yak See and Kangrong Li, “Inductively coupled on-line impedance measurement for condition monitoring of electrical equipment”, *IET Science, Measurement and Technology*, vol. 12, no. 3, p. 382 – 387, May 2018.

Conference Publications

1. Sooriya Bandara Rathnayaka and Kye Yak See, “Early detection of induction motor’s defects using an inductively coupled impedance extraction method”, *IEEE International Electric Machines and Drives Conference*, Florida, USA, May 2017, pp. 1-6.
2. Kye Yak See and Sooriya Bandara Rathnayaka, “Early detection of inter-turn stator winding short of an induction motor using an online frequency response method”, *1st World Congress on Condition Monitoring (WCCM)*, London, UK, June 2017, presented.
3. Sooriya Bandara Rathnayaka, Kye Yak See, Manish Prajapati, Kangrong Li and Nishshanka Bandara Narampanawe “Inductive coupling method for on-

- line FRA for transformer winding diagnostic”, *IEEE Region 10 International Technical Conference (TENCON)*, Penang, Malaysia, November 2017, pp. 88 - 92.
4. Sooriya Bandara Rathnayaka, Kye Yak See, Manish Prajapati, Kangrong Li and Nishshanka Bandara Narampanawe “Influence of temperature on transformer's winding defect analysis using inductive probes”, *Progress in Electromagnetics Research Symposium (PIERS)*, Singapore, November 2017, pp. 2285 - 2289.
 5. Nishshanka Bandara Narampanawe, Kye Yak See, Sooriya Bandara Rathnayaka, Jie Zhang, Kangrong Li, Eng Kee Chua and Wei Peng Goh “An empirical characterization of a flexible current probe for in-circuit impedance measurement”, *Progress in Electromagnetics Research Symposium (PIERS)*, Singapore, November 2017, pp. 2703 - 2706.

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