CONDITION MONITORING AND ASSESSMENT OF POWER TRANSFORMERS USING SWEEP FREQUENCY RESPONSE ANALYSIS AND DISSOLVE GAS ANALYSIS.

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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ABSTRACT

Power transformer can be considered as the key element in an electricity power system. Cost and the time of installation of a power transformer are significantly higher than the installation of other equipment. Applied electrical and thermal stresses due to various factors always deteriorate the condition of transformers. In this sense, it is important to monitor and assess the condition of Power Transformers to ensure longer operation as well as to maintain a reliable operation of a power system.

Sweep Frequency Response Analysis (SFRA) can be used to assess the mechanical integrity of transformers. The test measures the transfer function response of the active part of the transformer. The three frequency responses of three phases should be identical except to inherited variations, and therefore, it can be considered as a fingerprint for a transformer. If any physical changes occur within and between the elements of the transformer, it will affect the frequency response, which can be used to detect any abnormality. However, correct interpretation of the measured response in determining the transformer condition is a critical challenge, as interpretation of frequency response is still not fully established.

On the other hand, Dissolve Gas Analysis (DGA) can be used to assess the possible stresses that could have been applied on the oil immersed transformers based on the concentration of specific gases dissolved in oil. Several diagnosis tools recommended by international standards are available and they have been using by utilities over a period of time with reasonable reliability.

In this study, SFRA and DGA measurement data were collected from set of power transformers in operation, and analyzed those approaching to develop a methodology to assess the condition of power transformers, correlating outcomes from SFRA and DGA. For this, transformers taken for the study were categorized based on their SFRA data by analyzing behavior of the response of the three phases and their

similarity. Several indices were introduced to quantify the similarity. In the other hand, the selected transformers were categorized based on their DGA data considering the recommendations provided by available standards and diagnosis tools. Further, a Computing Tool was developed using MATLAB, for the easy evaluation of the SFRA and DGA measurements.

Finally, several case studies were carried out justifying the proposed methodology verifying the benchmarking of the introduced indices against several faulty and good transformers.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CCF	Cross Correlation Coefficient
CEB	Ceylon Electricity Board
DGA	Dissolve Gas Analysis
DGAI	Dissolve Gas Analysis Index
GS	Grid Substation
HV	High Voltage
LV	Low Voltage
SFRA	Sweep Frequency Response Analysis
TDCG	Total Dissolved Combustible Gas

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Chapter 1

INTRODUCTION

1.1 Background

Power transformer can be considered as the key element in an electricity power transmission system. Compared to other equipment, cost and time of installation of a power transformer is significantly higher. Further, at a failure of one transformer the time to replace it with another would be comparatively higher than the replacement of other equipment in similar case. As a result,

- Cost of outage time would be high
- Other transformers and associated transmission lines would be heavily loaded
- There may be load shedding in relevant areas

In this context, it is extremely important to monitor and assess the condition of transformers to ensure a reliable operation of the transformers as well as the system. Thus, a properly coordinated condition monitoring program for power transformers is necessary to address operation and maintenance aspects.

Various methods and techniques for condition monitoring and diagnostic testing of power transformers have been introduced in time to time while expanding the scope for condition monitoring of power transformers. Dissolve Gas Analysis (DGA) is a widely used method of assessing the gasses dissolved in transformer oil and thereby predict the condition of the transformer and possible stresses could have been applied on. Sweep Frequency Response Analysis (SFRA) is a non conventional technique which used to study the mechanical integrity by means of the transfer function of the transformer. Combination of these two analysis methods can be identified as a novel analysis method which leads the subject of condition monitoring of power transformers in to a new direction.

1.2 Requirement of Methodology for Condition Monitoring

Condition of a transformer in operation for a certain period of time cannot be expected to be the same as at its very first energization. Electrical and thermal stresses that could have applied externally as well as internally always deteriorate the condition of a transformer. Those stresses can be due to various factors as mentioned below.

- Aging of the transformer
- Loading pattern of the transformer
- Poor maintenance practices on the transformer
- Fault current flowing through the transformer
- Mechanical deformations due to transportation and installation issues

In this sense, transformers should be monitored regularly and assess their condition in order to operate and maintain them optimally. If the condition could have been monitored in certain intervals and thereby assess them based on proper methodology, operation and maintenance of the transformers could have been more effective, and driven towards to improve or at least to slowdown deteriorating the condition there on.

Further assessing of condition of transformers and indexing them could also be utilized in development and expansion planning of the network. Decision to retire a transformer after a certain period of time should not be based only upon its age, but the actual condition of it. This can be derived by a proper monitoring and assessing methodology, which helps to optimize the utilization of transformers and avoid un planned investment.

1.3 Objectives of the Study

The main objectives of the study is to develop a methodology to assess the condition of power transformers based on the results obtained from SFRA and DGA measurements of the transformer.

Transformers will be indexed according to their heath condition which will be predicted based on the condition reflected out form the SFRA and DGA results. Thereby the transformer will be categorized as shown the Table 1.1.

Table 1.1: Assessment of Transformer Health Condition

Description	Rating Code	Condition
Condition Index < L1	1	GOOD
L1 ≤ Condition Index < L2	2	ACCEPTABLE
L2 ≤ Condition Index < L3	3	POOR
L4 ≤ Condition Index	4	VERY POOR

Based on this assessment, transformers that are in operation can be ranked based on their health, so it can be used as a tool for customize and prioritize maintenance as well as in decision making related to the investment and system planning.

1.4 Methodology

The Magnetic Core and the Windings are the prime hardware of a transformer. Oil immersed paper acts as the major solid insulation between various parts like core to windings, High Voltage (HV) winding to Low Voltage (LV) windings, live to earth, etc. Core and winding with the solid insulation are hold together using a clamping structure. The combination of these is known as the active part of the transformer, and it is the prime factor that decides the heath condition of a transformer. In this sense, assessing the condition of the active part of a transformer means the assessing the condition of the transformer.

Therefore, in this study the condition of the transformer shall be assess by the means of studying the quality of winding, core, paper insulation and the condition of the associated clamps and supports structure.

SFRA is a tool which can be used to analyze the transfer function of the transformer. Two electrical transfer functions (amplitude response and phase response) can be obtained by performing the test on various winding arrangements over a wide frequency range. There are three basic analysis methods are used to diagnose power transformers. They are,

1. Time based (current SFRA results will be compared to previous results of the same unit)
2. Type based (SFRA of one transformer will be compared to another of the same design)
3. Phase comparison (SFRA results of one phase will be compared to the results of the other phases of the same transformer)

Those methods are basically used to evaluate the mechanical integrity of core, windings, leads and clamping structures of a power transformers. For this study, Phase comparison of three phase transformers was used. The core and winding assembly of power transformers can be seen as a complex electrical network of resistances (R), inductance (L) and capacitance (C). This includes self inductances, ground capacitances, coupling inductances and series capacitances (complex RLC network). The three frequency responses of three phases should be identical except inherited variations, and therefore, it can be considered as a fingerprint for a transformer. Geometrical changes within and between the elements of the network cause deviations in its frequency response. Thus, a deviation of the frequency response compared to other phases indicates a deviation of the RLC network of the transformer from its original state. Those kinds of deviations can be occurred due to shocks and vibrations on the transformer during transportation, flowing of a huge fault current through the transformer, imbalance of axial or radial forces due to design weaknesses, etc.

DGA is a tool which can be used to analyze the gas components dissolved in the insulating oil in the transformer by analyzing oil sample taken from the transformer. Gas components like H_2 (Hydrogen), CH_4 (Methane), CO (Carbon Monoxide), CO_2

(Carbon Dioxide), C_2H_4 (Ethylene), C_2H_6 (Ethane), C_2H_2 (Acetylene), O_2 (Oxygen), N_2 (Nitrogen) are measured in parts per million (ppm). Those kinds of gases can be generated due to various electrical and thermal stresses in the transformer. Some of these gasses are considered as dangerous as they are generated only under serious faults, while some of gasses are considered as not dangerous but should be alarmed depend on their quantity has been formed.

Analysis of the condition of the transformer using both methods (SFRA & DGA) can be more effective. Power transformers of the transmission network in Ceylon Electricity Board (CEB) shall be subjected to analyses and some of them will be specially considered for case studies. Further, ability to use both of these methods effectively on condition monitoring shall be studied and accordingly a correlation between SFRA and DGA on transformer diagnostics shall be developed. A computing tool shall be developed to calculate the acceptance and condition indexes based on pre defined algorithms, which are to be developed through the analysis of SFRA and DGA data.

Chapter 2

LITERATURE REVIEW

2.1 Sweep Frequency Response Analysis (SFRA)

2.1.1 SFRA theory

When a transformer is subjected to SFRA testing, the leads are configured in such a manner that four terminals are used. These four terminals can be divided into two unique pairs, one pair for the input and the other pair for the output. These terminals can be modeled in a two terminal pair or a two port network configuration. Figure 01 illustrates a two port network where Z11, Z22, Z12 and Z21 are the open circuit impedance parameters.

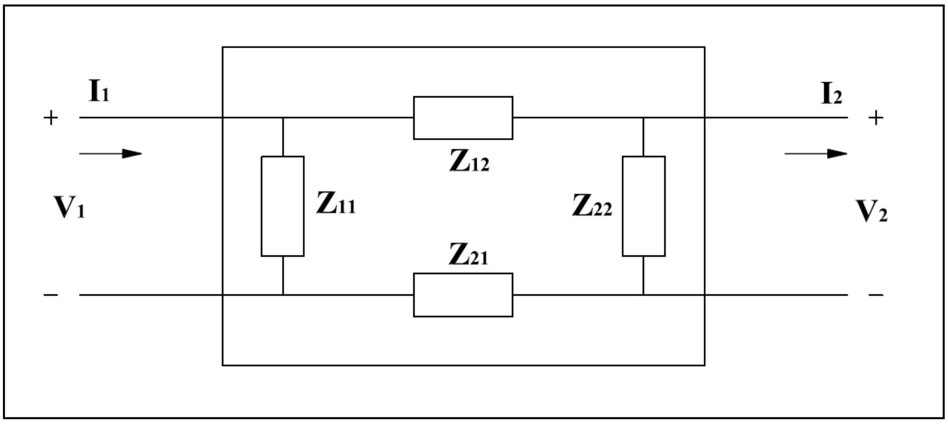


Figure 2.1: Two port network

The transfer function of this network is represented in the frequency domain and is denoted by the Fourier variable H(jω), where (jω) denotes the presence of a frequency dependent function and $\omega = 2\pi f$. The Fourier relationship for the input versus output transfer function is given by equation 2.1.

$$H(j\omega) = \frac{V_{output}(j\omega)}{V_{input}(j\omega)} \qquad (2.1)$$

When a transfer function is reduced to its simplest form, it generates a ratio of two polynomials. The main characteristics, such as half power and resonance of a transfer function occur at the roots of the polynomials. The roots of the numerator are referred to as “zeros” and the roots of the denominator are “poles”. Zeros produce an increase in gain while poles cause attenuation [3].

The goal of SFRA is to measure the impedance model of the test specimen. When the transfer function H(jω) is measured, the true specimen’s impedance Z(jω) is positioned between the instrument leads, but it does not include any impedance supplied by the test instrument.

The transfer function is presented in a Bode plot with its magnitude and phase as follows.

$$A(dB) = 20log_{10}\big(H(j\omega)\big) \qquad (2.2)$$

$$A(\Theta) = tan^{-1}\big(H(j\omega)\big) \qquad (2.3)$$

Figure 2.2 shows a typical response for a high voltage star connected winding. The frequency range of interest is between 20 Hz and 2 MHz.

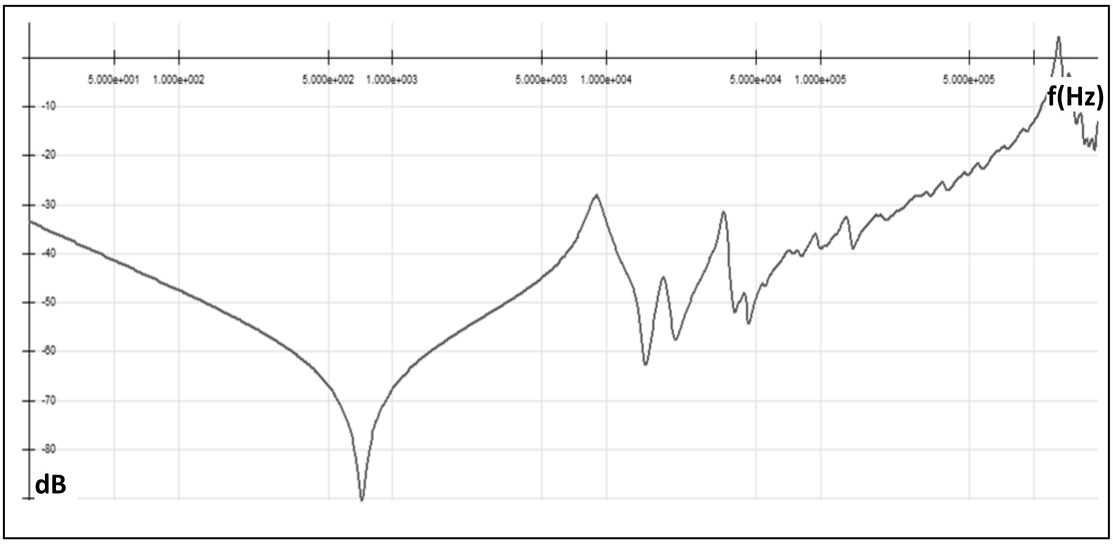


Figure 2.2: Typical SFRA plot

2.1.2 Use of SFRA

The SFRA technique has been using to compare the mechanical integrity of transformers in time vise, type vise or phase vise [1]. There are two categories for application of SFRA measurement, there are, baseline measurement and diagnostic measurement. In both cases, the procedures and precautions used to generate a good measurement are the same. However, there is a difference in motivation for the tests in each category.

2.1.2.1 SFRA base line measurement

The base line SFRA measurement may be done in either at the factory or the field, and it provides information that can be used for some future need. The several distinct reasons to generate base line SFRA measurements are as follows,

- To provide a standard of comparison for future diagnostic SFRA measurements
- Transportation diagnostics prior to relocation and commissioning
- Prior to short circuit testing
- Quality assurance

Important factors to consider when performing baseline SFRA measurements include determining the necessary tests and connections that might later be needed for diagnostic purposes. The test configuration can have an impact on the test results [1].

2.1.2.2 SFRA diagnostic application

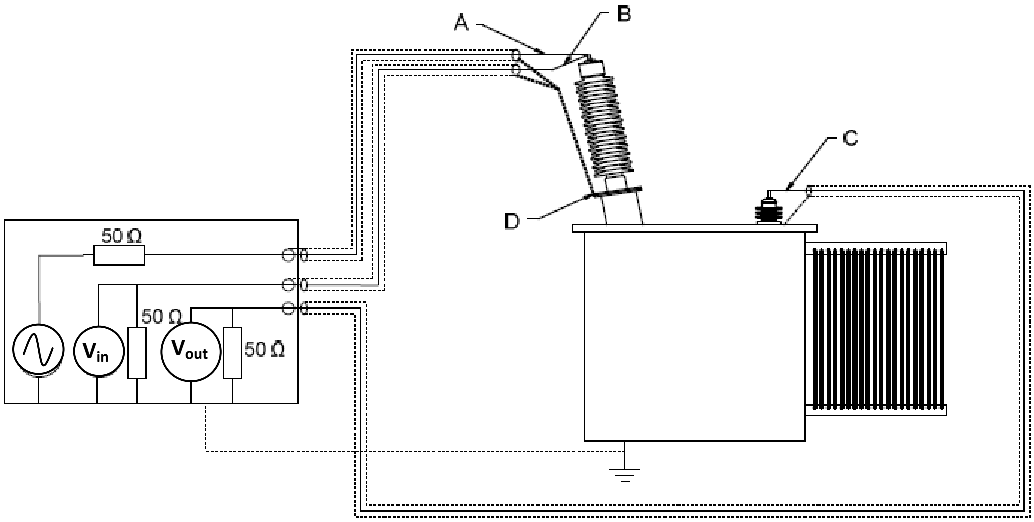
The several distinct reasons to generate diagnostic SFRA measurements within a factory or field environment are as follows,

- Verification that no damage occurred during a short circuit test
- Relocation and commissioning validation
- Post incident verification such as lightning, external through fault, internal short circuit, seismic event, etc.
- Condition assessment of older transformers
- Shipping and receiving

Important factors to consider when performing diagnostic SFRA measurements include matching the set up and instrumentation parameters used for the baseline measurements. When baseline data is not available, data on duplicate transformers or other identical phases of a three phase transformer may be used.

2.1.3 SFRA measurement method

To make a frequency response measurement, a low voltage signal is applied to one terminal of the test object with respect to the tank. The voltage measured at this input terminal is used as the reference signal and a second voltage signal (the response signal) is measured at a second terminal with reference to the tank. The response voltage measurement is made across an impedance which is the input impedance of the response measuring channel, and is chosen to be 50 Ω. To make an accurate ratio measurement, the reference and response measurement channels and leads are identical. A general layout of the measurement method is shown in Figure 2.3



A	Source Lead
B	Reference Lead
C	Response Lead
D	Earth Connection

Figure 2.3: Schematic of the frequency response measurement circuit
(Source IEC 60076-18)

2.1.4 Measurement types and test connections

Three basic types of measurements are recommended by both IEEE and IEC guidelines for SFRA measurements of Transformers namely, Open Circuit Measurement, Short Circuit measurement and Inter Winding measurement [1], [2].

2.1.4.1 Open circuit measurement

An open circuit measurement is made from one end of a winding to another with all other terminals floating. This measurement is done both for HV and LV windings. Open Circuit tests are primarily influenced by the core properties at or around the fundamental power frequency.

2.1.4.2 Short circuit measurement

The short circuit measurement is made from one end of a high voltage winding to another while the associated low voltage winding is shorted. This ensures all three phases are similarly shorted to give consistent impedance. The short circuit test isolates the winding impedance from the core properties at or around the fundamental power frequency.

2.1.4.3 Inter winding measurement

There are two types of inter winding measurements called capacitive inter winding measurement and inductive inter winding measurement. The capacitive inter winding is performed between two electrically isolated windings, where input signal from one end of a winding and measure the signal through one of the terminals of another winding, with all other terminals floating. The inductive inter winding measurement, is performed between two windings while one end of each winding is grounded.

2.1.5 Characteristics of SFRA plot

2.1.5.1 Regions of the SFRA plot

Different frequency response characteristics can be expected for the various types of transformers, since a transformer’s frequency response has a fundamental relationship with the core and winding structure. Experience has shown that different frequency bands are dominated by different internal components of the transformer, and there by the frequency response can be divided into three main regions based on the dominating component within the frequency band [3]. The lower frequency region dominated by the core, the middle frequencies dominated by the interactions between the windings and the higher frequency region controlled by the individual winding structure, internal connections [2]. For the study and diagnosis purpose the high frequency rage can be further divided so there will be total of four sub regions.

These regions are illustrated using a frequency response from the HV open winding of a three phase power transformer as an example in Figure 2.4.

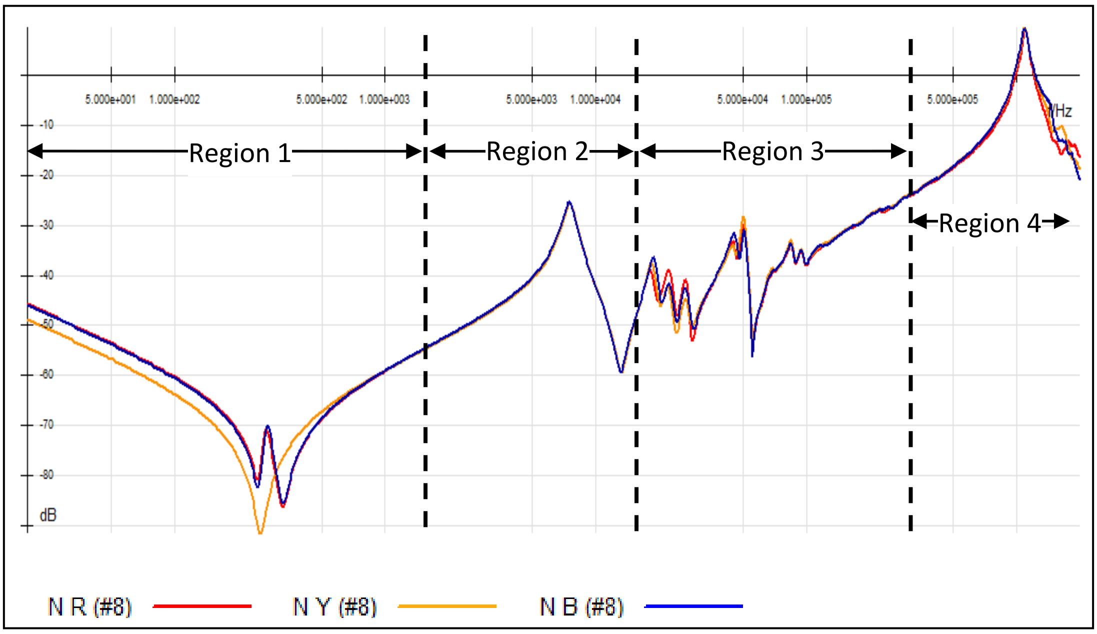


Figure 2.4: Separation of the regions for the study purpose

In the core influence region (up to about 2 kHz), the response is dominated by the core magnetizing inductances and the bulk capacitances of the transformer. For three phase three limbs of a "core" form power transformers, the middle phase would have a single anti resonance in this frequency region due to the symmetrical magnetic reluctance paths seen by the middle phase of the core through the other two phases. The outer phases generally have two anti resonances since they experience two different magnetic reluctance paths one through the nearest (middle) phase and one through the furthest phase (the other outer phase).

The response in the intermediate frequency region (in between 2 kHz and 20 kHz) is mostly affected by the coupling between windings, which depends significantly on the arrangement and connections of the windings, for example delta connection, auto transformer winding connection, single phase or three phase transformer configurations.

The response in the high frequency region (in between 20 kHz and 2 MHz) is determined by the winding leakage inductances together with the winding series and ground capacitances. In this region, the series capacitance is the most influential factor in determining the shape of the response.

2.1.5.2 Behavior of the SFRA plot

SFRA measurement of a transformer winding is quite complex and consists of decreasing and increasing magnitude with respect to frequency. The various resonances (maxima) and anti resonances (minima) are determined by the electrical characteristics of the transformer winding. These characteristics can be represented by the transformer equivalent circuit and would include the elements of resistance, inductance and capacitance. The inductance and capacitance values in this equivalent circuit are determined by winding structure & geometry, and insulation structure & clearance, and the resistance is contributed by conductive loss and dielectric loss.

The end to end frequency response of a winding is dependent on how the elements in this network behave together at different frequencies. At low frequencies, a transformer winding behaves as an inductive element, and the SFRA response follows a falling magnitude trend across the frequency range. A higher inductance causes the magnitude to decrease. Effectively there are two inductance components affecting the frequency response; one is the core magnetizing inductance, and the other is the leakage inductance of the winding.

At high frequencies, a transformer winding behaves as a capacitive element, and the end to end SFRA response follows a rising magnitude trend across the frequency range with a linearly increasing slope. A higher capacitance causes the magnitude to increase.

The combination of winding inductance and winding series capacitance results in paralleled inductance (L) and capacitance (C). LC in parallel will produce parallel anti resonance at a certain frequency, blocking the signal at that particular frequency. Therefore this produces a local anti resonance in the magnitude response at that particularly frequency. In the case that the winding series capacitance is relatively small, the shunt capacitance (capacitance between windings and earth) becomes significant. The combination of winding inductance and shunt capacitance will result in inductance and capacitance in series and produce series resonance.

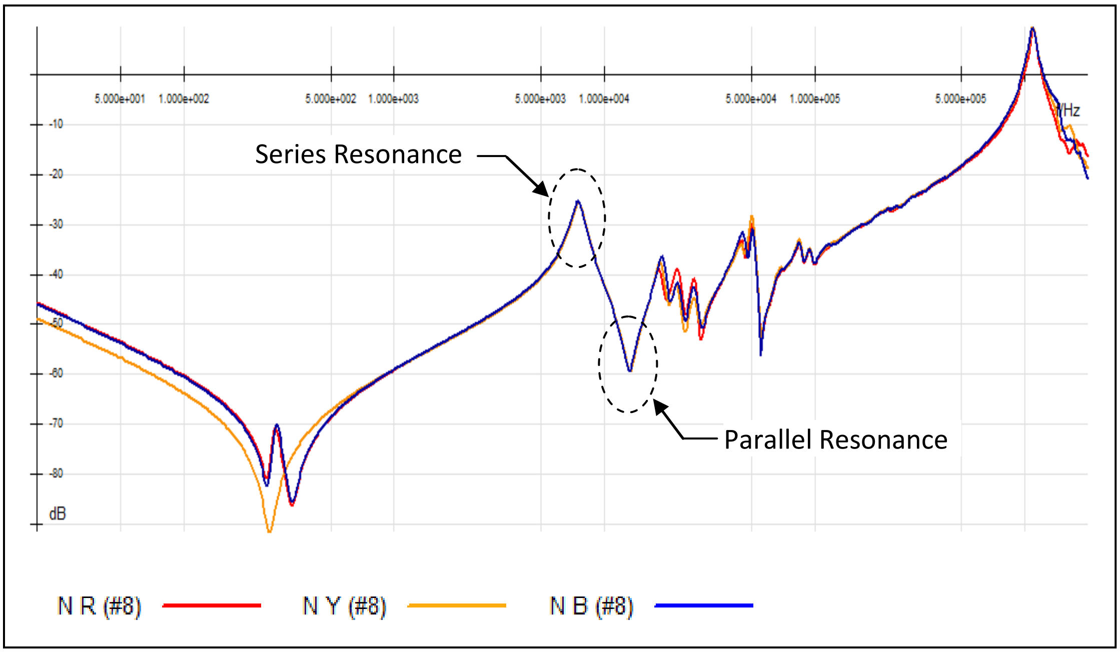


Figure 2.5: Parallel and series resonant point

The effect of resistance is to attenuate (smooth) the sharpness of the resonances and the anti resonances. In the equivalent circuit of a transformer winding, these are either connected in series with the inductance or connected in parallel with the capacitance. However, even in a single winding, these basic LC components are produced by mutual coupling between turns and parts of a winding, effectively resulting in a network of multiple lumped parameters.

Figure 2.6 show the ***n*** stage lumped network of equivalent circuit correspond to medium and high frequency responses [1].

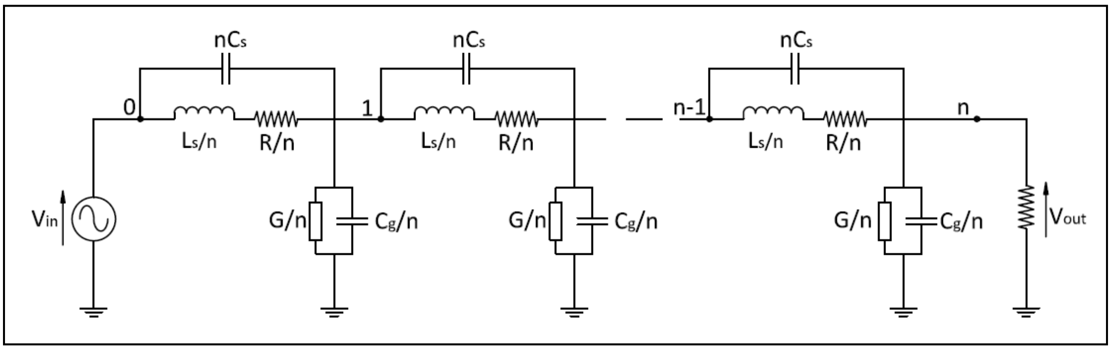


Figure 2.6: n-stage lumped network with mutual coupling

According to this network, the frequencies of the resonances are determined primarily by the winding leakage inductance L_S, the shunt capacitance Cg, and the winding series capacitance C_S. When the winding series capacitance is small enough to be neglected (where C_S tends to zero), there will be resonances with even frequency intervals. On the other hand, when the winding series capacitance is extremely large (where Cg tends to zero), there will be no resonance at all. With low C_S, the response begins with a flat magnitude trend and resonances at intervals of frequencies determined by the L_S, Cg, and C_S values and then followed by a decreasing inductive trend. An anti resonance appears at a frequency determined by L_S and C_S, which is followed by the increasing capacitive trend. As C_S is increased, some of the resonances diminish and the anti resonance appears at a lower frequency [1].

2.1.6 Classification of failure modes using SFRA

SFRA measurement variations can be caused by a single type of failure or a combination of two or more. Failure due to faults may create high over currents through the transformer. As a result, the transformer would experience strong and often violent electromagnetic forces. These violent events can sometimes lead to compounded failure modes. These compounded events can complicate the SFRA measurement, as difficult to diagnose actual failure. Below are listed known failure modes that can be identified through SFRA measurement analysis.

- Radial Deformation (Hoop or Force Buckling)
- Axial Winding Elongation (Telescoping)
- Overall Bulk & Localized Movement
- Core Defects
- Contact Resistance
- Winding Turn to Turn Short Circuit
- Open Circuited Winding
- Winding Looseness

As the different frequency bands are dominated by different internal components of the transformer, experiences have shown that study of behavior and deviations in the deferent frequency bands can be used for diagnosis of fault and condition of the transformers with respect to the possible failure modes, as summarized in Table 2.1 [3].

Table 2.1: Frequency sub band sensitivity.

Region	Frequency Sub Band	Component	Failure Sensitivity
1	< 2 kHz	core and winding inductance	Core deformation, open circuit, shorted turns
2	2 kHz – 20 kHz	Bulk winding and shunt impedances	Bulk winding movement between windings and clamping structure
3	20 kHz – 400 kHz	Main windings and tap windings	Deformation within the main or tap windings
4	400 kHz – 2 MHz	Main winding and tap winding leads, internal leads	Movement of the main & tap windings/ leads, ground impedance variations

2.2 Dissolve Gas Analysis (DGA)

2.2.1 Formation of gases

Various types of gases can be formed inside an oil immersed transformer mainly due to thermal and electrical faults as well as other natural chemical reactions. Formation of gases involves transformer oil, solid insulation and other metallic parts [11].

2.2.1.1 Decomposition of oil in power transformers

Mineral insulating oils are made of a blend of different hydrocarbon molecules containing linked together by carbon-carbon molecular bonds. Scission of some of the Hydrocarbon and Carbon bonds may occur as a result of electrical and thermal faults, with the formation of small unstable fragments, in radical or ionic form which recombine rapidly, through complex reactions, into gas molecules such as Hydrogen (H_2), Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4) and Acetylene (C_2H_2) [11]. The gases formed dissolve in oil, and can be analyzed by DGA.

Low energy faults, such as partial discharges, corona discharges cause to scission of the weakest Hydrocarbon bonds through ionization reactions and the accumulation of hydrogen as the main recombination gas. More and more energy and higher temperatures are needed for the scission of the Carbon bonds and their recombination into gases with a single bond, double bond or triple bond [11].

Ethylene is formed above temperatures of approximately 500 ˚C. Acetylene requires temperatures of at least 800 ˚C to 1,200 ˚C, and a rapid quenching to lower temperatures, in order to accumulate as a stable recombination product. Acetylene is formed in significant quantities mainly in arcs, where several thousands of degrees Celsius appear on the fault point [11].

2.2.1.2 Decomposition of cellulosic insulation

The polymeric chains of solid cellulosic insulation (paper, pressboard, wood blocks) contain a large number of anhydroglucose rings, and weak C-O molecular bonds and glycosidic bonds which are thermally less stable than the hydrocarbon bonds in oil.

Significant rates of polymer chain scission occur at temperatures higher than 105 ˚C, with complete decomposition and carbonization above 300 ˚C. Mostly carbon monoxide (CO) and carbon dioxide (CO_2), as well as water, are formed, in much larger quantities than by oxidation of oil at the same temperature, together with minor amounts of hydrocarbon gases and furanic compounds. This can be analyzed and used to complement DGA interpretation and confirm whether or not cellulosic insulation is involved in a fault. CO and CO_2 formation increases not only with temperature but also with the oxygen content of oil and the moisture content of paper [11].

2.2.1.3 Other sources of gas

Gases may be generated in some cases not as a result of faults in the equipment but through rusting or other chemical reactions involving steel, uncoated surfaces or protective paints. Gases may also be produced by exposure of oil to sunlight or may be formed during repair of the equipment.

Internal transformer paints may also form gases. The presence of hydrogen with the total absence of other hydrocarbon gases, for example, may be an indication of such a problem.

2.2.2 Types of faults

Following broad classes of faults are addressed by DGA [11].

- Partial discharges (PD) :
  - Discharges in gas filled cavities due to incomplete impregnation, high humidity in paper, oil super saturation or cavitations and leads to X-wax formation.
- Discharges of low energy (D1) :
  - Sparking or arcing between bad connections of different or floating potential, from shielding rings, adjacent disks or conductors of winding, broken brazing or closed loops in the core.
  - Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls.

  - Tracking in wooden blocks, glue of insulating beam, winding spacers, breakdown of oil, selector breaking current.
- Discharges of high energy (D2) :
  - Flashover, tracking or arcing of high local energy or with power follow through.
  - Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core.
  - Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs.
- Thermal faults below 300 ˚C (T1) :
  - Overloading of the transformer in emergency situations.
  - Blocked item restricting oil flow in windings.
  - Stray flux in damping beams of yokes.
- Thermal faults between 300 ˚C and 700 ˚C (T2) :
  - Defective contacts between bolted connections, gliding contacts, contacts within selector switches, connections from cable and draw rod of bushings.
  - Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields.
  - Abraded insulation between adjacent parallel conductors in windings.
- Thermal faults of temperatures above 700 ˚C (T3) :
  - Large circulating currents in tank and core.
  - Minor currents in tank walls created by a high uncompensated magnetic field.
  - Shorting links in core steel laminations.

2.2.3 Diagnosis tools

Several DGA diagnosis tools can be found in IEC, IEEE and CIGRE guidelines, which have been widely using by electric utilities.

2.2.3.1 Key Gas analysis

The key gas analysis is a diagnosis tool given in IEEE guidelines [10]. It uses the Total Dissolved Combustible Gas (TDCG) value and individual gas values to analyze the system state. The Table 2.2 and 2.3 shows the categorization of transformer condition based on presence of key gases and the status related to each condition respectively.

Table 2.2: Key gas analysis

H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2	TDCG	Condition
<100	<120	<50	<65	<1	<350	<2,500	<720	Condition 1
101–700	121-400	51-100	66-100	2-9	351-570	2,500-4,000	721-1,920	Condition 2
701–1,800	401-1,000	101-200	101-150	10-35	571-1,400	4,001-10,000	1,921-4,630	Condition 3
>1,800	>1,000	>200	>150	>35	>1,400	>10,000	>4,630	Condition 4

$TDCG = H_2 + CH_4 + C_2H_4 + C_2H_6 + C_2H_2 + CO$

Gas levels in Parts Per Million (ppm)

Table 2.3: Status information

Condition 1	TDCG below this level indicates normal operation. If any individual gas increases, additional investigation required.
Condition 2	TDCG in this limit indicates low level decomposition, requires individual gas investigation. If any individual gas increases, additional investigation required.
Condition 3	TDCG in this limit indicates high level decomposition, requires individual gas investigation. Plan outage may require.
Condition 4	TDCG above this limit indicates excessive decomposition, operation may result in failure. Removal from service may require.

The Table 2.4 shows the four type of faults diagnosis by the Key Gas method against the presence of the key gas.

Table 2.4: Key gas fault diagnosis

Gases						Principle gas	Fault
H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO		
2%	16%	63%	19%	-	-	C_2H_4	Overheated oil
-	-	-	-	-	92%	CO	Overheated cellulose
85%	13%	1%	1%	-	-	H_2	Corona in oil
60%	5%	3%	2%	30%	-	C_2H_2	Arcing in oil

The Key Gas Procedure is so frequently used for the diagnosis as it can be implemented quickly and easily. Key Gas method has been introduced in the IEEE guide as for the Qualitative determination of fault types, based on which gases are typical or predominant at various temperatures.

However, studies have shown that the Key Gas method provides incorrect diagnosis as a percentage around 50% [17], [18]. There are several issues that contribute to the Key Gas Method's poor diagnostic accuracy such that,

- There are only 4 generalized fault types named while other diagnostic methods offer more detailed fault type identification
- Transformers will typically not exhibit the exact relative proportions of gases outlined by the IEEE guide and users need to make judgments.

2.2.3.2 Dornenburg's analysis

Dornenburg's analysis uses four different gas ratios to analyze three different faults. This methodology sets boundary limits of individual gases, if any gas exceeds the limits, then fault diagnosis limits will be employed to gas ratios to diagnose the fault type. The Table 2.5 and Table 2.6 [12] shows the proposed limit values against each gas and the diagnosis subjected based on the gas ratios [10].

The method has fallen out due to its complexity as well as the evolution of it into the Rogers and Basic Gas Ratios. Incorrect diagnosis through the Dornenburg's method remains at a very low level. However it provides considerable percentage of unsolved diagnosis as a percentage around 25%. This is because there can be some combinations of gases that, when calculated, do not fit into the specified range of values so a diagnosis of the fault type cannot be given [17], [18].

Table 2.5: Dornenburg's limits for individual gases

Gas	Limit (ppm)
H_2	100
CH_4	120
C_2H_4	50
C_2H_6	65
C_2H_2	35
CO	350

Table 2.6: Dornenburg's diagnosis

Ratios				Fault Diagnosis
$\frac{CH_4}{H_2}$	$\frac{C_2H_2}{C_2H_4}$	$\frac{C_2H_2}{CH_4}$	$\frac{C_2H_6}{C_2H_2}$	
> 1.0	< 0.75	< 0.3	> 0.4	Thermal Decomposition
< 0.1	-	< 0.3	> 0.4	Corona (Low Intensity PD)
0.1 – 1.0	> 0.75	> 0.3	< 0.4	Arcing (High intensity PD)

2.2.3.3 Rogers's Ratio analysis

The Rogers method evolved from the Dornenburg's method and it uses only three gas ratios to analyze the system state as similar in IEC basic ratio method. With the magnitude of these ratios of gases, three digit code is generated as shown in Table 2.7.[10] The code number that is generated can be related to a diagnostic interpretation as shown in Table 2.8 [10].

As in the Dornenburg's method, incorrect diagnosis through the Roger's method remains at a very low level, and it provides considerable percentage of unsolved diagnosis as a percentage around 30%. However the Roger's ratio has been developed with better correlation specific ratio value ranges for fault types [17], [18].

Table 2.7: Fault gas ratios

Range	Ratio		
	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
≤ 0.1	0	1	0
0.1 - 1.0	1	0	0
1.0 - 3.0	1	2	1
≥ 3	2	2	2

Table 2.8: Roger's ratio diagnosis

Ratios			Case	Fault Diagnosis
$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$		
0	0	0	-	Normal
0	1	0	PD	Partial discharge of low energy
1	1	0		Partial discharge of high energy
1,2	0	1,2	D1	Discharge of low energy
1	0	2	D2	Discharge of high energy
0	0	1	T1	Thermal fault < 150 ˚C
0	2	0		Thermal fault 150 ˚C – 300 ˚C
0	2	1	T2	Thermal fault 300 ˚C – 700 ˚C
0	2	2	T3	Thermal fault > 700 ˚C

2.2.3.4 Duval's Triangle analysis

Duval's triangle employs triangular phenomenon between three gases CH_4, C_2H_4, C_2H_2. It uses percentage gas ratios of 3 gases to analyze system state [11].

$$\%CH_4 = \frac{CH_4}{CH_4 + C_2H_2 + C_2H_4} \times 100 \qquad (2.4)$$

$$\%C_2H_2 = \frac{C_2H_2}{CH_4 + C_2H_2 + C_2H_4} \times 100 \qquad (2.5)$$

$$\%C_2H_4 = \frac{C_2H_4}{CH_4 + C_2H_2 + C_2H_4} \times 100 \qquad (2.6)$$

The triangle method plots the relative percentage of the 3 gases on each side of the triangle, from 0% to 100%. The seven main zones of faults are indicated in the triangle as shown in Figure 2.7.

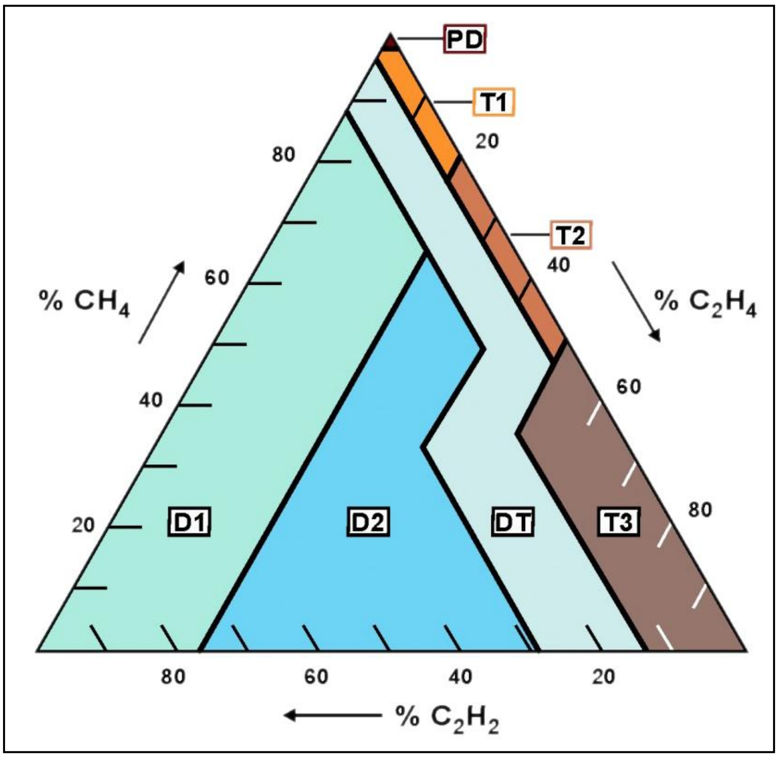


Figure 2.7: Graphical representation of Duval's triangle

The Table 2.9 shows the fault diagnosis and the percentages of each gas with respect to the each fault zone with respect to the graphical representation of the Duval's Triangle [12].

Table 2.9: Duval's triangle fault zones

Case	Fault Diagnosis	%CH_4	%C_2H_2	%C_2H_4
PD	Partial discharge of low energy	≥ 98%		
D1	Discharge of low energy		> 13%	< 23%
D2	Discharge of high energy		13% - 29%	23% - 38%
			> 29%	> 23%
T1	Thermal fault < 300 ˚C	< 98%	< 4%	< 20%
T2	Thermal fault 300 ˚C – 700 ˚C		< 4%	20% - 50%
T3	Thermal fault < 700 ˚C		< 15%	> 50%
DT	Thermal and electrical faults	Rest area		

Duval's Triangle analysis always provides a diagnosis, with a very low percentage of wrong diagnoses, and it has been a popular diagnosis tool within many systems. However it is desirable to apply the Duval's Triangle diagnosis when the transformer found to be having excessive gases than the recommended levels [17], [18].

2.2.4 Gas concentration levels

The probability or risk of having a failure of an in service transformer is related to its gas concentration levels. Below certain concentration levels identified as typical or normal values, the probability of having a failure is low and the equipment is considered as healthy. A first rough screening between healthy and suspect analyses can therefore be obtained by calculating typical values for the equipment.

2.2.4.1 Typical concentration values

Typical concentration values are the acceptable gas quantities below which field experience shows no detectable or possible faults in transformers. Typical concentration values are preferably to be considered as initial guidelines for decision making. However, using the rate of gas formation along with typical concentration values can direct to better diagnosis.

The Table 2.10 shows the typical gas concentration values recommended by different guides [10], [12].

Table 2.10: Typical gas levels of Power Transformers (ppm)

Gas	IEC	IEEE	Dornenburg
H_2	60-150	100	100
CH_4	40-110	120	120
C_2H_4	60-280	50	50
C_2H_6	50-90	65	65
C_2H_2	3-50	1	35
CO	540-900	350	350
CO_2	5,100-13,000	2,500	

Typical concentration values are affected by number of factors, mainly the load factor, nature of the fault (electrical or thermal), operating time since commissioning and type of oil protection.

For the calculation and development of typical values for the set of transformers in a utility, CIGRE and the IEC recommend the use of 90% typical values as a starting point [11], [13].

2.2.4.2 Calculating own 90% typical values for a network

It is recommended to use DGA data from the similar type of transformers for the calculation. If there are different type (i.e. sealed type, air breathing type, communicating OLTC (On Load Tap Changer), non communicating OLTC they shall be grouped and derive different 90% typical values [11]. (In this study three phase power transformers with air breathing and non communicating OLTC have been used for analysis.)

After gathering all the DGA results concerning a specific type of equipment, each gas shall be listed in the increasing order against its concentration level. If the total number of transformers selected is ***N***, the gas value correspondent to the $0.9\text{x}\boldsymbol{N}^{\text{th}}$ transformer shall be considered as the typical value of that particular gas. Then this shall be repeated for all the gases.

Chapter 3

DATA ANALYSIS AND OUTPUTS

3.1 SFRA Data Collection

In this study, SFRA measurement data from forty four (44) three phase power transformers operating in the Ceylon Electricity Board (CEB) transmission system were collected. All theses transformers have star connected Primary (HV) and delta connected Secondary (LV) configuration. Further these transformers have the "core" type construction where laminated core has only three limbs and the three phases are wound around each of the limb.

As these transformers were having the same winding configuration (vector group) the SFRA plots represented similar characteristic behavior such that they can be analyzed together taking as all the plots are belong to a same set of data.

Out of various measurement connection types recommended by IEC and IEEE guidelines, below three SFRA measurements were selected for this study, as they comprehensively cover mechanical integrity of the active part (core, winding and associated clamps and supports) of the transformer.

1) Measurement of HV winding, while all the other winding are opened (HV open circuit)
2) Measurement of HV winding, while all LV winding are shorted and other terminals are floated (HV short circuit)
3) Measurement of LV winding, while all the other winding are opened (LV open circuit)

Figure 3.1 show the test connections for the above three measurements.

Further other measurement connections such as capacitive inter winding and inductive inter winding measurements sometimes heavily distorted with ambient noise, and in such cases the measurements are not reliable enough for analysis. Therefore, not employed in this study.

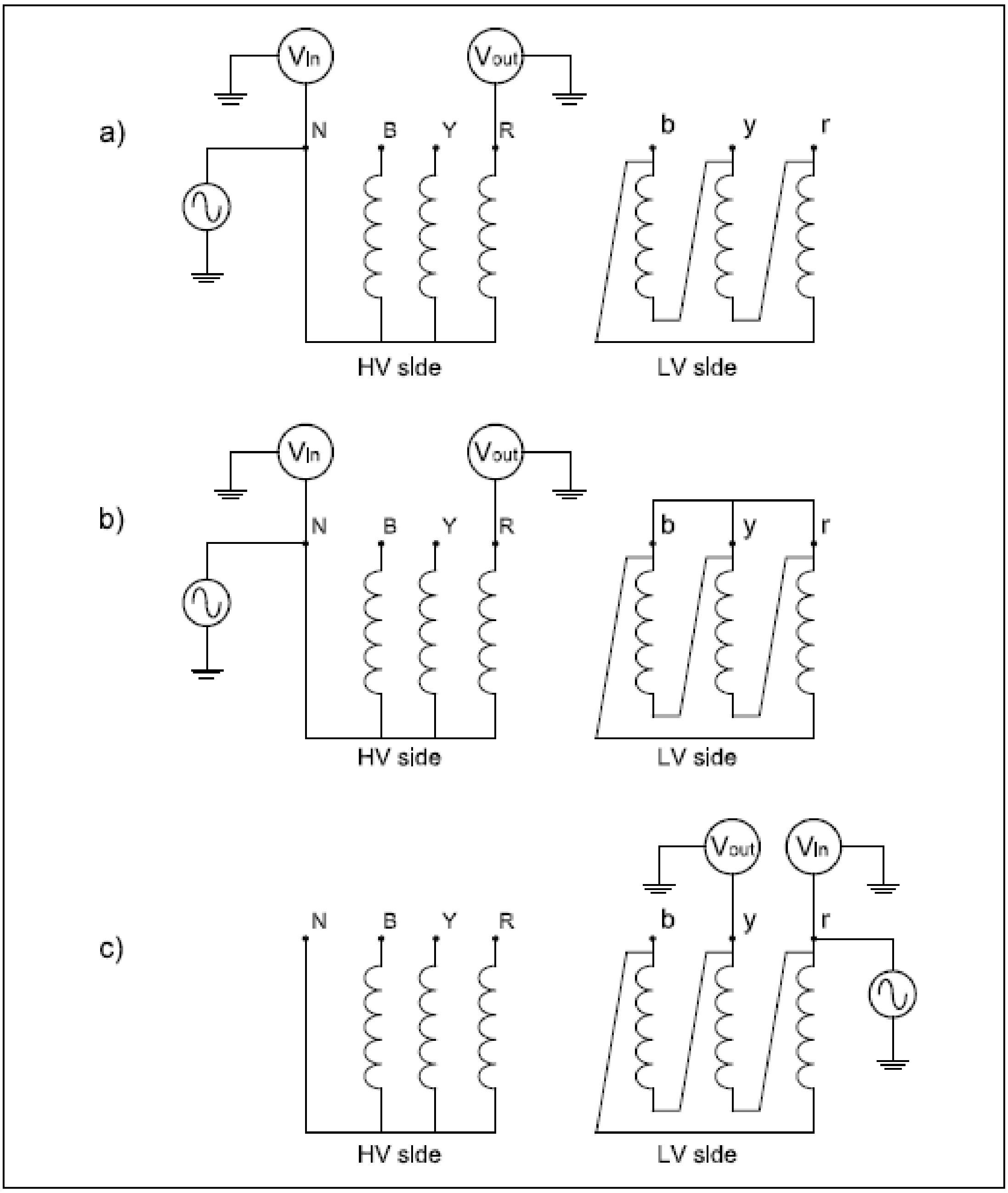


Figure 3.1: Test connections for the measurements; a) HV open circuit, b) HV short circuit, c) LV open circuit.

3.1.1 Measuring instrument

For the collection of SFRA measurements OMICRON FRAnalyzer measuring instrument was used. Figure 3.2 shows the front and back side of the instrument.

Coaxial cables with equal lengths are connected to “Source”, “Reference” and “Measurement” ports. The input signal to the transformer, which is a sin waveform of having constant magnitude of 1Vrms, is given by the “Source” port, and it is measured at the transformer terminal by the “Reference” port. The output is measured by the “Measurement” port. The coaxial cables are selected such that the impedance of the input and measuring circuits are known and as 50Ω each.

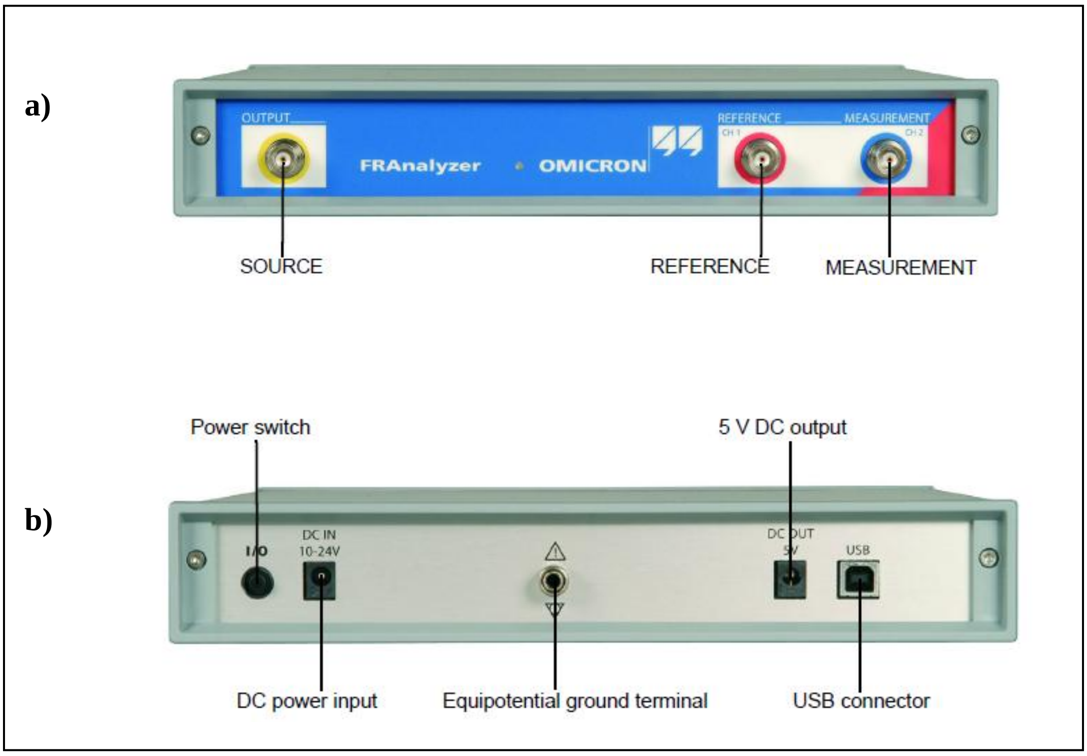


Figure 3.2: Overview of the OMICRON FRAnalizer; a) Front side, b) Back side

(Source: OMICRON FRAnalizer user manual)

The equipment grounding terminal is connected to the same earthing point where the transformer main earthing is connected, and thereby the whole earthing circuit (earth of the input, reference and output) of the test setup is brought to a single earthing point.

3.1.2 Measurement data format

The Measuring instrument is capable to measure frequency range from 10 Hz to 20 MHz. However measurements taken above the frequencies of 2 MHz are highly influenced by connection wiring, grounding system and ambient noises [2]. Therefore measurements over 2 MHz are not useful in a great extend for the comparison analysis. Further it has been proven that a frequency range between 20 Hz and 2 MHz is usually sufficient for the efficient analysis [7]. For a reliable and efficient analysis, the IEEE and IEC guidelines recommend minimum of 1 MHz as the upper limit for the frequency band for transformers operated above 72.5 kV [1], [2].

For this study, SFRA measurements have been taken for frequency sweep between 20 Hz and 2 MHz, and they have been recorder for 1,000 data points. A set of sample data of a SFRA measurement correspond to the three measurement test connections, ‘HV open circuit’, ‘HV short circuit’ and ‘LV open circuit’ is shown in Appendix-A. Here the gain (dB) with respect to the output over input is recorded against each frequency point (Hz). The computer software used with the measuring instrument also represents this data in a Bode plot, which is helpful for the quick and easy analysis with visual inspection.

3.2 SFRA Data Analysis

As discussed in the Chapter 2, SFRA technique has been using to compare the mechanical integrity of transformers in time vise, type vise or phase vise. In this study, phase vise comparison has been deployed to assess the condition of transformers. SFRA measurements of three phases of a three phase transformer were compared and evaluate the amount of deviation, which is a powerful indication of mechanical integrity. Higher the deviation (poor matching) lower the integrity and lower the deviation (good matching) higher the integrity [1].

For better analysis, the SFRA measurements were subdivided in to four sub frequency bands as discussed in Chapter 2, and evaluate the deviations with respect to each region.

3.2.1 Comparison tools

When SFRA measurements are represented in a Bode plot, they can be visually inspected for any deviation between each other. However visual inspection cannot quantify the deviation which is important for proper analysis. In order to quantify the deviation and thereby assess the condition of the transformer in a methodical way, it is important to develop numerical analysis. For this purpose in this study, three key comparison tools were utilized.

3.2.1.1 Absolute Sum of Logarithmic Error (ASLE)

Evaluation of the difference in gain of two SFRA measurements is the simplest method which can compare and quantify the deviation. Figure 3.3 shows the deviation of two SFRA measurements represented in a Bode plot. Here the value of the deviation of the gains of two measurements with respect to each frequency point will be calculated. These values will be added up along the frequencies and take the average of them. This is called the Absolute Sum of Logarithmic Error (ASLE) [6].

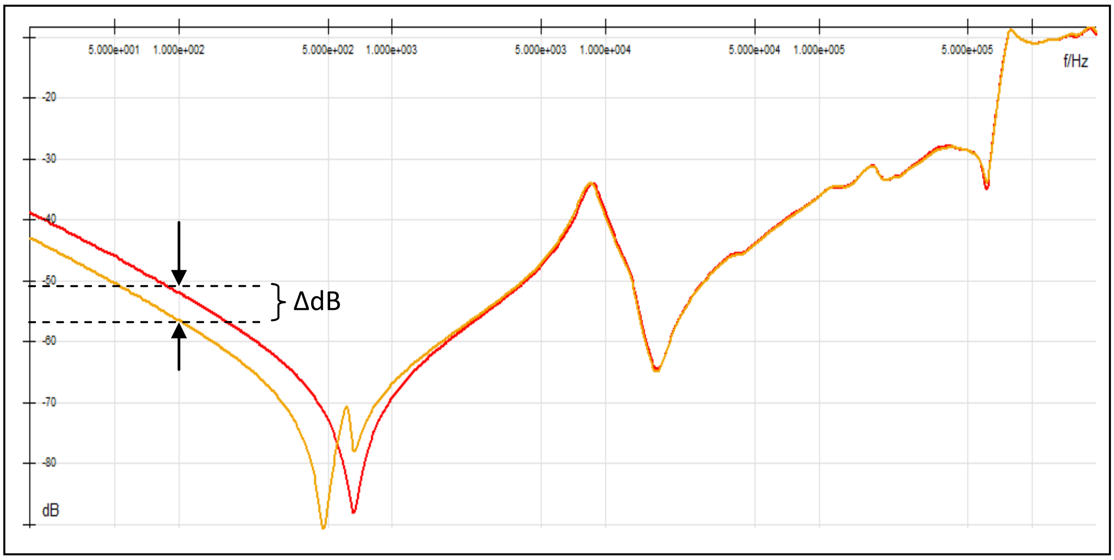


Figure 3.3:

ASLE can be calculated according to the equation 3.1.

$$ASLE = \frac{\sum_{i}^{n} |(X_i - Y_i)|}{n} \qquad (3.1)$$

Where,

X_i = Gain (dB) of the 1st SFRA plot at the i^{th} frequency

i = Data point at which the gain is recorded against the frequency

Y_i = Gain (dB) of the 2nd SFRA plot at the i^{th} frequency

n = Total number of data points

Low ASLE value indicates good matching, and higher the ASLE value matching is poor. The ASLE values with respect to the four regions were calculated for the three SFRA measurement test connections. Then this was continued for the all selected transformers. The calculated ASLE values are shown in the Appendix-B.

3.2.1.2 Cross correlation coefficient (CCF)

Correlation coefficients or CCF provide an indication of similarity between two traces. CCF was developed from correlation coefficient, and it has been identified as the most reliable statistical indicator to extract information from comparison method.

The CCF can be defined as [3],

$$CCF = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \ \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \qquad (3.2)$$

Where,

X_i = Gain (dB) of the 1st SFRA plot at the i^{th} frequency

i = Data point at which the gain is recorded against the frequency

$\bar{X}$ = Mean value of the values of X_i

Y_i = Gain (dB) of the 2nd SFRA plot at the i^{th} frequency

$\bar{Y}$ = Mean value of the values of Y_i

The CCF allows for the expression of how random or similar a range of numbers is. It has a value between −1 and 1. If the value is zero, this indicates complete randomness between the two traces under inspection. When the two traces are more similar, the CCF value closer is to one (1). If the value is minus one (-1), this indicates a complete inverse relationship.

The CCF values with respect to four regions were calculated for the three SFRA measurement test connections. Then this was continued for the all selected transformers, and the calculated CCF values are shown in the Appendix-C.

3.2.1.3 Turning function and trace comparison

Turning function, *ø(s)* measures the change of the angle (*ø*) along the curve as a function of the curve length (*s*). The curves are re scaled so that the total length equal to one (1). It increases with counter clockwise turn and decreases with clockwise turn, and accumulating the turns along the curve. The turning function is translation independent, scaling independent and rotation corresponds to a vertical shift.

The turning function can be used for comparison of two traces/curve, and matching is based on the distance between two turning function correspond to the two traces. Low distance indicates good matching, and higher the deviation matching goes out.

In this sense, the turning function can be recommended as suitable for comparison of two SFRA measurements. Here the distance of the two turning functions can be defined as [9],

$$Distance(L) = \left[\sum_{i}^{n} (\emptyset_1(s)_i - \emptyset_2(s)_i)^2\right]^{1/2} \qquad (3.3)$$

Where, $\emptyset_1(s)$ = Turning function of the 1st SFRA plot

$\emptyset_2(s)$ = Turning function of the 2nd SFRA plot

Further, following equations show how to derive turning function out from the SFRA Measurement data

$$\emptyset(s)_i = \emptyset_i + \emptyset(s)_{i-1} \qquad (3.4)$$

$$\emptyset_i = \Theta_i - \Theta_{i-1} \qquad (3.5)$$

$$\Theta_i = \tan^{-1}(\frac{S_{V_i}}{S_{H_i}}) \qquad (3.6)$$

$$S_{V_i} = X_{i+1} - X_i \qquad (3.7)$$

$$S_{H_i} = F_{i+1} - F_i \qquad (3.8)$$

Where, X_i = Gain (dB) of the SFRA plot at the i^{th} frequency

F_i = Frequency value corresponds to X_i

Figure 3.4 show the representation of turning function for a SFRA plot of HV open circuit.

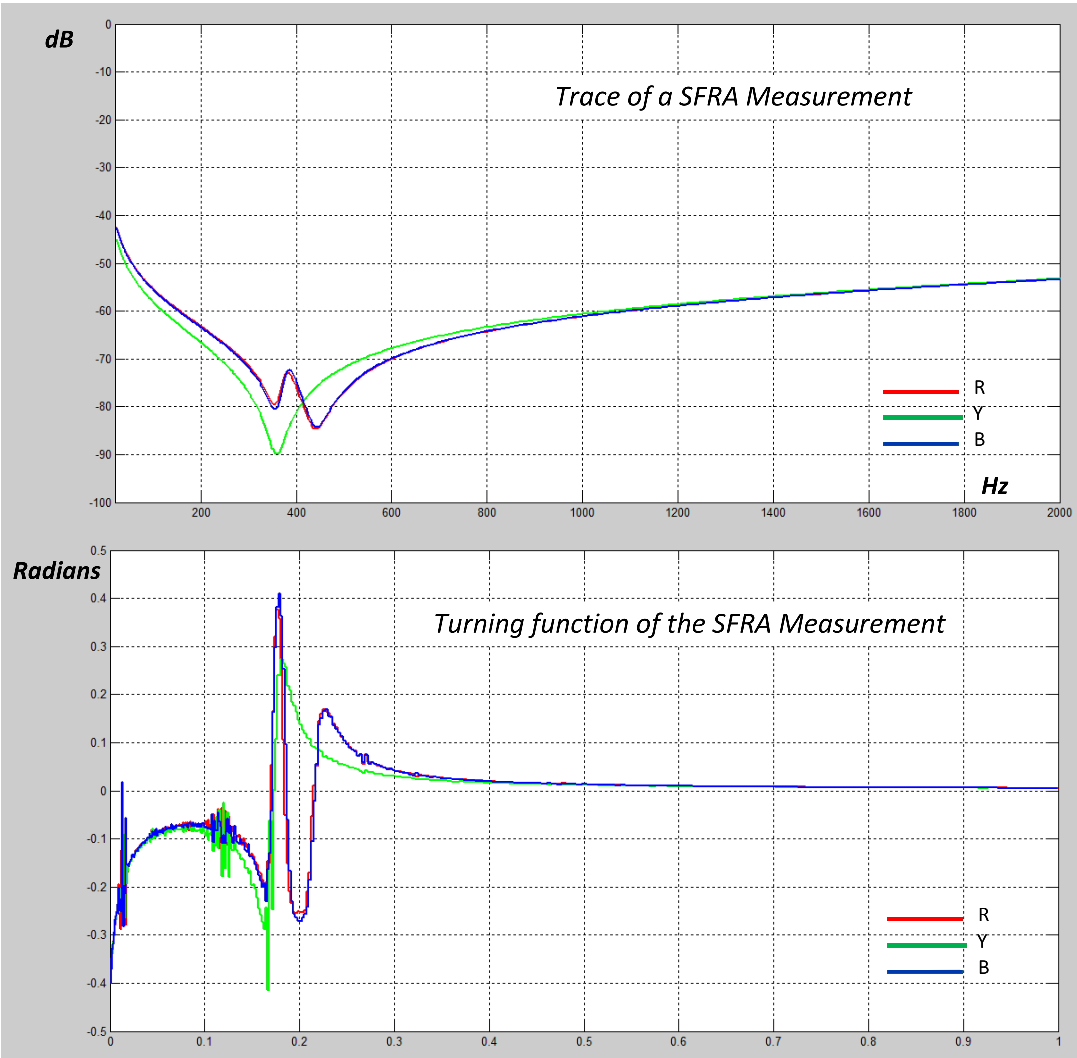


Figure 3.4: Representation of the Turning Function of a SFRA measurement

The distance values with respect to four regions were calculated for the three SFRA measurement test connections. Then this was continued for the all selected transformers, and the calculated distance values are shown in the Appendix-D. For the convenience, the distance value of the turning function shall be hereafter called as "*DisTF*".

3.3 DGA Data Collection

For this study, DGA data from one hundred and thirty (130) power transformers operating in the Ceylon Electricity Board (CEB) transmission system were collected. Out of these one hundred and six (106) were three phase transformers and twenty four (24) were single phase transformers.

All of these transformers are air breathing and non communicating OLTC type. Therefore DGA data collected from these transformers can be analyzed together taking as they belong to a same set of data category.

3.3.1 Oil sample collection and measurement of gases

Oil samples are collected at the bottom of the transformer through the provided sampling valve. For the collection special syringe as shown in the Figure 3.5 is used where the volume of the sample can be fixed all the time, and it minimizes the contact of oil with the atmospheric air while sampling.

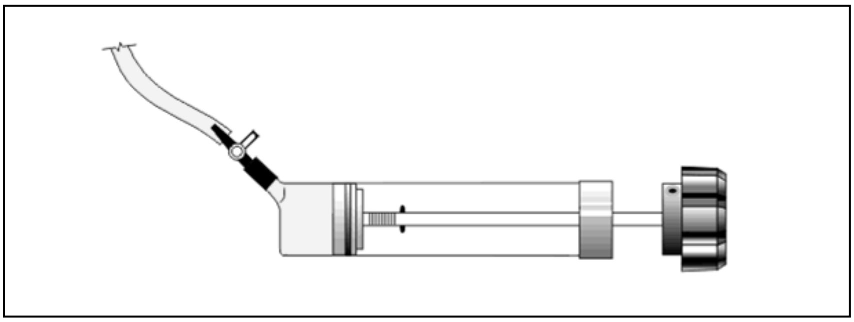


Figure 3.5: Glass syringe used to collect oil sample
(Source: Morgan Schaffer guide for preparation of oil sample)

Here the extraction of gases from oil is done by shaking the sample. The sample is mixed with a fixed volume of air which is drawn through CO_2 filter. The gas volume spare within the syringe is then feed to the measuring instrument.

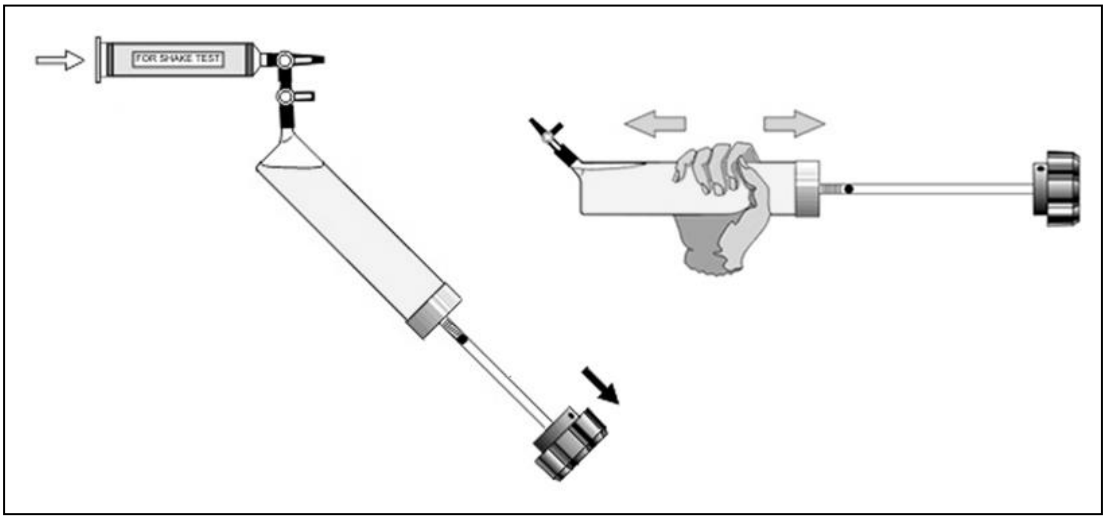


Figure 3.6: Adding air in to the syringe through a CO_2 filter and shake for gas extraction
(Source: Morgan Schaffer guide for preparation of oil sample)

The DGA measurements considered in this study were taken from the "Morgan Schaffer Portable Dissolved Gas Analyzer", which uses the gas chromatography technology to measure the concentration of gases

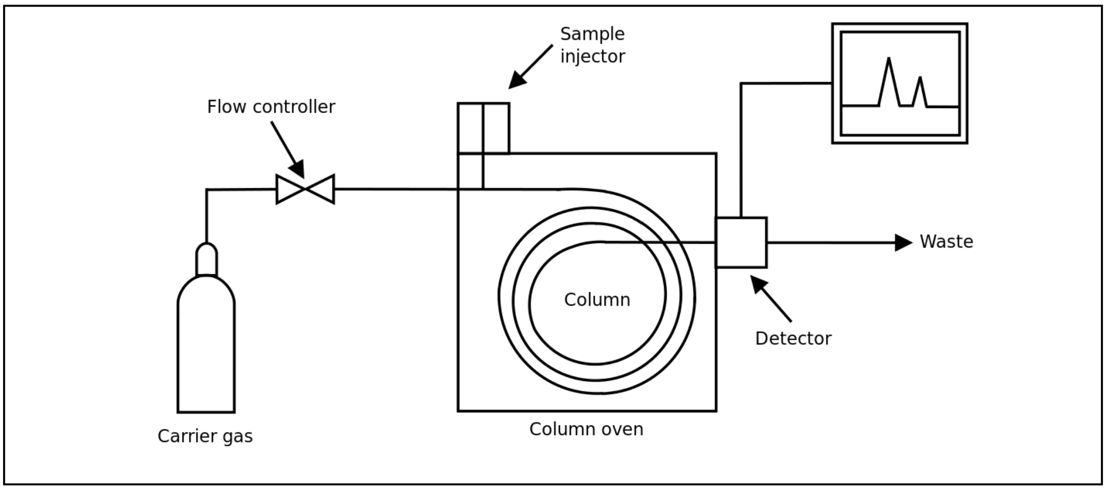


Figure 3.7: Diagram of gas chromatograph
(Source: Wikipedia)

The carrier gas act as a medium added to allow the gas sample to travel through the column. As the gas sample passes through the column, the gas is absorbed onto the column walls, as the column walls are coated with a stationary phase. Since different gases within the sample gas are attacked to the column wall with different strengths, the gasses separated as they pass through the column. A detector located at the end of the channel then detects different quantities of gases at the different arrival times to determine the gas concentration of each particular gas.

The equipment measures the seven standard gases namely Hydrogen (H_2), Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4) and Acetylene (C_2H_2), and the summation of Total Combustible Gases (TDCG). Oxygen (O_2) and Nitrogen (N_2) can also be measured using a second sample. However O_2 and N_2 gases have not been considered in this study as they are not been utilized in many diagnosis methods due to less accountability. A sample test report of dissolved gas concentration measured using the Morgan Schaffer instrument is shown in the Appendix-H.

3.4 DGA Data Analysis

Measured dissolved gas concentration values of the seven gases (H_2, CH_4, CO, CO_2, C_2H_4, C_2H_6 and C_2H_2) were recorded and listed against each transformer (As shown in Appendix-I). Then as recommended by CIGRE and IEC guidelines, the 90% value of all the gases were selected following the steps discussed in the Chapter 2.

The Table 3.1 show the values identified as the 90% values of the data set used for this study. These values are rounded such that they represent average values suitable to be used as limits or nominal values.

These obtained values compared with the ranges of 90% typical concentration values observed in power transformers as given in the IEC guidelines, show in Table 3.2. It was identified that the obtained values are more or less similar to the IEC observed values except for Ethane (C_2H_6), where its level is much higher that the guideline value.

Table 3.1: Calculated 90% gas concentration values

Gas	Value (ppm)
H_2	70
CH_4	130
C_2H_4	55
C_2H_6	275
C_2H_2	3
CO	750
CO_2	5,400

Table 3.2: Ranges of 90% typical concentration values observed in power transformers given in IEC guidelines.

Gas	Value (ppm)
H_2	60-150
CH_4	40-110
C_2H_4	60-280
C_2H_6	50-90
C_2H_2	3-50
CO	540-900
CO_2	5,100-13,000

The above ranges of 90% typical values shown in table 3.3 observed in power transformers have been derived from data collected from more than 15 individual networks worldwide and including more than 15,000 transformers [11].

This provides that the DGA data collected in this study follow the data collected from various networks worldwide in average. Therefore it is justifiable to adopt limit values provided by IEC, IEEE and CIGRE guidelines and the limit values derived based on these guidelines, in the aspect of categorization of the transformers under study based on their condition owing to DGA data. However the higher level of

Ethane concentration observed in the data of this study has to be considered when assessing the condition based on these limit values.

Then the diagnosis suggested by different diagnosis tools were identified for those transformers with higher levels of gases. Here the diagnosis were given only to the transformers having one or more gases with excessive levels with respect to the typical values provided by either IEC, IEEE or Dornenburg guidelines. As the Duval's Triangle method utilizes only H_2, C_2H_4 and C_2H_2 gases for the diagnosis, the suggestions were obtained only for the transformers that presented excessive levels for those gases. Further as Dornenburg's Analysis and Roger's Ratio methods do not involve CO, CO_2 for their diagnosis, the suggestions were not obtained for the transformers presented excessive levels only for CO and CO_2.

It was identified that Key Gas, Dornenburg and Roger's methods have failed to suggest diagnosis for some cases even excessive gases presented. This is due the reasons as discussed in Chapter 2.

The relevant diagnosis identified for the transformers are show in the Appendix-I with the concentration of each gas for the transformers taken for this study.

3.5 Development of the Methodology for Condition Assessment

3.5.1 SFRA approach

Calculated ASLE, CCF and DisTF values correspond to each test connection (HV open, HV short, LV open) based on above three comparison tools represent the mechanical integrity of a transformer, however in different sensitivities. For example, as the HV short circuit SFRA measurement is independent from the effect of the core, the corresponding ASLE, CCF and DisTF values are not that much of accountable to represent the integrity of total transformer compared to those values for HV open circuit.

Similarly calculated ASLE, CCF and DisTF values correspond to different phases (R-Y, Y-B and B-R) represent the mechanical integrity in different sensitivities. For example, as the R and B phases are wound on the either sides of the core, they should have similar SFRA behavior compared to the Y phase. Therefore any deviation corresponds to R-B phases have a higher impact on the integrity compared to that of R-Y and Y-B.

Considering these factors pertaining to the ASLE, CCF and DisTF values, three indexes (namely ASLEI, CCFI and DisTFI) were derived as shown below, such that these indexes represent the level of deviation in the SFRA measurements with respect to each phase, and the sensitivity of those values to represent the integrity of a transformer.

$$ASLEI, CCFI, DisTFI = \frac{\sum_{j=1}^{3}\{W2_j \times \sum_{i=1}^{3}(S_i \times W1_i)\}}{\sum_{j=1}^{3}(W2_j \times \sum_{i=1}^{3} W1_i)} \qquad (3.9)$$

Where,

i	=	Number of phase combination (R-Y, Y-B, B-R)
j	=	Number of test connection (HV open, HV short and LV open)
S_i	=	Score given to the ASLE, CCF or DisTF value
$W1_i$	=	Weight given for the phases considered
$W2_i$	=	Weight given for the test connection considered

To derive limit values in order to develop the scoring system, the transformers were listed according to the incremental order of the deviation. By doing this, limit values correspond to each test connection and phase were identified based on the population. Initially the values correspond to the first transformer goes beyond 90% of the transformer population was selected as the limit value (in this study the values correspond to the 40th transformer, as 44 x 0.9 = 39.6).

Considering the distribution of calculated ASLE, CCF and DisTF values separately for each three connection, three phases and for the four frequency regions, scoring systems were developed. This is to be used for the calculation of ASLEI, CCFI and

DisTFI. Hence, there were twelve (12) total indexes for one transformer such that, four values from each ASLEI, CCFI and DisTFI (one ASLEI, CCFI and DisTFI for each region).

The scoring system and the weight given to each test connection and phase considered are shown in the Appendix-E, and the calculated indexes are shown in Appendix-F.

For the purpose of categorization of transformers with respect to their mechanical integrity represented by the SFRA measurements, single index for a transformer for a one frequency range was then derived combining three indexes, ASLEI, CCFI and DisTFI. This was named as SFRAI (SFRA Index). Combination of the three indexes and the new SFRAI was derived as shown in the below equation.

$$SFRAI = \frac{DdBI \times W_{DdB} + \ CCFI \times W_{CCF} + DisTFI \times W_{DisTF}}{W_{DdB} + W_{CCF} + W_{DisTF}} \qquad (3.10)$$

Where, W_{ASLE}, W_{CCF} and W_{DisTF} are the weights given to ASLEI, CCFI and DisTFI respectively. CCF is a powerful tool which compares the similarity between two SFRA plots with respect to the value and the shape of the plots. ASLE compares the values whereas does not reflect the shape of the plot in great sense. However DisTF compare the plots against their deviation in the shape where as the change in the angle along the plot and do not compare the value.

In this sense the three of the indexes ASLEI, CCFI and DisTFI have different sensitivities in the respect of representing the mechanical integrity of a transformer, however they have different aspects. Therefore studying behavior of the SFRA measurement pattern and compare each index with SFRA plots visually the weights were derived such that, W_{CCF}, W_{ASLE} and W_{DisTF} equal to 3, 2 and 1 respectively.

The SFRAI values derived based on the above equation and the weight considered for the transformers under this study is shown in the Appendix-G.

Based on the distribution of these SFRAI values and the visual analysis of the SFRA plots the transformers were categorized under the four frequency ranges and develop the limit values as shown in the Table 3.3.

Table 3.3: Categorization limits for SFRAI

Frequency Region	Rating Code	Condition	Description
Region 1 (20Hz-2kHz)	1	GOOD	SFRAI < 1.7
	2	ACCEPTABLE	1.7 ≤ SFRAI < 2.1
	3	POOR	2.1 ≤ SFRAI < 2.55
	4	VERY POOR	SFRAI ≥ 2.55
Region 2 (2kHz-20kHz)	1	GOOD	SFRAI < 1.75
	2	ACCEPTABLE	1.75 ≤ SFRAI < 2.1
	3	POOR	2.1 ≤ SFRAI < 3.6
	4	VERY POOR	SFRAI ≥ 3.6
Region 3 (20kHz-400kHz)	1	GOOD	SFRAI < 1.45
	2	ACCEPTABLE	1.45 ≤ SFRAI < 2.1
	3	POOR	2.1 ≤ SFRAI < 3.5
	4	VERY POOR	SFRAI ≥ 3.5
Region 4 (400kHz-2MkHz)	1	GOOD	SFRAI < 1.56
	2	ACCEPTABLE	1.56 ≤ SFRAI < 1.9
	3	POOR	1.9 ≤ SFRAI < 2.75
	4	VERY POOR	SFRAI ≥ 2.75

3.5.2 DGA approach

Formation of gases over acceptable levels is an indication of deterioration of health condition of transformer. However formation of different gases represents different level of condition, whereas the level of each gas plays an important role in assessing the condition of a transformer. Therefore it is important to consider and give due importance to each gas and it level of present when assessing the health condition of the transformer.

The following equation has been using by many utilities in ranking the transformers based on DGA data in the aspect of health index calculation [14].

$$DGAI = \frac{\sum_{i=1}^{7} S_i \times W_i}{\sum_{i=1}^{7} W_i} \qquad (3.11)$$

Where;

$DGAI$ = DGA Index

W = Weight given to each gas

S = Score given according to the level of each gas (from 1 to 6)

Weight given to each gas depends upon the level of severity of the possible fault that the particular gas can be formed. For an example gases like CH_4 and C_2H_6 can be formed due to a thermal fault in oil less than 300 ˚C, whereas the formation of C_2H_2 would be only due a higher severity fault like arcing causes thermal fault over 700 ˚C. Considering criticality of presence of each gas, an initial value for the weight (W_i) is allocated.

Considering the different recommendations provided in IEC, IEEE, CIGRE guidelines and distribution of actual collected data, the scoring system was developed as shown in the Table 3.4, and the DGAI for each transformer were calculated. (See Appendix-J)

Table 3.4: Weights and scores allocated for the each gas based on their level of presence.

Gas	**Score (S_i)**						**Weigh (W_i)**
	1	**2**	**3**	**4**	**5**	**6**	
H_2	≤100	100-200	200-300	300-500	500-700	>700	2
CH_4	≤75	75-125	125-200	200-400	400-600	>600	3
C_2H_4	≤65	65-80	80-120	120-180	180-220	>220	3
C_2H_6	≤50	50-80	80-100	100-150	150-200	>200	3
C_2H_2	≤3	3-7	7-15	15-25	25-35	>35	5
CO	≤350	350-700	700-900	900-1100	1100-1400	>1400	1
CO_2	≤2500	2500-3000	3000-4000	4000-5000	5000-7000	>7000	1

Studying the distribution of the DGAI of these transformers and the different diagnosis suggested by different tools recommended in IEC, IEEE and CIGRE guidelines, transformers were categorized in to four levels of conditions namely "GOOD", "ACCEPTABLE", "POOR" and "VERY POOR". Ultimate Purpose of this effort is to develop the limit values for the DGAI which can be used to demarcate the level of condition of a transformer upon its DGA data. These values are shown in the Table 3.5.

Table 3.5: Categorization of transformers according to the level of gases

Rating Code	Condition	Description
1	GOOD	DGAI < 1.2
2	ACCEPTABLE	1.2 ≤ DGAI < 1.8
3	POOR	1.8 ≤ DGAI < 3
4	VERY POOR	DGAI ≥ 3

3.5.3 The method flow

Based on above calculated indexes, the transformers can be categorized and ranked according to their health conditions reflected from SFRA and DGA measurements.

DGA is a powerful tool and it can give the indication of internal abnormalities inside the transformer. However, it may not exactly pinpoint the exact fault area, and it may fail to detect winding movement due to short circuit force or any changes in the winding inductance or capacitance which may leads to a catastrophic failure [4]. On the other hand, the mechanical condition assessment is efficiently done using SFRA which is a well known diagnostic test for detecting internal abnormalities and identifying the affected areas. However, SFRA has less sensitivity for minor faults identification in relative sub frequency range [19]. Therefore, combination of these two techniques could provide better prediction for the health condition of a transformer. Figure 3.8 shows the flow chart of the Methodology developed for the condition assessment of power transformers combining SFRA and DGA techniques.

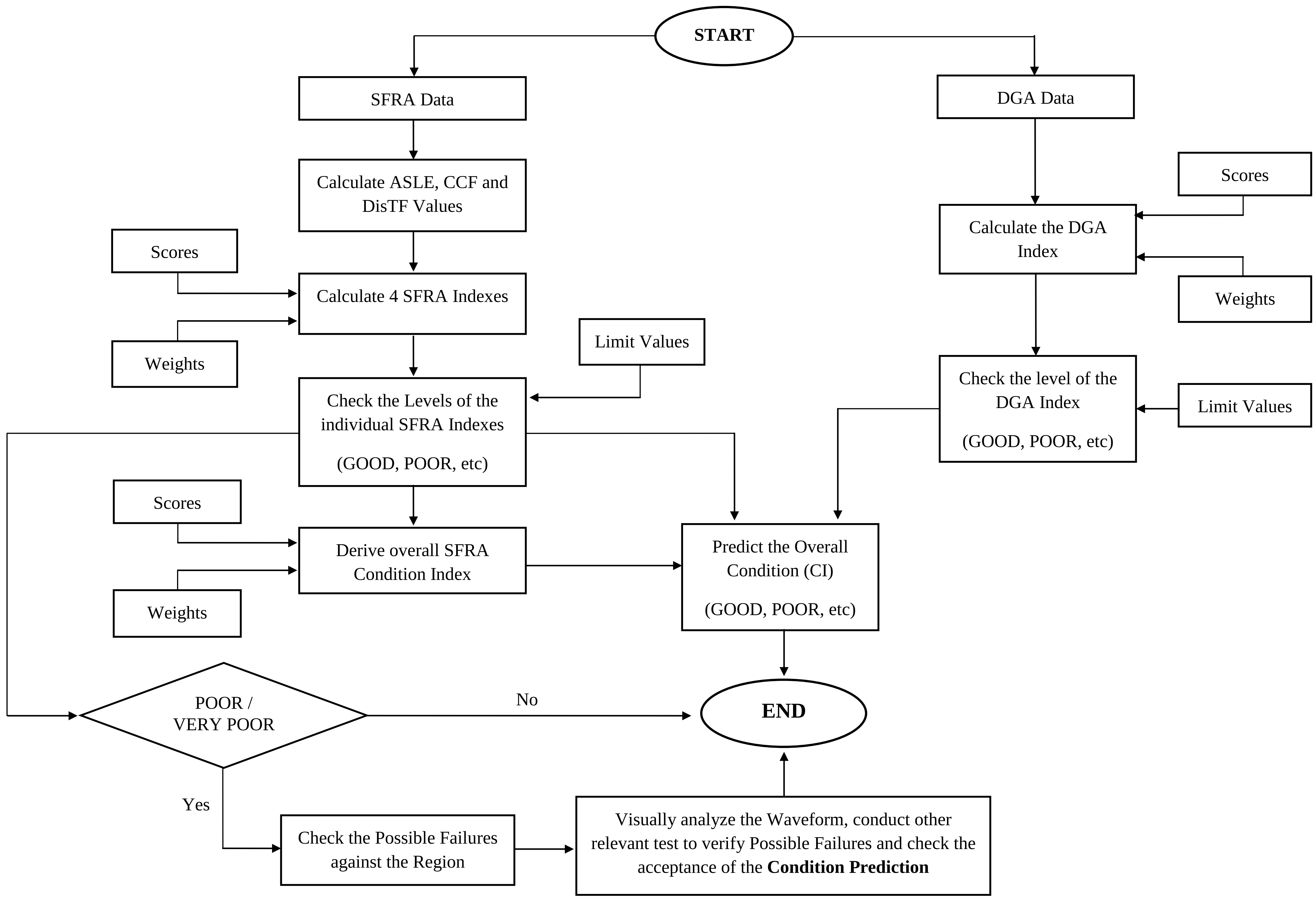


Figure 3.8: Flow chart of the method for concision assessment using SFRA and DGA data

As discussed in the previous stages of this Chapter, the condition is separately predicted based on the SFRA and DGA measurements initially. Subsequently an attempt was made to develop a combined condition index so that the results reflected form both SFRA and DGA can be taken in to account and give a single assessment out from several assessments made using 4 SFRA indexes and DGA Index.

In lieu of 4 SFRA indexes, a single index was derived considering the sensitivity of the SFRA measurements taken in various frequency ranges and their reliability in predicting the possible failures. The SFRA Condition Index (SFRA CI) can be represented as show in 3.12.

$$SFRA\ CI = \frac{W_1 \times SFRAI_1 + W_2 \times SFRAI_2 + W_3 \times SFRAI_3 + W_4 \times SFRAI_4}{W_1 + W_2 + W_3 + W_4} \quad (3.12)$$

Where, W_1, W_2, W_3 and W_4 are the weights given to the SFRAI respect to region 1 to region 4 respectively. Different frequency ranges of the SFRA measurement have different level of sensitivity to a possibility to have a failure. For example, as the low frequency region is highly dominated by the magnetic core, obvious deviation between three phases can be observed due to the non symmetry of the magnetic path, as discussed in Chapter 2. Further the middle frequency region is dominated by the winding structure and as the winding construction of a transformer is more or less exact for all the three phases, good matching between phases can be observed for a healthy transformer, in very often. The high frequency region (>400 kHz) is highly influenced by the winding leads and the measurement setup.

Therefore considering above factors, studying behavior of the SFRA measurement pattern and compare each index with SFRA plots visually and correlating the SFRA diagnosis with DGA diagnosis, the weights were derived such that, W_1, W_2, W_3 and W_4 equal to 1, 4, 3 and 2 respectively.

Hence, the following categorization criteria (as shown in Table 3.6) were developed for the overall condition assessment of the transformer with respect to the SFRA results.

Table 3.6: Overall condition prediction

Rating Coding	Overall Condition	Description
1	GOOD	SFRA CI ≤ 1.75
2	ACCEPTABLE	1.75 < SFRA CI ≤ 2.05
3	POOR	2.05 < SFRA CI ≤ 3.0
4	VERY POOR	3.0 < SFRA CI

3.5.4 MATLAB Computing Tool

A computing tool named "AssessCon" was developed using MTALAB to compute the indexes discussed above and display the outputs based on the limit values and the recommendations. The Figure 3.9 shows the snapshot of the Graphical User Interface (GUI) of the computing tool.

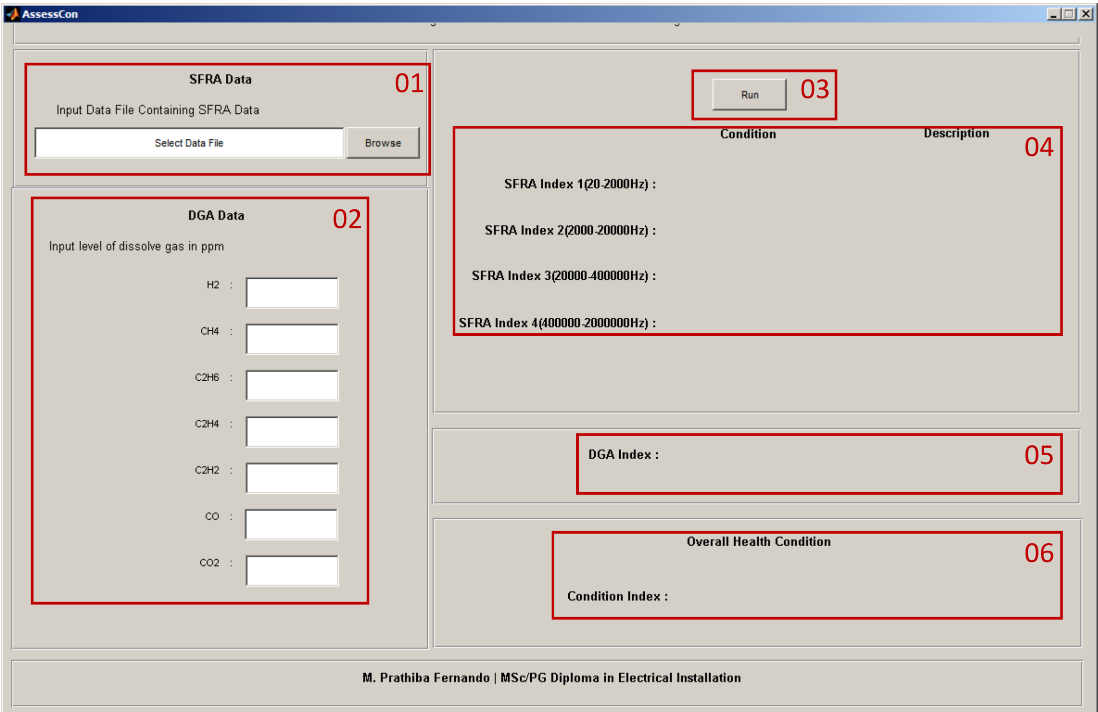


Figure 3.9: Snapshot of the GUI of the computing tool

The program was developed in two coding files such that the GUI is called by one file (namely AssessCon.m) including the functions related to the final display, while the main calculations are to be done by a separate set of functions written in the another file (namely Main.m).

The tool allows the user to input the SFRA measurement data (as shown in the segment 01 of the Figure 3.9) of a three phase transformer with respect to the three tests (HV open, HV short and LV open). For this the user shall first arrange the raw data file (MS Excel) in the order which is shown in Appendix-A.

After the SFRA data is fed to the programme, user can feed DGA data in to the space provided against each gas (as shown in the segment 02).

The run button (as shown in the segment 03) executes the programme. Here the programme calculates the relevant ASLE, CCF and DisTF values separately for the four regions, and compare them with the predefined limit values in order to identify the relevant score need to be assigned. Then it calculates the indexes, ASLEI, CCFI and DisTFl get involving corresponding scores and weights as shown in Appendix-E. Afterwards, it calculates the four SFRAI values using equation 3.10 as discussed above in this Chapter, and relevant diagnosis will be provided along with the condition prediction (as in Table 2.1 and 3.3) against each region based on the calculated SFRAI values (the diagnosis appears on the segment 04).

In the same time, the DGA data is also possessed and calculated the DGAI using the equation 3.11 and the Table 3.4 as discussed above. Based on the calculated DGAI and referring the limit values given in the Table 3.5, the condition with respect to the DGA data is output (the prediction appears on the segment 05)

The tool has been developed with the facility to output the overall condition of a transformer combining the condition prediction from both SFRA and DGA. As an initial point the following algorithm as shown in Table 3.7 has been adopted.

Table 3.7: Algorithm for the overall condition prediction

SFRA CI	DGAI	Overall Condition (CI)	
GOOD	GOOD	GOOD	
		ACCEPTABLE	; If one of the SFRAI is POOR/VERY POOR
GOOD	ACCEPTABLE	ACCEPTABLE	
GOOD	POOR	ACCEPTABLE	
GOOD	VERY POOR	POOR	
ACCEPTABLE	GOOD	ACCEPTABLE	
ACCEPTABLE	ACCEPTABLE	ACCEPTABLE	
ACCEPTABLE	POOR	ACCEPTABLE	
		POOR	; If one of the SFRAI is POOR/VERY POOR
ACCEPTABLE	VERY POOR	POOR	
POOR	GOOD	ACCEPTABLE	
POOR	ACCEPTABLE	POOR	
POOR	POOR	POOR	
		VERY POOR	; If one of the SFRAI is VERY POOR
POOR	VERY POOR	POOR	
		VERY POOR	; If one of the SFRAI is VERY POOR
VERY POOR	GOOD	POOR	
VERY POOR	ACCEPTABLE	POOR	
VERY POOR	POOR	VERY POOR	
VERY POOR	VERY POOR	VERY POOR	

The set of coding of this computing tool is shown in Appendix-K.

Chapter 4

CASE STUDIES

Several case studies will be carried out expressing the way of approaching of condition monitoring of transformers with SFRA and DGA. This will support to verify the proposed methodology and to justify the weights and scores that were used at the developing of various indices as discussed in the Chapter 3, which ultimately contribute to provide the assessment of the health condition through the proposed methodology.

1.5 Case Study 01

An old three phase power transformer manufactured in 1986 rated as 132/33 kV, 31.5 MVA with YNd1 vector group, has been operating around 30 years in Kiribathkumbura Grid Substation (GS).

Based on the SFRA measurements that were collected from this transformer, relevant indices were calculated and shown in the Table 4.1.

Table 4.1: Calculated indexes based on SFRA measurement data for Kiribathkumbura TR01

Index	Frequency Range			
	Range 1	**Range 2**	**Range 3**	**Range 4**
ASLEI	1.5000	1.9643	**2.8095**	1.4762
CCFI	1.1667	2.2143	**2.5238**	1.9048
DisTFI	1.7000	2.0714	1.0952	**3.1429**
SFRAI	1.3667	**2.1071**	**2.3810**	**1.9683**

The values corresponds to the ASLEI and CCFI at the Region 3 and DisTFI at Region 4 are quite higher and falls in the category of high possibility of having a failure, as defined in this study.

Further DGA test was carried out and the Table 4.2 shows the recorder gas levels of the above transformer.

Table 4.2: Gas concentrations recorded in Kiribathkumbura TR01

Gas	Value (ppm)
H_2	71
CH_4	102
C_2H_4	26
C_2H_6	127
C_2H_2	0
CO	649
CO_2	5227
TDCG	975

According to the indexing method proposed, it was found that the relevant DGAI is equal to **2.44** for this transformer, which falls under the “POOR” condition.

The SFRA and DGA data were fed in to the MATLAB computing tool, AssessCon and found that the overall condition prediction as “POOR” as shown in Figure 4.1.

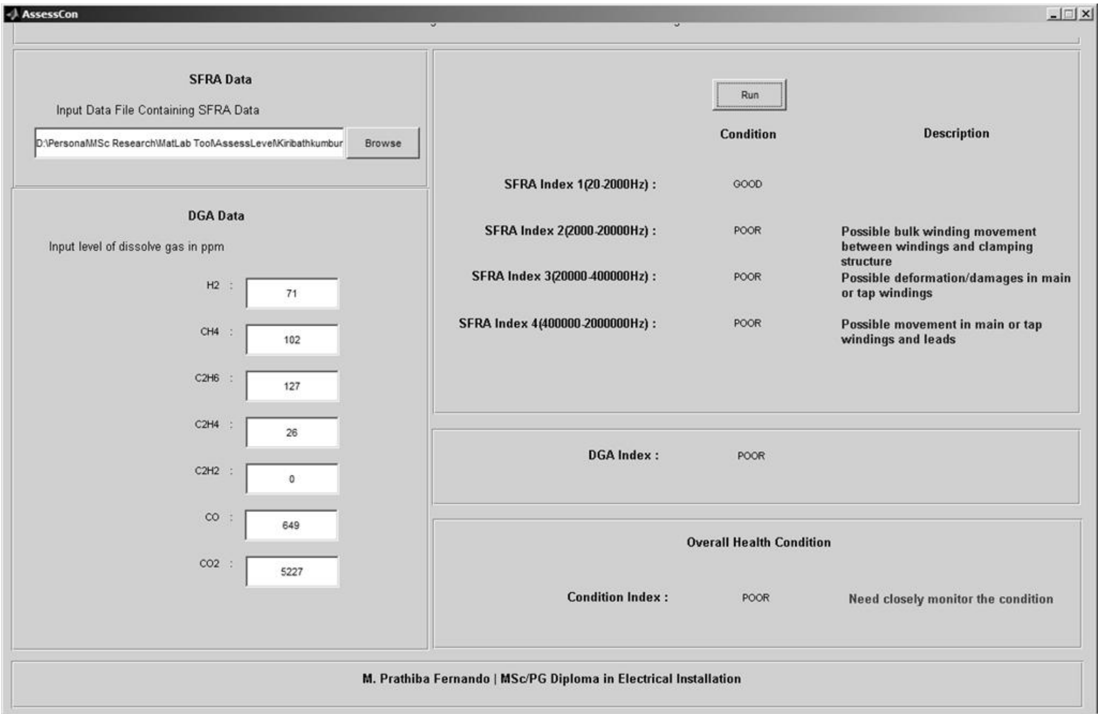


Figure 4.1: AssessCon condition prediction for Kiribathkumbura TR01

From the visual inspection of the SFRA plot it was found that the three plots of the three phases slightly deviate from each other at the middle (Region 2) and considerably at high frequency regions (Region 3 & 4). Figure 4.2 shows the SFRA plot of the Kiribathkumbura TR01 for the HV open configuration, and Figure 4.3 shows the zoomed view of the same plot at the deviated area.

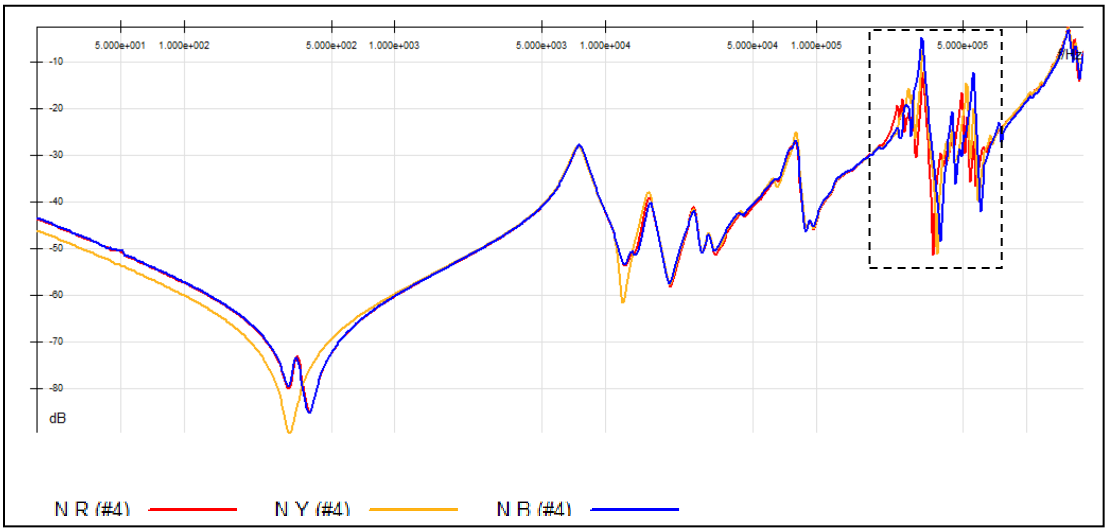


Figure 4.2: HV open SFRA measurement of Kiribathkumbura TR01

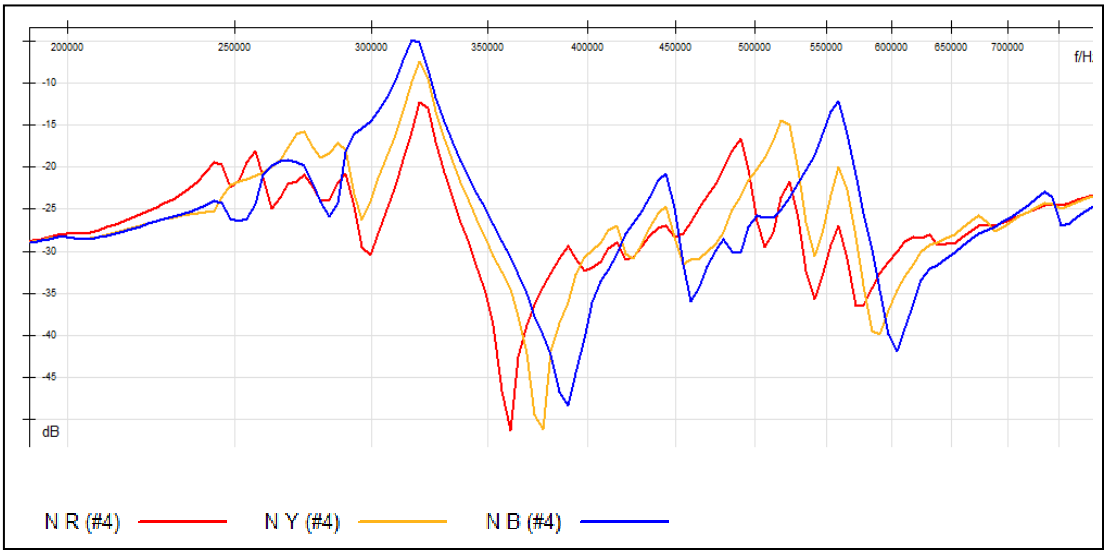


Figure 4.3: Zoomed view of the deviated area shown in Figure 4.2

According to the Figure 4.3, it is clear that there is a considerable deviation exists between three phases. Further it is observable that the resonance points have shifted with respect to each other.

Based on the range of the frequency that the deviations appeared, possible cause of the failures could have been,

- Radial Deformation (Hoop or Force Buckling)
- Axial Winding Elongation (Telescoping)
- Winding Turn to turn Short Circuit
- Winding Open Circuit

However there is no indication of winding turn to turn short circuit or winding open circuit, as no deviation located in the low frequency range. Therefore the most probable cause could have been winding deformation due to hoop buckling or telescoping effect.

From the gas concentrations, it could be seen that CH_4, C_2H_6 and TDCG has excessive gas levels with respect to the IEC and IEEE guidelines, and analyzing the concentrations of those gases it was found that the transformer falls under "Condition 2" according to the IEEE key gas method which indicated that the transformer condition is not in the acceptable level. Further Roger's ratio analysis and Duval's Triangle analysis provided the diagnosis predictions as "Thermal Faults 150 - 300 ˚C" and "Thermal Faults < 300 ˚C" respectively, which was also an indication of some abnormality within the transformer with respect to the DGA measurements.

In addition to above DGA and SFRA tests, several other tests (Tan δ, DC winding resistance and Turns ration test) were also carried out to investigate this case.

Out of these tests, DC winding resistance and turns ratio test further confirmed that there is no contribution of open circuit winding or short circuit turns for the deviation found in the SFRA plot. However Tan δ measurement indicated severe insulation weakness inside the transformer.

1.6 Case Study 02

Another old three phase generator transformer manufactured in 1975 rated as 132/12.5 kV, 27 MVA, had been in the operation for more than 40 years in Ukuwela Power Station. This transformer was taken out from the operation recently, as it was found that it could not deliver the output voltage to the rated level due to an unidentified internal failure.

SFRA test was carried out for this failed unit and calculated index are as shown in the Table 4.3.

Table 4.3: Calculated indexes based on SFRA measurement data for Ukuwela TR01

Index	**Frequency Range**			
	Range 1	**Range 2**	**Range 3**	**Range 4**
ASLEI	**2.6000**	**3.5357**	**2.5714**	1.9048
CCFI	**2.7667**	**2.7143**	1.8571	**2.7619**
DisTFI	**2.1667**	**3.3571**	1.0000	1.7143
SFRAI	**2.6111**	**3.0952**	1.9524	**2.3016**

The values correspond to the ASLEI, CCFI and DisTFI are quite high both at the Region 1 and 2. Further the values correspond to the ASLEI and CCFI at the region 3 and 4 respectively are also indicated as high. These are indication of high possibility of having failures relevant to those regions. However the SFRAI indicated considerable level of lack of similarities at the Region 1, 2 and 4.

Further DGA test was carried out and the Table 4.4 shows the recorded gas levels of the above transformer. Based on these gas levels the calculated DGAI was **2.56**. This indicates the condition of “POOR”.

Above SFRA and DGA data were fed in to the AssessCon and found that the overall condition prediction was “VERY POOR” as given as the Figure 4.4.

Table 4.4: Gas concentrations recorded in Ukuwela TR01

Gas	Value (ppm)
H_2	61
CH_4	25
C_2H_4	66
C_2H_6	5
C_2H_2	67
CO	139
CO_2	758
TDCG	363

Figure 4.4: AssessCon condition prediction for failed Ukuwela TR01

The relevant SFRA plots measured for this transformer were shown in the Figure 4.5, Figure 4.6 and Figure 4.7.

According to the Figure 4.4 and Figure 4.6 it can be seen a severe deviation between phases both in lower (Range 1), middle (Range 2) and high (Range 4) frequency ranges. Possible causes for the above deviation can be identified as,

- Core deformation

- Open circuit windings
- Turn to turn shorted windings

However as looking at the pattern of deviation, it is clear that this is not because of open circuit winding as the deviated plot has representing a decrease in impedance, whereas in case of open circuit winding, impedance should be increased and the plot should move downwards. Further as the deviation represent a loading on the open circuit windings and it is much closer to a pattern of a turn to turn short circuit winding [1].

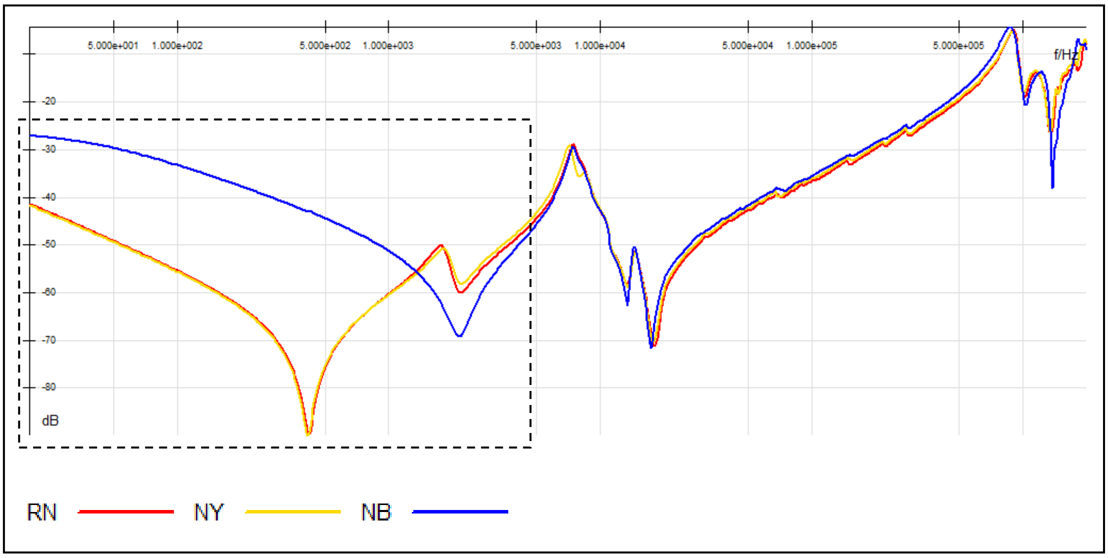


Figure 4.5: HV open SFRA measurement of Ukuwela TR01

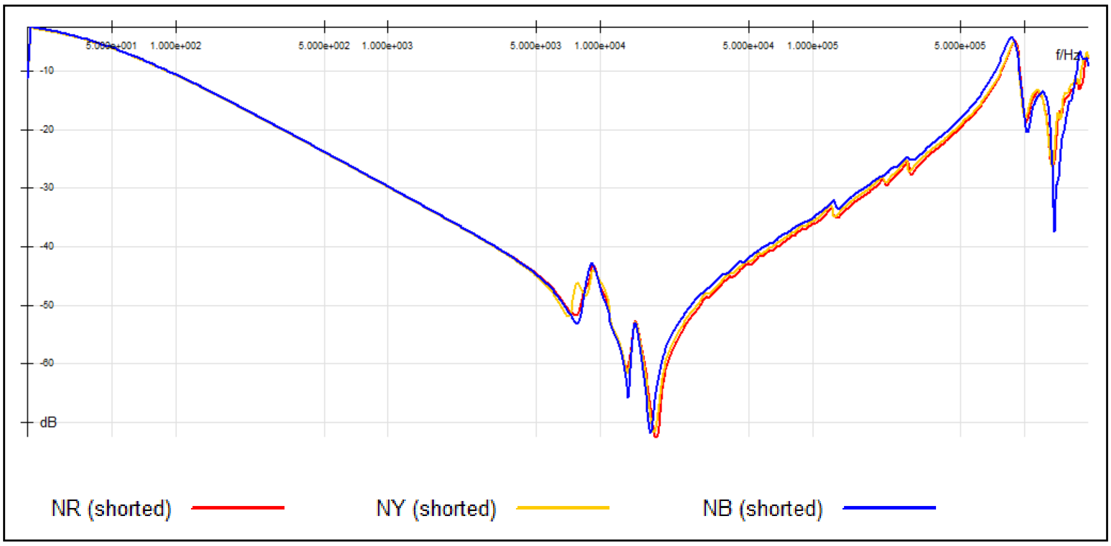


Figure 4.6: SFRA plot of Ukuwela TR01 for HV short configuration

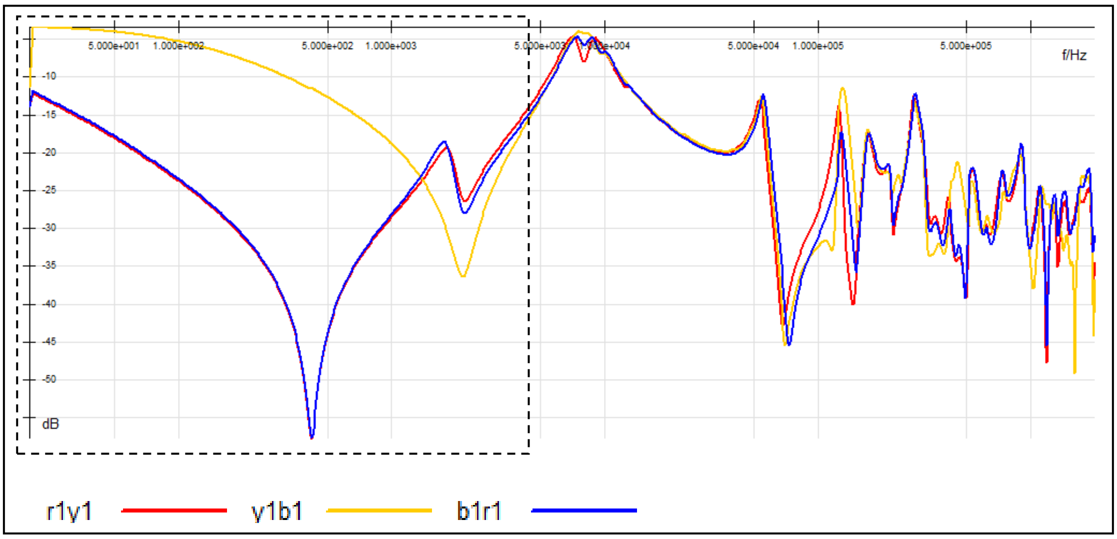


Figure 4.7: SFRA plot of Ukuwela TR01 for LV open configuration

Based on the gas levels as shown in Table 4.4, it indicates the presence of internal arcing, as the excessive concentration of C_2H_2 can be seen. This can be considered as an evidence of having shorted turns, as this kind of failure can generate internal arcing inside of a transformer.

However, as the post inspection of the transformer is still to be done and then after the actual reason for the failure could able to be identified.

1.7 Case Study 03

A modest aged 132/33 kV, 31.5 MVA three phase power transformer with YNd1 vector group which has been manufactured in 2000 has been operating for 16 years in Veyangoda GS.

SFRA measurement data were collected for this transformer and calculated indexes are as in the Table 4.5.

Table 4.5: Calculated indexes based on SFRA measurement data for Veyangoda TR02

Index	Frequency Range			
	Range 1	**Range 2**	**Range 3**	**Range 4**
ASLEI	1.7000	**2.9286**	2.2857	1.1905
CCFI	1.3667	**3.2857**	2.3810	1.0000
DisTFI	1.3333	**2.7500**	2.4286	1.1905
SFRAI	1.4722	**3.0774**	**2.3571**	1.0952

According to the individual indexes, the values relevant to the ASLEI, CCFI and DisTFI are high at the frequency region 2. However the SFRAI calculated combining above three tools indicate considerable deviation at the frequency Region 3 as well.

The data collected from DGA testing for this transformer is shown in the Table 4.6.

Table 4.6: Gas concentrations recorded in Veyangoda TR02

Gas	Value (ppm)
H_2	89
CH_4	556
C_2H_4	583
C_2H_6	271
C_2H_2	0
CO	257
CO_2	3068
TDCG	1765

Calculated DGAI based on above gas level is equal to 3.44, and this falls in to the “VERY POOR” category according to the proposed categorization.

The SFRA and DGA data were fed in to the AssessCon and found that the overall condition prediction was “POOR” as shown in Figure 4.8.

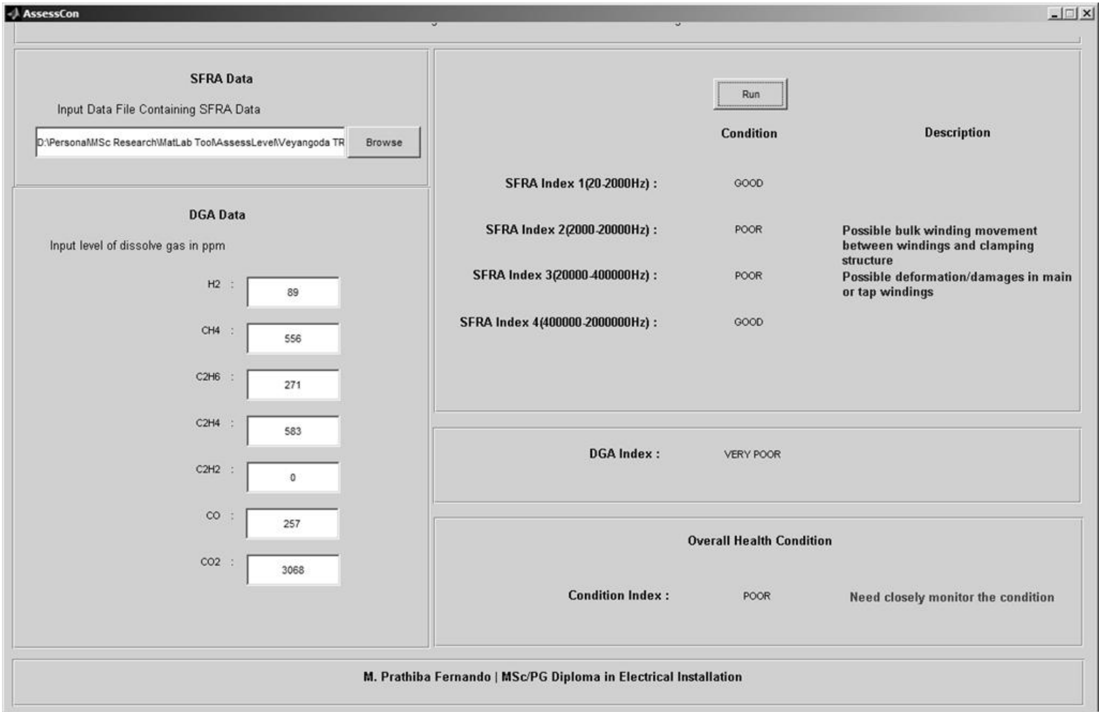


Figure 4.8: AssessCon condition prediction for Veyangoda TR02

Through the visual inspection of the SFRA plot collected for this transformer, it was found that the three plots of the three phases deviate from each other at the middle (Region 2) and high (Region 3 & 4) frequency regions.

Figure 4.9 shows the SFRA plot of the Veyangoda TR02 for the LV open configuration, and Figure 4.10 shows the zoomed view of the same plot at the deviated area.

However, by analyzing the deviation observed in the Region 4, it was identified that the observed deviation is acceptable compared to the several other similar transformers. Therefore it could be considered that the considerable deviations are present at only at the Region 2 & 4.

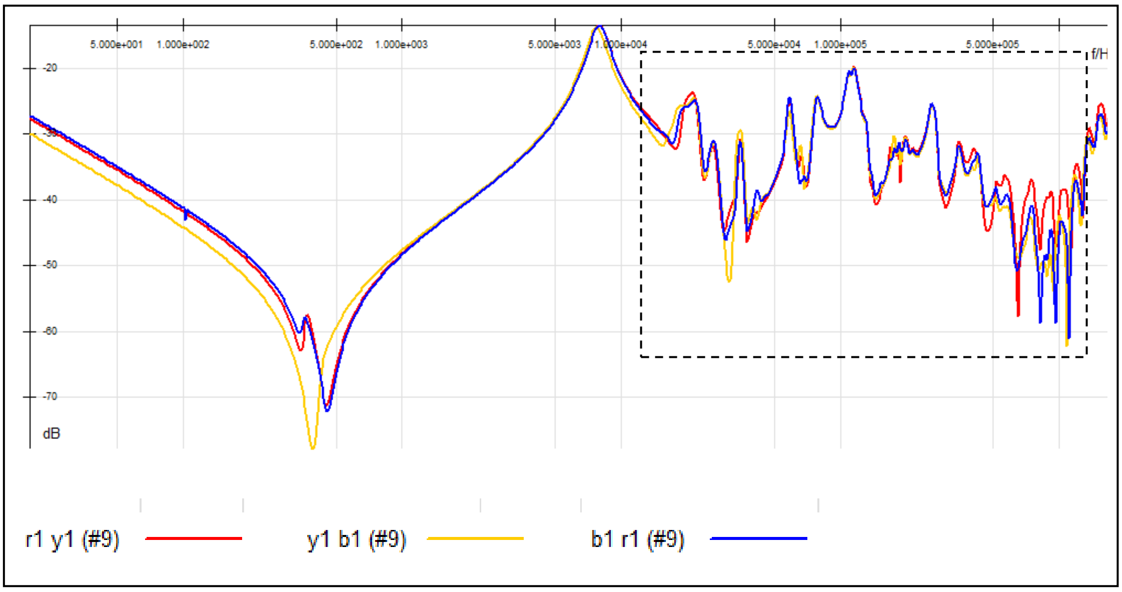


Figure 4.9: LV open SFRA measurement of Veyangoda TR02

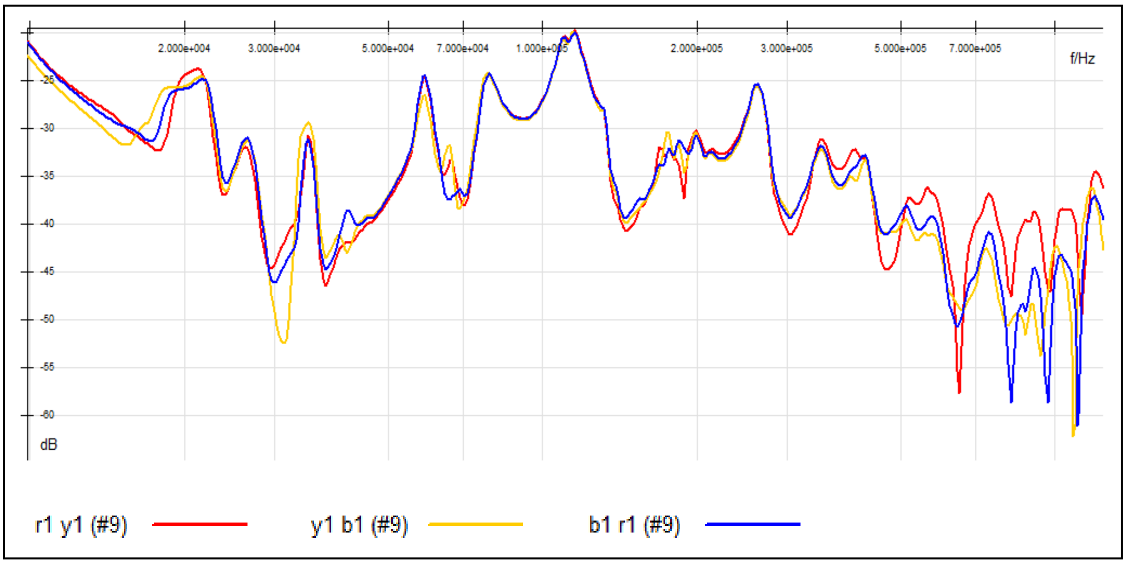


Figure 4.10: Zoomed view of the deviated area shown in Figure 4.9

Further, Figure 4.11 shows the SFRA plot of the Veyangoda TR02 for the HV short configuration, and Figure 4.12 shows the zoomed view of the same plot at the deviated area.

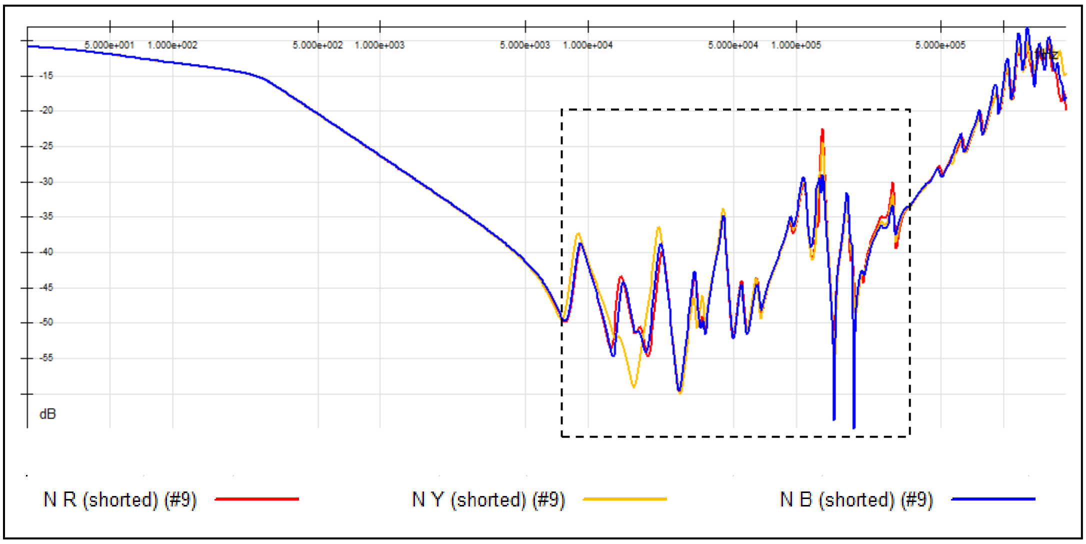


Figure 4.11: HV short SFRA measurement of Veyangoda TR02

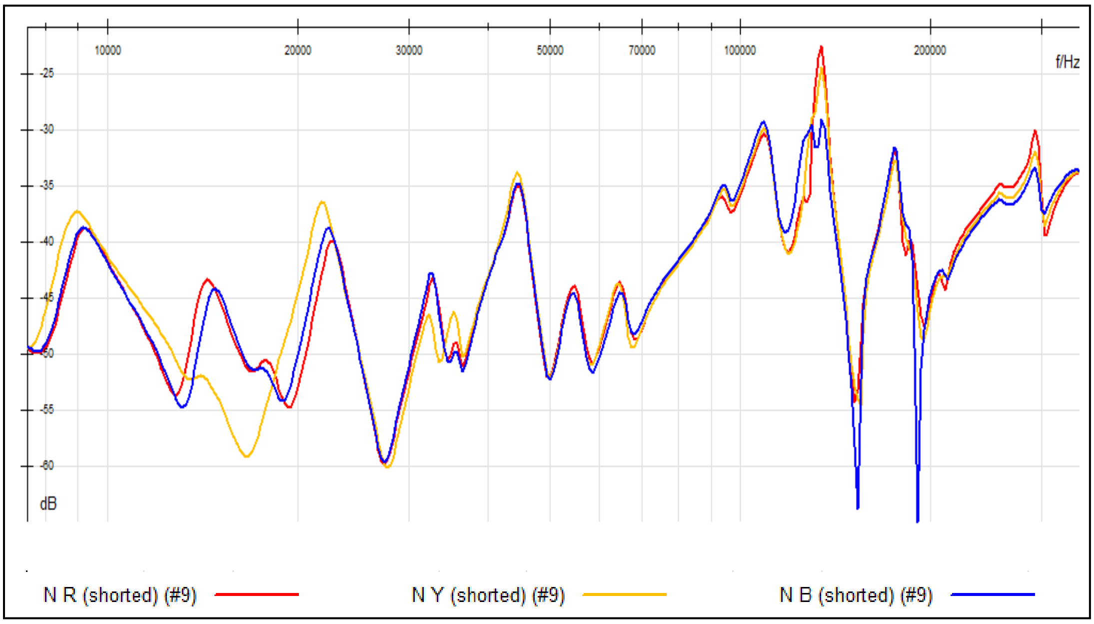


Figure 4.12: Zoomed view of the deviated area shown in Figure 4.11

According to the Figure 4.1 and Figure 4.12, it is clear that there is a considerable deviation exists between three phases. Further it is observable that the resonance points have shifted with respect to each other.

Based on the range of the frequency that the deviations appeared, possible cause of the failures could have been,

- Radial Deformation (Hoop or Force Buckling)
- Axial Winding Elongation (Telescoping)
- Winding Turn to turn Short Circuit
- Winding Open Circuit

However there is no indication of winding turn to turn short circuit or winding open circuit, as no deviation located in the low frequency range. Therefore the most probable cause could have been winding deformation due to buckling or telescoping effect.

From the DGA data, it could be seen that CH_4, C_2H_6 and C_2H_4 has excessive gas levels with respect to the IEC and IEEE guidelines, and analyzing the concentrations of those gases it was found that the transformer falls under "Condition 3" according to the IEEE key gas method which indicated that the transformer condition is not in the acceptable level. Further Roger's ratio analysis and Duval's Triangle analysis provided the diagnosis predictions as "Thermal Faults 300 - 700 ˚C" and "Thermal Faults > 700 ˚C" respectively, which was also an indication of some abnormality within the transformer with respect to the DGA measurements.

In addition to above DGA and SFRA tests, several other tests (Tan δ, DC winding resistance and Turns ration test) were also carried out to investigate this case.

Out of these tests, DC winding resistance and turns ratio test further confirmed that there is no contribution of open circuit winding or short circuit turns for the deviation found in the SFRA plot. Tan δ measurement was within the acceptable limits.

However these tests are not that much of sensitive to the winding deformation like Radial Buckling and Axial Winding Elongation [4] unless there is severe degradation of insulation or development of open/shorted windings due to the growth of initial fault to a catastrophic level.

1.8 Case Study 04

The magnetic balance test has been carried out at the commissioning stage of a newly installed 132/33 kV, 31.5MVA three phase power transformer, in Kilinochchi GS, and it has showed an imbalance in the core structure. Test results of magnetic balance test are summarized in Table 4.7.

Table 4.7: Test results of magnetic balance test of Kilinochchi TR03

Tap No.	Phase Removed	1R1Y (V)	1Y1B (V)	1B1R (V)
1	R	403.41	405.10	408.34
	Y	383.32	398.14	404.65
	B	405.82	401.92	409.09
8	R	430.90	405.20	404.17
	Y	383.60	399.78	404.76
	B	406.61	399.78	411.41
18	R	403.67	403.11	403.61
	Y	400.72	401.81	400.53
	B	403.01	390.91	410.39

Therefore, an SFRA test was carried out on this transformer with the purpose of identifying any defect on the core structure.

The collected SFRA measurement data were subjected to the calculation of indexes ASLEI, CCFI and DisTFI, and the outcomes are as in the Table 4.8.

Table 4.8: Calculated indexes based on SFRA measurement data for Kilinochchi TR03

Index	Frequency Range			
	Range 1	Range 2	Range 3	Range 4
ASLEI	**2.8000**	1.9643	1.4286	1.2381
CCFI	**2.3333**	1.6429	1.2857	1.1429
DisTFI	1.3333	1.5000	1.5714	1.4762
SFRAI	**2.3222**	1.7262	1.3810	1.2302

It was seen that there is a considerable deviation in the frequency Region 1 with relevant to the values for ASLEI and DisTFI. However the value correspond to DisTFI did not indicated a considerable deviation. The reason for this might be not having considerable deviation in the shape of the plots but only a shifting towards up or down. However the SFRAI indicated considerable deviation, hence prediction of high possibility of failure level with corresponding to the lower frequency region.

The SFRA measurement was fed in to the MATLAB computing tool, AssessCon, and output was given as shown in the Figure 4.13. Here DGA data have not fed as the transformer is not energized yet.

Figure 4.13: AssessCon condition prediction for Kilinochchi TR03

According to the AssessCon prediction, the lower frequency region is in POOR condition and has given diagnosis suggestions as “Possible Core deformations, open circuits or shorted turns or Residual Magnetism”.

When analyzing the frequency response plots, deviations were found in low frequency region of both HV open and LV open responses as shown in Figure 4.14 and Figure 4.15 respectively.

As described characteristics of SFRA plots in previous chapters, NR and NB plots and r1y1 and b1r1 plots should have been on top of each other for magnetic symmetry of the core. However, according to the Figure 4.14 and Figure 4.15, the SFRA measurement represents a magnetic imbalance in the core structure.

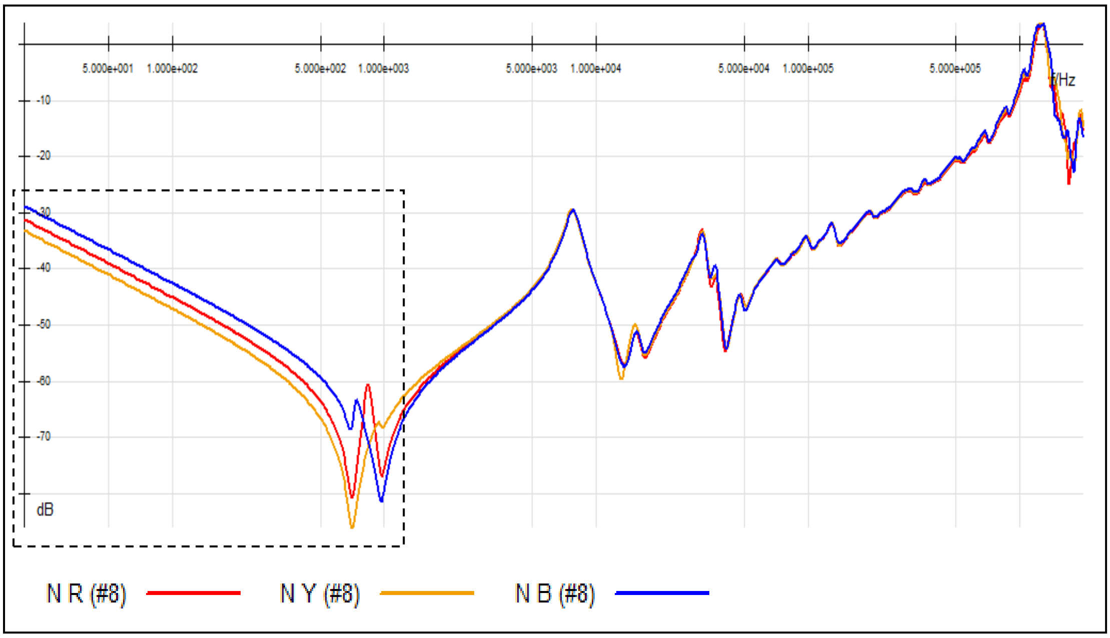


Figure 4.14: Deviation in the low frequency range of HV open SFRA measurement

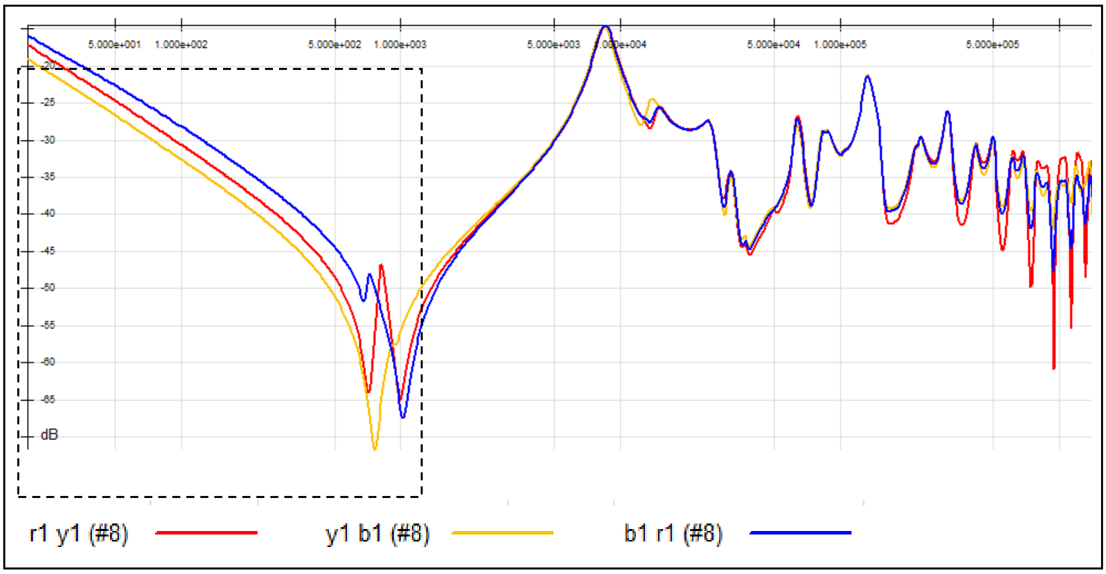


Figure 4.15: Deviation in the low frequency range of LV open SFRA measurement

Even though the SFRA and magnetic balance test showed abnormal results, other test results such as, excitation current, turns ration test, winding resistance showed normal behavior of the transformer. However, DGA analysis was not done, as this transformer was not energized at this moment, hence no gas formation could expect due to any electrical or thermal stresses.

Considering above test results, it was decided to demagnetize the core and repeat the SFRA test again. After demagnetizing the core, SFRA test was carried out and the below indexes were observed.

Table 4.9: Calculated indexes based on SFRA measurement data for Kilinochchi TR03 after demagnetization

Index	Frequency Range			
	Range 1	**Range 2**	**Range 3**	**Range 4**
ASLEI	2.0667	1.1429	1.0000	1.0952
CCFI	1.3333	1.0000	1.0000	1.0000
DisTFI	1.1333	1.0000	1.0000	1.2381
SFRAI	1.5444	1.0476	1.0000	1.0714

It was seen that there is no considerable deviation in any of the indexes. Further as this transformer is a new one and has not even energized for the operation, this can be considered as a faulty free unit. Therefore it is confirmed that the previously observed deviations in the low frequency Region were solely due to the presence of residual magnetism.

Figure 4.16 shows the prediction given by AssessCon for the SFRA measurement taken after the core demagnetization, and it indicated GOOD condition.

The relevant SFRA plots of the primary and secondary self winding after the demagnetization of the transformer are shown in figure 4.17 and Figure 4.18 respectively.

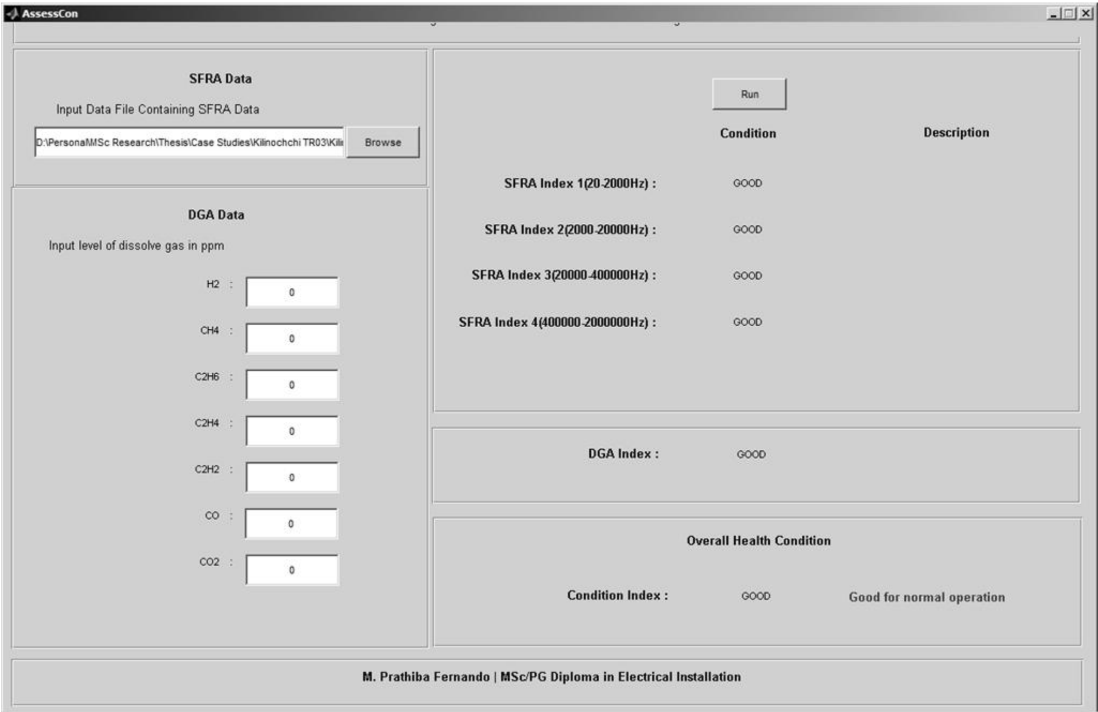


Figure 4.16: AssessCon condition prediction for Kilinochchi TR03 after core demagnetization.

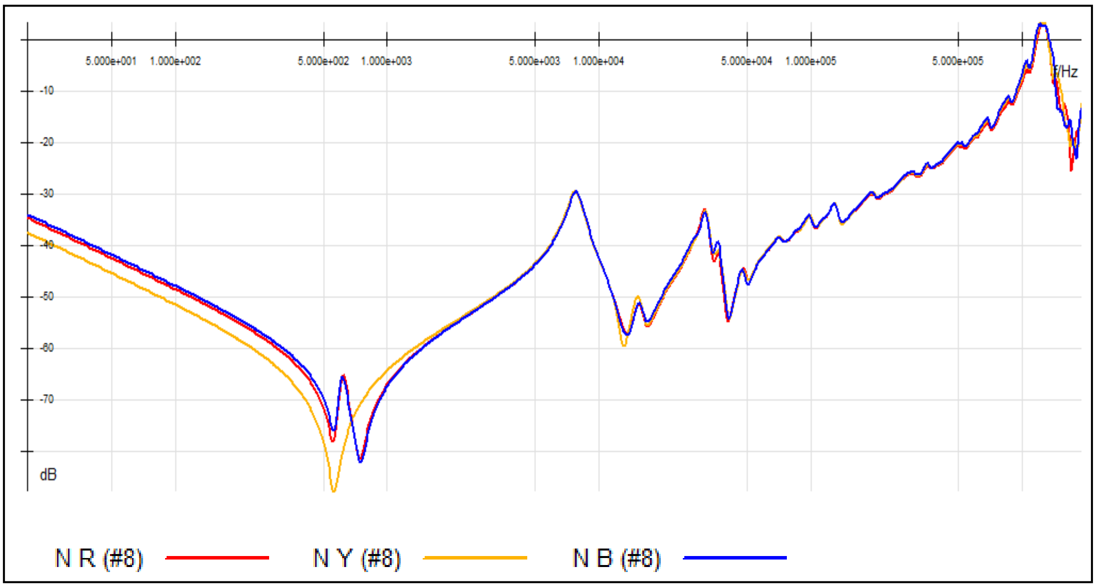


Figure 4.17: Frequency response of HV open after demagnetizing

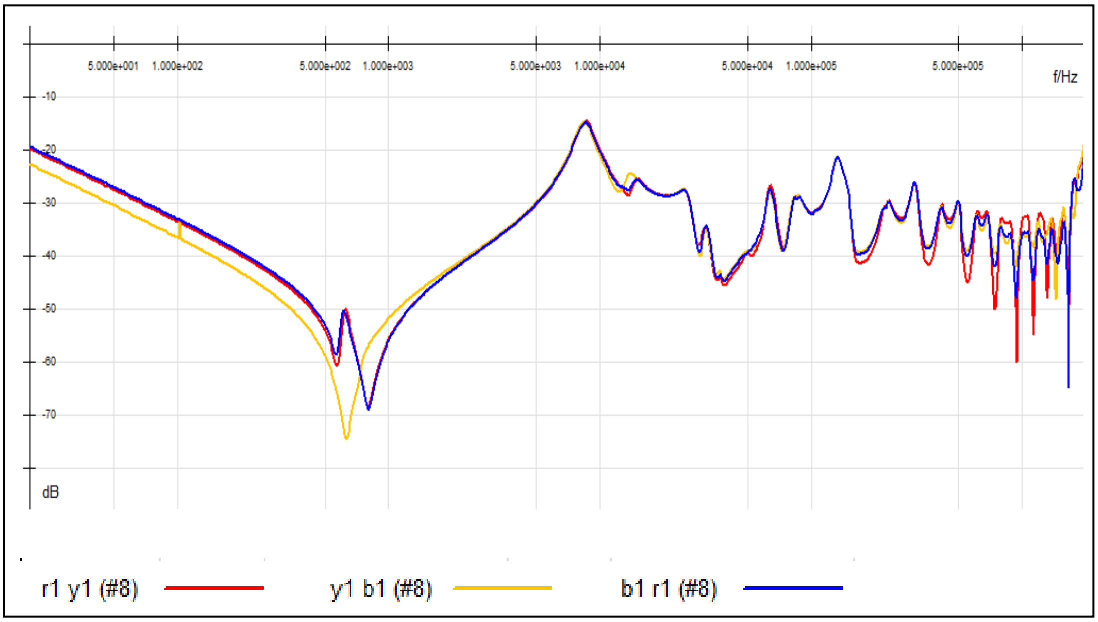


Figure 4.18: Frequency response of LV open after demagnetizing

After demagnetizing, both NR and NB plots (HV open) and r1y1 and b1r1 (LV open) plots are on top of each other. Hence, it was clear that, the residual magnetism that associates with the core structure was the reason for deviation in the low frequency range of the primary and secondary self winding responses. Therefore, evaluation of frequency responses should be done with caution as any third party phenomenon (such as residual magnetism) may mislead the frequency response diagnostics.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study presented analysis of SFRA and DGA for monitoring the condition of power transformers, and an approach was made to develop a methodology to assess the health condition of a power transformer based on the SFRA and DGA measurements.

SFRA is a tool which can be used to analyze the transfer function of the transformer. It is used to evaluate the mechanical integrity of core, windings, leads and clamping structures of the power transformers. The three frequency responses of three phases should be identical except to the inherited variations, and therefore, it can be considered as a fingerprint for a transformer. Geometrical changes within and between the elements of the network cause deviations in its frequency response. On the other hand DGA is a tool which can be used to analyze the gas components dissolved in the insulating oil in the transformer by analyzing oil sample taken from the transformer. Various gases and their level of dissolved indicate the condition of a transformer by the means of possible electrical and thermal stresses that could have been applied on a transformer.

The collected SFRA measurements were analyzed in the aspect of evaluating the deviation of the plots between three phases. The analysis was taken towards quantifying the deviation and thereby to develop a method to assess the health condition.

Three key analysis tools namely ASLE, CCF and DisTF were utilized in this regards, and developed indexing method which then could be used as an indication of the health condition of a transformer. ASLE measures the difference of magnitude between responses while the CCF measures the similarity of shape between responses. The DisTF is a new tool to be used for the frequency response matching and it also measures the similarity of shape between responses, however it highly determines the shape and only on the shape of the response with compared to the CCF. The benchmarks for the above three tools were selected based on the collected SFRA measurements. Initially the benchmarks were selected based on the data distribution. The results out from the three tools based on the selected benchmarks, showed more or less similar outcomes. Later the outcomes were compared with the DGA measurements and against some known transformer cases of having unacceptable conditions, and further improved for better acceptability.

Out from the studied network, below transformers were identified as most ten critical transformers based on the above analysis.

1. Valachchenai TR01
2. Valachchenai TR02
3. Valachchenai TR03
4. Biyagama TR03
5. Kiribathkumbura TR02
6. Veyangoda TR03
7. Veyangoda TR02
8. Old Anuradhapura TR01
9. Bolawatta TR02
10. Bolawatta TR01

Similarly, DGA measurements were subjected to the analysis according to the guidelines given in international standards. Threshold limits for gas components were defined by considering limit values given in international standards, previous study references and also the distribution of each gas concentration of the studied network. It was found that the 90% values of the gas levels, which recommended by IEC guidelines to be used as the typical gas levels, align within the international guidelines except the high concentration of C_2H_6. Accordingly, a health index was defined and allocated for each transformer. The outcome was further investigated and compare with the diagnosis predictions made upon several DGA diagnosis tools. Based on the actual cases of power transformers, it was identified that the indexing was relatively reasonable.

Out from the studied network, below transformers were identified as most ten critical transformers based on the above analysis.

1. Pannala TR01
2. Veyangoda TR02
3. Kotugoda TR01-B
4. Old Galle TR01
5. Veyangoda TR03
6. Kelaniya TR01
7. Mathugama TR01
8. Kiribathkumbura TR02
9. Thulhiriya TR03
10. Kiribathkumbura TR01

It was found that condition categorization of several transformers based on SFRA do not fall in to same categorization done based on DGA, and vise-versa. This is happened, as some of the faults addressed by SFRA do not Addressed by DGA and also in other way around. For example, while a development of PD activity reflecting through DGA measurement, same would not affect the SFRA measurement as long as no mechanical deformation in the active part of the transformer. On the other hand the any slight deformation in the active part would not be reflected through DGA measurements as long as no considerable damage to insulation or the thermal profile of the transformer. However these kinds of failures could be developed to a severe extent and cause catastrophic failure if not identified in advance. Therefore the importance of assessment of the condition from both the SFRA and DGA approaches was identified.

An overall prediction criterion was proposed correlating the outcomes from SFRA and DGA approaches, and attempted to justify upon specific cases of transformer failures and observed abnormalities. The proposed methodology was developed for the assessment of three phase power transformers, as the evaluation of the similarity between the responses of the three phases was considered. In this context, the following three phase transformers were identified as the ten most critical transformers in the studied network.

1. Valachchenai TR02
2. Kiribathkumbura TR02
3. Veyangoda TR03
4. Veyangoda TR02
5. Bolawatta TR01
6. Bolawatta TR03
7. Valachchenai TR01
8. Kiribathkumbura TR01
9. Valachchenai TR02
10. Bolawatta TR02

Finally, the approach to assess the mechanical integrity of a transformer, and thereby the heath condition based on the similarity analysis of the frequency responses of three phases was well justified by the case studies.

5.2 Recommendations

SFRA and DGA are two different techniques can be utilized for health condition monitoring of transformers. They have different aspects to address, as the SFRA mainly deal with the mechanical integrity of the transformer while DGA represent the possible weakness of the transformer that could have been generated due to electrical and thermal stresses. Therefore, it is recommended to utilize both of these two techniques in order to have a reliable condition assessment.

The three analysis tools ASLE, CCF and DisTF used for the SFRA data analysis have unique aspects such that they address the similarity of the responses differently. However each of them provides important indication towards the outcome to be more precise. It is hence recommended to utilize the indices that outcomes form all the three tools rather than relying on one tool.

Further, when a transformer is found to be non-acceptable based on the SFRA measurements and against the indices suggested in this study, it is advised to investigate the case further considering several aspects such as, the affected frequency region, the behavior of previous base case responses or responses of a similar type if available, before taking any important decision such as retiring the transformer, attending for repairs or opening for inspection. In addition is important to verify the accuracy of measurement taken such that the measurement has not influenced by environmental noises or any other third party phenomenon like residual magnetisms which could ultimately lead to a faulty assessment.

Dissolved gas concentration presented in the transformer oil is an indication of the level of applied stresses on a transformer. Once it is found that a transformer is not in the acceptable condition, again before taking any important decision attention shall also be given to monitor the rate of generation of gases. This helps to ensure whether the condition getting worse or not. Therefore it is an important indication to assess the severity of the condition and make cost optimal decisions.

5.2.1 Future works

Further to this study carried out for developing a methodology to assess the condition of power transformer, in future work, frequency response due to a faulty tap changer could also be studied to establish guidelines for condition analysis.

Although the proposed method was able to assess the condition by the means of condition index assigned, the result was not verified with visual inspection on the unit due to certain limitations. Therefore, future work may include make necessary arrangements to make inspection possible.

In addition, the MATLAB computing tool, the AssessCon shall also be enhanced with addition of another layer for GUI, so that user can access the calculated parameters and indexes separately and compare them with the limit values for detail analysis. Further the final prediction shall be represented as in the form of a "condition meter" giving more graphical interpretation instead of giving the output as "GOOD" or "POOR" or etc.

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APPENDICES

Appendix-A: Sample set of data of a SFRA measurement

No.	Frequency (Hz)	HV open circuit (dB)			HV short circuit (dB)			LV open circuit (dB)		
		R	Y	B	R	Y	B	R	Y	B
1	20	-30.5435	-34.5908	-32.8476	-10.8786	-10.8895	-10.8959	-18.4934	-21.1708	-19.6974
2	21	-30.7727	-34.8649	-33.0859	-10.9019	-10.9139	-10.9161	-18.9897	-21.6494	-20.0757
3	21	-31.0080	-35.1455	-33.3494	-10.9273	-10.9399	-10.9417	-19.3276	-21.9595	-20.3305
4	22	-31.2435	-35.4187	-33.6107	-10.9540	-10.9674	-10.9688	-19.5892	-22.2114	-20.5517
5	23	-31.4764	-35.6831	-33.8678	-10.9801	-10.9937	-10.9951	-19.8043	-22.4341	-20.7566
6	23	-31.7250	-35.9639	-34.1465	-11.0102	-11.0245	-11.0252	-20.0033	-22.6606	-20.9735
7	24	-31.9645	-36.2371	-34.4153	-11.0398	-11.0544	-11.0552	-20.1882	-22.8786	-21.1830
8	25	-32.1985	-36.5020	-34.6777	-11.0706	-11.0857	-11.0862	-20.3548	-23.0871	-21.3865
9	26	-32.4466	-36.7820	-34.9528	-11.1031	-11.1187	-11.1189	-20.5274	-23.3075	-21.6064
10	27	-32.6873	-37.0531	-35.2162	-11.1372	-11.1531	-11.1531	-20.6936	-23.5250	-21.8213
11	28	-32.9344	-37.3257	-35.4897	-11.1716	-11.1881	-11.1878	-20.8610	-23.7475	-22.0420
12	28	-33.1831	-37.6017	-35.7611	-11.2085	-11.2253	-11.2247	-21.0330	-23.9758	-22.2664
13	29	-33.4346	-37.8795	-36.0392	-11.2463	-11.2636	-11.2626	-21.2099	-24.2088	-22.4954
14	30	-33.6801	-38.1450	-36.3040	-11.2848	-11.3024	-11.3011	-21.3845	-24.4370	-22.7180
15	31	-33.9425	-38.4256	-36.5832	-11.3254	-11.3434	-11.3418	-21.5704	-24.6778	-22.9524
16	32	-34.1939	-38.6979	-36.8544	-11.3667	-11.3853	-11.3832	-21.7541	-24.9142	-23.1813
17	33	-34.4492	-38.9695	-37.1234	-11.4085	-11.4278	-11.4253	-21.9423	-25.1532	-23.4119
18	35	-34.7109	-39.2507	-37.4031	-11.4538	-11.4734	-11.4707	-22.1440	-25.4008	-23.6509
19	36	-34.9755	-39.5236	-37.6742	-11.4980	-11.5178	-11.5150	-22.3330	-25.6420	-23.8860
20	37	-35.2147	-39.8038	-37.9545	-11.5456	-11.5657	-11.5628	-22.5416	-25.8905	-24.1249
21	38	-35.4738	-40.0739	-38.2222	-11.5924	-11.6128	-11.6096	-22.7406	-26.1342	-24.3607
22	39	-35.7412	-40.3517	-38.5037	-11.6422	-11.6628	-11.6592	-22.9402	-26.3906	-24.6095
23	41	-36.0117	-40.6348	-38.7737	-11.6916	-11.7128	-11.7087	-23.1611	-26.6461	-24.8516
24	42	-36.2786	-40.9032	-39.0565	-11.7434	-11.7647	-11.7597	-23.3590	-26.9064	-25.1046
25	43	-36.5477	-41.1799	-39.3289	-11.7945	-11.8160	-11.8105	-23.5660	-27.1596	-25.3504
26	45	-36.7980	-41.4721	-39.6013	-11.8477	-11.8697	-11.8640	-23.7929	-27.4202	-25.5967
27	46	-37.0521	-41.7339	-39.8708	-11.8995	-11.9213	-11.9169	-24.0004	-27.6521	-25.8300
28	48	-37.3306	-42.0103	-40.1582	-11.9552	-11.9773	-11.9712	-24.2250	-27.9363	-26.0962
29	49	-37.5955	-42.2712	-40.4335	-12.0095	-12.0318	-12.0251	-24.4256	-28.1956	-26.3537
30	51	-37.8668	-42.5614	-40.7192	-12.0653	-12.0876	-12.0807	-24.6459	-28.4601	-26.6088
31	53	-38.1256	-42.8400	-40.9710	-12.1209	-12.1430	-12.1366	-24.8866	-28.7183	-26.8571
32	54	-38.3945	-43.1235	-41.2542	-12.1776	-12.1999	-12.1938	-25.1013	-28.9634	-27.1066
33	56	-38.6648	-43.4037	-41.5321	-12.2344	-12.2564	-12.2494	-25.3335	-29.2499	-27.3787
34	58	-38.9398	-43.6864	-41.8147	-12.2926	-12.3147	-12.3069	-25.5464	-29.5194	-27.6498
35	60	-39.2112	-43.9649	-42.0898	-12.3492	-12.3715	-12.3637	-25.7766	-29.7803	-27.9082
36	62	-39.4843	-44.2459	-42.3689	-12.4071	-12.4291	-12.4207	-26.0098	-30.0544	-28.1756
37	64	-39.7592	-44.5268	-42.6494	-12.4640	-12.4856	-12.4774	-26.2579	-30.3304	-28.4393
38	66	-40.0243	-44.8042	-42.9258	-12.5210	-12.5427	-12.5348	-26.4995	-30.5771	-28.6887
39	68	-40.3037	-45.0875	-43.2061	-12.5784	-12.6000	-12.5913	-26.7273	-30.8719	-28.9770
40	70	-40.5827	-45.3711	-43.4866	-12.6360	-12.6575	-12.6490	-26.9695	-31.1330	-29.2407
41	72	-40.8576	-45.6507	-43.7700	-12.6915	-12.7126	-12.7041	-27.2146	-31.3997	-29.5041
42	75	-41.1361	-45.9310	-44.0467	-12.7485	-12.7698	-12.7608	-27.4562	-31.6810	-29.7816
43	77	-41.4142	-46.2190	-44.3281	-12.8043	-12.8251	-12.8157	-27.7056	-31.9646	-30.0563
44	80	-41.6951	-46.5052	-44.6214	-12.8607	-12.8813	-12.8722	-27.9581	-32.2333	-30.3265
45	82	-41.9703	-46.7861	-44.8915	-12.9151	-12.9353	-12.9260	-28.2102	-32.5058	-30.5974
46	85	-42.2525	-47.0752	-45.1822	-12.9710	-12.9910	-12.9818	-28.4651	-32.7907	-30.8768
47	88	-42.5310	-47.3579	-45.4634	-13.0246	-13.0444	-13.0354	-28.7145	-33.0680	-31.1521
48	91	-42.8133	-47.6463	-45.7516	-13.0796	-13.0988	-13.0899	-28.9758	-33.3519	-31.4333
49	94	-43.0938	-47.9351	-46.0328	-13.1326	-13.1518	-13.1427	-29.2333	-33.6376	-31.7119
50	97	-43.3751	-48.2236	-46.3230	-13.1864	-13.2054	-13.1962	-29.4964	-33.9158	-31.9917

Appendix-B: Calculated ASLE

Region -1 (20 Hz – 2 kHz)

Item	Grid Substation	TR No.	ASLE (dB)								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	5.9918	2.7214	3.7002	0.0491	0.0357	0.0138	5.6120	2.8563	3.1992
2	Biyagama	TR03	2.9501	2.7818	0.2178	0.0533	0.0267	0.0799	3.6022	3.4154	0.2144
3	Biyagama	TR04	3.9125	4.0645	0.1903	0.0564	0.0869	0.1433	4.3495	4.3822	0.0450
4	Bolawattha	TR01	3.2165	2.9864	0.2945	0.0107	0.0409	0.0304	3.4434	3.1988	0.2967
5	Bolawattha	TR02	3.2633	2.6929	0.6522	0.0287	0.0167	0.0122	3.4275	2.9719	0.5091
6	Bolawattha	TR03	2.3549	3.7113	1.5405	0.0185	0.0097	0.0089	2.5127	3.8037	1.4069
7	Habarana	TR01	2.0603	3.2568	1.3477	0.0186	0.0629	0.0443	2.2126	3.3945	1.2487
8	Habarana	TR02	4.0879	4.0118	0.2122	0.0119	0.0456	0.0575	4.3776	4.2114	0.2191
9	Hambanthota	TR02	4.0620	3.6081	0.6059	0.0052	0.0794	0.0841	4.0552	4.5058	0.5711
10	Katunayake	TR02	0.8588	5.1333	4.4933	0.0224	0.0418	0.0195	0.9613	4.8145	4.0505
11	Kelaniya	TR01	3.2127	3.3701	0.1804	0.0129	0.0027	0.0130	3.1359	3.3972	0.3203
12	Kiribathkumbura	TR01	2.8422	2.9174	0.1685	0.0215	0.0590	0.0377	2.9524	3.1317	0.1967
13	Kiribathkumbura	TR02	2.7099	2.8575	0.2950	0.0390	0.0213	0.0177	2.9905	3.2178	0.2748
14	Kolonnawa	TR04	3.0675	2.8526	0.3515	0.1856	0.0032	0.1860	3.7442	3.4247	0.3766
15	Kolonnawa	TR05	3.0209	2.9388	0.3682	0.0634	0.1334	0.1967	3.3385	3.0062	0.3960
16	Mahiyangana	TR01	2.0861	5.7212	4.0386	0.0406	0.0101	0.0358	2.2737	5.4267	3.4874
17	Maho	TR02	3.4493	3.1147	0.3913	0.0461	0.0755	0.0294	3.5888	3.4945	0.1121
18	Monaragala	TR01	3.9146	4.5738	0.8487	0.0375	0.0132	0.0243	4.2632	4.8348	0.7333
19	Monaragala	TR02	4.9554	3.5565	1.7819	0.4911	0.4272	0.0726	5.1538	3.7721	1.7043
20	New Valachcheni	TR02	3.4089	3.5054	0.1376	0.0837	0.0113	0.0944	3.8263	3.7880	0.0512
21	Nuwara Eliya	TR01	3.6201	3.3840	0.2983	0.0281	0.0096	0.0197	4.0160	3.8336	0.2521
22	Nuwara Eliya	TR02	3.0554	3.3761	0.4501	0.0380	0.0627	0.0246	3.5175	3.8142	0.3553
23	Nuwara Eliya	TR03	4.4478	3.4700	1.2326	0.0498	0.0253	0.0750	4.6424	3.6428	1.1909
24	Old Anuradhapura	TR01	2.9953	3.0962	0.1600	0.0705	0.0427	0.1119	3.4620	3.4079	0.0800
25	Old Galle	TR01	2.8270	2.5716	0.2721	0.0185	0.0829	0.1004	2.8018	2.7515	0.2063
26	Old Galle	TR02	2.6519	2.6167	0.0708	0.1432	0.0512	0.0926	2.8486	2.7698	0.0959
27	Pannala	TR01	3.1918	2.8508	0.4030	0.0166	0.0282	0.0449	3.4906	3.2420	0.3131
28	Pannala	TR02	3.2692	2.4271	1.0009	0.0079	0.0551	0.0629	3.5422	2.8038	0.8415
29	Pannipitiya	TR03	3.6349	3.5431	0.1421	0.0524	0.0259	0.0779	4.0451	4.0745	0.1457
30	Sapugaskanda	TR01	3.6195	3.6341	0.1229	0.0240	0.0578	0.0816	4.2310	4.3037	0.0824
31	Sapugaskanda	TR03	1.7051	6.8047	5.5144	0.0181	0.0269	0.0091	1.7430	6.2790	4.9687
32	Sri Jayawardanapura	TR01	2.3031	3.3142	1.4913	0.0478	0.0975	0.0527	1.9428	2.9184	1.3586
33	Sri Jayawardanapura	TR02	2.8144	4.2385	2.0384	0.0691	0.1238	0.0550	6.8529	8.2274	2.1567
34	Thulhiriya	TR01	3.2108	3.2749	0.0768	0.0295	0.0398	0.0687	3.4212	3.4060	0.0283
35	Thulhiriya	TR02	3.2205	3.5938	0.4326	0.0178	0.0324	0.0500	3.4050	3.7215	0.3548
36	Trincomalee	TR01	1.9569	4.1554	2.4960	0.0561	0.0096	0.0469	2.1925	4.2154	2.1997
37	Trincomalee	TR02	3.1754	4.3941	1.4621	0.0062	0.0257	0.0318	3.4253	4.5437	1.2934
38	Valachchenei	TR01	2.9241	3.9763	1.2524	0.0781	0.0697	0.0193	3.1896	4.0860	1.0406
39	Valachchenei	TR02	3.0338	3.4401	0.4359	0.0306	0.1110	0.0803	3.3818	3.6051	0.2741
40	Valachchenei	TR03	2.8134	3.1309	0.3283	0.0608	0.0202	0.0408	3.1057	3.3225	0.2331
41	Vaunathiu	TR01	3.2625	4.3094	1.2436	0.0044	0.0396	0.0353	3.7096	4.5440	1.0250
42	Vaunathiu	TR02	3.9401	3.9912	0.1353	0.0217	0.0387	0.0604	4.3365	4.2933	0.0677
43	Veyangoda	TR02	2.6630	3.1809	0.6358	0.0038	0.0461	0.0491	2.8408	3.3521	0.5863
44	Veyangoda	TR03	2.5199	4.5159	2.3332	0.0040	0.0032	0.0043	2.5161	4.1152	1.9898

Region -2 (2 kHz – 20 kHz)

Item	Grid Substation	TR No.	ASLE (dB)								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	0.4414	0.4418	0.1674	0.3692	0.3645	0.2571	0.4486	0.3238	0.1254
2	Biyagama	TR03	1.7106	1.4594	0.2875	1.8565	1.8009	0.3919	1.6709	1.4636	0.2446
3	Biyagama	TR04	0.7565	0.6655	0.2774	0.9951	0.9000	0.4601	0.8118	0.7966	0.1020
4	Bolawattha	TR01	0.7834	0.9357	0.2158	1.3122	1.4079	0.2600	1.1590	0.7896	0.3904
5	Bolawattha	TR02	0.7894	0.8656	0.2673	1.2926	1.3998	0.2248	1.1984	0.8390	0.3857
6	Bolawattha	TR03	1.6160	1.4521	0.1862	1.7446	1.7218	0.1749	0.7956	0.6305	0.2887
7	Habarana	TR01	0.1626	0.1225	0.1305	0.2674	0.2744	0.1831	0.2595	0.2898	0.0768
8	Habarana	TR02	0.1413	0.2225	0.0965	0.2619	0.2717	0.1537	0.3252	0.2102	0.1170
9	Hambanthota	TR02	0.6352	0.6018	0.1224	0.7804	0.8070	0.1807	0.6555	0.5277	0.1346
10	Katunayake	TR02	0.5315	0.7326	0.2890	1.0454	1.0869	0.2275	0.6951	0.6047	0.2840
11	Kelaniya	TR01	0.9599	0.8597	0.1387	1.1426	1.0958	0.1819	0.3616	0.2733	0.2051
12	Kiribathkumbura	TR01	0.7155	0.8702	0.2276	1.2639	1.4356	0.2900	1.1529	0.8263	0.3558
13	Kiribathkumbura	TR02	0.8366	0.9975	0.2816	1.2905	1.4680	0.2772	1.1823	0.7677	0.4476
14	Kolonnawa	TR04	0.2925	0.4036	0.2797	0.5737	0.2489	0.6141	0.3403	0.5042	0.5498
15	Kolonnawa	TR05	0.3289	0.3903	0.3735	0.4387	0.6021	0.5827	0.4321	0.7849	0.5905
16	Mahiyangana	TR01	0.6228	0.5541	0.2411	0.9263	0.8344	0.1438	0.8978	0.8737	0.1637
17	Maho	TR02	0.8298	0.6112	0.2313	1.0556	0.9556	0.2006	0.6336	0.5550	0.0883
18	Monaragala	TR01	0.7883	0.5546	0.2898	0.9761	0.7620	0.2539	0.7595	0.7813	0.1373
19	Monaragala	TR02	0.7516	0.6019	0.3836	0.9725	0.7791	0.4536	0.7921	0.7443	0.0926
20	New Valachcheni	TR02	0.6790	0.5895	0.3765	1.0913	0.8077	0.4612	0.7300	0.7379	0.1002
21	Nuwara Eliya	TR01	0.3019	0.2855	0.1284	0.4379	0.3461	0.1976	0.2655	0.1697	0.1355
22	Nuwara Eliya	TR02	0.2640	0.3363	0.1331	0.4259	0.5077	0.1554	0.2374	0.1112	0.1860
23	Nuwara Eliya	TR03	0.8995	0.7023	0.2577	1.1746	0.9990	0.3174	0.7237	0.6421	0.0854
24	Old Anuradhapura	TR01	1.2949	0.9995	0.4302	1.6964	1.4346	0.6423	0.6800	0.5565	0.1644
25	Old Galle	TR01	0.2067	0.2363	0.1761	0.3546	0.3824	0.1905	0.2990	0.2966	0.1428
26	Old Galle	TR02	0.4798	0.2957	0.2641	0.3597	0.1250	0.3446	0.1833	0.2434	0.1537
27	Pannala	TR01	0.6176	0.5632	0.1413	0.9960	0.9902	0.1766	0.7563	0.5816	0.2374
28	Pannala	TR02	0.5293	0.5367	0.1003	0.9747	1.0125	0.2172	0.7817	0.5317	0.2793
29	Pannipitiya	TR03	1.2826	1.1038	0.4136	1.8367	1.6748	0.3759	0.9172	0.7746	0.2912
30	Sapugaskanda	TR01	0.6026	0.4932	0.1269	0.6924	0.6763	0.1156	1.1921	1.0776	0.1259
31	Sapugaskanda	TR03	1.1015	1.1593	0.2437	1.3037	1.3758	0.1630	0.6510	0.4118	0.3207
32	Sri Jayawardanapura	TR01	0.8857	0.7179	0.4396	0.9065	0.7488	0.2629	0.2694	0.3361	0.3211
33	Sri Jayawardanapura	TR02	1.0267	0.8375	0.4504	1.0890	0.9061	0.3131	5.0836	5.1142	0.2913
34	Thulhiriya	TR01	0.4280	0.5365	0.1210	0.6440	0.6380	0.2323	0.3825	0.3398	0.0532
35	Thulhiriya	TR02	0.3618	0.4206	0.1011	0.5588	0.5336	0.1960	0.3992	0.3791	0.0626
36	Trincomalee	TR01	0.2010	0.1079	0.1289	0.4121	0.2076	0.2673	0.1881	0.2409	0.1151
37	Trincomalee	TR02	0.1420	0.1711	0.0560	0.2277	0.2358	0.0868	0.2278	0.2001	0.0355
38	Valachchenei	TR01	1.5703	1.2990	0.6874	2.3060	1.9032	0.5543	1.4269	1.2262	0.5303
39	Valachchenei	TR02	1.7188	1.3844	0.6319	2.4383	2.1430	0.5812	1.6564	1.2092	0.6490
40	Valachchenei	TR03	1.4844	1.2661	0.4428	2.2868	2.0879	0.4167	1.6650	1.2406	0.6109
41	Vaunathiu	TR01	0.6276	0.5390	0.1509	0.9172	0.8646	0.1505	0.9168	0.8506	0.1458
42	Vaunathiu	TR02	0.8421	0.7233	0.2905	1.0414	0.9302	0.3286	0.7398	0.7430	0.0945
43	Veyangoda	TR02	1.6830	1.3270	0.4253	1.7631	1.6722	0.4263	0.9477	0.7888	0.2522
44	Veyangoda	TR03	1.6913	1.4844	0.2438	1.7640	1.6905	0.2819	0.7257	0.3979	0.7167

Region -3 (20 kHz – 400 kHz)

Item	Grid Substation	TR No.	ASLE (dB)								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	0.8254	1.4101	1.0628	0.7370	1.5574	1.6153	1.0988	1.0461	0.8795
2	Biyagama	TR03	0.7940	0.9632	1.3423	0.9038	1.1832	1.0686	2.5131	2.5886	1.1225
3	Biyagama	TR04	0.5457	0.3198	0.8015	0.5987	0.3787	0.7448	0.8557	1.0170	1.0659
4	Bolawattha	TR01	1.4850	1.2426	1.6514	1.6221	1.2237	1.6935	0.5940	0.8748	0.6814
5	Bolawattha	TR02	1.6407	1.2490	1.8079	1.6580	1.1831	1.8968	0.6675	0.8704	0.5628
6	Bolawattha	TR03	0.4367	0.5702	0.6050	0.5818	0.6008	0.5897	0.8735	0.6777	0.7051
7	Habarana	TR01	0.4600	0.4743	0.4181	0.5251	0.5555	0.3449	1.4728	1.2537	0.7223
8	Habarana	TR02	0.4599	0.4297	0.5199	0.5752	0.4507	0.3891	1.3460	0.6911	0.9554
9	Hambanthota	TR02	0.5023	0.5212	0.5998	0.5318	0.5324	0.5168	0.9426	0.7755	0.3384
10	Katunayake	TR02	0.2619	0.3503	0.4288	0.2840	0.3622	0.3850	0.9970	1.3347	0.4694
11	Kelaniya	TR01	0.5510	0.7775	0.9203	0.6509	0.9489	0.9186	1.5259	0.8344	0.8534
12	Kiribathkumbura	TR01	1.4319	1.1340	1.8098	1.5220	1.1041	1.8480	0.7152	0.7844	0.4995
13	Kiribathkumbura	TR02	1.3965	1.2328	1.7337	1.4519	1.2469	1.7953	1.2054	0.9865	0.5511
14	Kolonnawa	TR04	0.7898	0.6439	0.5793	1.2359	0.5274	1.2817	5.1964	0.6128	4.9437
15	Kolonnawa	TR05	0.5234	0.4915	0.4176	0.3583	1.2229	1.0178	0.5578	4.4342	4.2336
16	Mahiyangana	TR01	0.4236	0.4216	0.7139	0.4711	0.4367	0.5648	0.8966	0.8006	0.3653
17	Maho	TR02	0.5157	0.5298	0.5232	0.5961	0.6103	0.4567	0.8212	0.9870	0.8823
18	Monaragala	TR01	0.6711	0.2989	0.7544	0.7090	0.4019	0.5968	0.7768	0.7330	0.4721
19	Monaragala	TR02	0.7692	0.3683	1.0604	0.7518	0.4596	0.8519	1.2169	0.6182	1.1686
20	New Valachcheni	TR02	0.7991	0.4282	1.0264	0.8523	0.4934	0.8938	0.7252	0.7505	0.7154
21	Nuwara Eliya	TR01	0.7481	0.4896	0.5681	0.8170	0.7462	0.4369	1.0799	1.0439	0.8826
22	Nuwara Eliya	TR02	0.7023	0.4113	0.5051	0.7944	0.7019	0.3528	1.1851	1.0490	0.9064
23	Nuwara Eliya	TR03	0.4848	0.5637	0.7572	0.4598	0.6176	0.6201	0.9724	0.9568	0.7344
24	Old Anuradhapura	TR01	0.9177	0.5691	1.0105	0.8803	0.7032	1.1015	1.0611	0.9870	1.5175
25	Old Galle	TR01	0.2816	0.4331	0.4652	0.2251	0.3654	0.3866	0.4368	0.5385	0.2999
26	Old Galle	TR02	0.2668	0.3011	0.3527	0.2047	0.2617	0.2889	0.2917	0.3037	0.3061
27	Pannala	TR01	0.3505	0.3451	0.2986	0.3979	0.4059	0.2374	0.5467	0.8253	0.4798
28	Pannala	TR02	0.2993	0.2638	0.4475	0.2478	0.3094	0.4256	0.8946	0.8950	1.3085
29	Pannipitiya	TR03	0.6350	0.7296	1.0026	0.6912	0.8411	0.8078	1.3997	1.1545	1.1765
30	Sapugaskanda	TR01	0.7543	0.6611	0.8009	0.5760	0.4274	0.6621	2.1486	1.9415	0.8876
31	Sapugaskanda	TR03	0.7047	0.6248	0.9448	0.7029	0.6177	0.7379	1.2790	0.9235	0.6866
32	Sri Jayawardanapura	TR01	0.8772	0.8527	0.8256	0.8840	0.8527	0.8374	0.5258	0.7288	0.6470
33	Sri Jayawardanapura	TR02	0.7170	0.8139	0.8950	0.7167	0.8105	0.8901	1.6892	1.7522	0.4803
34	Thulhiriya	TR01	1.0236	0.6015	0.7510	0.8420	0.6633	0.6011	2.2324	1.3209	1.0963
35	Thulhiriya	TR02	0.8573	0.6279	0.7242	0.7166	0.6248	0.5301	2.1952	1.2567	1.2415
36	Trincomalee	TR01	0.5347	0.4348	0.5384	0.6148	0.4395	0.5051	1.6596	0.6007	1.5564
37	Trincomalee	TR02	0.4179	0.4317	0.4591	0.4208	0.4663	0.4530	0.9401	0.6192	0.9565
38	Valachchenei	TR01	2.6943	2.8669	4.4248	2.8208	2.9523	4.4427	1.9698	1.2456	1.2818
39	Valachchenei	TR02	2.3313	3.0199	4.2955	2.5516	3.1965	4.4765	1.8232	1.1747	1.1385
40	Valachchenei	TR03	2.4451	2.9026	4.3223	2.5106	3.0960	4.4038	1.7003	1.1704	1.2161
41	Vaunathiu	TR01	0.4337	0.4027	0.7370	0.4535	0.5048	0.5708	0.7428	1.1074	0.6825
42	Vaunathiu	TR02	0.6445	0.3874	0.9077	0.6798	0.4304	0.7892	0.9429	0.7175	0.6077
43	Veyangoda	TR02	0.9278	0.9533	1.4070	1.0055	1.2038	1.1113	1.1939	0.9214	0.8992
44	Veyangoda	TR03	0.9100	0.8663	1.2667	0.9670	1.1830	1.0884	1.6054	2.2377	1.7507

Region -4 (400 kHz – 2 MHz)

Item	Grid Substation	TR No.	ASLE (dB)								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	0.7706	1.4386	1.9229	0.8524	1.3264	2.0126	3.4637	4.5424	1.7813
2	Biyagama	TR03	0.9071	0.9644	1.1224	0.8240	0.9726	1.0605	4.1579	2.7352	3.0028
3	Biyagama	TR04	1.2175	1.8484	2.4801	1.2253	1.7014	2.4376	3.2854	3.9997	1.1231
4	Bolawattha	TR01	1.4296	1.8364	2.4841	1.4056	1.7916	2.4286	3.8379	4.3189	2.1505
5	Bolawattha	TR02	1.2838	1.8694	2.0859	1.2636	1.8210	2.0474	4.6677	3.1650	1.9187
6	Bolawattha	TR03	2.3778	3.2268	3.5133	2.3340	3.1469	3.3411	3.2757	1.4444	2.4541
7	Habarana	TR01	1.2868	1.4956	2.6713	1.2845	1.4892	2.6417	4.8984	3.4836	3.1711
8	Habarana	TR02	1.1759	1.5819	2.6006	1.1761	1.5930	2.5856	5.3469	4.8697	3.3982
9	Hambanthota	TR02	1.2129	1.0266	2.1229	0.9381	1.2456	2.0489	2.8262	2.8920	1.3173
10	Katunayake	TR02	0.6647	1.7628	2.2579	0.6849	1.7244	2.2394	3.7378	3.8232	1.8037
11	Kelaniya	TR01	6.0702	6.1653	1.8794	6.1180	6.1870	1.8427	2.7809	1.5657	1.5257
12	Kiribathkumbura	TR01	1.2877	1.7991	2.2352	1.2693	1.7552	2.1971	3.4217	3.8802	1.9466
13	Kiribathkumbura	TR02	1.3467	1.7181	2.2798	1.3206	1.6794	2.2367	4.9382	4.9238	0.9207
14	Kolonnawa	TR04	1.3277	0.7353	1.5549	1.3364	0.7453	1.5269	2.4602	2.1633	2.0459
15	Kolonnawa	TR05	1.2755	1.1456	2.1355	1.2720	1.1625	2.1234	2.5167	3.1476	1.9399
16	Mahiyangana	TR01	1.4835	2.4520	3.5925	1.5892	2.2534	3.5201	3.5865	4.4859	1.6007
17	Maho	TR02	1.2721	2.5203	3.0709	1.2592	2.2855	2.9522	2.5866	4.3107	2.6128
18	Monaragala	TR01	1.3748	1.7313	2.1431	1.3698	1.6178	2.0962	3.6018	4.8683	1.9066
19	Monaragala	TR02	1.7100	1.9083	2.1727	1.8781	1.5834	2.1266	3.4307	4.1523	1.3944
20	New Valachcheni	TR02	1.4959	1.7738	2.3904	1.3842	1.6701	2.3433	3.4727	4.1714	1.1900
21	Nuwara Eliya	TR01	1.1231	0.7027	0.9864	1.1363	0.7227	0.9721	5.3118	3.3611	4.8573
22	Nuwara Eliya	TR02	0.9702	0.7194	0.8839	1.0761	0.7198	0.9316	5.8556	3.3994	4.9825
23	Nuwara Eliya	TR03	1.5377	2.2396	3.3345	1.6285	2.0040	3.2093	4.4972	4.5950	1.5550
24	Old Anuradhapura	TR01	4.5924	1.5037	5.8694	4.6438	1.4451	5.8588	4.9861	2.7091	4.8205
25	Old Galle	TR01	0.3158	0.9746	0.9907	0.3373	0.9691	1.0285	0.9865	0.8691	0.7917
26	Old Galle	TR02	0.4991	0.3158	0.6944	0.5052	0.3665	0.7167	0.7499	0.8936	1.2385
27	Pannala	TR01	7.7741	8.2226	2.5464	7.6857	7.9899	2.5439	1.0643	3.0188	2.5015
28	Pannala	TR02	0.6356	1.8902	2.3306	0.6602	1.8513	2.3045	0.8720	3.7323	2.9928
29	Pannipitiya	TR03	0.9511	1.0213	1.7402	0.9420	0.9986	1.6747	4.8589	2.0440	4.4780
30	Sapugaskanda	TR01	2.4248	1.9014	3.1436	2.4335	1.7894	3.2240	5.8004	3.1182	3.3141
31	Sapugaskanda	TR03	1.8159	2.5876	2.4142	1.7407	2.6515	2.4484	5.0918	1.7565	4.5693
32	Sri Jayawardanapura	TR01	1.6536	2.0490	3.5742	1.6920	2.0557	3.5870	4.5401	9.0490	6.5456
33	Sri Jayawardanapura	TR02	2.1427	2.0174	3.6482	2.1281	2.0174	3.6201	4.5444	5.0565	6.1806
34	Thulhiriya	TR01	0.4549	0.7835	0.9961	0.4591	0.7192	0.9655	4.8660	2.8139	3.1233
35	Thulhiriya	TR02	0.5849	0.4516	0.9808	0.5969	0.4125	0.9384	5.2167	1.7861	4.2353
36	Trincomalee	TR01	1.2805	1.5222	2.6527	1.2873	1.5241	2.6365	4.7916	3.3126	3.4260
37	Trincomalee	TR02	1.4756	1.2547	2.6446	1.4509	1.2104	2.5182	5.3394	3.8979	3.3611
38	Valachchenei	TR01	0.7839	0.6368	1.2968	0.8156	0.6047	1.2946	4.8685	4.9956	1.2619
39	Valachchenei	TR02	0.6670	0.9271	1.1006	0.6793	0.9015	1.1066	4.3883	4.7049	0.5529
40	Valachchenei	TR03	0.3527	0.7189	0.8262	0.4627	0.6945	0.9760	3.8307	4.0675	1.2741
41	Vaunathiu	TR01	0.9152	1.6907	2.2159	0.9973	1.5107	2.1548	3.2588	4.6634	1.7299
42	Vaunathiu	TR02	1.3447	1.9761	2.4904	1.3297	1.8132	2.4149	4.0581	5.0723	1.4455
43	Veyangoda	TR02	0.9643	1.0132	1.1001	0.9267	1.0055	1.0531	4.1055	2.0966	3.1783
44	Veyangoda	TR03	1.0603	1.0528	1.2214	0.9975	1.0542	1.1654	4.5957	2.4748	3.4309

Appendix-C: Calculated CCF values

Region -1 (20 Hz – 2 kHz)

Item	Grid Substation	TR No.	Cross Correlation Coefficient (CCF)								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	0.8707	0.9666	0.9420	1.0000	1.0000	1.0000	0.8802	0.9433	0.9539
2	Biyagama	TR03	0.9302	0.9371	0.9994	1.0000	1.0000	1.0000	0.8822	0.8886	0.9996
3	Biyagama	TR04	0.9311	0.9256	0.9997	1.0000	1.0000	1.0000	0.8900	0.8901	1.0000
4	Bolawattha	TR01	0.9075	0.9201	0.9989	1.0000	1.0000	1.0000	0.8794	0.8882	0.9990
5	Bolawattha	TR02	0.9053	0.9342	0.9958	1.0000	1.0000	1.0000	0.8848	0.9026	0.9974
6	Bolawattha	TR03	0.9538	0.8897	0.9779	1.0000	1.0000	1.0000	0.9279	0.8836	0.9840
7	Habarana	TR01	0.9661	0.9196	0.9845	1.0000	1.0000	1.0000	0.9458	0.9134	0.9889
8	Habarana	TR02	0.8752	0.8793	0.9995	1.0000	1.0000	1.0000	0.8366	0.8418	0.9995
9	Hambanthota	TR02	0.8908	0.9095	0.9964	1.0000	1.0000	1.0000	0.8570	0.8478	0.9971
10	Katunayake	TR02	0.9950	0.8798	0.9015	1.0000	1.0000	1.0000	0.9892	0.9059	0.9325
11	Kelaniya	TR01	0.9186	0.9105	0.9996	1.0000	1.0000	1.0000	0.8993	0.8900	0.9991
12	Kiribathkumbura	TR01	0.9295	0.9256	0.9997	1.0000	1.0000	1.0000	0.9057	0.8999	0.9996
13	Kiribathkumbura	TR02	0.9322	0.9255	0.9994	1.0000	1.0000	1.0000	0.8986	0.8924	0.9994
14	Kolonnawa	TR04	0.9044	0.9163	0.9983	1.0000	1.0000	1.0000	0.8387	0.8496	0.9988
15	Kolonnawa	TR05	0.9109	0.9137	0.9979	1.0000	1.0000	1.0000	0.8834	0.8962	0.9986
16	Mahiyangana	TR01	0.9768	0.8640	0.9220	1.0000	1.0000	1.0000	0.9579	0.8716	0.9429
17	Maho	TR02	0.9180	0.9328	0.9987	1.0000	1.0000	1.0000	0.8988	0.9012	0.9999
18	Monaragala	TR01	0.9201	0.8980	0.9952	1.0000	1.0000	1.0000	0.8729	0.8660	0.9961
19	Monaragala	TR02	0.8861	0.9322	0.9791	0.9904	0.9905	1.0000	0.8687	0.8881	0.9825
20	New Valachcheni	TR02	0.9327	0.9287	0.9998	1.0000	1.0000	1.0000	0.8990	0.8994	1.0000
21	Nuwara Eliya	TR01	0.8816	0.8946	0.9990	1.0000	1.0000	1.0000	0.8272	0.8304	0.9992
22	Nuwara Eliya	TR02	0.9153	0.8985	0.9975	1.0000	1.0000	1.0000	0.8526	0.8446	0.9987
23	Nuwara Eliya	TR03	0.8612	0.9117	0.9853	1.0000	1.0000	1.0000	0.8373	0.8723	0.9877
24	Old Anuradhapura	TR01	0.9256	0.9207	0.9997	1.0000	1.0000	1.0000	0.8763	0.8772	0.9999
25	Old Galle	TR01	0.9197	0.9334	0.9992	1.0000	1.0000	1.0000	0.9108	0.9151	0.9999
26	Old Galle	TR02	0.9259	0.9279	0.9999	1.0000	1.0000	1.0000	0.9086	0.9122	0.9999
27	Pannala	TR01	0.9067	0.9242	0.9982	1.0000	1.0000	1.0000	0.8716	0.8776	0.9988
28	Pannala	TR02	0.9064	0.9452	0.9896	1.0000	1.0000	1.0000	0.8839	0.9049	0.9933
29	Pannipitiya	TR03	0.9030	0.9055	0.9998	1.0000	1.0000	1.0000	0.8490	0.8450	0.9982
30	Sapugaskanda	TR01	0.9363	0.9366	0.9999	1.0000	1.0000	1.0000	0.8961	0.8945	1.0000
31	Sapugaskanda	TR03	0.9790	0.7128	0.7924	1.0000	1.0000	1.0000	0.9635	0.7576	0.8312
32	Sri Jayawardanapura	TR01	0.9471	0.8853	0.9642	1.0000	1.0000	1.0000	0.9530	0.9113	0.9815
33	Sri Jayawardanapura	TR02	0.9212	0.8316	0.9368	1.0000	1.0000	1.0000	0.6769	0.5516	0.9576
34	Thulhiriya	TR01	0.9301	0.9276	0.9999	1.0000	1.0000	1.0000	0.9067	0.9066	1.0000
35	Thulhiriya	TR02	0.9276	0.9119	0.9985	1.0000	1.0000	1.0000	0.9015	0.8925	0.9991
36	Trincomalee	TR01	0.9683	0.8753	0.9480	1.0000	1.0000	1.0000	0.9438	0.8773	0.9647
37	Trincomalee	TR02	0.9185	0.8515	0.9797	1.0000	1.0000	1.0000	0.8798	0.8344	0.9851
38	Valachchenei	TR01	0.9289	0.8772	0.9857	1.0000	1.0000	1.0000	0.8846	0.8600	0.9904
39	Valachchenei	TR02	0.9258	0.9064	0.9983	1.0000	1.0000	1.0000	0.8853	0.8799	0.9995
40	Valachchenei	TR03	0.9335	0.9189	0.9991	1.0000	1.0000	1.0000	0.8998	0.8938	0.9996
41	Vaunathiu	TR01	0.9443	0.9137	0.9917	1.0000	1.0000	1.0000	0.9002	0.8916	0.9933
42	Vaunathiu	TR02	0.9204	0.9181	0.9997	1.0000	1.0000	1.0000	0.8809	0.8817	1.0000
43	Veyangoda	TR02	0.9420	0.9202	0.9960	1.0000	1.0000	1.0000	0.9156	0.9026	0.9973
44	Veyangoda	TR03	0.9484	0.8547	0.9546	1.0000	1.0000	1.0000	0.9211	0.8814	0.9691

Region -2 (2 kHz – 20 kHz)

Item	Grid Substation	TR No.	Cross Correlation Coefficient (CCF)								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	0.9992	0.9990	0.9993	0.9973	0.9975	0.9979	0.9991	0.9995	0.9999
2	Biyagama	TR03	0.9056	0.9312	0.9951	0.8728	0.8799	0.9936	0.9549	0.9680	0.9961
3	Biyagama	TR04	0.9823	0.9892	0.9969	0.9633	0.9748	0.9980	0.9894	0.9914	0.9997
4	Bolawattha	TR01	0.9705	0.9618	0.9987	0.9332	0.9237	0.9975	0.9572	0.9767	0.9964
5	Bolawattha	TR02	0.9747	0.9650	0.9983	0.9352	0.9225	0.9975	0.9566	0.9784	0.9953
6	Bolawattha	TR03	0.8998	0.9136	0.9983	0.8752	0.8756	0.9985	0.9807	0.9911	0.9969
7	Habarana	TR01	0.9997	0.9997	0.9998	0.9981	0.9989	0.9991	0.9992	0.9991	0.9999
8	Habarana	TR02	0.9997	0.9994	0.9999	0.9982	0.9985	0.9998	0.9989	0.9995	0.9998
9	Hambanthota	TR02	0.9815	0.9811	0.9995	0.9683	0.9655	0.9993	0.9951	0.9969	0.9997
10	Katunayake	TR02	0.9901	0.9887	0.9993	0.9642	0.9653	0.9986	0.9887	0.9949	0.9980
11	Kelaniya	TR01	0.9634	0.9721	0.9992	0.9409	0.9430	0.9986	0.9961	0.9984	0.9989
12	Kiribathkumbura	TR01	0.9793	0.9698	0.9973	0.9382	0.9264	0.9956	0.9576	0.9791	0.9951
13	Kiribathkumbura	TR02	0.9621	0.9506	0.9974	0.9264	0.9093	0.9953	0.9579	0.9808	0.9944
14	Kolonnawa	TR04	0.9981	0.9970	0.9937	0.9969	0.9977	0.9935	0.9964	0.9885	0.9767
15	Kolonnawa	TR05	0.9989	0.9899	0.9940	0.9936	0.9787	0.9938	0.9935	0.9537	0.9542
16	Mahiyangana	TR01	0.9831	0.9899	0.9981	0.9673	0.9742	0.9988	0.9884	0.9915	0.9997
17	Maho	TR02	0.9755	0.9856	0.9979	0.9536	0.9674	0.9985	0.9895	0.9927	0.9995
18	Monaragala	TR01	0.9788	0.9875	0.9968	0.9617	0.9753	0.9973	0.9896	0.9914	0.9998
19	Monaragala	TR02	0.9797	0.9909	0.9928	0.9619	0.9811	0.9947	0.9896	0.9913	0.9998
20	New Valachcheni	TR02	0.9768	0.9860	0.9942	0.9581	0.9746	0.9963	0.9896	0.9907	0.9998
21	Nuwara Eliya	TR01	0.9964	0.9943	0.9994	0.9942	0.9952	0.9991	0.9976	0.9998	0.9978
22	Nuwara Eliya	TR02	0.9970	0.9948	0.9996	0.9948	0.9932	0.9996	0.9980	1.0000	0.9983
23	Nuwara Eliya	TR03	0.9668	0.9798	0.9962	0.9382	0.9561	0.9971	0.9885	0.9912	0.9998
24	Old Anuradhapura	TR01	0.9403	0.9646	0.9921	0.8883	0.9134	0.9850	0.9919	0.9953	0.9989
25	Old Galle	TR01	0.9993	0.9982	0.9995	0.9975	0.9974	0.9997	0.9968	0.9975	0.9999
26	Old Galle	TR02	0.9976	0.9985	0.9990	0.9980	0.9998	0.9983	0.9997	0.9988	0.9995
27	Pannala	TR01	0.9896	0.9894	0.9996	0.9710	0.9725	0.9994	0.9866	0.9936	0.9981
28	Pannala	TR02	0.9902	0.9890	0.9998	0.9721	0.9713	0.9997	0.9869	0.9945	0.9980
29	Pannipitiya	TR03	0.9359	0.9467	0.9945	0.8799	0.8977	0.9949	0.9842	0.9917	0.9971
30	Sapugaskanda	TR01	0.9897	0.9931	0.9996	0.9820	0.9840	0.9999	0.9871	0.9902	0.9996
31	Sapugaskanda	TR03	0.9595	0.9624	0.9988	0.9380	0.9282	0.9987	0.9873	0.9956	0.9971
32	Sri Jayawardanapura	TR01	0.9904	0.9941	0.9986	0.9783	0.9875	0.9978	0.9990	0.9987	0.9979
33	Sri Jayawardanapura	TR02	0.9831	0.9902	0.9982	0.9609	0.9781	0.9964	0.7532	0.7463	0.9993
34	Thulhiriya	TR01	0.9944	0.9930	0.9995	0.9843	0.9876	0.9994	0.9983	0.9987	1.0000
35	Thulhiriya	TR02	0.9966	0.9955	0.9998	0.9887	0.9916	0.9994	0.9982	0.9985	1.0000
36	Trincomalee	TR01	0.9990	0.9996	0.9998	0.9958	0.9989	0.9987	0.9996	0.9994	0.9998
37	Trincomalee	TR02	0.9998	0.9996	0.9999	0.9983	0.9988	0.9999	0.9994	0.9996	1.0000
38	Valachchenei	TR01	0.9423	0.9661	0.9875	0.8552	0.9042	0.9879	0.9517	0.9690	0.9905
39	Valachchenei	TR02	0.9395	0.9639	0.9911	0.8297	0.8762	0.9896	0.9435	0.9683	0.9887
40	Valachchenei	TR03	0.9547	0.9688	0.9947	0.8658	0.8873	0.9926	0.9420	0.9663	0.9884
41	Vaunathiu	TR01	0.9861	0.9900	0.9993	0.9691	0.9746	0.9994	0.9874	0.9910	0.9996
42	Vaunathiu	TR02	0.9757	0.9836	0.9960	0.9500	0.9626	0.9971	0.9888	0.9906	0.9998
43	Veyangoda	TR02	0.9124	0.9466	0.9918	0.8830	0.8993	0.9894	0.9802	0.9895	0.9966
44	Veyangoda	TR03	0.9136	0.9340	0.9967	0.8835	0.8926	0.9960	0.9853	0.9980	0.9896

Region -3 (20 kHz – 400 kHz)

Item	Grid Substation	TR No.	Cross Correlation Coefficient (CCF)								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	0.9654	0.9313	0.9777	0.9825	0.9220	0.9311	0.9668	0.9672	0.9775
2	Biyagama	TR03	0.9817	0.9760	0.9608	0.9710	0.9654	0.9671	0.8649	0.8493	0.9716
3	Biyagama	TR04	0.9959	0.9989	0.9921	0.9946	0.9979	0.9945	0.9668	0.9765	0.9693
4	Bolawattha	TR01	0.9551	0.9672	0.9250	0.9541	0.9707	0.9269	0.9920	0.9782	0.9897
5	Bolawattha	TR02	0.9284	0.9518	0.9171	0.9432	0.9634	0.9243	0.9910	0.9804	0.9923
6	Bolawattha	TR03	0.9912	0.9952	0.9893	0.9901	0.9950	0.9941	0.9828	0.9826	0.9854
7	Habarana	TR01	0.9951	0.9933	0.9970	0.9938	0.9921	0.9986	0.9447	0.9515	0.9838
8	Habarana	TR02	0.9952	0.9935	0.9965	0.9946	0.9934	0.9987	0.9622	0.9859	0.9816
9	Hambanthota	TR02	0.9939	0.9913	0.9938	0.9918	0.9927	0.9944	0.9771	0.9825	0.9964
10	Katunayake	TR02	0.9989	0.9977	0.9964	0.9987	0.9974	0.9968	0.9713	0.9473	0.9901
11	Kelaniya	TR01	0.9928	0.9921	0.9884	0.9873	0.9867	0.9891	0.9200	0.9651	0.9813
12	Kiribathkumbura	TR01	0.9605	0.9698	0.9261	0.9616	0.9724	0.9292	0.9865	0.9802	0.9937
13	Kiribathkumbura	TR02	0.9570	0.9721	0.9307	0.9596	0.9743	0.9338	0.9675	0.9678	0.9938
14	Kolonnawa	TR04	0.9874	0.9916	0.9925	0.9789	0.9938	0.9733	0.5166	0.9924	0.5434
15	Kolonnawa	TR05	0.9934	0.9931	0.9959	0.9963	0.9776	0.9848	0.9918	0.6452	0.6658
16	Mahiyangana	TR01	0.9951	0.9979	0.9919	0.9945	0.9976	0.9962	0.9627	0.9810	0.9925
17	Maho	TR02	0.9942	0.9923	0.9945	0.9930	0.9913	0.9970	0.9684	0.9727	0.9819
18	Monaragala	TR01	0.9961	0.9983	0.9962	0.9964	0.9972	0.9982	0.9719	0.9878	0.9890
19	Monaragala	TR02	0.9919	0.9988	0.9909	0.9941	0.9963	0.9946	0.9619	0.9893	0.9718
20	New Valachcheni	TR02	0.9921	0.9979	0.9916	0.9931	0.9971	0.9961	0.9738	0.9851	0.9876
21	Nuwara Eliya	TR01	0.9858	0.9927	0.9925	0.9825	0.9874	0.9967	0.9736	0.9689	0.9688
22	Nuwara Eliya	TR02	0.9869	0.9923	0.9936	0.9846	0.9861	0.9977	0.9663	0.9686	0.9654
23	Nuwara Eliya	TR03	0.9933	0.9965	0.9954	0.9948	0.9961	0.9977	0.9608	0.9728	0.9827
24	Old Anuradhapura	TR01	0.9923	0.9945	0.9906	0.9889	0.9926	0.9869	0.9703	0.9732	0.9487
25	Old Galle	TR01	0.9979	0.9964	0.9914	0.9984	0.9972	0.9931	0.9977	0.9974	0.9986
26	Old Galle	TR02	0.9986	0.9972	0.9952	0.9991	0.9977	0.9960	0.9993	0.9989	0.9987
27	Pannala	TR01	0.9983	0.9986	0.9987	0.9981	0.9984	0.9991	0.9888	0.9724	0.9903
28	Pannala	TR02	0.9990	0.9992	0.9987	0.9990	0.9989	0.9987	0.9762	0.9717	0.9620
29	Pannipitiya	TR03	0.9944	0.9875	0.9815	0.9886	0.9881	0.9899	0.9291	0.9478	0.9690
30	Sapugaskanda	TR01	0.9942	0.9945	0.9933	0.9952	0.9977	0.9944	0.8829	0.8982	0.9802
31	Sapugaskanda	TR03	0.9922	0.9937	0.9820	0.9912	0.9928	0.9891	0.9554	0.9715	0.9870
32	Sri Jayawardanapura	TR01	0.9916	0.9845	0.9924	0.9918	0.9842	0.9920	0.9989	0.9979	0.9973
33	Sri Jayawardanapura	TR02	0.9940	0.9863	0.9884	0.9942	0.9864	0.9884	0.9800	0.9782	0.9968
34	Thulhiriya	TR01	0.9838	0.9940	0.9920	0.9914	0.9922	0.9953	0.8793	0.9415	0.9696
35	Thulhiriya	TR02	0.9857	0.9943	0.9948	0.9925	0.9927	0.9973	0.8740	0.9453	0.9552
36	Trincomalee	TR01	0.9937	0.9947	0.9970	0.9924	0.9948	0.9977	0.9458	0.9911	0.9557
37	Trincomalee	TR02	0.9958	0.9950	0.9960	0.9963	0.9948	0.9969	0.9762	0.9901	0.9758
38	Valachchenei	TR01	0.9009	0.9073	0.7575	0.8692	0.8714	0.7077	0.8627	0.9638	0.8970
39	Valachchenei	TR02	0.9174	0.9012	0.7678	0.8882	0.8504	0.7002	0.8805	0.9634	0.9131
40	Valachchenei	TR03	0.9090	0.9071	0.7628	0.8822	0.8611	0.7121	0.8645	0.9610	0.8884
41	Vaunathiu	TR01	0.9944	0.9988	0.9913	0.9943	0.9972	0.9952	0.9740	0.9730	0.9911
42	Vaunathiu	TR02	0.9940	0.9984	0.9939	0.9945	0.9976	0.9968	0.9692	0.9856	0.9897
43	Veyangoda	TR02	0.9796	0.9771	0.9563	0.9675	0.9577	0.9565	0.9495	0.9646	0.9794
44	Veyangoda	TR03	0.9812	0.9774	0.9586	0.9707	0.9491	0.9406	0.9266	0.8781	0.9382

Region -4 (400 kHz – 2 MHz)

Item	Grid Substation	TR No.	Cross Correlation Coefficient								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	0.9914	0.9583	0.9447	0.9869	0.9623	0.9349	0.9221	0.8722	0.9738
2	Biyagama	TR03	0.9765	0.9841	0.9886	0.9783	0.9838	0.9895	0.7743	0.8456	0.8885
3	Biyagama	TR04	0.9409	0.9550	0.9092	0.9444	0.9628	0.9114	0.8967	0.8477	0.9873
4	Bolawattha	TR01	0.9491	0.9312	0.8723	0.9503	0.9336	0.8764	0.6479	0.5644	0.8673
5	Bolawattha	TR02	0.9543	0.9403	0.8904	0.9556	0.9426	0.8944	0.5291	0.8052	0.8434
6	Bolawattha	TR03	0.8010	0.8583	0.7995	0.8169	0.8673	0.8167	0.8259	0.9651	0.9106
7	Habarana	TR01	0.9770	0.9711	0.9113	0.9764	0.9716	0.9114	0.2850	0.5992	0.7485
8	Habarana	TR02	0.9777	0.9682	0.9110	0.9779	0.9676	0.9106	0.0655	0.1720	0.7782
9	Hambanthota	TR02	0.9927	0.9863	0.9719	0.9866	0.9929	0.9722	0.7891	0.7741	0.9609
10	Katunayake	TR02	0.9936	0.9515	0.9260	0.9932	0.9531	0.9268	0.6892	0.6717	0.9398
11	Kelaniya	TR01	0.4676	0.5993	0.9385	0.4624	0.5934	0.9413	0.7036	0.8471	0.9085
12	Kiribathkumbura	TR01	0.9543	0.9420	0.8847	0.9554	0.9441	0.8881	0.7828	0.7524	0.8703
13	Kiribathkumbura	TR02	0.9607	0.9359	0.8835	0.9618	0.9386	0.8875	0.4604	0.4382	0.9580
14	Kolonnawa	TR04	0.9825	0.9905	0.9764	0.9815	0.9903	0.9760	0.6616	0.8014	0.8241
15	Kolonnawa	TR05	0.9720	0.9809	0.9464	0.9718	0.9806	0.9461	0.6535	0.5956	0.8905
16	Mahiyangana	TR01	0.8946	0.9024	0.7875	0.8982	0.9224	0.7996	0.8911	0.8274	0.9563
17	Maho	TR02	0.9273	0.9217	0.8596	0.9335	0.9364	0.8692	0.9290	0.8262	0.9285
18	Monaragala	TR01	0.9451	0.9626	0.9330	0.9476	0.9701	0.9354	0.8829	0.8003	0.9709
19	Monaragala	TR02	0.9526	0.9582	0.9323	0.9426	0.9611	0.9347	0.8986	0.8278	0.9737
20	New Valachcheni	TR02	0.9439	0.9564	0.9192	0.9474	0.9622	0.9218	0.8948	0.8554	0.9765
21	Nuwara Eliya	TR01	0.9834	0.9937	0.9909	0.9827	0.9933	0.9911	0.2357	0.5735	0.7070
22	Nuwara Eliya	TR02	0.9824	0.9946	0.9912	0.9821	0.9945	0.9923	0.2645	0.6046	0.7049
23	Nuwara Eliya	TR03	0.8936	0.9129	0.8091	0.8996	0.9334	0.8227	0.8496	0.8448	0.9730
24	Old Anuradhapura	TR01	0.8656	0.9887	0.8244	0.8670	0.9890	0.8274	0.2567	0.7477	0.5772
25	Old Galle	TR01	0.9932	0.9590	0.9612	0.9929	0.9515	0.9507	0.9729	0.9785	0.9697
26	Old Galle	TR02	0.9869	0.9925	0.9779	0.9866	0.9922	0.9778	0.9825	0.9670	0.9419
27	Pannala	TR01	0.3652	0.0778	0.8994	0.3658	0.0846	0.9035	0.9057	0.5045	0.6621
28	Pannala	TR02	0.9930	0.9395	0.9115	0.9926	0.9423	0.9136	0.8724	0.5138	0.8106
29	Pannipitiya	TR03	0.9868	0.9947	0.9831	0.9875	0.9947	0.9840	0.3740	0.8420	0.5729
30	Sapugaskanda	TR01	0.8884	0.8985	0.7966	0.8853	0.8976	0.7921	0.4367	0.8118	0.7640
31	Sapugaskanda	TR03	0.8925	0.8593	0.8559	0.9030	0.8484	0.8436	0.6359	0.9307	0.7012
32	Sri Jayawardanapura	TR01	0.9341	0.9734	0.8786	0.9283	0.9717	0.8674	0.5961	0.1365	0.4301
33	Sri Jayawardanapura	TR02	0.8809	0.9449	0.8250	0.8823	0.9447	0.8285	0.7377	0.5786	0.4052
34	Thulhiriya	TR01	0.9974	0.9948	0.9860	0.9973	0.9954	0.9867	0.7185	0.9250	0.8691
35	Thulhiriya	TR02	0.9964	0.9965	0.9865	0.9964	0.9971	0.9877	0.6563	0.9560	0.7349
36	Trincomalee	TR01	0.9737	0.9724	0.9098	0.9734	0.9723	0.9093	0.3906	0.6247	0.7523
37	Trincomalee	TR02	0.9737	0.9804	0.9248	0.9736	0.9800	0.9244	0.2964	0.5074	0.7627
38	Valachchenei	TR01	0.9977	0.9980	0.9975	0.9978	0.9980	0.9976	0.5673	0.5548	0.9342
39	Valachchenei	TR02	0.9945	0.9954	0.9969	0.9947	0.9955	0.9969	0.6004	0.5867	0.9924
40	Valachchenei	TR03	0.9983	0.9989	0.9990	0.9979	0.9989	0.9990	0.6175	0.6647	0.9392
41	Vaunathiu	TR01	0.9562	0.9580	0.9279	0.9577	0.9685	0.9323	0.8971	0.7874	0.9632
42	Vaunathiu	TR02	0.9407	0.9423	0.9034	0.9430	0.9557	0.9095	0.8641	0.7869	0.9773
43	Veyangoda	TR02	0.9752	0.9787	0.9872	0.9763	0.9788	0.9877	0.8153	0.9154	0.9095
44	Veyangoda	TR03	0.9675	0.9798	0.9860	0.9690	0.9790	0.9871	0.8130	0.8830	0.8149

Appendix-D: Calculated distance values correspond to turning functions of SFRA measurement.

Region -1 (20 Hz – 2 kHz)

Item	Grid Substation	TR No.	Distance								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	8.6E-01	6.3E-01	9.0E-01	5.1E-03	7.3E-03	5.7E-03	9.0E-01	9.4E-01	9.9E-01
2	Biyagama	TR03	1.5E+00	1.5E+00	5.5E-01	7.8E-03	1.5E-02	1.3E-02	2.2E+00	2.3E+00	4.2E-01
3	Biyagama	TR04	1.1E+00	1.0E+00	1.5E-01	5.5E-03	7.6E-03	1.2E-02	1.6E+00	1.6E+00	1.2E-01
4	Bolawattha	TR01	2.2E+00	1.7E+00	1.2E+00	1.6E-02	1.0E-02	1.8E-02	2.5E+00	2.5E+00	9.1E-01
5	Bolawattha	TR02	2.3E+00	2.0E+00	2.0E+00	4.1E-02	1.9E-02	2.7E-02	2.3E+00	2.5E+00	1.9E+00
6	Bolawattha	TR03	1.1E+00	1.4E+00	1.1E+00	1.0E-02	9.1E-03	1.7E-02	1.9E+00	1.5E+00	1.1E+00
7	Habarana	TR01	9.2E-01	1.2E+00	8.0E-01	1.3E-02	9.2E-03	1.7E-02	2.2E+00	1.3E+00	1.7E+00
8	Habarana	TR02	1.4E+00	1.4E+00	3.0E-01	7.7E-03	6.4E-03	9.7E-03	1.9E+00	2.1E+00	1.3E+00
9	Hambanthota	TR02	1.5E+00	1.5E+00	7.3E-01	3.3E-03	7.6E-03	6.9E-03	2.5E+00	2.2E+00	8.2E-01
10	Katunayake	TR02	5.4E-01	1.6E+00	1.7E+00	9.8E-03	1.5E-02	9.8E-03	8.0E-01	1.2E+00	1.2E+00
11	Kelaniya	TR01	1.5E+00	1.6E+00	3.0E-01	5.8E-03	3.4E-03	7.0E-03	2.2E+00	2.2E+00	4.1E-01
12	Kiribathkumbura	TR01	1.6E+00	1.8E+00	8.2E-01	1.6E-02	1.2E-02	8.8E-03	2.5E+00	2.3E+00	6.0E-01
13	Kiribathkumbura	TR02	1.8E+00	1.8E+00	3.8E-01	1.1E-02	1.0E-02	7.6E-03	2.7E+00	2.5E+00	6.5E-01
14	Kolonnawa	TR04	2.3E+00	2.3E+00	5.9E-01	1.7E-02	1.2E-02	2.3E-02	3.5E+00	3.6E+00	3.9E-01
15	Kolonnawa	TR05	2.1E+00	2.1E+00	6.5E-01	6.5E-03	1.0E-02	1.6E-02	2.2E+00	2.4E+00	4.5E-01
16	Mahiyangana	TR01	5.2E-01	9.2E-01	9.5E-01	5.1E-03	4.5E-03	5.2E-03	7.7E-01	8.3E-01	9.0E-01
17	Maho	TR02	1.1E+00	1.1E+00	3.6E-01	4.7E-03	8.1E-03	3.9E-03	2.0E+00	2.8E+00	9.5E-01
18	Monaragala	TR01	1.1E+00	1.2E+00	6.3E-01	4.0E-03	3.8E-03	2.5E-03	1.8E+00	1.6E+00	7.8E-01
19	Monaragala	TR02	1.1E+00	9.9E-01	9.9E-01	1.6E+00	1.6E+00	7.4E-03	2.1E+00	2.4E+00	1.3E+00
20	New Valachcheni	TR02	1.1E+00	1.1E+00	9.8E-02	6.8E-03	1.9E-03	7.6E-03	1.7E+00	1.5E+00	7.9E-01
21	Nuwara Eliya	TR01	2.0E+00	2.1E+00	4.6E-01	1.1E-02	1.1E-02	1.8E-02	3.1E+00	3.1E+00	1.2E+00
22	Nuwara Eliya	TR02	1.8E+00	1.9E+00	6.4E-01	6.8E-03	1.2E-02	9.0E-03	3.9E+00	3.8E+00	5.8E-01
23	Nuwara Eliya	TR03	1.3E+00	1.1E+00	8.4E-01	8.7E-03	8.7E-03	9.8E-03	1.7E+00	1.9E+00	9.9E-01
24	Old Anuradhapura	TR01	1.6E+00	1.6E+00	3.3E-01	1.2E-02	8.3E-03	1.2E-02	3.3E+00	2.9E+00	1.5E+00
25	Old Galle	TR01	2.5E+00	2.4E+00	3.5E-01	3.2E-03	1.0E-02	1.1E-02	3.3E+00	3.3E+00	8.6E-01
26	Old Galle	TR02	2.6E+00	2.6E+00	2.3E-01	1.4E-02	1.2E-02	1.2E-02	3.4E+00	3.3E+00	2.0E-01
27	Pannala	TR01	1.9E+00	1.9E+00	1.1E+00	1.2E-02	1.7E-02	2.3E-02	2.6E+00	2.8E+00	8.2E-01
28	Pannala	TR02	1.7E+00	1.5E+00	9.6E-01	5.8E-03	1.2E-02	1.2E-02	2.2E+00	2.4E+00	1.3E+00
29	Pannipitiya	TR03	1.6E+00	1.6E+00	8.9E-01	6.8E-02	5.0E-02	9.9E-02	2.7E+00	3.6E+00	2.4E+00
30	Sapugaskanda	TR01	9.3E-01	9.4E-01	1.0E-01	1.9E-02	3.5E-02	4.7E-02	1.5E+00	1.5E+00	7.6E-02
31	Sapugaskanda	TR03	1.2E+00	1.6E+00	1.7E+00	1.7E-02	2.6E-02	3.9E-02	1.3E+00	1.7E+00	1.7E+00
32	Sri Jayawardanapura	TR01	2.9E+00	3.8E+00	3.4E+00	2.2E-01	4.9E-01	4.3E-01	2.5E+00	2.0E+00	2.4E+00
33	Sri Jayawardanapura	TR02	2.6E+00	3.3E+00	3.3E+00	1.1E-01	1.1E-01	8.4E-02	4.2E+00	3.0E+00	3.5E+00
34	Thulhiriya	TR01	1.2E+00	1.2E+00	2.7E-01	3.7E-02	4.0E-02	1.1E-02	1.6E+00	1.6E+00	2.5E-01
35	Thulhiriya	TR02	1.2E+00	1.2E+00	3.8E-01	4.1E-03	5.2E-02	5.1E-02	1.7E+00	1.6E+00	4.7E-01
36	Trincomalee	TR01	9.1E-01	1.3E+00	1.2E+00	5.7E-03	3.1E-03	4.5E-03	2.1E+00	1.2E+00	1.8E+00
37	Trincomalee	TR02	1.2E+00	1.4E+00	8.9E-01	2.0E-03	4.9E-03	5.3E-03	1.9E+00	1.7E+00	9.6E-01
38	Valachchenei	TR01	1.5E+00	1.6E+00	1.1E+00	8.0E-03	1.2E-02	5.9E-03	2.3E+00	1.9E+00	1.1E+00
39	Valachchenei	TR02	1.5E+00	1.5E+00	3.8E-01	6.5E-03	1.0E-02	5.5E-03	2.2E+00	2.7E+00	1.6E+00
40	Valachchenei	TR03	1.5E+00	1.5E+00	3.2E-01	1.1E-02	5.4E-03	1.1E-02	2.2E+00	2.1E+00	1.7E-01
41	Vaunathiu	TR01	9.9E-01	1.1E+00	6.9E-01	7.6E-03	5.6E-03	5.9E-03	1.6E+00	1.3E+00	9.4E-01
42	Vaunathiu	TR02	1.1E+00	1.1E+00	1.7E-01	3.9E-03	7.6E-03	9.8E-03	1.7E+00	1.7E+00	6.4E-02
43	Veyangoda	TR02	1.3E+00	1.4E+00	6.3E-01	8.4E-03	1.0E-02	4.8E-03	2.1E+00	2.3E+00	1.5E+00
44	Veyangoda	TR03	1.1E+00	1.4E+00	1.3E+00	8.0E-03	4.3E-03	1.1E-02	1.9E+00	1.4E+00	1.4E+00

Region -2 (2 kHz – 20 kHz)

Item	Grid Substation	TR No.	Distance								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	5.8E-03	4.8E-03	5.5E-03	1.0E-02	9.9E-03	7.6E-03	5.5E-03	3.6E-03	2.3E-03
2	Biyagama	TR03	5.2E-02	5.0E-02	1.1E-02	4.7E-02	4.4E-02	1.6E-02	2.7E-02	2.4E-02	1.3E-02
3	Biyagama	TR04	2.8E-02	2.6E-02	1.5E-02	3.8E-02	3.2E-02	9.6E-03	1.9E-02	1.8E-02	3.2E-03
4	Bolawattha	TR01	4.6E-02	4.8E-02	7.4E-03	4.7E-02	4.7E-02	9.6E-03	3.5E-02	2.9E-02	1.0E-02
5	Bolawattha	TR02	4.1E-02	4.3E-02	6.3E-03	4.4E-02	4.6E-02	8.0E-03	3.3E-02	2.6E-02	1.1E-02
6	Bolawattha	TR03	9.9E-02	9.8E-02	5.6E-03	4.9E-02	5.0E-02	5.9E-03	2.1E-02	1.5E-02	1.1E-02
7	Habarana	TR01	5.9E-03	6.6E-03	3.7E-03	1.2E-02	7.5E-03	7.0E-03	5.2E-03	4.6E-03	2.6E-03
8	Habarana	TR02	6.4E-03	8.0E-03	2.5E-03	1.1E-02	1.1E-02	2.4E-03	5.2E-03	3.4E-03	2.9E-03
9	Hambanthota	TR02	1.6E-02	1.8E-02	3.2E-03	1.9E-02	2.0E-02	3.6E-03	9.1E-03	7.3E-03	2.3E-03
10	Katunayake	TR02	2.1E-02	2.3E-02	7.9E-03	4.4E-02	4.4E-02	6.8E-03	1.7E-02	1.3E-02	7.1E-03
11	Kelaniya	TR01	2.5E-02	2.2E-02	3.6E-03	2.8E-02	2.7E-02	5.5E-03	8.4E-03	5.4E-03	5.0E-03
12	Kiribathkumbura	TR01	3.7E-02	3.8E-02	9.0E-03	4.7E-02	4.8E-02	1.1E-02	3.3E-02	2.6E-02	1.1E-02
13	Kiribathkumbura	TR02	6.2E-02	6.2E-02	9.0E-03	4.9E-02	5.1E-02	1.2E-02	3.2E-02	2.5E-02	1.1E-02
14	Kolonnawa	TR04	1.1E-02	1.1E-02	1.8E-02	1.2E-02	8.9E-03	1.3E-02	1.5E-02	1.6E-02	1.7E-02
15	Kolonnawa	TR05	7.3E-03	2.1E-02	1.7E-02	1.4E-02	1.8E-02	1.1E-02	1.7E-02	5.1E-02	5.6E-02
16	Mahiyangana	TR01	2.7E-02	2.3E-02	8.5E-03	3.2E-02	2.9E-02	6.5E-03	1.8E-02	1.7E-02	3.5E-03
17	Maho	TR02	3.4E-02	3.0E-02	8.6E-03	3.8E-02	3.3E-02	5.8E-03	1.7E-02	1.5E-02	4.1E-03
18	Monaragala	TR01	3.2E-02	3.0E-02	1.4E-02	4.0E-02	3.4E-02	1.1E-02	1.9E-02	1.8E-02	2.6E-03
19	Monaragala	TR02	2.8E-02	2.4E-02	2.1E-02	3.6E-02	2.7E-02	1.3E-02	1.9E-02	1.7E-02	2.7E-03
20	New Valachcheni	TR02	3.4E-02	3.4E-02	2.1E-02	4.0E-02	3.3E-02	1.2E-02	1.9E-02	1.8E-02	2.8E-03
21	Nuwara Eliya	TR01	9.9E-03	1.4E-02	5.7E-03	1.9E-02	1.6E-02	7.1E-03	8.5E-03	2.9E-03	8.0E-03
22	Nuwara Eliya	TR02	1.2E-02	1.6E-02	5.0E-03	2.0E-02	2.2E-02	4.7E-03	9.6E-03	2.2E-03	8.4E-03
23	Nuwara Eliya	TR03	4.4E-02	4.1E-02	1.2E-02	4.7E-02	4.3E-02	9.5E-03	1.9E-02	1.7E-02	3.0E-03
24	Old Anuradhapura	TR01	3.7E-02	3.2E-02	1.6E-02	3.8E-02	3.5E-02	2.2E-02	1.1E-02	7.7E-03	7.3E-03
25	Old Galle	TR01	6.6E-03	1.1E-02	7.9E-03	2.0E-02	1.8E-02	6.7E-03	1.3E-02	1.3E-02	2.5E-03
26	Old Galle	TR02	1.7E-02	1.2E-02	1.1E-02	1.7E-02	5.4E-03	1.4E-02	6.4E-03	1.0E-02	7.2E-03
27	Pannala	TR01	2.1E-02	2.1E-02	4.5E-03	3.7E-02	3.6E-02	3.7E-03	1.8E-02	1.3E-02	6.8E-03
28	Pannala	TR02	2.0E-02	2.1E-02	2.6E-03	3.6E-02	3.7E-02	4.0E-03	1.8E-02	1.2E-02	7.1E-03
29	Pannipitiya	TR03	6.1E-02	6.0E-02	1.2E-02	4.7E-02	4.3E-02	1.4E-02	1.8E-02	1.2E-02	1.1E-02
30	Sapugaskanda	TR01	1.9E-02	1.6E-02	3.3E-03	2.3E-02	2.2E-02	2.4E-03	1.6E-02	1.4E-02	3.1E-03
31	Sapugaskanda	TR03	3.2E-02	3.2E-02	3.6E-03	3.3E-02	3.5E-02	4.2E-03	1.8E-02	1.2E-02	1.0E-02
32	Sri Jayawardanapura	TR01	2.3E-02	2.1E-02	2.7E-02	5.1E-02	3.7E-02	2.5E-02	7.4E-03	1.1E-02	1.3E-02
33	Sri Jayawardanapura	TR02	2.5E-02	2.2E-02	1.7E-02	3.6E-02	2.7E-02	1.2E-02	1.2E-01	1.2E-01	6.7E-03
34	Thulhiriya	TR01	1.2E-02	1.2E-02	2.2E-03	2.2E-02	1.9E-02	5.1E-03	5.6E-03	5.0E-03	1.4E-03
35	Thulhiriya	TR02	9.7E-03	1.1E-02	2.4E-03	2.1E-02	1.8E-02	6.2E-03	5.9E-03	5.5E-03	1.0E-03
36	Trincomalee	TR01	7.4E-03	5.9E-03	3.2E-03	1.3E-02	7.9E-03	6.5E-03	4.1E-03	3.8E-03	4.3E-03
37	Trincomalee	TR02	3.8E-03	6.1E-03	2.9E-03	1.1E-02	9.3E-03	3.7E-03	3.8E-03	3.1E-03	1.3E-03
38	Valachchenei	TR01	1.1E-01	1.0E-01	2.4E-02	1.1E-01	9.3E-02	3.4E-02	5.5E-02	4.7E-02	2.8E-02
39	Valachchenei	TR02	1.0E-01	9.2E-02	2.2E-02	1.1E-01	9.4E-02	3.4E-02	5.9E-02	4.8E-02	2.8E-02
40	Valachchenei	TR03	8.3E-02	7.8E-02	1.7E-02	1.0E-01	9.5E-02	2.2E-02	6.0E-02	4.9E-02	2.8E-02
41	Vaunathiu	TR01	2.4E-02	2.2E-02	7.2E-03	3.4E-02	3.1E-02	5.6E-03	2.0E-02	1.8E-02	3.8E-03
42	Vaunathiu	TR02	3.4E-02	3.5E-02	1.8E-02	5.0E-02	4.7E-02	1.2E-02	2.0E-02	1.9E-02	2.4E-03
43	Veyangoda	TR02	4.5E-02	4.0E-02	1.5E-02	4.4E-02	4.0E-02	2.1E-02	2.0E-02	1.4E-02	1.2E-02
44	Veyangoda	TR03	4.7E-02	4.4E-02	6.9E-03	4.4E-02	4.0E-02	1.0E-02	1.7E-02	9.1E-03	1.8E-02

Region -3 (20 kHz – 400 kHz)

Item	Grid Substation	TR No.	Distance								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	4.9E-02	5.8E-02	2.7E-02	4.1E-02	4.9E-02	5.0E-02	1.9E-02	1.9E-02	1.6E-02
2	Biyagama	TR03	1.7E-02	1.3E-02	1.5E-02	2.2E-02	2.0E-02	1.3E-02	4.1E-02	4.2E-02	1.5E-02
3	Biyagama	TR04	1.0E-02	3.7E-03	1.2E-02	9.3E-03	6.1E-03	6.0E-03	2.0E-02	1.5E-02	9.8E-03
4	Bolawattha	TR01	8.6E-03	7.2E-03	8.5E-03	9.2E-03	6.9E-03	8.3E-03	7.1E-03	7.8E-03	7.3E-03
5	Bolawattha	TR02	1.3E-02	1.2E-02	1.0E-02	1.1E-02	1.0E-02	9.3E-03	6.1E-03	7.0E-03	5.4E-03
6	Bolawattha	TR03	1.7E-02	6.1E-03	1.7E-02	1.9E-02	1.3E-02	9.7E-03	8.2E-03	2.0E-02	2.0E-02
7	Habarana	TR01	9.1E-03	8.9E-03	6.8E-03	9.6E-03	9.6E-03	3.6E-03	1.1E-02	1.2E-02	1.5E-02
8	Habarana	TR02	9.7E-03	8.6E-03	7.6E-03	8.6E-03	8.7E-03	2.9E-03	1.1E-02	9.3E-03	1.4E-02
9	Hambanthota	TR02	6.2E-03	6.4E-03	5.2E-03	1.1E-02	1.1E-02	3.8E-03	1.3E-02	1.0E-02	4.8E-03
10	Katunayake	TR02	3.2E-03	4.2E-03	4.2E-03	5.8E-03	8.7E-03	4.6E-03	1.3E-02	2.0E-02	1.1E-02
11	Kelaniya	TR01	8.9E-03	7.2E-03	5.7E-03	1.4E-02	1.1E-02	6.5E-03	2.8E-02	2.2E-02	1.2E-02
12	Kiribathkumbura	TR01	7.6E-03	6.8E-03	8.4E-03	7.6E-03	7.1E-03	1.0E-02	9.2E-03	8.8E-03	7.4E-03
13	Kiribathkumbura	TR02	8.8E-03	7.6E-03	8.9E-03	8.4E-03	8.8E-03	9.6E-03	1.1E-02	1.0E-02	5.0E-03
14	Kolonnawa	TR04	1.4E-02	1.3E-02	1.6E-02	1.4E-02	1.3E-02	1.9E-02	3.1E-02	1.6E-02	2.8E-02
15	Kolonnawa	TR05	1.3E-02	1.3E-02	8.3E-03	1.1E-02	2.3E-02	1.5E-02	7.9E-03	2.6E-02	2.4E-02
16	Mahiyangana	TR01	1.0E-02	5.1E-03	1.0E-02	1.0E-02	7.1E-03	5.6E-03	2.3E-02	1.7E-02	1.1E-02
17	Maho	TR02	1.3E-02	1.3E-02	7.2E-03	1.2E-02	1.4E-02	4.5E-03	2.0E-02	1.4E-02	1.2E-02
18	Monaragala	TR01	1.0E-02	6.8E-03	6.2E-03	9.4E-03	8.1E-03	2.7E-03	2.0E-02	1.1E-02	1.3E-02
19	Monaragala	TR02	1.5E-02	4.1E-03	1.4E-02	1.0E-02	8.1E-03	6.2E-03	1.9E-02	1.1E-02	1.2E-02
20	New Valachcheni	TR02	1.6E-02	5.6E-03	1.3E-02	1.2E-02	8.0E-03	6.3E-03	1.9E-02	1.4E-02	8.9E-03
21	Nuwara Eliya	TR01	2.5E-02	1.4E-02	2.2E-02	1.9E-02	1.6E-02	7.0E-03	2.0E-02	3.1E-02	3.6E-02
22	Nuwara Eliya	TR02	2.8E-02	1.5E-02	2.3E-02	1.8E-02	1.6E-02	5.7E-03	2.2E-02	3.1E-02	3.7E-02
23	Nuwara Eliya	TR03	1.2E-02	8.2E-03	7.3E-03	1.1E-02	8.9E-03	4.4E-03	2.4E-02	1.5E-02	1.4E-02
24	Old Anuradhapura	TR01	1.4E-02	9.2E-03	8.7E-03	1.9E-02	1.1E-02	1.6E-02	2.3E-02	9.8E-03	2.3E-02
25	Old Galle	TR01	4.9E-03	3.6E-03	7.2E-03	3.6E-03	2.9E-03	5.3E-03	1.3E-02	1.1E-02	6.6E-03
26	Old Galle	TR02	1.9E-03	2.7E-03	2.9E-03	1.4E-03	2.3E-03	2.6E-03	2.2E-03	4.8E-03	4.9E-03
27	Pannala	TR01	3.2E-03	3.1E-03	3.4E-03	4.9E-03	7.0E-03	3.0E-03	1.1E-02	1.9E-02	1.1E-02
28	Pannala	TR02	3.0E-03	2.8E-03	2.6E-03	4.5E-03	7.1E-03	4.0E-03	1.1E-02	1.9E-02	1.2E-02
29	Pannipitiya	TR03	1.2E-02	1.1E-02	1.4E-02	2.3E-02	1.7E-02	9.3E-03	3.3E-02	2.7E-02	1.9E-02
30	Sapugaskanda	TR01	7.4E-03	9.3E-03	5.8E-03	9.7E-03	6.9E-03	6.5E-03	2.3E-02	2.2E-02	6.3E-03
31	Sapugaskanda	TR03	1.4E-02	8.2E-03	1.3E-02	1.5E-02	1.4E-02	7.1E-03	2.5E-02	2.2E-02	1.7E-02
32	Sri Jayawardanapura	TR01	2.3E-02	2.8E-02	1.0E-02	2.4E-02	2.9E-02	1.1E-02	3.8E-03	6.0E-03	4.0E-03
33	Sri Jayawardanapura	TR02	1.6E-02	2.2E-02	1.3E-02	1.6E-02	2.2E-02	1.3E-02	9.5E-03	8.6E-03	3.6E-03
34	Thulhiriya	TR01	2.4E-02	1.0E-02	1.7E-02	1.5E-02	1.4E-02	6.1E-03	4.4E-02	3.6E-02	1.7E-02
35	Thulhiriya	TR02	2.3E-02	1.2E-02	1.4E-02	1.4E-02	1.4E-02	4.9E-03	4.6E-02	3.6E-02	2.1E-02
36	Trincomalee	TR01	1.0E-02	6.8E-03	6.7E-03	9.1E-03	7.4E-03	2.9E-03	1.1E-02	9.8E-03	1.5E-02
37	Trincomalee	TR02	9.8E-03	8.1E-03	8.2E-03	8.7E-03	8.3E-03	4.8E-03	1.2E-02	7.1E-03	1.3E-02
38	Valachchenei	TR01	4.6E-02	3.9E-02	5.9E-02	6.2E-02	5.6E-02	6.4E-02	5.6E-02	3.3E-02	4.4E-02
39	Valachchenei	TR02	4.3E-02	4.2E-02	5.7E-02	5.5E-02	5.3E-02	5.9E-02	5.0E-02	2.6E-02	3.9E-02
40	Valachchenei	TR03	4.0E-02	3.9E-02	5.4E-02	5.6E-02	5.0E-02	5.7E-02	7.6E-02	3.3E-02	6.8E-02
41	Vaunathiu	TR01	7.7E-03	4.5E-03	9.0E-03	8.8E-03	7.3E-03	6.2E-03	2.0E-02	1.6E-02	8.7E-03
42	Vaunathiu	TR02	1.4E-02	5.3E-03	1.2E-02	1.1E-02	7.3E-03	6.3E-03	2.1E-02	1.5E-02	1.0E-02
43	Veyangoda	TR02	1.7E-02	1.2E-02	1.6E-02	2.1E-02	2.1E-02	1.6E-02	2.8E-02	2.7E-02	1.4E-02
44	Veyangoda	TR03	1.8E-02	1.3E-02	2.0E-02	2.1E-02	2.8E-02	2.7E-02	3.2E-02	3.5E-02	2.5E-02

Region -4 (400 kHz – 2 MHz)

Item	Grid Substation	TR No.	Distance								
			HV open circuit			HV short circuit			LV open circuit		
			R - Y	Y - B	B - R	R - Y	Y - B	B - R	R - Y	Y - B	B - R
1	Badulla	TR03	3.9E-04	1.1E-03	1.2E-03	3.7E-04	1.1E-03	1.1E-03	3.0E-03	4.2E-03	3.0E-03
2	Biyagama	TR03	5.4E-04	5.8E-04	7.2E-04	5.3E-04	5.5E-04	7.2E-04	2.9E-03	3.5E-03	2.1E-03
3	Biyagama	TR04	1.1E-03	8.7E-04	9.8E-04	1.0E-03	8.3E-04	9.6E-04	3.1E-03	3.6E-03	1.3E-03
4	Bolawattha	TR01	2.8E-03	3.2E-03	3.9E-03	2.7E-03	3.2E-03	3.8E-03	4.0E-03	5.4E-03	4.4E-03
5	Bolawattha	TR02	2.9E-03	3.5E-03	4.0E-03	2.8E-03	3.4E-03	4.0E-03	6.2E-03	4.9E-03	2.7E-03
6	Bolawattha	TR03	1.4E-03	1.5E-03	1.3E-03	1.4E-03	1.4E-03	1.2E-03	3.8E-03	1.5E-03	3.2E-03
7	Habarana	TR01	2.8E-04	3.8E-04	4.8E-04	2.8E-04	3.9E-04	4.7E-04	3.1E-03	3.0E-03	2.2E-03
8	Habarana	TR02	2.9E-04	3.8E-04	4.8E-04	2.8E-04	3.9E-04	4.8E-04	3.9E-03	4.0E-03	2.8E-03
9	Hambanthota	TR02	4.0E-04	5.2E-04	6.8E-04	5.0E-04	3.8E-04	6.8E-04	2.9E-03	2.6E-03	1.2E-03
10	Katunayake	TR02	2.8E-04	5.2E-04	6.8E-04	2.8E-04	5.2E-04	6.9E-04	2.3E-03	3.6E-03	2.6E-03
11	Kelaniya	TR01	9.5E-04	7.1E-04	1.0E-03	9.4E-04	7.0E-04	9.9E-04	2.8E-03	1.8E-03	2.4E-03
12	Kiribathkumbura	TR01	2.8E-03	3.5E-03	4.3E-03	2.7E-03	3.5E-03	4.2E-03	2.8E-03	2.5E-03	2.8E-03
13	Kiribathkumbura	TR02	2.7E-03	3.4E-03	4.2E-03	2.6E-03	3.3E-03	4.2E-03	4.9E-03	5.1E-03	1.6E-03
14	Kolonnawa	TR04	2.4E-04	3.0E-04	3.1E-04	2.5E-04	3.0E-04	3.2E-04	2.3E-03	1.9E-03	2.0E-03
15	Kolonnawa	TR05	2.8E-04	3.8E-04	3.6E-04	2.8E-04	3.8E-04	3.7E-04	1.9E-03	2.8E-03	2.0E-03
16	Mahiyangana	TR01	1.3E-03	1.7E-03	1.9E-03	1.3E-03	1.4E-03	1.7E-03	4.1E-03	7.1E-03	7.2E-03
17	Maho	TR02	1.3E-03	1.4E-03	1.7E-03	1.2E-03	1.2E-03	1.5E-03	4.5E-03	5.3E-03	3.2E-03
18	Monaragala	TR01	1.1E-03	8.1E-04	9.4E-04	1.0E-03	7.6E-04	9.3E-04	4.5E-03	5.0E-03	2.8E-03
19	Monaragala	TR02	9.8E-04	8.9E-04	9.2E-04	1.0E-03	9.0E-04	9.1E-04	3.9E-03	4.8E-03	2.5E-03
20	New Valachcheni	TR02	1.1E-03	8.9E-04	9.3E-04	1.0E-03	8.5E-04	9.2E-04	4.9E-03	4.9E-03	3.0E-03
21	Nuwara Eliya	TR01	3.6E-04	3.4E-04	4.3E-04	3.6E-04	3.4E-04	4.3E-04	2.4E-03	3.4E-03	2.6E-03
22	Nuwara Eliya	TR02	3.5E-04	2.2E-04	3.6E-04	3.5E-04	2.3E-04	3.4E-04	2.2E-03	3.8E-03	3.3E-03
23	Nuwara Eliya	TR03	1.3E-03	1.6E-03	1.8E-03	1.2E-03	1.2E-03	1.6E-03	4.3E-03	3.9E-03	3.2E-03
24	Old Anuradhapura	TR01	1.0E-03	6.9E-04	1.2E-03	1.0E-03	7.0E-04	1.2E-03	3.3E-03	2.4E-03	2.8E-03
25	Old Galle	TR01	2.5E-04	4.1E-04	4.6E-04	3.1E-04	5.3E-04	6.4E-04	7.8E-04	6.9E-04	8.8E-04
26	Old Galle	TR02	2.1E-04	2.5E-04	2.7E-04	2.4E-04	2.9E-04	3.4E-04	1.1E-03	1.1E-03	1.9E-03
27	Pannala	TR01	8.5E-04	1.0E-03	8.2E-04	2.1E-03	2.3E-03	8.3E-04	1.0E-03	2.1E-03	1.5E-03
28	Pannala	TR02	3.4E-04	6.3E-04	8.0E-04	3.5E-04	6.3E-04	8.1E-04	5.8E-04	4.1E-03	3.9E-03
29	Pannipitiya	TR03	6.2E-04	5.1E-04	6.8E-04	6.0E-04	5.1E-04	6.7E-04	3.3E-03	1.8E-03	3.0E-03
30	Sapugaskanda	TR01	1.3E-03	1.0E-03	1.3E-03	1.3E-03	1.0E-03	1.3E-03	5.1E-03	2.3E-03	4.3E-03
31	Sapugaskanda	TR03	1.1E-03	1.2E-03	1.3E-03	9.6E-04	1.4E-03	1.4E-03	2.9E-03	2.2E-03	2.4E-03
32	Sri Jayawardanapura	TR01	7.7E-04	6.1E-04	8.6E-04	7.8E-04	6.2E-04	8.6E-04	4.3E-03	4.8E-03	4.6E-03
33	Sri Jayawardanapura	TR02	1.2E-03	8.4E-04	1.3E-03	1.2E-03	8.4E-04	1.3E-03	3.3E-03	3.0E-03	3.2E-03
34	Thulhiriya	TR01	2.5E-04	4.1E-04	5.7E-04	2.5E-04	3.8E-04	5.6E-04	4.5E-03	2.6E-03	3.5E-03
35	Thulhiriya	TR02	1.4E-04	2.4E-04	3.2E-04	1.4E-04	2.2E-04	3.1E-04	5.0E-03	2.7E-03	4.9E-03
36	Trincomalee	TR01	2.9E-04	3.9E-04	4.8E-04	2.9E-04	4.0E-04	4.8E-04	2.5E-03	2.8E-03	2.4E-03
37	Trincomalee	TR02	3.1E-04	3.4E-04	4.5E-04	3.0E-04	3.5E-04	4.5E-04	2.9E-03	4.0E-03	3.2E-03
38	Valachchenei	TR01	8.1E-04	6.0E-04	6.5E-04	8.1E-04	5.9E-04	6.5E-04	3.4E-03	5.1E-03	4.0E-03
39	Valachchenei	TR02	4.2E-04	7.2E-04	6.5E-04	4.2E-04	7.1E-04	6.4E-04	3.0E-03	3.4E-03	1.1E-03
40	Valachchenei	TR03	6.0E-04	4.7E-04	4.7E-04	6.0E-04	4.7E-04	4.7E-04	4.9E-03	4.3E-03	3.1E-03
41	Vaunathiu	TR01	9.9E-04	9.1E-04	9.9E-04	9.3E-04	8.5E-04	9.4E-04	2.6E-03	4.0E-03	2.4E-03
42	Vaunathiu	TR02	1.1E-03	1.1E-03	1.2E-03	1.1E-03	9.4E-04	1.1E-03	3.5E-03	4.8E-03	3.1E-03
43	Veyangoda	TR02	5.3E-04	5.0E-04	7.2E-04	5.3E-04	4.7E-04	7.1E-04	3.4E-03	3.5E-03	2.7E-03
44	Veyangoda	TR03	5.4E-04	6.9E-04	7.5E-04	5.4E-04	6.7E-04	7.4E-04	4.6E-03	4.7E-03	4.3E-03

Appendix-E: Weights and scores derived for the calculation of each index, for four regions.

(a) Weights and scores derived for ASLEI

Region -1 (20 Hz – 2 kHz)

Test Connection	Phases	ASLE Value	Score (S_i)	Weight	
				$W1_i$	$W2_j$
HV open	R-Y	< 2.4000	4	1	3
		2.4000 - 1.8500	3		
		1.8500 - 1.3000	2		
		1.3000 >	1		
	Y-B	< 3.2000	4	1	
		3.2000 - 2.4500	3		
		2.4500 - 1.7000	2		
		1.7000 >	1		
	B-R	< 3.5000	4	3	
		3.5000 - 2.8500	3		
		2.8500 - 2.2000	2		
		2.2000 >	1		
HV short	R-Y	< 3.5000	4	1	1
		3.5000 - 2.3850	3		
		2.3850 - 1.2700	2		
		1.2700 >	1		
	Y-B	< 3.0000	4	1	
		3.0000 - 2.3000	3		
		2.3000 - 1.6000	2		
		1.6000 >	1		
	B-R	< 3.5000	4	3	
		3.5000 - 2.8500	3		
		2.8500 - 2.2000	2		
		2.2000 >	1		
LV open	R-Y	< 4.3000	4	1	2
		4.3000 - 3.8650	3		
		3.8650 - 3.4300	2		
		3.4300 >	1		
	Y-B	< 4.8000	4	1	
		4.8000 - 4.3000	3		
		4.3000 - 3.8000	2		
		3.8000 >	1		
	B-R	< 3.2000	4	3	
		3.2000 - 1.8500	3		
		1.8500 - 0.5000	2		
		0.5000 >	1		

Region -2 (2 kHz – 20 kHz)

Test Connection	Phases	ASLE Value	Score (S_i)	Weight $W1_i$	Weight $W2_j$
HV open	R-Y	< 1.5000	4	1	3
		1.5000 - 1.1250	3		
		1.1250 - 0.7500	2		
		0.7500 >	1		
	Y-B	< 1.3000	4	1	
		1.3000 - 1.0000	3		
		1.0000 - 0.7000	2		
		0.7000 >	1		
	B-R	< 0.4400	4	2	
		0.4400 - 0.3500	3		
		0.3500 - 0.2600	2		
		0.2600 >	1		
HV short	R-Y	< 1.8000	4	1	2
		1.8000 - 1.3900	3		
		1.3900 - 0.9800	2		
		0.9800 >	1		
	Y-B	< 1.7000	4	1	
		1.7000 - 1.2800	3		
		1.2800 - 0.8600	2		
		0.8600	1		
	B-R	< 0.4500	4	2	
		0.4500 - 0.3500	3		
		0.3500 - 0.2500	2		
		0.2500 >	1		
LV open	R-Y	< 1.4000	4	1	2
		1.4000 - 1.0650	3		
		1.0650 - 0.7300	2		
		0.7300 >	1		
	Y-B	< 1.1000	4	1	
		1.1000 - 0.8500	3		
		0.8500 - 0.6000	2		
		0.6000 >	1		
	B-R	< 0.5000	4	2	
		0.5000 - 0.3500	3		
		0.3500 - 0.2000	2		
		0.2000 >	1		

Region -3 (20 kHz – 400 kHz)

Test Connection	Phases	ASLE Value	Score (S_i)	Weight	
				$W1_i$	$W2_j$
HV open	R-Y	< 1.4000	4	1	3
		1.4000 - 1.0600	3		
		1.0600 - 0.7200	2		
		0.7200 >	1		
	Y-B	< 1.2000	4	1	
		1.2000 - 0.8850	3		
		0.8850 - 0.5700	2		
		0.5700 >	1		
	B-R	< 1.7000	4	1	
		1.7000 - 1.2500	3		
		1.2500 - 0.8000	2		
		0.8000 >	1		
HV short	R-Y	< 1.6000	4	1	2
		1.6000 - 1.1500	3		
		1.1500 - 0.7000	2		
		0.7000 >	1		
	Y-B	< 1.2500	4	1	
		1.2500 - 0.9350	3		
		0.9350 - 0.6200	2		
		0.6200 >	1		
	B-R	< 1.8000	4	1	
		1.8000 - 1.3000	3		
		1.3000 - 0.8000	2		
		0.8000 >	1		
LV open	R-Y	< 2.0000	4	1	2
		2.0000 - 1.5000	3		
		1.5000 - 1.0000	2		
		1.0000 >	1		
	Y-B	< 1.3000	4	1	
		1.3000 - 1.1400	3		
		1.1400 - 0.9800	2		
		0.9800 >	1		
	B-R	< 1.3000	4	1	
		1.3000 - 1.0900	3		
		1.0900 - 0.8800	2		
		0.8800 >	1		

Region -4 (400 kHz – 2 MHz)

Test Connection	**Phases**	**ASLE Value**	**Score (S_i)**	**Weight**	
				$W1_i$	***$W2_j$***
HV open	R-Y	< 2.4000	4	1	3
		2.4000 - 1.8500	3		
		1.8500 - 1.3000	2		
		1.3000 >	1		
	Y-B	3.2000	4	1	
		3.2000 - 2.4500	3		
		2.4500 - 1.7000	2		
		1.7000 >	1		
	B-R	< 3.5000	4	1	
		3.5000 - 2.8500	3		
		2.8500 - 2.2000	2		
		2.2000 >	1		
HV short	R-Y	< 3.5000	4	1	2
		3.5000 - 2.3850	3		
		2.3850 - 1.2700	2		
		1.2700 >	1		
	Y-B	< 3.0000	4	1	
		3.0000 - 2.3000	3		
		2.3000 - 1.6000	2		
		1.6000 >	1		
	B-R	< 3.5000	4	1	
		3.5000 - 2.8500	3		
		2.8500 - 2.2000	2		
		2.2000 >	1		
LV open	R-Y	5.3000	4	1	2
		5.3000 - 4.6500	3		
		4.6500 - 4.0000	2		
		4.0000 >	1		
	Y-B	< 4.8000	4	1	
		4.8000 - 4.2500	3		
		4.2500 - 3.7000	2		
		3.7000 >	1		
	B-R	< 4.8000	4	1	
		4.8000 - 3.4000	3		
		3.4000 - 2.0000	2		
		2.0000 >	1		

(b) Weights and scores derived for CCFI

Region -1 (20 Hz – 2 kHz)

Test Connection	Phases	CCF Value	Score (S_i)	Weight	
				$W1_i$	$W2_j$
HV open	R-Y	< 0.9200	1	1	3
		0.9200 - 0.9100	2		
		0.9100 - 0.9000	3		
		0.9000 >	4		
	Y-B	< 0.9100	1	1	
		0.9100 - 0.8850	2		
		0.8850 - 0.8600	3		
		0.8600 >	4		
	B-R	< 0.9900	1	3	
		0.9900 - 0.9700	2		
		0.9700 - 0.9500	3		
		0.9500 >	4		
HV short	R-Y	< 1.0000	1	1	1
		1.0000 - 0.9995	2		
		0.9995 - 0.9990	3		
		0.9990 >	4		
	Y-B	< 1.0000	1	1	
		1.0000 - 0.9995	2		
		0.9995 - 0.9990	3		
		0.9990 >	4		
	B-R	< 1.0000	1	3	
		1.0000 - 0.9995	2		
		0.9995 - 0.9990	3		
		0.9990 >	4		
LV open	R-Y	< 0.8900	1	1	2
		0.8900 - 0.8700	2		
		0.8700 - 0.8500	3		
		0.8500 >	4		
	Y-B	< 0.8900	1	1	
		0.8900 - 0.8650	2		
		0.8650 - 0.8400	3		
		0.8400 >	4		
	B-R	< 0.9980	1	3	
		0.9980 - 0.9740	2		
		0.9740 - 0.9500	3		
		0.9500 >	4		

Region -2 (2 kHz – 20 kHz)

Test Connection	**Phases**	**CCF Value**	**Score (S_i)**	**Weight** $W1_i$	**Weight** $W2_j$
HV open	R-Y	< 0.9800	1	1	3
		0.9800 - 0.9600	2		
		0.9600 - 0.9400	3		
		0.9400 >	4		
	Y-B	< 0.9800	1	1	
		0.9800 - 0.9650	2		
		0.9650 - 0.9500	3		
		0.9500 >	4		
	B-R	< 0.9980	1	2	
		0.9980 - 0.9960	2		
		0.9960 - 0.9940	3		
		0.9940 >	4		
HV short	R-Y	< 0.9600	1	1	2
		0.9600 - 0.9200	2		
		0.9200 - 0.8800	3		
		0.8800 >	4		
	Y-B	< 0.9700	1	1	
		0.9700 - 0.9300	2		
		0.9300 - 0.8900	3		
		0.8900	4		
	B-R	< 0.9980	1	2	
		0.9980 - 0.9955	2		
		0.9955 - 0.9930	3		
		0.9930 >	4		
LV open	R-Y	< 0.9890	1	1	2
		0.9890 - 0.9730	2		
		0.9730 - 0.9570	3		
		0.9570 >	4		
	Y-B	< 0.9920	1	1	
		0.9920 - 0.9845	2		
		0.9845 - 0.9770	3		
		0.9770 >	4		
	B-R	< 0.9990	1	2	
		0.9990 - 0.9945	2		
		0.9945 - 0.9900	3		
		0.9900 >	4		

Region -3 (20 kHz – 400 kHz)

Test Connection	**Phases**	**CCF Value**	**Score (S_i)**	**Weight $W1_i$**	**Weight $W2_j$**
HV open	R-Y	< 0.9930	1	1	3
		0.9930 - 0.9765	2		
		0.9765 - 0.9600	3		
		0.9600 >	4		
	Y-B	< 0.9930	1	1	
		0.9930 - 0.9765	2		
		0.9765 - 0.9600	3		
		0.9600 >	4		
	B-R	< 0.9920	1	1	
		0.9920 - 0.9560	2		
		0.9560 - 0.9200	3		
		0.9200 >	4		
HV short	R-Y	< 0.9920	1	1	2
		0.9920 - 0.9760	2		
		0.9760 - 0.9600	3		
		0.9600 >	4		
	Y-B	< 0.9920	1	1	
		0.9920 - 0.9760	2		
		0.9760 - 0.9600	3		
		0.9600 >	4		
	B-R	< 0.9940	1	1	
		0.9940 - 0.9620	2		
		0.9620 - 0.9300	3		
		0.9300 >	4		
LV open	R-Y	< 0.9680	1	1	2
		0.9680 - 0.9240	2		
		0.9240 - 0.8800	3		
		0.8800 >	4		
	Y-B	< 0.9730	1	1	
		0.9730 - 0.9590	2		
		0.9590 - 0.9450	3		
		0.9450 >	4		
	B-R	< 0.9820	1	1	
		0.9820 - 0.9610	2		
		0.9610 - 0.9400	3		
		0.9400 >	4		

Region -4 (400 kHz – 2 MHz)

Test Connection	**Phases**	**CCF Value**	**Score (S_i)**	**Weight**	
				$W1_i$	***$W2_j$***
		< 0.9600	1		
	R-Y	0.9600 - 0.9200	2	1	
		0.9200 - 0.8800	3		
		0.8800 >	4		
		< 0.9600	1		
HV open	Y-B	0.9600 - 0.9100	2	1	3
		0.9100 - 0.8600	3		
		0.8600 >	4		
		< 0.9200	1		
	B-R	0.9200 - 0.8600	2	1	
		0.8600 - 0.8000	3		
		0.8000	4		
		< 0.9600	1		
	R-Y	0.9600 - 0.9200	2	1	
		0.9200 - 0.8800	3		
		0.8800 >	4		
		< 0.9630	1		
HV short	Y-B	0.9630 - 0.9315	2	1	2
		0.9315 - 0.9000	3		
		0.9000 >	4		
		< 0.9200	1		
	B-R	0.9200 - 0.8700	2	1	
		0.8700 - 0.8200	3		
		0.8200 >	4		
		< 0.7000	1		
	R-Y	0.7000 - 0.5000	2	1	
		0.5000 - 0.3000	3		
		0.3000 >	4		
		< 0.8000	1		
LV open	Y-B	0.8000 - 0.6550	2	1	2
		0.6550 - 0.5100	3		
		0.5100 >	4		
		< 0.8900	1		
	B-R	0.8900 - 0.7750	2	1	
		0.7750 - 0.6600	3		
		0.6600 >	4		

(c) Weights and scores derived for DisTF

Region -1 (20 Hz – 2 kHz)

Test Connection	Phases	DisTF	Score (Si)	Weight $W1_i$	Weight $W2_j$
HV open	R-Y	< 2.6000	4	1	3
		2.6000 - 2.0000	3		
		2.0000 - 1.4500	2		
		1.4500 >	1		
	Y-B	< 2.6000	4	1	
		2.6000 - 2.0000	3		
		2.0000 - 1.5000	2		
		1.5000 >	1		
	B-R	< 1.6000	4	3	
		1.6000 - 1.1500	3		
		1.1500 - 0.7000	2		
		0.7000 >	1		
HV short	R-Y	< 0.1000	4	1	1
		0.1000 - 0.0500	3		
		0.0500 - 0.0080	2		
		0.0080 >	1		
	Y-B	< 0.1000	4	1	
		0.1000 - 0.0550	3		
		0.0550 - 0.0100	2		
		0.0100 >	1		
	B-R	< 0.0800	4	3	
		0.0800 - 0.0450	3		
		0.0450 - 0.0100	2		
		0.0100 >	1		
LV open	R-Y	< 3.2600	4	1	2
		3.2600 - 2.7300	3		
		2.7300 - 2.2000	2		
		2.2000 >	1		
	Y-B	< 3.0000	4	1	
		3.0000 - 2.5000	3		
		2.5000 - 2.0000	2		
		2.0000 >	1		
	B-R	< 2.3000	4	3	
		2.3000 - 1.6500	3		
		1.6500 - 1.0000	2		
		1.0000 >	1		

Region -2 (2 kHz – 20 kHz)

Test Connection	**Phases**	**DisTF**	**Score *(Si)***	**Weight**	
				W1$_i$	***W2$_j$***
HV open	R-Y	< 0.0600	4	1	3
		0.0600 - 0.0400	3		
		0.0400 - 0.0200	2		
		0.0200 >	1		
	Y-B	< 0.0600	4	1	
		0.0600 - 0.0400	3		
		0.0400 - 0.0200	2		
		0.0200 >	1		
	B-R	< 0.0206	4	2	
		0.0206 - 0.0150	3		
		0.0150 - 0.0090	2		
		0.0090 >	1		
HV short	R-Y	< 0.0500	4	1	2
		0.0500 - 0.0400	3		
		0.0400 - 0.0300	2		
		0.0300 >	1		
	Y-B	< 0.0501	4	1	
		0.0501 - 0.0400	3		
		0.0400 - 0.0300	2		
		0.0300 >	1		
	B-R	< 0.0200	4	2	
		0.0200 - 0.0150	3		
		0.0150 - 0.0095	2		
		0.0095 >	1		
LV open	R-Y	< 0.0400	4	1	2
		0.0400 - 0.0290	3		
		0.0290 - 0.0180	2		
		0.0180 >	1		
	Y-B	< 0.0500	4	1	
		0.0500 - 0.0200	3		
		0.0200 - 0.0140	2		
		0.0140 >	1		
	B-R	< 0.0270	4	2	
		0.0270 - 0.0170	3		
		0.0170 - 0.0070	2		
		0.0070 >	1		

Region -3 (20 kHz – 400 kHz)

Test Connection	Phases	DisTF	Score (Si)	Weight	
				W1$_i$	***W2$_j$***
HV open	R-Y	< 0.0250	4	1	3
		0.0250 - 0.0175	3		
		0.0175 - 0.0100	2		
		0.0100 >	1		
	Y-B	< 0.0200	4	1	
		0.0200 - 0.0145	3		
		0.0145 - 0.0090	2		
		0.0090 >	1		
	B-R	< 0.0220	4	1	
		0.0220 - 0.0155	3		
		0.0155 - 0.0090	2		
		0.0090 >	1		
HV short	R-Y	< 0.0240	4	1	2
		0.0240 - 0.0170	3		
		0.0170 - 0.0100	2		
		0.0100 >	1		
	Y-B	< 0.0300	4	1	
		0.0300 - 0.0200	3		
		0.0200 - 0.0100	2		
		0.0100 >	1		
	B-R	< 0.0270	4	1	
		0.0270 - 0.0165	3		
		0.0165 - 0.0060	2		
		0.0060 >	1		
LV open	R-Y	< 0.0400	4	1	2
		0.0400 - 0.0300	3		
		0.0300 - 0.0200	2		
		0.0200 >	1		
	Y-B	< 0.0330	4	1	
		0.0330 - 0.0250	3		
		0.0250 - 0.0170	2		
		0.0170 >	1		
	B-R	< 0.0360	4	1	
		0.0360 - 0.0245	3		
		0.0245 - 0.0130	2		
		0.0130 >	1		

Region -4 (400 kHz – 2 MHz)

Test Connection	Phases	DisTF	Score (Si)	Weight $W1_i$	Weight $W2_j$
HV open	R-Y	< 0.0015	4	1	3
		0.0015 - 0.0012	3		
		0.0012 - 0.0008	2		
		0.0008 >	1		
	Y-B	< 0.0016	4	1	
		0.0016 - 0.0012	3		
		0.0012 - 0.0007	2		
		0.0007 >	1		
	B-R	< 0.0020	4	1	
		0.0020 - 0.0014	3		
		0.0014 - 0.0009	2		
		0.0009 >	1		
HV short	R-Y	< 0.0008	4	1	2
		0.0008 - 0.0014	3		
		0.0014 - 0.0020	2		
		0.0020 >	1		
	Y-B	< 0.0023	4	1	
		0.0023 - 0.0015	3		
		0.0015 - 0.0007	2		
		0.0007 >	1		
	B-R	< 0.0017	4	1	
		0.0017 - 0.0012	3		
		0.0012 - 0.0008	2		
		0.0008 >	1		
LV open	R-Y	< 0.0050	4	1	2
		0.0050 - 0.0040	3		
		0.0040 - 0.0030	2		
		0.0030 >	1		
	Y-B	< 0.0050	4	1	
		0.0050 - 0.0043	3		
		0.0043 - 0.0035	2		
		0.0035 >	1		
	B-R	< 0.0040	4	1	
		0.0040 - 0.0035	3		
		0.0035 - 0.0030	2		
		0.0030 >	1		

Appendix-F: Calculated values for ASLEI, CCFI and DisTF for four regions

(a) Values calculated for ASLEI for four regions

Item	Grid Substation	TR No.	Range 1	Range 2	Range 3	Range 4
1	Badulla	TR03	3.0000	1.1429	2.4762	1.1905
2	Biyagama	TR03	1.5667	3.1429	2.8571	1.1905
3	Biyagama	TR04	1.9333	2.0357	1.3333	1.5714
4	Bolawattha	TR01	1.5667	2.0714	2.8095	2.0000
5	Bolawattha	TR02	1.7000	2.1429	3.0476	1.4286
6	Bolawattha	TR03	1.7667	2.2857	1.1429	2.8095
7	Habarana	TR01	1.7000	1.0000	1.2857	1.6190
8	Habarana	TR02	1.8667	1.0000	1.1905	1.9048
9	Hambanthota	TR02	2.0667	1.0000	1.0000	1.0000
10	Katunayake	TR02	3.0000	1.6786	1.2857	1.5714
11	Kelaniya	TR01	1.6000	1.5000	1.7619	2.4286
12	Kiribathkumbura	TR01	1.5000	1.9643	2.8095	1.4762
13	Kiribathkumbura	TR02	1.5000	2.2857	2.9048	2.1905
14	Kolonnawa	TR04	1.5667	2.0714	2.1429	1.3333
15	Kolonnawa	TR05	1.5000	2.3571	1.8571	1.0952
16	Mahiyangana	TR01	3.2000	1.2143	1.0000	2.5238
17	Maho	TR02	1.5667	1.2500	1.1905	2.1429
18	Monaragala	TR01	2.1333	1.6071	1.0952	1.7619
19	Monaragala	TR02	2.0000	2.1071	1.7619	1.4762
20	New Valachcheni	TR02	1.6667	2.0714	1.4762	1.8095
21	Nuwara Eliya	TR01	1.8000	1.0000	1.6190	1.5714
22	Nuwara Eliya	TR02	1.7333	1.0000	1.4762	1.5714
23	Nuwara Eliya	TR03	2.0000	1.5714	1.0000	2.2381
24	Old Anuradhapura	TR01	1.5667	2.4643	2.0476	2.9048
25	Old Galle	TR01	1.5000	1.0000	1.0000	1.0000
26	Old Galle	TR02	1.5000	1.3571	1.0000	1.0000
27	Pannala	TR01	1.5667	1.3571	1.0000	2.7619
28	Pannala	TR02	1.6667	1.2857	1.2857	1.6667
29	Pannipitiya	TR03	1.8000	2.7857	1.9524	1.3810
30	Sapugaskanda	TR01	1.8667	1.2857	2.0952	2.7143
31	Sapugaskanda	TR03	3.1000	1.6786	1.4762	2.3333
32	Sri Jayawardanapura	TR01	1.7000	1.9286	1.7143	2.8571
33	Sri Jayawardanapura	TR02	2.4000	2.7143	2.0476	3.0000
34	Thulhiriya	TR01	1.6000	1.0000	2.2381	1.2857
35	Thulhiriya	TR02	1.6000	1.0000	2.1429	1.3810
36	Trincomalee	TR01	2.2667	1.1429	1.4762	1.7143
37	Trincomalee	TR02	1.9333	1.0000	1.0952	1.9524
38	Valachchenei	TR01	1.8667	3.8929	3.7143	1.4762
39	Valachchenei	TR02	1.6000	4.0000	3.7143	1.2857
40	Valachchenei	TR03	1.5000	3.6429	3.7143	1.0952
41	Vaunathiu	TR01	2.0000	1.2857	1.0952	1.3333
42	Vaunathiu	TR02	1.8667	1.8571	1.1429	2.0952
43	Veyangoda	TR02	1.7000	2.9286	2.2857	1.1905
44	Veyangoda	TR03	2.3667	2.5000	2.7143	1.2857

(b) Values calculated for CCFI for four regions

Item	Grid Substation	TR No.	Range 1	Range 2	Range 3	Range 4
1	Badulla	TR03	2.8333	1.1429	2.7143	1.2381
2	Biyagama	TR03	1.3000	3.3571	2.7143	1.0952
3	Biyagama	TR04	1.2333	1.4286	1.1905	1.7143
4	Bolawattha	TR01	1.5000	2.1786	2.7619	2.0952
5	Bolawattha	TR02	1.6333	2.1786	3.0476	1.9048
6	Bolawattha	TR03	1.8333	2.3571	1.3810	3.1429
7	Habarana	TR01	1.6667	1.0000	1.2857	1.9048
8	Habarana	TR02	2.0000	1.0000	1.1905	1.9048
9	Hambanthota	TR02	2.0333	1.0714	1.2381	1.0952
10	Katunayake	TR02	2.8667	1.2857	1.1905	1.4286
11	Kelaniya	TR01	1.3333	1.5000	2.0952	2.4286
12	Kiribathkumbura	TR01	1.1667	2.2143	2.5238	1.9048
13	Kiribathkumbura	TR02	1.1667	2.6071	2.8571	1.9524
14	Kolonnawa	TR04	1.7000	2.4286	2.0476	1.1905
15	Kolonnawa	TR05	1.3333	2.5714	1.7619	1.2857
16	Mahiyangana	TR01	2.9333	1.1429	1.2381	2.6667
17	Maho	TR02	1.2667	1.4643	1.4286	1.9524
18	Monaragala	TR01	1.6000	1.5357	1.0000	1.2381
19	Monaragala	TR02	2.3000	2.1071	1.4762	1.4762
20	New Valachcheni	TR02	1.1667	1.8214	1.2857	1.6190
21	Nuwara Eliya	TR01	1.9667	1.1429	1.6667	1.6667
22	Nuwara Eliya	TR02	1.6333	1.1429	1.7619	1.6667
23	Nuwara Eliya	TR03	2.2333	1.8571	1.1905	2.1905
24	Old Anuradhapura	TR01	1.3000	2.9286	1.6667	2.8571
25	Old Galle	TR01	1.2667	1.0000	1.2381	1.2381
26	Old Galle	TR02	1.1667	1.0000	1.0000	1.0000
27	Pannala	TR01	1.5000	1.2143	1.0952	3.1429
28	Pannala	TR02	1.9333	1.2143	1.1905	1.7619
29	Pannipitiya	TR03	1.8000	3.0000	1.9524	1.4762
30	Sapugaskanda	TR01	1.1667	1.1429	1.5714	3.1429
31	Sapugaskanda	TR03	3.1667	1.8571	1.6667	2.9524
32	Sri Jayawardanapura	TR01	2.0667	1.2857	1.5714	2.2381
33	Sri Jayawardanapura	TR02	3.1667	1.5714	1.4762	2.6667
34	Thulhiriya	TR01	1.1667	1.0000	2.0476	1.0952
35	Thulhiriya	TR02	1.1667	1.0000	1.8095	1.2857
36	Trincomalee	TR01	2.7333	1.0000	1.2857	1.8095
37	Trincomalee	TR02	2.3333	1.0000	1.0952	1.7619
38	Valachchenei	TR01	2.0667	3.4643	3.8095	1.2857
39	Valachchenei	TR02	1.4000	3.8929	3.7143	1.2857
40	Valachchenei	TR03	1.1667	3.4643	3.8095	1.1905
41	Vaunathiu	TR01	1.3667	1.1429	1.2381	1.4762
42	Vaunathiu	TR02	1.3000	1.9643	1.0000	1.8095
43	Veyangoda	TR02	1.3667	3.2857	2.3810	1.0000
44	Veyangoda	TR03	2.5333	2.7857	2.7619	1.0952

(c) Values calculated for DisTFI

Item	Grid Substation	TR No.	Range 1	Range 2	Range 3	Range 4
1	Badulla	TR03	1.3000	1.0000	3.3333	1.6667
2	Biyagama	TR03	1.3667	2.5714	2.5714	1.0000
3	Biyagama	TR04	1.1000	2.0714	1.3333	2.0952
4	Bolawattha	TR01	2.2000	2.2857	1.0952	3.9048
5	Bolawattha	TR02	2.9000	2.1429	1.6190	3.6190
6	Bolawattha	TR03	1.6333	2.2143	2.0000	2.3810
7	Habarana	TR01	1.8333	1.0000	1.0952	1.0952
8	Habarana	TR02	1.2667	1.0000	1.0952	1.1905
9	Hambanthota	TR02	1.5333	1.0000	1.1905	1.0000
10	Katunayake	TR02	2.2667	1.6429	1.0952	1.0952
11	Kelaniya	TR01	1.3333	1.2143	1.4762	1.8095
12	Kiribathkumbura	TR01	1.7000	2.0714	1.0952	3.1429
13	Kiribathkumbura	TR02	1.4000	2.7857	1.0952	3.6190
14	Kolonnawa	TR04	1.9667	1.9286	2.3333	1.0000
15	Kolonnawa	TR05	1.6667	2.3214	1.9524	1.0000
16	Mahiyangana	TR01	1.3000	1.4286	1.5714	3.4286
17	Maho	TR02	1.1333	1.4286	1.5714	3.0000
18	Monaragala	TR01	1.0000	1.8571	1.2381	2.2857
19	Monaragala	TR02	1.7667	2.2143	1.4762	2.1905
20	New Valachcheni	TR02	1.0000	2.1429	1.4762	2.3810
21	Nuwara Eliya	TR01	2.1000	1.1429	2.7619	1.0000
22	Nuwara Eliya	TR02	1.6333	1.1429	3.0000	1.1905
23	Nuwara Eliya	TR03	1.3333	2.0714	1.4286	2.8095
24	Old Anuradhapura	TR01	1.8000	2.3571	1.8571	1.7619
25	Old Galle	TR01	1.9333	1.0000	1.0000	1.0000
26	Old Galle	TR02	2.0667	1.5000	1.0000	1.0000
27	Pannala	TR01	1.8667	1.3571	1.0952	1.9524
28	Pannala	TR02	1.9667	1.5000	1.0952	1.3810
29	Pannipitiya	TR03	2.8333	2.4286	2.2857	1.0952
30	Sapugaskanda	TR01	1.2667	1.0714	1.4286	2.7143
31	Sapugaskanda	TR03	2.5667	1.5714	1.8571	2.1429
32	Sri Jayawardanapura	TR01	3.6667	2.7143	2.3333	1.9048
33	Sri Jayawardanapura	TR02	3.9000	2.2857	2.0952	2.3333
34	Thulhiriya	TR01	1.1667	1.0000	2.6667	1.2857
35	Thulhiriya	TR02	1.2333	1.0000	2.4286	1.4762
36	Trincomalee	TR01	2.0000	1.0000	1.0952	1.0000
37	Trincomalee	TR02	1.3000	1.0000	1.0000	1.1905
38	Valachchenei	TR01	1.8333	3.9286	3.9048	2.0952
39	Valachchenei	TR02	1.6000	3.9286	3.9048	1.2381
40	Valachchenei	TR03	1.4000	3.7143	3.9048	1.4762
41	Vaunathiu	TR01	1.0000	1.5000	1.0952	2.0000
42	Vaunathiu	TR02	1.0000	2.2857	1.5714	2.2857
43	Veyangoda	TR02	1.3333	2.7500	2.4286	1.1905
44	Veyangoda	TR03	1.9000	2.0714	3.0476	1.6667

Appendix-G: The SFRAI values for the four regions

Item	Grid Substation	TR No.	Range 1	Range 2	Range 3	Range 4
1	Badulla	TR03	2.6333	1.1190	2.7381	1.2937
2	Biyagama	TR03	1.4000	3.1548	2.7381	1.1111
3	Biyagama	TR04	1.4444	1.7381	1.2619	1.7302
4	Bolawattha	TR01	1.6389	2.1607	2.5000	2.3651
5	Bolawattha	TR02	1.8667	2.1607	2.8095	2.0317
6	Bolawattha	TR03	1.7778	2.3095	1.4048	2.9048
7	Habarana	TR01	1.7056	1.0000	1.2540	1.6746
8	Habarana	TR02	1.8333	1.0000	1.1746	1.7857
9	Hambanthota	TR02	1.9611	1.0357	1.1508	1.0476
10	Katunayake	TR02	2.8111	1.4762	1.2063	1.4206
11	Kelaniya	TR01	1.4222	1.4524	1.8810	2.3254
12	Kiribathkumbura	TR01	1.3667	2.1071	2.3810	1.9683
13	Kiribathkumbura	TR02	1.3167	2.5298	2.5794	2.3095
14	Kolonnawa	TR04	1.7000	2.2262	2.1270	1.2063
15	Kolonnawa	TR05	1.4444	2.4583	1.8254	1.1746
16	Mahiyangana	TR01	2.7500	1.2143	1.2143	2.7460
17	Maho	TR02	1.3444	1.3869	1.3730	2.1905
18	Monaragala	TR01	1.6778	1.6131	1.0714	1.5873
19	Monaragala	TR02	2.1111	2.1250	1.5714	1.5952
20	New Valachcheni	TR02	1.3056	1.9583	1.3810	1.8095
21	Nuwara Eliya	TR01	1.9333	1.0952	1.8333	1.5238
22	Nuwara Eliya	TR02	1.6667	1.0952	1.8730	1.5556
23	Nuwara Eliya	TR03	2.0056	1.7976	1.1667	2.3095
24	Old Anuradhapura	TR01	1.4722	2.6786	1.8254	2.6905
25	Old Galle	TR01	1.4556	1.0000	1.1190	1.1190
26	Old Galle	TR02	1.4278	1.2024	1.0000	1.0000
27	Pannala	TR01	1.5833	1.2857	1.0635	2.8175
28	Pannala	TR02	1.8500	1.2857	1.2063	1.6667
29	Pannipitiya	TR03	1.9722	2.8333	2.0079	1.3810
30	Sapugaskanda	TR01	1.4167	1.1786	1.7222	2.9286
31	Sapugaskanda	TR03	3.0444	1.7500	1.6349	2.6111
32	Sri Jayawardanapura	TR01	2.2111	1.7381	1.7460	2.3889
33	Sri Jayawardanapura	TR02	3.0333	2.0714	1.7698	2.7222
34	Thulhiriya	TR01	1.3111	1.0000	2.2143	1.1905
35	Thulhiriya	TR02	1.3222	1.0000	2.0238	1.3492
36	Trincomalee	TR01	2.4556	1.0476	1.3175	1.6429
37	Trincomalee	TR02	2.0278	1.0000	1.0794	1.7302
38	Valachchenei	TR01	1.9611	3.6845	3.7937	1.4841
39	Valachchenei	TR02	1.5000	3.9345	3.7460	1.2778
40	Valachchenei	TR03	1.3167	3.5655	3.7937	1.2063
41	Vaunathiu	TR01	1.5167	1.2500	1.1667	1.5159
42	Vaunathiu	TR02	1.4389	1.9821	1.1429	1.9841
43	Veyangoda	TR02	1.4722	3.0774	2.3571	1.0952
44	Veyangoda	TR03	2.3722	2.5714	2.7937	1.2540

Appendix-H: A sample test report of dissolved gas concentration measurement

Transformer Fault Gas Analysis

MORGAN SCHAFFER
Transformers - The Inside View

Results

Sample

Equipment ID:	DC TR03	Serial Number:	99.4.0009
Apparatus Type:	TRN	Sampling Point:	BOTTOM
Designation:	Galle TR03	Syringe ID:	6736
Sampled By:	Charaka	Date Sampled:	2015/03/18
Oil Temperature:	50 ℃	Tank Pressure:	1 psig
Comment:	Oil type: ASTM 3612		

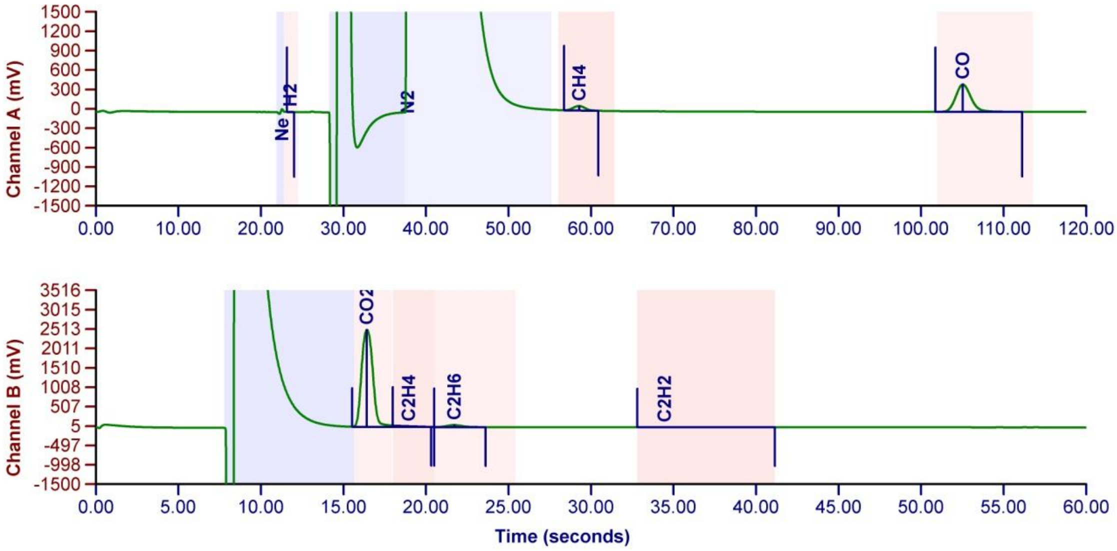
Analysis Identification

Method File:	20150320 Daily Method.prm
Calgas File:	20150320112043 Calibration.prs
Air File:	20150320112543 Air.prs
Oil File:	20150320125435 Oil.prs
Calgas O2N2 File:	20150320112043 Calibration.prs
Air O2N2 File:	20150320112543 Air.prs
Oil O2N2 File:	
Analyzed By:	Charaka
Date Acquired:	2015/03/20
Instrument ID:	11009003
Version:	PPMreport 3.2.0

Measurement Results

H2 (Hydrogen)	**23**	ppm
CH4 (Methane)	**57**	ppm
CO (Carbon Monoxide)	**158**	ppm
CO2 (Carbon Dioxide)	**1565**	ppm
C2H4 (Ethylene)	**0**	ppm
C2H6 (Ethane)	**102**	ppm
C2H2 (Acetylene)	**0**	ppm
O2 (Oxygen)	**-**	ppm
N2 (Nitrogen)	**-**	ppm
TDG:	**-**	%
TDCG:	**0.03**	%
THCG (O2N2):	**-**	%
THCG (Pressure):	**0.17**	%

Graphs



Appendix-I: Concentration levels of dissolved gases and the different diagnoses based on the concentration

Item	Grid Substation	TR No.	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2	Diagnosis				
										Key Gas Analysis		Dornenburg's Ratio Analysis	Roger's Ratio Analysis	Duval's Triangle Analysis
1	Ambalangoda	TR01	12	127	235	1932	13	308	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
2	Ambalangoda	TR02	17	127	308	2334	7	283	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
3	Ampara	TR01	18	89	508	3072	31	173	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault 300 ˚C – 700 ˚C
4	Ampara	TR02	0	0	48	364	0	2	0	Condition 1				
5	Ampara	TR03	22	48	173	725	4	104	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	
6	Badulla	TR01	36	19	74	1350	0	49	0	Condition 1	Not Available	Not Available	Not Available	
7	Badulla	TR02	22	6	167	1239	0	13	0	Condition 1				
8	Badulla	TR03	37	8	231	992	0	4	0	Condition 1				
9	Balangoda	TR01	82	5	125	804	2	0	0	Condition 1				
10	Balangoda	TR03	31	0	92	396	0	0	0	Condition 1				
11	Beliaththa	TR01	41	6	735	1926	1	0	0	Condition 2	Overheated cellulose			
12	Beliaththa	TR02	43	7	583	1818	5	0	0	Condition 1	Overheated cellulose			
13	Biyagama	TR01-R	36	47	95	1456	15	229	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	
14	Biyagama	TR01-Y	47	50	104	1461	19	246	2	Condition 2	Not Available	Thermal Decomposition	Not Available	Thermal fault 300 ˚C – 700 ˚C
15	Biyagama	TR01-B	37	159	15	546	418	59	4	Condition 2	Overheated oil	Thermal Decomposition	Thermal fault > 700 ˚C	Thermal fault > 700 ˚C
16	Biyagama	TR02-R	77	39	75	1246	35	176	5	Condition 2	Not Available	Not Available	Not Available	Discharge of low energy
17	Biyagama	TR02-Y	44	44	78	1608	18	224	2	Condition 2	Not Available	Thermal Decomposition	Not Available	
18	Biyagama	TR02-B	40	37	93	676	18	200	0	Condition 1	Not Available	Not Available	Normal	
19	Biyagama	TR03	23	57	158	1565	0	102	0	Condition 1	Not Available	Not Available	Not Available	Partial discharge of low energy
20	Biyagama	TR04	26	9	103	507	2	5	0	Condition 1				
21	Bolawattha	TR01	107	115	707	6387	31	127	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault 300 ˚C – 700 ˚C
22	Bolawattha	TR02	99	75	529	5397	25	73	0	Condition 2	Not Available	Not Available	Normal	Thermal fault 300 ˚C – 700 ˚C
23	Bolawattha	TR03	17	101	171	2350	5	274	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
24	Dehiwala	TR02	30	51	261	2183	3	72	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
25	Embilipitiya	TR01	22	76	273	1437	5	182	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
26	Embilipitiya	TR02	15	79	254	1562	5	201	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
27	Habarana	TR01	51	5	71	533	2	0	0	Condition 1				
28	Habarana	TR02	1162	38	125	1237	3	0	0	Condition 2	Corona in oil	Not Available	Not Available	
29	Hambanthota	TR01	0	64	599	2149	6	110	0	Condition 2	Not Available	Not Available	Not Available	Thermal fault < 300 ˚C
30	Hambanthota	TR02	30	2	302	792	0	0	0	Condition 1				
31	Horana	TR01	12	21	2055	10498	0	4	0	Condition 3	Overheated cellulose			
32	Horana	TR02	11	22	2282	11406	0	4	0	Condition 3	Overheated cellulose			
33	Horana	TR03	34	21	163	728	4	26	0	Condition 1				
34	Katunayake	TR02	10	132	412	2988	14	245	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
35	Kelanitissa	TR01	29	0	266	11	37	4	0	Condition 1				
36	Kelanitissa	TR02	24	52	201	25	44	31	0	Condition 1	Not Available	Not Available	Thermal fault 300 ˚C – 700 ˚C	Thermal fault 300 ˚C – 700 ˚C
37	Kelaniya	TR01	35	190	736	4921	110	271	1	Condition 2	Not Available	Thermal Decomposition	Thermal fault 150 ˚C – 300 ˚C	Thermal fault 300 ˚C – 700 ˚C
38	Kiribathkumbura	TR01	64	154	921	7294	36	184	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
39	Kiribathkumbura	TR02	70	195	1103	7232	42	242	0	Condition 3	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
40	Kiribathkumbura	TR03	9	124	148	2188	9	360	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
41	Kolonnawa	TR01	0	77	139	2919	5	172	0	Condition 2	Not Available	Not Available	Not Available	Thermal fault < 300 ˚C
42	Kolonnawa	TR02	0	98	130	2939	7	215	0	Condition 2	Not Available	Not Available	Not Available	Thermal fault < 300 ˚C
43	Kolonnawa	TR03	0	119	134	2797	18	269	0	Condition 2	Not Available	Not Available	Not Available	Thermal fault < 300 ˚C
44	Kolonnawa	TR04	11	119	72	3362	27	244	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
45	Kolonnawa	TR05	12	127	235	1932	13	308	0	Condition 1	Not Available	Not Available	Not Available	Thermal fault < 300 ˚C

Item	Grid Substation	TR No.	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2	Diagnosis				
										Key Gas Analysis		Dornenburg's Ratio Analysis	Roger's Ratio Analysis	Duval's Triangle Analysis
46	Kosgama	TR02	12	93	86	2180	5	114	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
47	Kotugoda	TR01-R	89	54	77	713	11	184	0	Condition 1	Not Available	Not Available	Normal	Thermal fault < 300 ˚C
48	Kotugoda	TR01-Y	73	43	79	715	13	188	0	Condition 1	Not Available	Not Available	Normal	
49	Kotugoda	TR01-B	84	472	118	932	458	311	2	Condition 3	Not Available	Thermal Decomposition	Thermal fault 300 ˚C – 700 ˚C	Thermal fault 300 ˚C – 700 ˚C
50	Kotugoda	TR02-R	64	65	112	1412	30	231	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault 300 ˚C – 700 ˚C
51	Kotugoda	TR02-Y	67	61	122	1195	27	212	0	Condition 1	Not Available	Not Available	Normal	Thermal fault 300 ˚C – 700 ˚C
52	Kotugoda	TR02-B	52	66	130	1431	18	273	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault 300 ˚C – 700 ˚C
53	Kotugoda	TR03	0	73	311	2774	5	126	0	Condition 2	Not Available	Not Available	Not Available	Thermal fault < 300 ˚C
54	Kotugoda	TR04	0	45	476	2996	4	62	0	Condition 1	Not Available	Not Available	Not Available	
55	Kurunegala	TR01	28	104	274	3208	6	289	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
56	Kurunegala	TR02	32	112	267	3804	7	339	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
57	Kurunegala	TR03	31	33	118	684	5	42	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	
58	Mahiyangana	TR01	27	3	93	416	2	10	1	Condition 1				
59	Mahiyangana	TR02	30	0	341	1163	0	0	0	Condition 1				
60	Maho	TR02	43	7	71	474	2	10	1	Condition 1				
61	Matara	TR01	110	43	146	1185	5	18	2	Condition 1	Not Available	Not Available	Not Available	
62	Matara	TR02	20	74	289	2046	12	68	2	Condition 1	Not Available	Thermal Decomposition	Not Available	Thermal fault < 300 ˚C
63	Matara	TR03	34	0	92	554	0	0	0	Condition 1				
64	Mathugama	TR01	17	166	245	1713	133	569	0	Condition 3	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault 300 ˚C – 700 ˚C
65	Mathugama	TR02	29	132	370	717	10	197	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
66	Mathugama	TR03	36	35	1056	403	5	7	0	Condition 2	Overheated cellulose			
67	Monaragala	TR01	14	0	92	284	5	20	0	Condition 1				
68	Monaragala	TR02	0	0	110	592	2	0	0	Condition 1				
69	New Anuradhapura	TR01-R	40	12	942	4742	6	0	0	Condition 3	Overheated cellulose			
70	New Anuradhapura	TR01-Y	58	12	1002	3823	13	0	0	Condition 2	Overheated cellulose			
71	New Anuradhapura	TR01-B	47	12	761	1245	8	7	0	Condition 2	Overheated cellulose			
72	New Anuradhapura	TR02-R	26	11	929	3920	6	0	0	Condition 2	Overheated cellulose			
73	New Anuradhapura	TR02-Y	36	10	566	2650	15	4	25	Condition 2	Not Available	Arcing (High intensity PD)	Discharge of high energy	Discharge of high energy
74	New Anuradhapura	TR02-B	45	11	953	3313	14	0	0	Condition 2	Overheated cellulose			
75	New Valachcheni	TR01	45	59	166	600	9	96	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
76	New Valachcheni	TR02	11	3	109	348	0	0	0	Condition 1				
77	Nuwara Eliya	TR01	0	40	303	842	5	70	0	Condition 1	Not Available	Not Available	Not Available	
78	Nuwara Eliya	TR02	0	26	42	386	3	58	0	Condition 1	Not Available	Not Available	Not Available	
79	Nuwara Eliya	TR03	39	3	130	265	0	0	0	Condition 1				
80	Old Anuradhapura	TR01	9	1	120	2077	3	0	0	Condition 1				
81	Old Anuradhapura	TR02	12	14	772	6052	5	3	0	Condition 2	Overheated cellulose			
82	Old Anuradhapura	TR03	9	6	547	5571	3	0	4	Condition 1	Overheated cellulose	Arcing (High intensity PD)	Not Available	Discharge of high energy
83	Old Galle	TR01	29	26	775	6503	70	19	47	Condition 3	Not Available	Not Available	Discharge of high energy	Discharge of high energy
84	Old Galle	TR02	47	58	669	4302	211	58	7	Condition 3	Not Available	Thermal Decomposition	Thermal fault > 700 ˚C	Thermal fault > 700 ˚C
85	Panadura	TR01	16	137	97	2279	10	377	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
86	Panadura	TR02	11	118	79	1553	7	336	1	Condition 1	Not Available	Thermal Decomposition	Not Available	Thermal fault < 300 ˚C
87	Panadura	TR03	43	0	155	1191	4	19	0	Condition 1				
88	Pannala	TR01	70	144	302	5667	279	361	8	Condition 3	Not Available	Thermal Decomposition	Thermal fault 150 ˚C – 300 ˚C	Thermal fault > 700 ˚C
89	Pannala	TR02	8	110	214	2236	7	275	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
90	Pannipitiya	TS01-R	0	44	83	1209	0	98	0	Condition 1	Not Available	Not Available	Not Available	

Item	Grid Substation	TR No.	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2	Diagnosis				
										Key Gas Analysis		Dornenburg's Ratio Analysis	Roger's Ratio Analysis	Duval's Triangle Analysis
91	Pannipitiya	TS01-Y	0	44	84	1244	0	102	0	Condition 1	Not Available	Not Available	Not Available	
92	Pannipitiya	TS01-B	0	42	86	1280	0	99	0	Condition 1	Not Available	Not Available	Not Available	
93	Pannipitiya	TS01-R	0	45	87	1277	0	102	0	Condition 1	Not Available	Not Available	Not Available	
94	Pannipitiya	TS01-Y	0	45	93	1382	0	97	0	Condition 1	Not Available	Not Available	Not Available	
95	Pannipitiya	TS01-B	0	47	98	1391	0	109	0	Condition 1	Not Available	Not Available	Not Available	
96	Pannipitiya	TR01	32	0	449	1682	0	0	0	Condition 1	Overheated cellulose			
97	Pannipitiya	TR02	0	6	101	2252	144	22	13	Condition 2	Overheated oil	Not Available	Not Available	Thermal fault > 700 ˚C
98	Pannipitiya	TR03	11	0	80	1147	0	0	0	Condition 1				
99	Polonnaruwa	TR01	16	2	75	224	0	3	0	Condition 1				
100	Rathnapura	TR01	11	0	0	657	0	0	0	Condition 1				
101	Rathnapura	TR02	18	6	612	2546	0	0	0	Condition 1	Overheated cellulose			
102	Rathmalana	TR01	30	112	95	1765	11	337	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
103	Rathmalana	TR02	32	76	444	6682	19	168	0	Condition 3	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault 300 ˚C – 700 ˚C
104	Rathmalana	TR03	0	0	103	2433	2	0	0	Condition 1				
105	Sapugaskanda	TR01	0	0	84	389	0	0	0	Condition 1				
106	Sapugaskanda	TR02	13	8	545	3909	0	2	0	Condition 1	Overheated cellulose			
107	Sapugaskanda	TR03	14	130	165	3001	7	359	0	Condition 2	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	Thermal fault < 300 ˚C
108	Sapugaskanda	TR04	261	65	458	3238	4	9	0	Condition 2	Not Available	Not Available	Normal	Thermal fault < 300 ˚C
109	Seethawaka	TR01	0	0	78	2039	1	0	0	Condition 1				
110	Seethawaka	TR02	9	12	96	1932	57	12	0	Condition 1	Not Available	Not Available	Thermal fault > 700 ˚C	Thermal fault > 700 ˚C
111	Seethawaka	TR03	29	19	88	419	2	50	0	Condition 1	Not Available	Not Available	Normal	
112	Sri Jayawardanapura	TR01	23	3	522	2066	0	0	0	Condition 1	Overheated cellulose			
113	Sri Jayawardanapura	TR02	43	3	411	1280	0	2	0	Condition 1	Overheated cellulose			
114	Thulhiriya	TR01	68	27	479	6455	11	27	0	Condition 1	Not Available			
115	Thulhiriya	TR02	30	6	455	7868	4	3	0	Condition 1	Overheated cellulose			
116	Thulhiriya	TR03	25	128	12	491	346	47	4	Condition 2	Overheated oil	Thermal Decomposition	Thermal fault > 700 ˚C	Thermal fault > 700 ˚C
117	Trincomalee	TR01	14	3	636	4170	27	0	0	Condition 2	Overheated cellulose			
118	Trincomalee	TR02	40	11	1188	6008	0	0	0	Condition 2	Overheated cellulose			
119	Valachchenei	TR01	28	20	416	1837	4	5	13	Condition 2	Not Available	Arcing (High intensity PD)	Not Available	Discharge of low energy
120	Valachchenei	TR02	23	8	371	2890	4	0	17	Condition 2	Not Available	Arcing (High intensity PD)	Not Available	Discharge of low energy
121	Valachchenei	TR03	18	10	631	4995	8	0	7	Condition 2	Overheated cellulose	Arcing (High intensity PD)	Not Available	Discharge of high energy
122	Vaunathiu	TR01	24	4	70	250	2	10	0	Condition 1				
123	Vaunathiu	TR02	17	8	60	278	3	13	0	Condition 1				
124	Vauniya	TR01	32	2	359	1217	0	0	3	Condition 1	Overheated cellulose	Not Available	Not Available	Discharge of low energy
125	Vauniya	TR02	0	37	477	2555	6	61	3	Condition 1	Not Available	Not Available	Not Available	Discharge of low energy
126	Veyangoda	TR01	26	28	140	588	4	37	0	Condition 1	Not Available	Not Available	Thermal fault 150 ˚C – 300 ˚C	
127	Veyangoda	TR02	89	556	257	3068	583	271	0	Condition 3	Not Available	Not Available	Thermal fault 300 ˚C – 700 ˚C	Thermal fault > 700 ˚C
128	Veyangoda	TR03	0	255	14	416	377	139	0	Condition 3	Not Available	Not Available	Not Available	Thermal fault > 700 ˚C
129	Veyangoda	IBT01	13	6	656	3187	0	6	0	Condition 1	Overheated cellulose			
130	Veyangoda	IBT02	11	3	752	4400	0	0	0	Condition 2	Overheated cellulose			

Appendix-J: DGAI and categorization of transformers

Item	Grid Substation	TR No.	DGAI	Condition Level
1	Ambalangoda	TR01	2.17	POOR
2	Ambalangoda	TR02	2.17	POOR
3	Ampara	TR01	1.83	POOR
4	Ampara	TR02	1.00	GOOD
5	Ampara	TR03	1.33	ACCEPTABLE
6	Badulla	TR01	1.00	GOOD
7	Badulla	TR02	1.00	GOOD
8	Badulla	TR03	1.00	GOOD
9	Balangoda	TR01	1.00	GOOD
10	Balangoda	TR03	1.00	GOOD
11	Beliaththa	TR01	1.11	GOOD
12	Beliaththa	TR02	1.06	GOOD
13	Biyagama	TR01-R	1.83	POOR
14	Biyagama	TR01-Y	1.83	POOR
15	Biyagama	TR01-B	2.44	POOR
16	Biyagama	TR02-R	1.78	ACCEPTABLE
17	Biyagama	TR02-Y	1.83	POOR
18	Biyagama	TR02-B	1.67	ACCEPTABLE
19	Biyagama	TR03	1.33	ACCEPTABLE
20	Biyagama	TR04	1.00	GOOD
21	Bolawattha	TR01	2.11	POOR
22	Bolawattha	TR02	1.44	ACCEPTABLE
23	Bolawattha	TR03	2.00	POOR
24	Dehiwala	TR02	1.17	GOOD
25	Embilipitiya	TR01	1.83	POOR
26	Embilipitiya	TR02	1.83	POOR
27	Habarana	TR01	1.00	GOOD
28	Habarana	TR02	1.56	ACCEPTABLE
29	Hambanthota	TR01	1.39	ACCEPTABLE
30	Hambanthota	TR02	1.00	GOOD
31	Horana	TR01	1.56	ACCEPTABLE
32	Horana	TR02	1.56	ACCEPTABLE
33	Horana	TR03	1.00	GOOD
34	Katunayake	TR02	2.28	POOR
35	Kelanitissa	TR01	1.00	GOOD
36	Kelanitissa	TR02	1.00	GOOD
37	Kelaniya	TR01	2.78	POOR
38	Kiribathkumbura	TR01	2.44	POOR
39	Kiribathkumbura	TR02	2.67	POOR
40	Kiribathkumbura	TR03	2.00	POOR
41	Kolonnawa	TR01	1.72	ACCEPTABLE
42	Kolonnawa	TR02	1.89	POOR
43	Kolonnawa	TR03	2.06	POOR
44	Kolonnawa	TR04	2.11	POOR
45	Kolonnawa	TR05	2.00	POOR

Item	Grid Substation	TR No.	DGAI	Condition Level
46	Kosgama	TR02	1.50	ACCEPTABLE
47	Kotugoda	TR01-R	1.67	ACCEPTABLE
48	Kotugoda	TR01-Y	1.67	ACCEPTABLE
49	Kotugoda	TR01-B	3.33	VERY POOR
50	Kotugoda	TR02-R	1.83	POOR
51	Kotugoda	TR02-Y	1.67	ACCEPTABLE
52	Kotugoda	TR02-B	1.83	POOR
53	Kotugoda	TR03	1.56	ACCEPTABLE
54	Kotugoda	TR04	1.11	GOOD
55	Kurunegala	TR01	2.11	POOR
56	Kurunegala	TR02	2.11	POOR
57	Kurunegala	TR03	1.00	GOOD
58	Mahiyangana	TR01	1.00	GOOD
59	Mahiyangana	TR02	1.00	GOOD
60	Maho	TR02	1.00	GOOD
61	Matara	TR01	1.11	GOOD
62	Matara	TR02	1.17	GOOD
63	Matara	TR03	1.00	GOOD
64	Mathugama	TR01	2.67	POOR
65	Mathugama	TR02	2.06	POOR
66	Mathugama	TR03	1.17	GOOD
67	Monaragala	TR01	1.00	GOOD
68	Monaragala	TR02	1.00	GOOD
69	New Anuradhapura	TR01-R	1.33	ACCEPTABLE
70	New Anuradhapura	TR01-Y	1.28	ACCEPTABLE
71	New Anuradhapura	TR01-B	1.11	GOOD
72	New Anuradhapura	TR02-R	1.28	ACCEPTABLE
73	New Anuradhapura	TR02-Y	1.94	POOR
74	New Anuradhapura	TR02-B	1.28	ACCEPTABLE
75	New Valachcheni	TR01	1.33	ACCEPTABLE
76	New Valachcheni	TR02	1.00	GOOD
77	Nuwara Eliya	TR01	1.17	GOOD
78	Nuwara Eliya	TR02	1.00	GOOD
79	Nuwara Eliya	TR03	1.00	GOOD
80	Old Anuradhapura	TR01	1.00	GOOD
81	Old Anuradhapura	TR02	1.33	ACCEPTABLE
82	Old Anuradhapura	TR03	1.56	ACCEPTABLE
83	Old Galle	TR01	2.89	POOR
84	Old Galle	TR02	2.33	POOR
85	Panadura	TR01	2.17	POOR
86	Panadura	TR02	2.00	POOR
87	Panadura	TR03	1.00	GOOD
88	Pannala	TR01	3.78	VERY POOR
89	Pannala	TR02	2.00	POOR
90	Pannipitiya	TS01-R	1.33	ACCEPTABLE

Item	Grid Substation	TR No.	DGAI	Condition Level
91	Pannipitiya	TS01-Y	1.33	ACCEPTABLE
92	Pannipitiya	TS01-B	1.33	ACCEPTABLE
93	Pannipitiya	TS01-R	1.33	ACCEPTABLE
94	Pannipitiya	TS01-Y	1.33	ACCEPTABLE
95	Pannipitiya	TS01-B	1.33	ACCEPTABLE
96	Pannipitiya	TR01	1.06	GOOD
97	Pannipitiya	TR02	2.06	POOR
98	Pannipitiya	TR03	1.00	GOOD
99	Polonnaruwa	TR01	1.00	GOOD
100	Rathnapura	TR01	1.00	GOOD
101	Rathnapura	TR02	1.11	GOOD
102	Rathmalana	TR01	2.00	POOR
103	Rathmalana	TR02	1.94	POOR
104	Rathmalana	TR03	1.00	GOOD
105	Sapugaskanda	TR01	1.00	GOOD
106	Sapugaskanda	TR02	1.17	GOOD
107	Sapugaskanda	TR03	2.28	POOR
108	Sapugaskanda	TR04	1.39	ACCEPTABLE
109	Seethawaka	TR01	1.00	GOOD
110	Seethawaka	TR02	1.17	GOOD
111	Seethawaka	TR03	1.00	GOOD
112	Sri Jayawardanapura	TR01	1.06	GOOD
113	Sri Jayawardanapura	TR02	1.06	GOOD
114	Thulhiriya	TR01	1.28	ACCEPTABLE
115	Thulhiriya	TR02	1.33	ACCEPTABLE
116	Thulhiriya	TR03	2.44	POOR
117	Trincomalee	TR01	1.22	ACCEPTABLE
118	Trincomalee	TR02	1.44	ACCEPTABLE
119	Valachchenei	TR01	1.61	ACCEPTABLE
120	Valachchenei	TR02	1.94	POOR
121	Valachchenei	TR03	1.50	ACCEPTABLE
122	Vaunathiu	TR01	1.00	GOOD
123	Vaunathiu	TR02	1.00	GOOD
124	Vauniya	TR01	1.06	GOOD
125	Vauniya	TR02	1.11	GOOD
126	Veyangoda	TR01	1.00	GOOD
127	Veyangoda	TR02	3.44	VERY POOR
128	Veyangoda	TR03	2.83	POOR
129	Veyangoda	IBT01	1.17	GOOD
130	Veyangoda	IBT02	1.28	ACCEPTABLE

Appendix-K: MATLAB coding of the computing tool

(a) MATLAB coding for the AssessCon.m file

```
function varargout = AssessCon(varargin)
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @AssessCon_OpeningFcn, ...
                   'gui_OutputFcn',  @AssessCon_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before AssessCon is made visible.
function AssessCon_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to AssessCon (see VARARGIN)

% Choose default command line output for AssessCon
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);
set(handles.edit1,'String','Select Data File');
set(handles.edit2,'String','');
set(handles.edit3,'String','');
set(handles.edit4,'String','');
set(handles.edit5,'String','');
set(handles.edit6,'String','');
set(handles.edit7,'String','');
set(handles.edit8,'String','');
set(handles.text11,'String','');
set(handles.text12,'String','');
set(handles.text13,'String','');
set(handles.text14,'String','');
set(handles.text15,'String','');
set(handles.text16,'String','');
set(handles.text22,'String','');
set(handles.text23,'String','');
set(handles.text24,'String','');
set(handles.text25,'String','');
set(handles.text26,'String','');
set(handles.text27,'String','');
% UIWAIT makes AssessCon wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = AssessCon_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
[filename filepath] = uigetfile();
path = [filepath filename];
set(handles.edit1,'String',path);


function edit1_Callback(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit1 as text
%        str2double(get(hObject,'String')) returns contents of edit1 as a double



% --- Executes during object creation, after setting all properties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
filepath = get(handles.edit1,'String');
data(1) = str2double(get(handles.edit2,'String'));
data(2) = str2double(get(handles.edit3,'String'));
data(3) = str2double(get(handles.edit4,'String'));
data(4) = str2double(get(handles.edit5,'String'));
data(5) = str2double(get(handles.edit6,'String'));
data(6) = str2double(get(handles.edit7,'String'));
data(7) = str2double(get(handles.edit8,'String'));
[SFRAI_1 SFRAI_2 SFRAI_3 SFRAI_4 DGAI] = Main(filepath,data);

SFRAI_1_L = [1.7 2.1 2.55];
SFRAI_2_L = [1.75 2.1 3.6];
SFRAI_3_L = [1.45 2.2 3.5];
SFRAI_4_L = [1.55 2.0 3.0];

if(SFRAI_1<=SFRAI_1_L(1))   SFRAI_code(1) = 1;  set(handles.text22,'String','GOOD');
%set(handles.text11,'String',' Annually Regular Checkups');
elseif((SFRAI_1<=SFRAI_1_L(2)) && (SFRAI_1>SFRAI_1_L(1)))   SFRAI_code(1) = 2;
set(handles.text22,'String','ACCEPTABLE'); %set(handles.text11,'String','Annually Regular
Checkups');
elseif((SFRAI_1<=SFRAI_1_L(3)) && (SFRAI_1>SFRAI_1_L(2)))   SFRAI_code(1) = 3;
set(handles.text22,'String','POOR'); set(handles.text11,'String','Possible Core deformations,
open circuits or shorted turns OR Residual Magnetism');
else SFRAI_code(1) = 4; set(handles.text22,'String','VERY POOR');
set(handles.text11,'String','Severe Core Defect, Possible open circuits or shorted turns OR
Residual Magnetism');
end

if(SFRAI_2<=SFRAI_2_L(1))   SFRAI_code(2) = 1;  set(handles.text23,'String','GOOD');
%set(handles.text12,'String',' Annually Regular Checkups');
elseif((SFRAI_2<=SFRAI_2_L(2)) && (SFRAI_2>SFRAI_2_L(1)))   SFRAI_code(2) = 2;
set(handles.text23,'String','ACCEPTABLE'); %set(handles.text12,'String','Annually Regular
Checkups');
elseif((SFRAI_2<=SFRAI_2_L(3)) && (SFRAI_2>SFRAI_2_L(2)))   SFRAI_code(2) = 3;
set(handles.text23,'String','POOR'); set(handles.text12,'String','Possible bulk winding movement
between windings and clamping structure');
else SFRAI_code(2) = 4; set(handles.text23,'String','VERY POOR');
set(handles.text12,'String','Severe bulk winding movement');
end

if(SFRAI_3<=SFRAI_3_L(1))   SFRAI_code(3) = 1;  set(handles.text24,'String','GOOD');
%set(handles.text13,'String',' Annually Regular Checkups');
elseif((SFRAI_3<=SFRAI_3_L(2)) && (SFRAI_3>SFRAI_3_L(1)))   SFRAI_code(3) = 2;
set(handles.text24,'String','ACCEPTABLE'); %set(handles.text13,'String','Annually Regular
Checkups');
elseif((SFRAI_3<=SFRAI_3_L(3)) && (SFRAI_3>SFRAI_3_L(2)))   SFRAI_code(3) = 3;
set(handles.text24,'String','POOR'); set(handles.text13,'String','Possible deformation/damages in
main or tap windings');
```

```
else SFRAI_code(3) = 4; set(handles.text24,'String','VERY POOR');
set(handles.text13,'String','Severe deformation/damages in main or tap windings');
end

if(SFRAI_4<=SFRAI_4_L(1))   SFRAI_code(4) = 1;  set(handles.text25,'String','GOOD');
%set(handles.text14,'String',' Annually Regular Checkups');
elseif((SFRAI_4<=SFRAI_4_L(2)) && (SFRAI_4>SFRAI_4_L(1)))   SFRAI_code(4) = 2;
set(handles.text25,'String','ACCEPTABLE'); %set(handles.text14,'String','Annually Regular
Checkups');
elseif((SFRAI_4<=SFRAI_4_L(3)) && (SFRAI_4>SFRAI_4_L(2)))   SFRAI_code(4) = 3;
set(handles.text25,'String','POOR'); set(handles.text14,'String','Possible movement in main or
tap windings/leads, Ground impedance variation');
else SFRAI_code(4) = 4; set(handles.text25,'String','VERY POOR');
set(handles.text14,'String','Movement in main or tap windings/leads, Ground impedance
variations');
end


DGAI_L = [1.2 1.8 3];

if ( DGAI < DGAI_L(1) ) DGAI_code = 1; set(handles.text26,'String','GOOD');
%set(handles.text15,'String','DGAI Decription 1');
elseif ( (DGAI < DGAI_L(2)) && (DGAI >= DGAI_L(1)) )  DGAI_code = 2;
set(handles.text26,'String','ACCEPTABLE'); %set(handles.text15,'String','DGAI Decription 2');
elseif ( (DGAI < DGAI_L(3)) && (DGAI >= DGAI_L(2)) )  DGAI_code = 3;
set(handles.text26,'String','POOR'); %set(handles.text15,'String','DGAI Decription 3');
else    DGAI_code = 4; set(handles.text26,'String','VERY POOR');
%set(handles.text15,'String','DGAI Decription 4');
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%calculating CI

SFRA_CI = (1 * SFRAI_1 + 4 * SFRAI_2 + 3 * SFRAI_3 + 2 * SFRAI_4)/10;
SFRA_CI_L = [ 1.75 2.05 3.0 ];
if ( SFRA_CI < SFRA_CI_L(1) ) SFRA_CI_code = 1;
elseif ( (SFRA_CI < SFRA_CI_L(2)) && (SFRA_CI >= SFRA_CI_L(1)) ) SFRA_CI_code = 2;
elseif ( (SFRA_CI < SFRA_CI_L(3)) && (SFRA_CI >= SFRA_CI_L(2)) ) SFRA_CI_code = 3;
else   SFRA_CI_code = 4;
end

% disp('Condition Index Description')
if ( (SFRAI_code(1) <= 2) && (SFRAI_code(2) <= 2) && (SFRAI_code(3) <= 2) && (SFRAI_code(4) <= 2)
&& (SFRA_CI_code == 1) && (DGAI_code == 1)) CI_code = 1; set(handles.text27,'String','GOOD');
set(handles.text16,'String','Good for normal operation');
elseif ( (SFRA_CI_code == 1) && (DGAI_code == 1)) CI_code = 2;
set(handles.text27,'String','ACCEPTABLE'); set(handles.text16,'String','Good for normal operation
with regular monitoring');
elseif ( (SFRAI_code(1) <= 2) && (SFRAI_code(2) <= 2) && (SFRAI_code(3) <= 2) && (SFRAI_code(4)
<= 2) && (SFRA_CI_code == 1) && (DGAI_code == 2)) CI_code = 1;
set(handles.text27,'String','GOOD'); set(handles.text16,'String','Good for normal operation');
elseif ( (SFRA_CI_code == 1) && (DGAI_code == 2)) CI_code = 2;
set(handles.text27,'String','ACCEPTABLE'); set(handles.text16,'String','Good for normal operation
with regular monitoring');
elseif ( (SFRA_CI_code == 1) && (DGAI_code == 3)) CI_code = 2;
set(handles.text27,'String','ACCEPTABLE'); set(handles.text16,'String','Need regular
monitoring');
elseif ( (SFRA_CI_code == 1) && (DGAI_code == 4)) CI_code = 3;
set(handles.text27,'String','POOR'); set(handles.text16,'String','Need closely monitor the
condition');
elseif ( (SFRA_CI_code == 2) && (DGAI_code == 1)) CI_code = 2;
set(handles.text27,'String','ACCEPTABLE'); set(handles.text16,'String','Need regular
monitoring');
elseif ( (SFRA_CI_code == 2) && (DGAI_code == 2)) CI_code = 2;
set(handles.text27,'String','ACCEPTABLE'); set(handles.text16,'String','Need regular
monitoring');
elseif ( (SFRA_CI_code == 2) && (DGAI_code == 3)) CI_code = 2;
set(handles.text27,'String','ACCEPTABLE'); set(handles.text16,'String','Need regular
monitoring');
elseif ( (SFRA_CI_code == 2) && (DGAI_code == 4)) CI_code = 3;
set(handles.text27,'String','POOR'); set(handles.text16,'String','Need closely monitor the
condition');
elseif ( (SFRA_CI_code == 3) && (DGAI_code == 1)) CI_code = 2;
set(handles.text27,'String','ACCEPTABLE'); set(handles.text16,'String','Need regular
Monitoring');
elseif ( (SFRA_CI_code == 3) && (DGAI_code == 2)) CI_code = 3;
set(handles.text27,'String','POOR'); set(handles.text16,'String','Need closely monitor the
condition');
elseif ( (SFRAI_code(1) <= 3) && (SFRAI_code(2) <= 3) && (SFRAI_code(3) <= 3) && (SFRAI_code(4)
<= 3) && (SFRA_CI_code == 3) && (DGAI_code == 3)) CI_code = 3;
set(handles.text27,'String','POOR'); set(handles.text16,'String','Need closely monitor the
condition');
```

```
elseif ( (SFRA_CI_code == 3) && (DGAI_code == 3)) CI_code = 4; set(handles.text27,'String','VERY
POOR'); set(handles.text16,'String','Need extra attention and consideration for replacements');
elseif ( (SFRAI_code(1) <= 3) && (SFRAI_code(2) <= 3) && (SFRAI_code(3) <= 3) && (SFRAI_code(4)
<= 3) && (SFRA_CI_code == 3) && (DGAI_code == 4)) CI_code = 3;
set(handles.text27,'String','POOR'); set(handles.text16,'String','Need closely monitor the
condition');
elseif ( (SFRA_CI_code == 3) && (DGAI_code == 4)) CI_code = 4; set(handles.text27,'String','VERY
POOR'); set(handles.text16,'String','Need extra attention and consideration for replacements');
elseif ( (SFRA_CI_code == 4) && (DGAI_code == 1)) CI_code = 3;
set(handles.text27,'String','POOR'); set(handles.text16,'String','Need closely monitor the
condition');
elseif ( (SFRA_CI_code == 4) && (DGAI_code == 2)) CI_code = 3;
set(handles.text27,'String','POOR'); set(handles.text16,'String','Need closely monitor the
condition');
elseif ( (SFRA_CI_code == 4) && (DGAI_code == 3)) CI_code = 4; set(handles.text27,'String','VERY
POOR'); set(handles.text16,'String','Need extra attention and consideration for replacements');
elseif ( (SFRA_CI_code == 4) && (DGAI_code == 4)) CI_code = 4; set(handles.text27,'String','VERY
POOR'); set(handles.text16,'String','Need extra attention and consideration for replacements');
%else   set(handles.text27,'String','VERY POOR');   set(handles.text16,'String','Extra attention
and consideration for replacements');
end



function edit2_Callback(hObject, eventdata, handles)
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit2 as text
%        str2double(get(hObject,'String')) returns contents of edit2 as a double


% --- Executes during object creation, after setting all properties.
function edit2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit3_Callback(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit3 as text
%        str2double(get(hObject,'String')) returns contents of edit3 as a double

% --- Executes during object creation, after setting all properties.
function edit3_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit4_Callback(hObject, eventdata, handles)
% hObject    handle to edit4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit4 as text
%        str2double(get(hObject,'String')) returns contents of edit4 as a double


% --- Executes during object creation, after setting all properties.
function edit4_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
```

```
% handles    empty - handles not created until after all CreateFcns called


% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit5_Callback(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit5 as text
%        str2double(get(hObject,'String')) returns contents of edit5 as a double


% --- Executes during object creation, after setting all properties.
function edit5_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit6_Callback(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit6 as text
%        str2double(get(hObject,'String')) returns contents of edit6 as a double


% --- Executes during object creation, after setting all properties.
function edit6_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit7_Callback(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit7 as text
%        str2double(get(hObject,'String')) returns contents of edit7 as a double


% --- Executes during object creation, after setting all properties.
function edit7_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit8_Callback(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit8 as text
%        str2double(get(hObject,'String')) returns contents of edit8 as a double
```

```
% --- Executes during object creation, after setting all properties.
function edit8_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function update_waitbar(handles,value)

h=handles.waitbar_axes;set(h,'Visible','On');

axes(h);cla;h=patch([0,value,value,0],[0,0,1,1],'b');

axis([0,1,0,1]);axis off;drawnow;
```

(b) MATLAB coding for the Main.m file

```
function [SFRAI_1 SFRAI_2 SFRAI_3 SFRAI_4 DGAI] = Main(filepath,data)

Data_xls = xlsread(filepath);
r_1_LB = 20;     %region 1 lower bound
r_1_UB = 1999;    %region 1 upper bound
r_2_LB = 2000;    %region 2 lower bound
r_2_UB = 20000;    %region 2 upper bound
r_3_LB = 20000;    %region 3 lower bound
r_3_UB = 400000;    %region 3 upper bound
r_4_LB = 400000;    %region 4 lower bound
r_4_UB = 2000000;    %region 4 upper bound

%Divide in to regions
Region1=Data_xls(Data_xls(:,1)>=r_1_LB & Data_xls(:,1)<r_1_UB,:);
Region2=Data_xls(Data_xls(:,1)>=r_2_LB & Data_xls(:,1)<r_2_UB,:);
Region3=Data_xls(Data_xls(:,1)>=r_3_LB & Data_xls(:,1)<r_3_UB,:);
Region4=Data_xls(Data_xls(:,1)>=r_4_LB & Data_xls(:,1)<=r_4_UB,:);

[N1, ~] = size(Region1);
[N2, ~] = size(Region2);
[N3, ~] = size(Region3);
[N4, ~] = size(Region4);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculatin CCFI
%R-Y  -> R-B  ->  Y-B
CCF_L_R1 = [[0.9200 0.9100 0.9000],
[0.9900 0.9700 0.9500],
[0.9100 0.8850 0.8600],
[1.0000 0.9995 0.9990],
[1.0000 0.9995 0.9990],
[1.0000 0.9995 0.9990],
[0.8900 0.8700 0.8500],
[0.9980 0.9740 0.9500],
[0.8900 0.8650 0.8400]];

CCF_L_R2 = [[0.9800 0.9600 0.9400],
[0.9980 0.9960 0.9940],
[0.9800 0.9650 0.9500],
[0.9600 0.9200 0.8800],
[0.9980 0.9955 0.9930],
[0.9700 0.9300 0.8900],
[0.9890 0.9730 0.9570],
[0.9990 0.9945 0.9900],
[0.9920 0.9845 0.9770]];

CCF_L_R3 = [[0.9930 0.9765 0.9600],
[0.9920 0.9560 0.9200],
[0.9930 0.9765 0.9600],
[0.9920 0.9760 0.9600],
[0.9940 0.9620 0.9300],
[0.9920 0.9760 0.9600],
[0.9680 0.9240 0.8800],
[0.9820 0.9610 0.9400],
[0.9730 0.9590 0.9450]];

CCF_L_R4 = [[0.9600 0.9200 0.8800],
[0.9200 0.8600 0.8000],
[0.9600 0.9100 0.8600],
[0.9600 0.9200 0.8800],
[0.9200 0.8700 0.8200],
[0.9630 0.9315 0.9000],
[0.7000 0.5000 0.3000],
[0.8900 0.7750 0.6600],
[0.8000 0.6550 0.5100]];


W11 = [1 3 1];
W12 = [1 2 1];
W13 = [1 1 1];
W14 = [1 1 1];
W2 = [3 1 2 3 2 2 3 2 2 3 2 2];

%R-Y  -> R-B  ->  Y-B
n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
```

```
                CoMat = cov(Region1(:,j+i),Region1(:,k+i))*(N1-1);
                CCF1(n) = (CoMat(1,2)/sqrt(CoMat(1,1)*CoMat(2,2)));
                if (CCF1(n) >= CCF_L_R1(n,1)),S1(n)=1;elseif(CCF1(n) < CCF_L_R1(n,1) && CCF1(n)
>= CCF_L_R1(n,2)),S1(n)=2;elseif(CCF1(n) < CCF_L_R1(n,2) && CCF1(n) >=
CCF_L_R1(n,3)),S1(n)=3;else S1(n)=4;end
                n = n + 1;
            end
        end
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                CoMat = cov(Region2(:,j+i),Region2(:,k+i))*(N2-1);
                CCF2(n) = (CoMat(1,2)/sqrt(CoMat(1,1)*CoMat(2,2)));
                if (CCF2(n) >= CCF_L_R2(n,1)),S2(n)=1;elseif(CCF2(n) < CCF_L_R2(n,1) && CCF2(n)
>= CCF_L_R2(n,2)),S2(n)=2;elseif(CCF2(n) < CCF_L_R2(n,2) && CCF2(n) >=
CCF_L_R2(n,3)),S2(n)=3;else S2(n)=4;end
                n = n + 1;
            end
        end
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                CoMat = cov(Region3(:,j+i),Region3(:,k+i))*(N3-1);
                CCF3(n) = (CoMat(1,2)/sqrt(CoMat(1,1)*CoMat(2,2)));
                if (CCF3(n) >= CCF_L_R3(n,1)),S3(n)=1;elseif(CCF3(n) < CCF_L_R3(n,1) && CCF3(n)
>= CCF_L_R3(n,2)),S3(n)=2;elseif(CCF3(n) < CCF_L_R3(n,2) && CCF3(n) >=
CCF_L_R3(n,3)),S3(n)=3;else S3(n)=4;end
                n = n + 1;
            end
        end
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                CoMat = cov(Region4(:,j+i),Region4(:,k+i))*(N4-1);
                CCF4(n) = (CoMat(1,2)/sqrt(CoMat(1,1)*CoMat(2,2)));
                if (CCF4(n) >= CCF_L_R4(n,1)),S4(n)=1;elseif(CCF4(n) < CCF_L_R4(n,1) && CCF4(n)
>= CCF_L_R4(n,2)),S4(n)=2;elseif(CCF4(n) < CCF_L_R4(n,2) && CCF4(n) >=
CCF_L_R4(n,3)),S4(n)=3;else S4(n)=4;end
                n = n + 1;
            end
        end
    end
end

CCFI_1 =
(W2(1)*sum(S1(1:3).*W11)+W2(2)*sum(S1(4:6).*W11)+W2(3)*sum(S1(7:9).*W11))/(sum(W2(1:3)*sum(W11)))
;
CCFI_2 =
(W2(4)*sum(S2(1:3).*W12)+W2(5)*sum(S2(4:6).*W12)+W2(6)*sum(S2(7:9).*W12))/(sum(W2(4:6)*sum(W12)))
;
CCFI_3 =
(W2(7)*sum(S3(1:3).*W13)+W2(8)*sum(S3(4:6).*W13)+W2(9)*sum(S3(7:9).*W13))/(sum(W2(7:9)*sum(W13)))
;
CCFI_4 =
(W2(10)*sum(S4(1:3).*W14)+W2(11)*sum(S4(4:6).*W14)+W2(12)*sum(S4(7:9).*W14))/(sum(W2(10:12)*sum(W
14)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculatin DBI
%R-Y  -> R-B  ->  Y-B

DB_L_R1 = [[2.4000 1.8500 1.3000],
[3.5000 2.8500 2.2000],
[3.2000 2.4500 1.7000],
[3.5000 2.3850 1.2700],
[3.5000 2.8500 2.2000],
[3.0000 2.3000 1.6000],
```

```
[4.3000 3.8650 3.4300],
[3.2000 1.8500 0.5000],
[4.8000 4.3000 3.8000]];

DB_L_R2 = [[1.5000 1.1250 0.7500],
[0.4400 0.3500 0.2600],
[1.3000 1.0000 0.7000],
[1.8000 1.3900 0.9800],
[0.4500 0.3500 0.2500],
[1.7000 1.2800 0.8600],
[1.4000 1.0650 0.7300],
[0.5000 0.3500 0.2000],
[1.1000 0.8500 0.6000]];

DB_L_R3 = [[1.4000 1.0600 0.7200],
[1.7000 1.2500 0.8000],
[1.2000 0.8850 0.5700],
[1.6000 1.1500 0.7000],
[1.8000 1.3000 0.8000],
[1.2500 0.9350 0.6200],
[2.0000 1.5000 1.0000],
[1.3000 1.0900 0.8800],
[1.3000 1.1400 0.9800]];

DB_L_R4 = [[2.4000 1.8500 1.3000],
[3.5000 2.8500 2.2000],
[3.2000 2.4500 1.7000],
[3.5000 2.3850 1.2700],
[3.5000 2.8500 2.2000],
[3.0000 2.3000 1.6000],
[5.3000 4.6500 4.0000],
[4.8000 3.4000 2.0000],
[4.8000 4.2500 3.7000]];

W11 = [1 3 1];
W12 = [1 2 1];
W13 = [1 1 1];
W14 = [1 1 1];
W2 = [3 1 2 3 2 2 3 2 2 3 2 2];

%R-Y  -> R-B  ->  Y-B
n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DB1(n) = sum(abs(Region1(:,j+i)-Region1(:,k+i)))/N1;
                if (DB1(n) >= DB_L_R1(n,1)),S1(n)=4;elseif(DB1(n) < DB_L_R1(n,1) && DB1(n) >=
DB_L_R1(n,2)),S1(n)=3;elseif(DB1(n) < DB_L_R1(n,2) && DB1(n) >= DB_L_R1(n,3)),S1(n)=2;else
S1(n)=1;end
                n = n + 1;
            end
        end
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DB2(n) = sum(abs(Region2(:,j+i)-Region2(:,k+i)))/N2;
                if (DB2(n) >= DB_L_R2(n,1)),S2(n)=4;elseif(DB2(n) < DB_L_R2(n,1) && DB2(n) >=
DB_L_R2(n,2)),S2(n)=3;elseif(DB2(n) < DB_L_R2(n,2) && DB2(n) >= DB_L_R2(n,3)),S2(n)=2;else
S2(n)=1;end
                n = n + 1;
            end
        end
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DB3(n) = sum(abs(Region3(:,j+i)-Region3(:,k+i)))/N3;
                if (DB3(n) >= DB_L_R3(n,1)),S3(n)=4;elseif(DB3(n) < DB_L_R3(n,1) && DB3(n) >=
DB_L_R3(n,2)),S3(n)=3;elseif(DB3(n) < DB_L_R3(n,2) && DB3(n) >= DB_L_R3(n,3)),S3(n)=2;else
S3(n)=1;end
                n = n + 1;
            end
```

```
        end
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DB4(n) = sum(abs(Region4(:,j+i)-Region4(:,k+i)))/N4;
                if (DB4(n) >= DB_L_R4(n,1)),S4(n)=4;elseif(DB4(n) < DB_L_R4(n,1) && DB4(n) >=
DB_L_R4(n,2)),S4(n)=3;elseif(DB4(n) < DB_L_R4(n,2) && DB4(n) >= DB_L_R4(n,3)),S4(n)=2;else
S4(n)=1;end
                n = n + 1;
            end
        end
    end
end

DBI_1 =
(W2(1)*sum(S1(1:3).*W11)+W2(2)*sum(S1(4:6).*W11)+W2(3)*sum(S1(7:9).*W11))/(sum(W2(1:3)*sum(W11)))
;
DBI_2 =
(W2(4)*sum(S2(1:3).*W12)+W2(5)*sum(S2(4:6).*W12)+W2(5)*sum(S2(7:9).*W12))/(sum(W2(4:6)*sum(W12)))
;
DBI_3 =
(W2(7)*sum(S3(1:3).*W13)+W2(5)*sum(S3(4:6).*W13)+W2(5)*sum(S3(7:9).*W13))/(sum(W2(7:9)*sum(W13)))
;
DBI_4 =
(W2(10)*sum(S4(1:3).*W14)+W2(11)*sum(S4(4:6).*W14)+W2(12)*sum(S4(7:9).*W14))/(sum(W2(10:12)*sum(W
14)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculatin DISI
%R-Y  -> R-B  ->  Y-B

DIS_L_R1 = [[2.6000 2.0000 1.4500],
[1.6000 1.1500 0.7000],
[2.6000 2.0000 1.5000],
[0.1000 0.0500 0.0080],
[0.0800 0.0450 0.0100],
[0.1000 0.0550 0.0100],
[3.2600 2.7300 2.2000],
[2.3000 1.6500 1.0000],
[3.0000 2.5000 2.0000]];

DIS_L_R2 = [[0.0600 0.0400 0.0200],
[0.0206 0.0150 0.0090],
[0.0600 0.0400 0.0200],
[0.0500 0.0400 0.0300],
[0.0200 0.0150 0.0095],
[0.0501 0.0400 0.0300],
[0.0400 0.0290 0.0180],
[0.0270 0.0170 0.0070],
[0.0500 0.0200 0.0140]];

DIS_L_R3 = [[0.0250 0.0175 0.0100],
[0.0220 0.0155 0.0090],
[0.0200 0.0145 0.0090],
[0.0240 0.0170 0.0100],
[0.0270 0.0165 0.0060],
[0.0300 0.0200 0.0100],
[0.0400 0.0300 0.0200],
[0.0360 0.0245 0.0130],
[0.0330 0.0250 0.0170]];

DIS_L_R4 = [[0.0015 0.0012 0.0008],
[0.0020 0.0014 0.0009],
[0.0016 0.0012 0.0007],
[0.0008 0.0014 0.0020],
[0.0017 0.0012 0.0008],
[0.0023 0.0015 0.0007],
[0.0050 0.0040 0.0030],
[0.0040 0.0035 0.0030],
[0.0050 0.0043 0.0035]];


W11 = [1 3 1];
W12 = [1 2 1];
W13 = [1 1 1];
W14 = [1 1 1];
W2 = [3 1 2 3 2 2 3 2 2 3 2 2];
```

```
%R-Y  -> R-B  ->  Y-B
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%calculating DIS
%-------------------------------------------Region1 - DIS-----------------------------------------
theta = 0;
ps = 0;
p = 0;
Sv = 0;
Sh = 0;
for i=3:5:7:9:11:13
    for x=1:(N1-1)
        Sv = Region1(x+1,i) - Region1(x,i);
        Sh = Region1(x+1,1) - Region1(x,1);
        theta(x,i) = atan(Sv/Sh);
    end
    theta(N1,i) = atan(Region1(N1,i)/Region1(N1,1));
end

for i=3:5:7:9:11:13
    p(1,i) = theta(1,i);
    ps(1,i) = p(1,i);
    for x=2:N1
        p(x,i) = theta(x,i) - theta(x-1,i);
        ps(x,i) = p(x,i) + ps(x-1,i);
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DIS1(n) =sqrt( sum( ( ps(:,j+i) - ( ps(:,k+i) )).^2 ) );
                if (DIS1(n) >= DIS_L_R1(n,1)),S1(n)=4;elseif(DIS1(n) < DIS_L_R1(n,1) && DIS1(n)
>= DIS_L_R1(n,2)),S1(n)=3;elseif(DIS1(n) < DIS_L_R1(n,2) && DIS1(n) >=
DIS_L_R1(n,3)),S1(n)=2;else S1(n)=1;end
                n = n + 1;
            end
        end
    end
end

%-------------------------------------------Region2 - DIS-----------------------------------------

theta = 0;
ps = 0;
p = 0;
Sv = 0;
Sh = 0;
for i=3:5:7:9:11:13
    for x=1:(N2-1)
        Sv = Region2(x+1,i) - Region2(x,i);
        Sh = Region2(x+1,1) - Region2(x,1);
        theta(x,i) = atan(Sv/Sh);
    end
    theta(N2,i) = atan(Region2(N2,i)/Region2(N2,1));
end

for i=3:5:7:9:11:13
    p(1,i) = theta(1,i);
    ps(1,i) = p(1,i);
    for x=2:N2
        p(x,i) = theta(x,i) - theta(x-1,i);
        ps(x,i) = p(x,i) + ps(x-1,i);
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DIS2(n) =sqrt( sum( ( ps(:,j+i) - ( ps(:,k+i) )).^2 ) );
                if (DIS2(n) >= DIS_L_R2(n,1)),S2(n)=4;elseif(DIS2(n) < DIS_L_R2(n,1) && DIS2(n)
>= DIS_L_R2(n,2)),S2(n)=3;elseif(DIS2(n) < DIS_L_R2(n,2) && DIS2(n) >=
DIS_L_R2(n,3)),S2(n)=2;else S2(n)=1;end
                n = n + 1;
            end
        end
    end
end
```

```
%------------------------------------------Region3 - DIS----------------------------------------
theta = 0;
ps = 0;
p = 0;
Sv = 0;
Sh = 0;
for i=3:5:7:9:11:13
    for x=1:(N3-1)
        Sv = Region3(x+1,i) - Region3(x,i);
        Sh = Region3(x+1,1) - Region3(x,1);
        theta(x,i) = atan(Sv/Sh);
    end
    theta(N3,i) = atan(Region3(N3,i)/Region3(N3,1));
end

for i=3:5:7:9:11:13
    p(1,i) = theta(1,i);
    ps(1,i) = p(1,i);
    for x=2:N3
        p(x,i) = theta(x,i) - theta(x-1,i);
        ps(x,i) = p(x,i) + ps(x-1,i);
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DIS3(n) =sqrt( sum( ( ps(:,j+i) - ( ps(:,k+i) )).^2 ) );
                if (DIS3(n) >= DIS_L_R3(n,1)),S3(n)=4;elseif(DIS3(n) < DIS_L_R3(n,1) && DIS3(n)
>= DIS_L_R3(n,2)),S3(n)=3;elseif(DIS3(n) < DIS_L_R3(n,2) && DIS3(n) >=
DIS_L_R3(n,3)),S3(n)=2;else S3(n)=1;end
                n = n + 1;
            end
        end
    end
end

%------------------------------------------Region4 - DIS----------------------------------------
theta = 0;
ps = 0;
p = 0;
Sv = 0;
Sh = 0;
for i=3:5:7:9:11:13
    for x=1:(N4-1)
        Sv = Region4(x+1,i) - Region4(x,i);
        Sh = Region4(x+1,1) - Region4(x,1);
        theta(x,i) = atan(Sv/Sh);
    end
    theta(N4,i) = atan(Region4(N4,i)/Region4(N4,1));
end

for i=3:5:7:9:11:13
    p(1,i) = theta(1,i);
    ps(1,i) = p(1,i);
    for x=2:N4
        p(x,i) = theta(x,i) - theta(x-1,i);
        ps(x,i) = p(x,i) + ps(x-1,i);
    end
end

n = 1;
for i=0:4:8
    for j=3:5
        for k=3:5
            if(j<k)
                DIS4(n) =sqrt( sum( ( ps(:,j+i) - ( ps(:,k+i) )).^2 ) );
                if (DIS4(n) >= DIS_L_R4(n,1)),S4(n)=4;elseif(DIS4(n) < DIS_L_R4(n,1) && DIS4(n)
>= DIS_L_R4(n,2)),S4(n)=3;elseif(DIS4(n) < DIS_L_R4(n,2) && DIS4(n) >=
DIS_L_R4(n,3)),S4(n)=2;else S4(n)=1;end
                n = n + 1;
            end
        end
    end
end

DISI_1 =
(W2(1)*sum(S1(1:3).*W11)+W2(2)*sum(S1(4:6).*W11)+W2(3)*sum(S1(7:9).*W11))/(sum(W2(1:3)*sum(W11)))
;
```

```
DISI_2 =
(W2(4)*sum(S2(1:3).*W12)+W2(5)*sum(S2(4:6).*W12)+W2(6)*sum(S2(7:9).*W12))/(sum(W2(4:6)*sum(W12)))
;
DISI_3 =
(W2(7)*sum(S3(1:3).*W13)+W2(8)*sum(S3(4:6).*W13)+W2(9)*sum(S3(7:9).*W13))/(sum(W2(7:9)*sum(W13)))
;
DISI_4 =
(W2(10)*sum(S4(1:3).*W14)+W2(11)*sum(S4(4:6).*W14)+W2(12)*sum(S4(7:9).*W14))/(sum(W2(10:12)*sum(W
14)));


SFRAI_1 = (CCFI_1 * 2 + DBI_1 * 1+ DISI_1 * 1 )/4;
SFRAI_2 = (CCFI_2 * 2 + DBI_2 * 1+ DISI_2 * 1 )/4;
SFRAI_3 = (CCFI_3 * 2 + DBI_3 * 1+ DISI_3 * 1 )/4;
SFRAI_4 = (CCFI_4 * 2 + DBI_4 * 1+ DISI_4 * 1 )/4;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%calculating DGAI
W = [2 3 3 3 5 1 1];

level(:,1) = [100 200 300 500 700];
level(:,2)   = [75  125 200 400 600];
level(:,3)   = [65  80  120 180 220];
level(:,4)   = [50  80  100 150 200];
level(:,5)   = [3   7   15  25  35 ];
level(:,6)   = [350 700 900 1100 1400];
level(:,7)   = [2500 3000 4000 5000 7000];

for i =1:7
    if ((data(i)) <=  level(1,i)) s(i) = 1;
    elseif (((data(i)) <=  level(2,i)) && ((data(i)) >  level(1,i))) s(i) = 2;
    elseif (((data(i)) <=  level(3,i)) && ((data(i)) >  level(2,i))) s(i) = 3;
    elseif (((data(i)) <=  level(4,i)) && ((data(i)) >  level(3,i))) s(i) = 4;
    elseif (((data(i)) <=  level(5,i)) && ((data(i)) >  level(4,i))) s(i) = 5;
    else s(i) = 6;
    end
end

DGAI = sum(s.*W) / sum(W);

end
```