# Unified Reliability Index Development for Utility Quality Assessment

by

Hatem Sindi

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2012

# AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Hatem Sindi

# Abstract

With the great potential smart distribution systems have to cause a paradigm shift in conventional distribution systems, many areas need investigation. Throughout the past few decades, many distribution systems reliability indices have been developed. Varying in their calculation techniques, burden, and purpose of calculation, these indices covered wide range of reliability issues that face both utilities and regulators. The major purpose of the continuous development of reliability indices is to capture a comprehensive idea of systems performance. While systems are evolving to a much more smarter and robust ones, so do the assessment tools need to be improved. The lack of consensus among utilities and regulators on which indices should be used complicate the problem more. Furthermore, regulators still come short when it comes to standard implementation because no final standard have been developed. However, regulators tend to advice or impose certain numbers on utilities based on historic performances. Because of the inevitable comparisons made by regulators on the routinely practiced process of utilities' reporting of some of their indices, adequate and fair process needs to be implemented. The variation in utilities perspective on the advice or imposed indices cause an additional burden to achieving fair and adequate designs, upgrade requirements, and public goodwill. Some utilities consider these regulators recommendations guidelines; others treat them as strict standards, and yet others consider them goals. In this work, a development of a unified reliability index, which can yield proper performance assessment, fair comparisons, and reflection of all the knowledge imbedded within all current indices, will be developed. The developed unified index provides several benefits, among which is adequate standards design, improved tools for planning and design optimization, and less technical burden on operators. In addition, the development of a unified reliability index required the development of a standard normalization methodology.

## Acknowledgements

*First, thank God for all the blessings I have in my life.*

I would like to express the greatest gratitude to my supervisor, mentor and teacher Prof. Ehab El-Saadaney whom without this work would have never seen light. His professional and personal supports are very much appreciated. From the beginning of the program, Prof. El-Saadaney’s knowledge, dedication to work, and much appreciated comments have been the backbone, not only to this thesis, to all degree requirements. For that and many more, I thank and pray for him.

My family played an essential part in the completion of this work. Without their understanding and unconditional love and support, I would have never been able to make the decision I made to pursue my dreams. I would like also to thank my colleagues and friends for their support to my work and me.

# Dedication

This work is dedicated to my dear family.

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# List of Abbreviations

| | |
|---|---|
| $i$ | Load Point (LP) Location; |
| $\lambda_{L_j}^{S}$ | LP $j$ Annual Sustained Interruption Frequency*;* |
| $\lambda_{L_j}^{M}$ | LP $j$ Annual Momentary Interruption Frequency*;* |
| $\lambda_{L_j}^{ME}$ | LP $j$ Annual Momentary Event Interruption Frequency*;* |
| $r_j$ | LP $j$ Annual Interruption Duration*;* |
| $U_j$ | LP $j$ Annual Interruption Duration*;* |
| $NLP$ | Number of Load Points; |
| $N_{L_j}$ | Number of Customers Connected to the $j^{th}$ LP; |
| SAIFI | System Average Interruption Frequency Index; |
| SAIDI | System Average Interruption Duration Index; |
| CAIDI | Customer Average Interruption Duration Index; |
| CTAIDI | Customer Total Average Interruption Duration Index; |
| CAIFI | Customer Average Interruption Frequency Index; |
| ASIFI | Average System Interruption Frequency Index; |
| ASIDI | Average System Interruption Duration Index; |
| CEMI**n** | Customers Experiencing Multiple Interruptions; |
| MAIFI | Momentary Average Interruption Frequency Index; |
| MAIFI-E | Momentary Event Average Interruption Frequency Index; |
| CEMSMI**n** | Customers Experiencing Multiple Sustained interruption and Momentary Interruption events |
| IOR | Index of Reliability; |
| ASAI | Average Service Available Index; |
| ASUI | Average Service Unavailable Index; |
| $devFR$ | Deviations in Interruption Frequency; |
| $devDR$ | Deviations in Interruption Duration; |
| $SM$ | Sustained to Momentary Ratio; |

$MME$ Momentary to Momentary Event Ratio;

$uA$ Unavailability Standard;

# Chapter 1
# Introduction

## 1.1 Preamble

Power systems have been undergoing challenges and changes over the past several decades. A continuous challenge has been demand growth. Accommodating increased demand with older techniques faces many technical and non-technical difficulties, such as: regulatory, environmental, fuel cost, project cost, and transmission infrastructure. Therefore, regulators recommend several practices in order to overcome these challenges. Demand side management, sustainable distributed generation, and distribution system reliability enhancements are examples of such recommendations.

A significant point is that neither regulators nor utilities come with a complete understanding of how to improve system reliability. Regulators use utilities' historic data in order to assess performance, while utilities vary with respect to historic data. Some consider them guidelines, others consider them goals to achieve, and yet others consider them absolute standards. Nevertheless, regulators will invariably compare and cross-compare performance.

Assessments are made on the basis of several reliability indices. There has not been consensus on which indices should be used. While reliability indices have accommodated development over the recent years, these indices do not provide the proper tools to achieve adequate standard design or impartial comparisons.

Enhancing performance, penalizing, or awarding different parties in distribution systems requires adequate, simple, and accurate assessment. These parties include utilities, operators, customers, or any other party that positively or negatively impacts performance of distribution systems. Whether it is a regulated or deregulated environment, proper assessment tools are necessary.

There are several reasons for electric energy being the most broadly used form of energy, among which are cost, transferability, and efficiency. Electricity has become an essential part of our daily lives. Demand of electric energy not only concerns leisure reasons but has become a national security measure. Countries strive to secure stable means of generating electricity. As a result, significant investments are made for renewable sources development and deployment.

Electric power systems are generally composed of four major subsystems: Bulk Generation Systems, Transmission and Sub-transmission Systems, Distribution Systems, and Loads. The main role of a power system is to secure electric power (energy) to consumers (Loads) at an adequate quality level while minimizing losses and maximizing profit [1].

Each subsystem plays a key role in the overall goal of the power system. On one hand, generation systems transform energy from one form (usually mechanical) to electric energy while minimizing costs associated with this transformation, among which is fuel, operational costs, and outages. On the other hand, transmission systems only deal with electric energy. From output terminals of step-up transformers until the reaching of distribution substations, the role of a transmission system is to transfer electric power with the best possible feasible efficiency. By the time electric power reaches distribution systems, the role of transmission is continued on a lower voltage level until it reaches the consumer as service voltage. Consumers have variable requests in terms of demand level, quality demanded, and location. Consumers are generally labeled according to the aforementioned criteria: Residential, Commercial, and Industrial. However, each group contains subgroups. For example, in industrial, there are subgroups reflecting industry type and/or outage impact. These are the major categories for load types, but this does not reflect an exhaustive list. For instance, industrial can be further classified by type of industry and residential can also be classified by geographical location. However, many paradigm shifts are taking place in recent years with regard to power systems. Deregulation, smart grids, renewable sources, distributed generation, and community welfare are examples of causes of shifts in overall thinking about power systems [1, 2].

## 1.2 Motivation

Following customers' demand of a more reliable service, and steps toward a smart distribution system, better tools to assess and enhance system performance should be targeted. In addition, smart distribution systems need tools beyond smart meters and system automation. For instance, in order to reach smart grid ideology, tools to collect, analyze and act upon system data must be developed. These tools require faster, accurate, impartial techniques.

Current methodologies, although usage varies between utilities and regulators, have an imbedded bias in the output of assessment for systems reliability. Comparisons cannot be accurately and impartially conducted due to several reasons, among which is deciding on a wide range of metrics, system topology variation, type of customer, perception of these metrics, and technical background requirements.

## 1.3 Objectives

Not only does assessment and improvement of system reliability require a high level of technical background, but these are increasingly recommended, required, and, in many times, inevitable for both utilities and regulators. This work explores and summarizes challenges associated with these tasks.

Proceeding from the growing need to assess performance of distribution systems in such a way that allows fair historical and current comparisons within one system (subsystems) and cross comparisons between different systems and subsystems, this work tackles the goal of a simple, representative, and easily interpreted single index. The main objective of this single index is to evaluate distribution system performance using one number.

The developed single number should be adequate for assessment and comparison purposes. Moreover, the derived index ought to reflect information from reliability indices. Therefore, a unified index based on all reliability indices recommended by the IEEE Guide for Electric Power Distribution Reliability Indices (IEEE Std 1366™-2003) has been developed [3]. The developed unified index will accurately and fairly assess systems or subsystems without the need for highly qualified personnel. In addition, the unified index will carry information from all indices and will reflect major components of systems topology in terms of customer count, loading level, and number of serving points (i.e. load points). This unified index will also allow for penalty/reward policies to be easily implemented. With some modifications, reliability standards can be achieved based on the developed unified index. The following figure (Figure 1) illustrates a diagram of the objective and some of the main sub-objectives of this work.

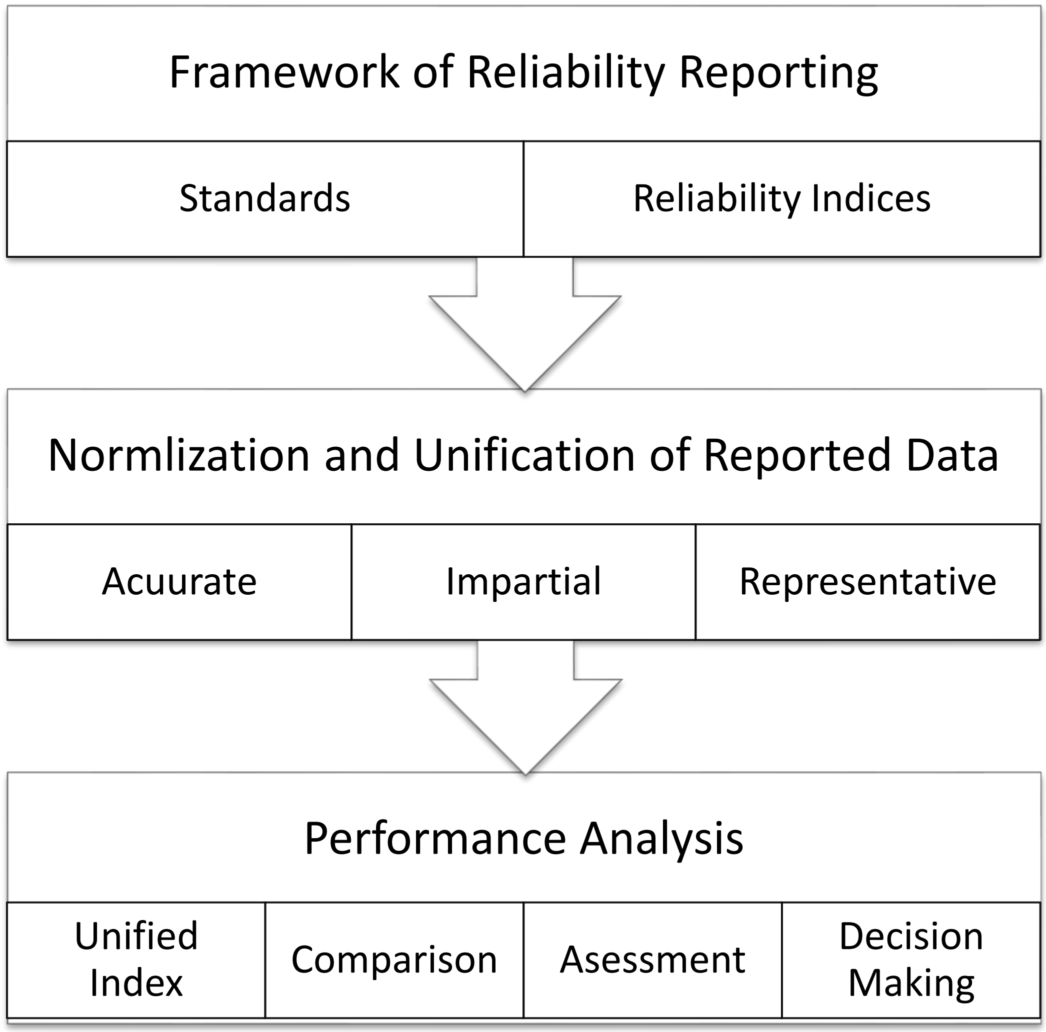


**FIGURE 1: OBJECTIVES DIAGRAM**

### 1.4 Thesis Structure

The organization of this work begins with an introductory section (Chapter 1) that highlights the background and motivation behind the thesis. The first chapter also includes the objectives that this work is aiming to achieve.

Following the motivations and objectives of the work, Chapter 2 contains a literature survey describing and summarizing work that has been previously conducted regarding distribution system reliability analysis and assessment. This section also provides a general understating of terms and their definitions with regard to this area of research; it also includes an objective criticism of relatively similar approaches.

Next, the developed index mathematical modeling and analysis are presented in Chapter 3. Following the development formulation, verification using several approaches is conducted in Chapter 4. Then, test results from the developed unified index are presented in Chapter 5. Finally, a discussion, exploration of possible future research, and conclusions from the unified index are summarized in Chapter 6. Figure 2 summarizes the way in which the thesis was structured.

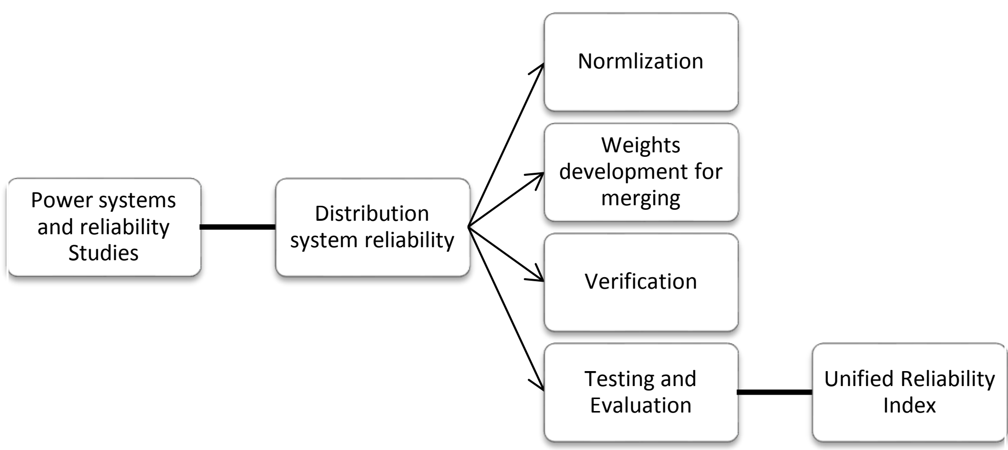


**FIGURE 2: THESIS STRUCTURE**

Chapter 2

# Literature Review

## 2.1 Power System Reliability

The concept of reliability is not restricted to power systems or electrical engineering. On the contrary, reliability studies are necessary in almost all engineering, scientific, and business related studies [4]. However, reliability in power systems is generally defined as: the system's ability to provide power continually with adequate level of quality.

The three major subsystems considered in power system reliability studies are Generation, Transmission, and Distribution. Reliability is the byproduct of the interaction between these three components and the load. Usually, reliability studies are conducted separately amongst subsystems. Generation reliability studies take into account random failures, outages, and maintenance (scheduled and forced). However, transmission takes this process a step forward to include transmission system components. This process usually is typically referred to as a hierarchal level of reliability.

Though it is important to study each system's reliability, this work focuses on the later part of power systems: Distribution Systems. These are not only the mostly affected systems with regard to reliability problems but also have reliability issues which occur in Generation and Transmission, depending on severity, which can be tolerated or otherwise cascaded until they reach distribution systems. This is the highest level of hierarchy in reliability. However, whether deterministic or probabilistic, it is not practical to always solve and study reliability at this level because the system is so large and the studies would take substantial time and resources.

## 2.2 Distribution System Reliability

People have been coping with reliability problems in their homes, offices, factories, and a variety of other settings. People do not always seem to mind a weak system configuration that promotes lower electricity prices yet some people, especially those in the commercial and industrial sectors of the system, require certain availability levels.

Utilities and regulators have always mattered to distribution system reliability. However, attention paid to this area has been significantly less than generation in terms of reliability studies [5]. These studies are mainly concerned with modeling and evaluation. Nonetheless, attention was given even prior to any form of practical model experience. This began to change in the 1960's after developing failure rates and the Markov process in reliability studies [6-8].

In distribution systems, the security of the supply to end customers can be interrupted by many factors. Generally, the main causes for reliability problems are known, and reliability studies include static and dynamic problems. For instance, there are evaluations of reliability in a normal steady state or surviving a major interruption event. Reliable system should provide a minimum amount of security to consumers in the case of emergencies. Therefore, adequacy and security are two subdivisions of reliability, as shown in Figure 3, where adequacy relates to availability of a sufficient amount of facilities producing power to the load and security relates to tolerating severe events without worsening the system [9].

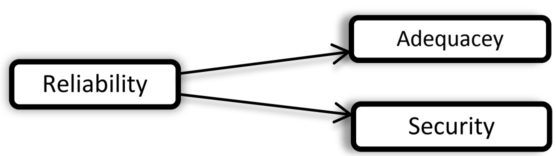


**FIGURE 3: TWO SUBDIVISIONS OF RELIABILITY**

For reliability studies in distribution systems, some metrics were developed to conduct further analyses. These metrics differ in their hierarchal level within the distribution system. Some provide information about the distribution system as a whole; others reflect the performance of specific parts, such as feeders, load point, or the collected part of the system. However, further studies explore the new concepts introduced in systems, such as introducing distributed generation and new regulations which require for new studies to be conducted.

In 2009, [10] conducted an investigational survey to further understand the implications of the new (2007) regulations, in the United States, for “smart” grid. Their investigation was primarily seeking a definition for a smart distribution system. Additionally, they investigated technical tools that could be migrated from transmission systems into smart grids and the new challenges and technical requirements imbedded in this notion (i.e. smart grids). Figure 4, adapted from the Energy Independence and Security Act of 2007, represent the eight tools of smart distribution.

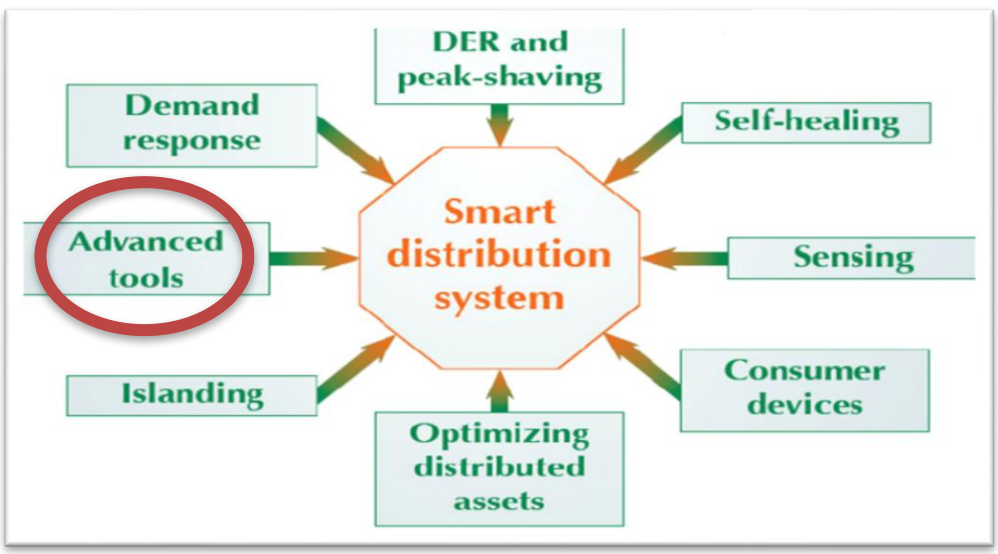


**FIGURE 4: ADVANCED TOOLS FOR SMART DISTRIBUTION SYSTEMS [10]**

It is important to highlight the need for advanced tools in the new paradigm, as that is the scope of this work. These tools involve, but are not restricted to, reliability studies. New technologies and implementations in data acquisition, data mining, and analysis are necessary. The need for these is not only the result of improving tool efficiency but is also due to the novel nature of smart distribution systems. In such systems, new regulations are necessary with regard to reliability, contracts, customer-utility-regulator relationships, and the paradigm shift in thinking of distribution systems as passive.

## 2.3 Reliability Importance

Reliability studies are generally vital to distribution system studies. One can understand the significance of the amount of literature that has been written on this topic. In [9], the reliability library consulted includes over 100 references, including books, reports and, journal articles. The authors of [9] were trying to reach the goal of understanding reliability in electric power distribution systems. From a customer perspective, ease of communication with the utility during an interruption of service, and the time needed to restore the service, are key factors in the assessment of service quality [9]. On the other hand, for [9], utilities usually assess the service reliability at load point or at customer level rather than from the generation or transmission. Nevertheless, these concepts, amongst others, can highlight how important reliability is for both customers and utilities.

Reliability studies are crucial in planning and typically involve compromise between service quality and cost [9]. Utilities invest a lot of money to upgrade, build, or maintain systems. The use of reliability studies, although they do not guarantee global optimality, minimizes losses.

The following figure (Figure 5) illustrates the tradeoff between enhancing service quality (reliability) and total cost. Unfortunately, customers tend not to fully understand this compromise [11].

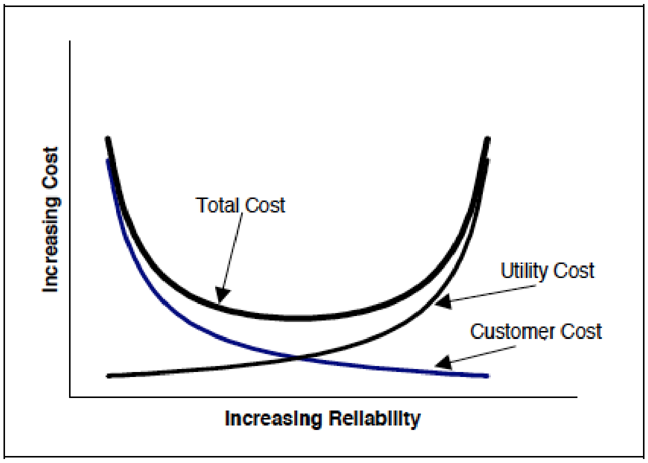


**FIGURE 5: TOTAL COST WITH INCREASING RELIABILITY [9]**

Reliability studies play a vital role in enhancing operational conditions. During restoration and reconfiguration, reliability studies, such as reliability worth or reliability indices, are used [12]. Regulators have also been actively involved in reliability studies [13]. Utilities routinely report reliability data to regulators [14, 15].

Power quality can be an ambiguous term, as mentioned by [16]. However, [16] better defined it as voltage quality as it is connected to voltage waveform. When it comes to reliability, voltage quality can be considered the main subject, and reliability is the state of interruption to the level of zero voltage to the waveform. The following two figures (Figure 6 and Figure 7) summarize the interconnection between reliability and voltage quality.

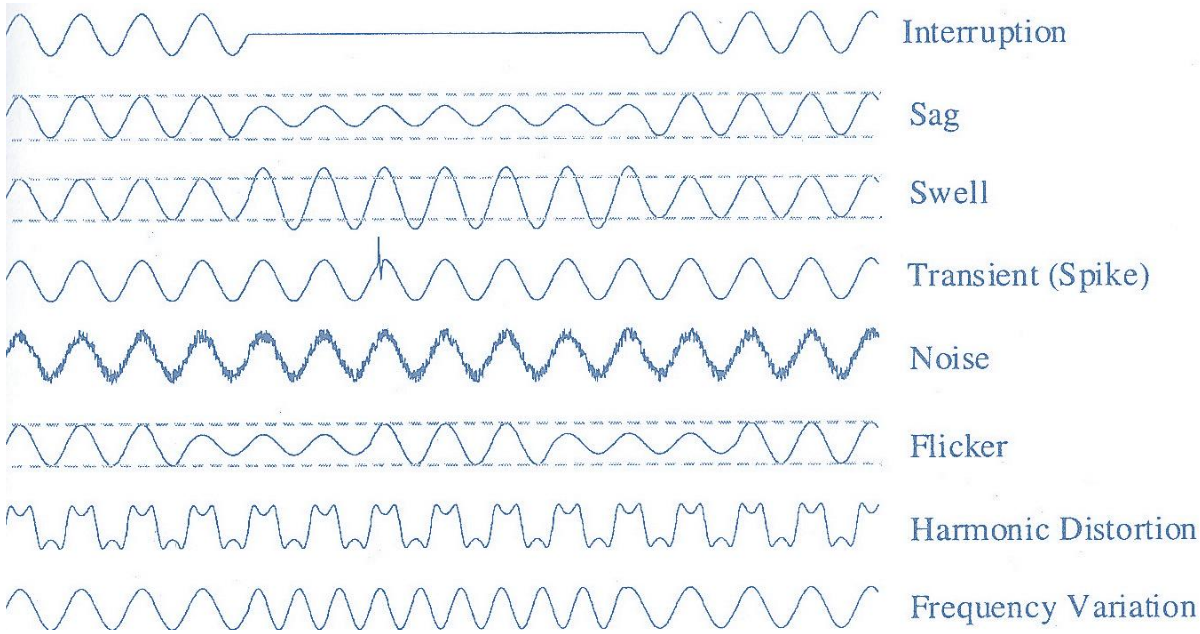


**FIGURE 6: VOLTAGE QUALITY ISSUES [16]**

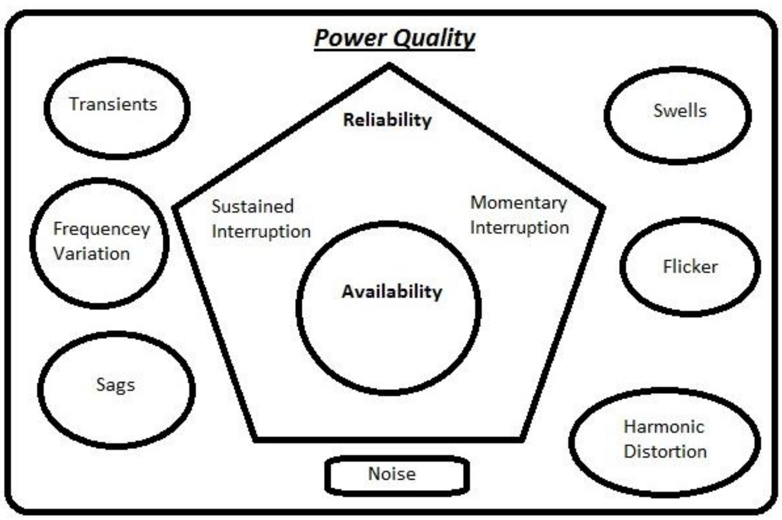


**FIGURE 7: AVAILABILITY AS A SUBSET OF RELIABILITY SUBSET OF POWER QUALITY**

### 2.4 Reliability Indices

While technical advancement is rapidly growing in many aspects of power systems, adequate tools to assess reliability are still necessary. In a general sense, reliability metrics (indices) were developed to reflect system performance in a mathematical manner. Consequently, additional benefits have been derived from these indices. Although in distribution systems the methodology includes starting with basic components, then aggregating different probabilities to arrive at an average number, the derived number is only partially reflective of the reliability of the system.

This section explores the indices included in [3], which are gaining more popularity and greater adoption amongst electric power utilities in their service continuity report on distribution system performance. The adoption of [3] and the IEEE 2.5 beta methodology that classifies normal daily operational reliability data and major events data are highly recommended by [3, 17]. These indices can be categorized into two major sections: Load point and System Indices. One major assumption in this study is that all reported indices are from utilities who adopted [3] and the IEEE 2.5 beta methodology. In [18], there is an example of a utility report that reports in accordance with [3]. Almost all indices are derived from customer information systems (CIS); therefore, averaging is used in calculating the indices, due to ease of access to customer data [19]. According to [19], utilities are continuing to understand the need for more than one or two indices in order to capture service quality and to design a good implementation plan accordingly.

#### 2.4.1 Load Point Indices

##### 2.4.1.1 Introduction

Reliability indices are an aggregation of several systems, areas, feeders, components, or component parameters. Whether in regard to load point indices or system indices, the principles are similar.

It is important to mention that load point indices are vital to calculating system reliability indices, as discussed in the next section. However, the description and definition of load point indices in this section is merely for the purposes of differentiating between them and the system indices and in the purpose of calculating system indices.

#### 2.4.1.2 Indices

For load point indices, three main indices are commonly used in load point reliability metrics [20]. These indices characterize: first, the frequency of interruption the load point has suffered over the study period; second, the average outage time for each interruption over the study period; lastly, the average unavailability time for load point due to all interruption suffered over the reporting epoch. (2.1)-(2.3) describe the mathematical representation and methodology used in calculating such indices [14, 16].

$$\boldsymbol{\lambda_i = \sum_k \lambda_{i,k}} \tag{2.1}$$

$$\boldsymbol{r_i = \sum_k r_{i,k}} \tag{2.2}$$

$$\boldsymbol{U_i = \sum_k U_{i,k}} \tag{2.3}$$

where $k$ represents all components branches affecting load point $i$.

#### 2.4.1.3 Problems with Existing Indices

Although the three indices have been heavily studied for improving the accuracy of their calculation, they are still predictive [21-24]. They are predictive rather than being deterministic because they are composed of aggregated averages that directly depend on several probabilities [25].

Another issue arises when trying to compare load points. The values are usually conflicting [26-28]. If frequency of interruption is low and duration of a load point is long, decisions can be challenging to make when compared with a load point with higher frequency of interruption and shorter duration.

### 2.4.2 System Level Reliability Indices

#### 2.4.2.1 Introduction

The three primary load point indices introduced above are very important from a customer standpoint [15]. The system performance can also be assessed on an overall system basis. The indices reflect the adequacy of overall system supply and indicate system behavior and response.

#### 2.4.2.2 Indices

According to [3], 12 indices are recommended for assessing system reliability performance. Some of these indices were developed as early as the 60's [6,7,29,30]. Some other indices were introduced more recently [22, 31]. However, the recommended indices do not represent all of the available electric power reliability in distribution systems metrics [32-34]. The following set of equations describes, verbally and mathematically, each index of the 12. In numerous reliability surveys, the general decision was that utilities are increasingly interested in incorporating more indices [15,35]. Moreover, comparison and cross-comparison of reported data amongst utilities becomes inevitable for regulators [14]. However, the current infrastructure of indices does not promote fair and accurate comparison.

##### 2.4.2.2.1 System Average Interruption Frequency Index (SAIFI)

This index counts the average number of sustained interruptions (more than 5 min) during the reporting period (usually annual). This is one of the mostly used indices by utilities. The following, (2.4), describes its mathematical formula.

$$SAIFI = \frac{Total\ number\ of\ customers\ interrupted}{Total\ number\ of\ customers} \quad \textbf{(2.4)}$$

$$= \frac{\sum_{j=1}^{NLP} \left( \lambda_{L_j}^{S} * N_{L_j} \right)}{\sum_{j=1}^{NLP} N_{L_j}}, ({}^{f}/_{yr})$$

2.4.2.2.2 System Average Interruption Duration Index (SAIDI)

SAIDI is also very commonly used. It is the average duration of an interruption and is usually reported annually. The following, (2.5), describes its mathematical formula.

$$SAIDI = \frac{Customer\ Interruption\ Durations}{Total\ number\ of\ customers} \quad \textbf{(2.5)}$$

$$= \frac{\sum_{j=1}^{NLP} \left( U_{L_j}^{S} * N_{L_j} \right)}{\sum_{j=1}^{NLP} N_{L_j}}, ({}^{hr}/_{yr})$$

2.4.2.2.3 Customer Average Interruption Duration Index (CAIDI)

This index has been gaining popularity recently. It describes the duration of an average customer suffering from interruption. The following, (2.6), describes its mathematical formula.

$$CAIDI = \frac{Customer\ Interruption\ Durations}{Total\ number\ of\ customers\ interrupted} \quad \textbf{(2.6)}$$

$$= \frac{\sum_{j=1}^{NLP} \left( U_{L_j}^{S} * N_{L_j} \right)}{\sum_{j=1}^{NLP} \left( \lambda_{L_j}^{S} * N_{L_j} \right)}, (hr)$$

2.4.2.2.4 Customer total average interruption duration index (CTAIDI)

This describes the duration of an average customer suffering from an interruption. The following, (2.7), describes its mathematical formula.

$$CTAIDI = \frac{Customer\ Interruption\ Duration}{Total\ number\ of\ customers\ interrupted\ counted\ once} \quad (2.7)$$

$$= \frac{\sum_{j=1}^{NLP}\left(U_{L_j}^{S} * N_{L_j}\right)}{CN}, (hr)$$

2.4.2.2.5 Customer average interruption frequency index (CAIFI)

This describes the average interruption frequency for customers who were counted as suffering from interruption only once. The following, (2.8), describes its mathematical formula.

$$CAIFI = \frac{Total\ number\ of\ customers\ interrupted}{Total\ number\ of\ customers\ interrupted\ counted\ once} \quad (2.8)$$

$$= \frac{\sum_{j=1}^{NLP}\left(\lambda_{L_j}^{S} * N_{L_j}\right)}{CN}, ({}^{f}/_{yr})$$

2.4.2.2.6 Average system interruption frequency index (ASIFI)

This index is similar to SAIFI. The difference is that ASIFI uses kVA instead of the number of customers. The following, (2.9), describes its mathematical formula.

$$ASIFI = \frac{Total\ connected\ kVA\ of\ Load\ Interrupted}{Total\ number\ of\ customers\ interrupted\ counted\ once} \quad (2.9)$$

$$= \frac{\sum_{j=1}^{NLP}\left(\lambda_{L_j}^{S} * L_{L_j}\right)}{LT}, ({}^{f}/_{yr})$$

2.4.2.2.7 Average system interruption duration index (ASIDI)

This index is similar to SAIDI. The difference is that ASIDI uses kVA instead of number of customers. The following, (2.10), describes its mathematical formula.

$$ASIDI = \frac{Total\ connected\ kVA\ of\ Load\ Interrupted}{Total\ number\ of\ customers\ interrupted\ counted\ once} = \frac{\sum_{j=1}^{NLP}\left(U_{L_j}^{S} * L_{L_j}\right)}{LT}, (hr/yr) \quad (2.10)$$

2.4.2.2.8 Customers experiencing multiple interruptions (CEMI**n**)

This index represents a ratio of customers suffering from n sustained interruptions to the total number of customers served. The following, (2.11), describes its mathematical formula.

$$CEMIn = \frac{Total\ Number\ of\ Customers\ that\ experience\ more\ than\ n\ sustained\ interruptions}{Total\ number\ of\ customers} = \frac{CN_{k>n}}{\sum_{j=1}^{NLP} N_{L_j}}, (p.u.) \quad (2.11)$$

2.4.2.2.9 Momentary average interruption frequency index (MAIFI)

This is the index used for average momentary interruption. The following, (2.12), describes its mathematical formula.

$$MAIFI = \frac{Total\ number\ of\ customers\ interrupted}{Total\ number\ of\ customers} = \frac{\sum_{j=1}^{NLP}\left(\lambda_{L_j}^{M} * N_{L_j}\right)}{\sum_{j=1}^{NLP} N_{L_j}}, (f/yr) \quad (2.12)$$

2.4.2.2.10 Momentary event average interruption frequency index (MAIFI-E)

The difference between this index and MAIFI is that in MAIFI-E momentary interruptions resulting from one event are counted only once. The following, (2.13), describes its mathematical formula.

$$\boldsymbol{MAIFI-E} = \frac{\textbf{Total number of customers interrupted}}{\textbf{Total number of customers}} = \frac{\sum_{j=1}^{NLP}\left(\lambda_{L_j}^{ME} * N_{L_j}\right)}{\sum_{j=1}^{NLP} N_{L_j}}, (f/yr) \quad \textbf{(2.13)}$$

2.4.2.2.11 Customers experiencing multiple sustained interruption and momentary interruption events (CEMSMI**n**)

This index represents a ratio of customers suffering from n momentary interruptions to the total number of customers served. The following equation (2.14) describes its mathematical formula.

$$\boldsymbol{CEMSMIn} = \frac{\textbf{Total Number of Customers that experience more than n interruptions}}{\textbf{Total number of customers}} = \frac{CNT_{k>n}}{\sum_{j=1}^{NLP} N_{L_j}}, (p.u.) \quad \textbf{(2.14)}$$

2.4.2.2.12 Index of Reliability (IOR) or Average Service Available Index (ASAI) or Average Service Unavailable Index (ASUI)

IOR and ASAI are identical. They represent the percentage of time per reporting period (e.g. one year) that average service was available. ASUI is the direct opposite. As all other indices are considered good when their values decrease, ASUI will be used to follow the same favorability in lowering its value. It would be redundant to use all three indices, IOR, ASAI, and ASUI, simultaneously. The following equation (2.15) describes its mathematical formula

$$\boldsymbol{ASUI} = \mathbf{1} - \frac{\boldsymbol{Customer\ Interruption\ Durations}}{\boldsymbol{Total\ number\ of\ customers} * \boldsymbol{Number\ of\ hours/reporting\ period}} = \frac{\sum_{j=1}^{NLP}\left(\boldsymbol{U}_{L_j}^{S} * \boldsymbol{N}_{L_j}\right)}{\sum_{j=1}^{NLP}\boldsymbol{N}_{L_j} * \mathbf{8760}}\ (\boldsymbol{p.u.}) \tag{2.15}$$

## 2.5 Normalization and Combining of Indices

Authors in [36] studied the impact of momentary and sustained interruptions on design process. They concluded that momentary interruptions are as important as sustained ones when it comes to reliability-based distribution system design. Moreover, this, among other reasons, is a push toward system design based on reliability studies. The more reliability indices are included, the more comprehensive the study becomes. In [37], conclusions can be drawn with regard to the importance of incorporating momentary interruption for distribution feeders. The aforementioned IEEE standard [3] and the IEEE 2.5 beta methodology for severe weather promote and recommend the use of the 12 reliability indices, including momentary interruptions.

Normalization is required for bringing data with different ranges and units to a common level. This process is completed to enable further manipulation of the data and is rarely conducted for the mere purpose of normalization. However, normalization requires knowledge of the data and knowing the ultimate purpose of normalization.

It is highly noticeable in both practice and research that regulations and regulators are leaning toward-performance based assessment; therefore, performance-based regulations are attracting attention [14]. Performance-based regulations were introduced in order to overcome several difficulties faced by customers. Utilities in the deregulated environment have one major objective: maximizing profit. Whether they accomplish this by minimizing loss, providing cheaper power, or poor quality power, regulators' roles in distribution systems become vital.

Multiple methods are used for normalization: maximum, minimum, maximum norm, Euclidian norm, average …etc. However, any method that uses one number for normalizing each index will not be sufficient. Moreover, it will normalize all indices mathematically but will not include in its normalization any known superiorities amongst systems. From an engineering perspective, equal indices in two systems do not necessarily reflect equal performance. Therefore, development of a new normalization methodology is necessary.

In [16], simple normalization to the maximum amongst load point indices will be sufficient to combine indices. Moreover, after normalization, weights are assigned by a reliability engineer in order to combine all indices. However, this is not fair in comparative studies and merely deals with the problem mathematically, without an understanding of the problem.

Another approach was made by [38]. In this work, some indices (reliability and power quality) were assigned weights (X $/unit index) in order to convert all indices into dollars; then, comparisons may be performed or further explored. However, this technique also suffers from equal bases as it normalizes by the maximum; this is assuming equal weights. In case of different weights, comparative studies will become unfair because systems' reliability (service) performance should be made on similar environments to eliminate bias. For instance, an outage of a silicon factory will certainly not equal the value of an outage in an equally sized (loading) residential load. Thus, results will not directly reflect performance of the design but will rather highlight how severe an outage financially is.

Developing a completely new index which incorporates as many indices as possible was the methodology used in [26]. Author in [26] suggests a survey for distribution among customers in order to gain feedback on the question of effective time. Effective time was used as a compromise for what customers think of specific outage duration. This methodology only reflects some indices. Moreover, it lacks the ability to aggregate the effects of system size and loading conditions. In other words, it is more reflective of reliability from customers' perspectives rather than service quality.

Authors in [27] used a similar approach to [38]. However, in [27] the methodology involved reliability worth rather than assigning weights. This leads to the fundamental problem, as described in [15, 19, 39], that using reliability worth, in deciding which system is the better design, is weak; therefore, they also reported that many utilities are adopting reliability indices based distribution system designs or performance-based assessment in the decision making process. This weakness comes from the fact that reliability worth is system dependent and cost of not served energy differs from one system to the other.

Analytic Hierarchy Process was used in [28] to unify indices. However, authors neglected the use of nine of the recommended reliability indices by [3]. Moreover, cost-based decision is eventually mimicked as cost dominates the decision.

Chapter 3

# The Unified Index

## 3.1 Introduction

In this chapter, the methodology and steps toward reaching the unified index is elaborated. First, decisions on which indices are to be incorporated in the unification process are presented. The selected indices must reflect the entire system performance in regard of optimization. This means that if these indices were to be optimized, best possible system performance will be achieved. Following the first step, the normalization part of the problem is presented and modeled.

The normalized numbers should reach a place that overcomes some of the aforementioned difficulties in cross comparisons and comparative studies. Proceeding from the normalized selected indices, the combining phase illustrates the methodology used in order to combine all different indices into one unified index reflective of overall system performance in terms of reliability.

## 3.2 Incorporated Indices

In this section, mathematical analysis will be conducted to further understand the most important indices. Nonetheless, it will highlight the fact that some indices are correlated with one another and will show the effects of system (or subsystem) size. The following equation (3.1) represents a general formulation for a multi-objective unified index. This general formulation can be used in a variety of studies, except comparative ones. In addition, the weights are unknown and need to be assigned. However, there is not one precise methodology for assigning values to these weights.

By using the general formulation, some algebraic manipulations are made to reflect the correlation between indices and system size effect.

$$\begin{aligned} \boldsymbol{UI} = \boldsymbol{w_1}\frac{\boldsymbol{SAIFI_{actual}}}{\boldsymbol{SAIFI_{base}}} + \boldsymbol{w_2}\frac{\boldsymbol{SAIDI_{actual}}}{\boldsymbol{SAIDI_{base}}} + \boldsymbol{w_3}\frac{\boldsymbol{CAIDI_{actual}}}{\boldsymbol{CAIDI_{base}}} + \boldsymbol{w_4}\frac{\boldsymbol{CAIFI_{actual}}}{\boldsymbol{CAIFI_{base}}} \\ + \boldsymbol{w_5}\frac{\boldsymbol{CTAIDI_{actual}}}{\boldsymbol{CTAIDI_{base}}} + \boldsymbol{w_6}\frac{\boldsymbol{ASIFI_{actual}}}{\boldsymbol{ASIFI_{base}}} + \boldsymbol{w_7}\frac{\boldsymbol{ASIDI_{actual}}}{\boldsymbol{ASIDI_{base}}} \\ + \boldsymbol{w_8}\frac{\boldsymbol{MAIFI_{actual}}}{\boldsymbol{MAIFI_{base}}} + \boldsymbol{w_9}\frac{\boldsymbol{MAIFI_{E_{actual}}}}{\boldsymbol{MAIFI_{E_{base}}}} + \boldsymbol{w_{10}}\frac{\boldsymbol{ASUI_{actual}}}{\boldsymbol{ASUI_{base}}} \\ + \sum_{n=1}^{k} \boldsymbol{w_{11_n}}\frac{\boldsymbol{CEMI_{n_{actual}}}}{\boldsymbol{CEMI_{n_{base}}}} + \sum_{m=1}^{l} \boldsymbol{w_{12_n}}\frac{\boldsymbol{CEMSMI_{m_{actual}}}}{\boldsymbol{CEMSMI_{m_{base}}}} \end{aligned} \qquad \textbf{(3.1)}$$

Assuming that the two indices $CEMI_n$ and $CEMSMI_m$ are being calculated for a specific value of $n$ (number of sustained interruption) and $m$ (number of sustained and momentary interruptions), respectively in (3.2);

$$UI = w_1 \frac{SAIFI_{actual}}{SAIFI_{base}} + w_2 \frac{SAIDI_{actual}}{SAIDI_{base}} + w_3 \frac{CAIDI_{actual}}{CAIDI_{base}} + w_4 \frac{CAIFI_{actual}}{CAIFI_{base}} + w_5 \frac{CTAIDI_{actual}}{CTAIDI_{base}} + w_6 \frac{ASIFI_{actual}}{ASIFI_{base}} + w_7 \frac{ASIDI_{actual}}{ASIDI_{base}} + w_8 \frac{MAIFI_{actual}}{MAIFI_{base}} + w_9 \frac{MAIFI_{E_{actual}}}{MAIFI_{E_{base}}} + w_{10} \frac{ASUI_{actual}}{ASUI_{base}} + w_{11} \frac{CEMI_{k_{actual}}}{CEMI_{k_{base}}} + w_{12} \frac{CEMSMI_{l_{actual}}}{CEMSMI_{l_{base}}} \quad (3.2)$$

In the following equation (3.3),expansions are made by substituting each actual value by its corresponding function and rearranging each index into two fractions where the first contains weight and base values, and the second has the index function.

$$UI = \frac{w_1}{SAIFI_{base}} \frac{CI}{N_T} + \frac{w_2}{SAIDI_{base}} \frac{CMI}{N_T} + \frac{w_3}{CAIDI_{base}} \frac{CMI}{CI} + \frac{w_4}{CAIFI_{base}} \frac{CI}{CN} + \frac{w_5}{CTAIDI_{base}} \frac{CMI}{CN} + \frac{w_6}{ASIFI_{base}} \frac{\sum_{i=1}^{NLP} L_i}{LT} + \frac{w_7}{ASIDI_{base}} \frac{\sum_{i=1}^{NLP} L_i * r_i}{LT} + \frac{w_8}{MAIFI_{base}} \frac{\sum_{i=1}^{NLP} IM_i * N_{mi}}{N_T} + \frac{w_9}{MAIFI_{E_{base}}} \frac{\sum_{i=1}^{NLP} IM_E * N_{mi}}{N_T} + \frac{w_{10}}{ASUI_{base}} \frac{CMI}{8760 * N_T} + \frac{w_{11}}{CEMI_{k_{base}}} \frac{CN_k}{N_T} + \frac{w_{12}}{CEMSMI_{l_{base}}} \frac{CNT_l}{N_T} \quad (3.3)$$

Where CI is the number of customers interrupted and CMI is the number of customer minutes interrupted. In the following equation (3.4), further simplifications are made to reach the final general form;

$$UI = \left[\frac{w_1}{SAIFI_{base}} + \frac{w_4 * N_T}{CAIFI_{base} * CN}\right] SAIFI + \left[\frac{w_2}{SAIDI_{base}} + \frac{w_{10}}{ASUI_{base} * 8760} + \frac{w_5 * N_T}{CTAIDI_{base} * CN}\right] SAIDI + \frac{w_3}{CAIDI_{base}} \frac{SAIDI}{SAIFI} + \frac{w_6}{ASIFI_{base}} ASIFI + \frac{w_7}{ASIDI_{base}} ASIDI + \frac{w_8}{MAIFI_{base}} MAIFI + \frac{w_9}{MAIFI_{E_{base}}} MAIFI_E + \frac{w_{11}}{CEMI_{k_{base}}} CEMI_k + \frac{w_{12}}{CEMSMI_{l_{base}}} CEMSMI_l$$

$$\boldsymbol{UI = W_1 SAIFI + W_2 SAIDI + W_3 \frac{SAIDI}{SAIFI} + W_4 ASIFI + W_5 ASIDI + W_6 MAIFI + W_7 MAIFI_E + W_8 CEMI_k + W_9 CEMSMI_l} \quad \textbf{(3.4)}$$

For $CEMI_{k_{base}}$ and $CEMSMI_{l_{base}}$, worst-case scenarios are when both equal to one. Therefore, the weights will be;

$CEMI_{k_{base}} = CEMSMI_{l_{base}} = 1$

For $CAIDI_{base}$, values of $SAIFI_{base}$ and $SAIDI_{base}$ can be used instead. By doing so we arrive to;

$$CAIDI_{base} = \frac{SAIDI_{base}}{SAIFI_{base}}$$

For $CAIFI_{base}$ and $CTAIDI_{base}$, worst-case scenarios for both indices are being equal to $SAIFI_{base}$ and $SAIDI_{base}$ respectively. Because the denominator of both $CAIFI_{base}$ and $CTAIDI_{base}$, in the worst-case scenario, will be equal to the total number of customers served, yielding values equal to $SAIFI_{base}$ and $SAIDI_{base}$. This is true with the fact that the nominators of $CAIFI_{base}$ and $SAIFI_{base}$ are always equal and nominators of $CTAIDI_{base}$ and $SAIDI_{base}$ are also always equal. This will yield to;

$CAIFI_{base} = SAIFI_{base}$

$CTAIDI_{base} = SAIDI_{base}$

For $ASUI_{base}$, it can be noticed that $ASUI = \frac{SAIDI}{8760}$. The number (8760) represents the total number of hours in a year. This number can be changed according to the common usage of hours in a year. However, it is irrelevant in this specific case, as the same number will eventually be multiplied by the $ASUI_{base}$ again. Therefore;

$$ASUI_{base} = \frac{SAIDI_{base}}{8760}$$

Finally, for $ASIFI_{base}$ and $ASIDI_{base}$, these indices differ from $SAIFI_{base}$ and $SAIDI_{base}$ in non-homogeneous systems only. The definition of homogeneous used here is that: in a homogeneous system, the ratio of the total number of customers served and the total kVA or kW of the system is 1. Therefore, one base can be used for both under the condition of being the largest. By choosing a $SAIFI_{base}$ and $SAIDI_{base}$ larger than $ASIFI$ and $ASIDI$, which is common as the values of $SAIFI$ and $SAIDI$ are usually larger than $ASIFI$ and $ASIDI$, we will reach;

$$ASIFI_{base} = SAIFI_{base}$$

$$ASIDI_{base} = SAIDI_{base}$$

For $SAIFI_{base}$, in general, if normalizing to the maximum, it should not be less the maximum frequency of interruption within the components of the system under study. Therefore;

$$W_1 = \frac{w_1}{SAIFI_{base}} + \frac{w_4 * N_T}{SAIFI_{base} * CN}$$

$$W_2 = \frac{w_2}{SAIDI_{base}} + \frac{w_{10}}{SAIDI_{base}} + \frac{w_5 * N_T}{SAIDI_{base} * CN}$$

$$W_3 = \frac{w_3}{\frac{SAIDI_{base}}{SAIFI_{base}}}$$

$$W_4 = \frac{w_6}{SAIFI_{base}}$$

$$W_5 = \frac{w_7}{SAIDI_{base}}$$

$$W_6 = \frac{w_8}{MAIFI_{base}}$$

$$W_7 = \frac{w_9}{MAIFI_{E_{base}}}$$

$$W_8 = w_{11}$$

$$W_9 = w_{12}$$

Weights $w_1 \cdots w_{12}$ selection process will be discussed in section (3.4 ). However, for all other values, the next section (3.3 ) discusses the proposed methodology for calculating them.

### 3.3 Normalization

The previously mentioned methods for normalization in literature are broadly used. However, normalizing by maximum, minimum, norm, or any other method of normalization that uses self-data, is not sufficient. Therefore, to achieve our objectives, they carry the same problems. To develop a unified reliability index, a new normalization technique is developed. In this technique, the problem of having indices with different ranges and weights is overcome. In addition, the normalized indices will be comparison-ready after normalization.

The key idea in this normalization methodology is using more information to distinguish between one system and the other. For instance, two systems with the same final SAIFI values do not necessarily report equal performance in a distribution engineering sense. They provide a mere number of how many times an average customer of this system has been interrupted during the study period. However, one of the systems could be significantly larger than the other. Thus, the larger system is more susceptible to outages and events. In the engineering sense of the number, the larger system should reflect some better performance indications compared to the smaller system.

Proceeding from (3.4), the main parts of the equation that needs to be reconsidered while calculating the unified index are the base values. These values should be calculated separately and inserted into the equation of the unified index. In other words, the base should not only normalize the values in a pure mathematical sense, it should also normalize the differences between one system and the other.

Generally, the differences between one system and the other are significant. However, the literature has shown that the number of customers and the loading level of these customers significantly affect the calculation of reliability indices. Though the current indices are calculated based on an average customer or average unit of power basis, it is unfair to compare a whole system with a relatively large number of customers and a high loading level with one that has a smaller number of customers and lower loading levels.

Therefore, the normalization will be conducted similarly to the per unit system in power systems. In the per unit system, the values are calculated based on a base value that has been assigned or calculated from other bases. Similarly, the base values of each system will be different from the others. For example, in a power system, the voltage base in a line can be different from the voltage base in the bus or the generator. Consequently, bases for each system will be calculated according to the same idea. Some bases will be assigned and others will be calculated.

The following table (Table 1) summarizes the values that utilities (operators) should report in their reliability reporting. These values are assumed to be calculated according to IEEE Std 1366™-2003 [3].

**TABLE 1: SUMMARY OF REQUIRED REPORTING DATA**

| Symbol | Description |
|---|---|
| $SAIFI$ | System Average Interruption Frequency Index |
| $SAIDI$ | System Average Interruption Duration Index |
| $ASIFI$ | Average System Interruption Frequency Index |
| $ASIDI$ | Average System Interruption Duration Index |
| $MAIFI$ | Momentary Average Interruption Frequency Index |
| $MAIFI_E$ | Momentary Average Interruption Event Frequency Index |
| $CEMI_k$ | Customers Experiencing Multiple Interruptions (sustained $> k$) |
| $CEMSMI_l$ | Customers Experiencing Multiple Sustained Interruption and Momentary Interruption Events (sustained and momentary $> l$) |
| $NT$ | Total number of customers served |
| $CN$ | Total number of customers who suffered sustained interruption |
| $CNT$ | Total number of customers momentarily interrupted |
| $\lambda_{s_{max}}$ | Maximum frequency of sustained interruption within the system (at load points level) |
| $\lambda_{m_{max}}$ | Maximum frequency of momentary interruption within the system (at load points level) |
| $\lambda_{me_{max}}$ | Maximum frequency of momentary interruption event within the system (at load points level) |

| | |
|---|---|
| $r_{max}$ | Maximum repair time within the system (at load points level) |

At this level, (3.4) unknowns for a system under study are the weights $w_1 \cdots w_{12}$, $SAIFI_{base}$, $SAIDI_{base}$, $MAIFI_{base}$, and $MAIFI_{E\,base}$.

General normalization tools suggest simple rescaling by dividing by the maximum. However, in situations for cross comparisons and other studies involving multiple systems, this is not adequate, as previously discussed. Therefore, incorporating the global maximum among all systems under study will make it more adequate. The next set of equations represents the proposed modification to $SAIFI_{base}$, $SAIDI_{base}$, $MAIFI_{base}$ and $MAIFI_{E\,base}$.

$$\boldsymbol{SAIFI_{base}} = \frac{\lambda_{s_{max_{local}}} + \lambda_{s_{max_{global}}}}{2} \tag{3.5}$$

$$\boldsymbol{SAIDI_{base}} = \frac{\lambda_{s_{max_{local}}} * r_{max_{local}} + \lambda_{s_{max_{global}}} * r_{max_{global}}}{2} \tag{3.6}$$

$$\boldsymbol{MAIFI_{base}} = \frac{\lambda_{m_{max_{local}}} + \lambda_{m_{max_{global}}}}{2} \tag{3.7}$$

$$\boldsymbol{MAIFI_{E_{base}}} = \frac{\lambda_{me_{max_{local}}} + \lambda_{me_{max_{global}}}}{2} \tag{3.8}$$

Following from the previous developed bases, the weights set $W_1 \cdots W_9$ becomes as follows;

$$\boldsymbol{W_1 = \frac{2 * w_1 + 2 * w_4 * \frac{N_T}{CN}}{\lambda_{s_{max_{local}}} + \lambda_{s_{max_{global}}}}} \quad \textbf{(3.9)}$$

$$\boldsymbol{W_2 = \frac{2 * (w_2 + w_{10}) + 2 * w_5 * \frac{N_T}{CN}}{\lambda_{s_{max_{local}}} * r_{max_{local}} + \lambda_{s_{max_{global}}} * r_{max_{global}}}} \quad \textbf{(3.10)}$$

$$\boldsymbol{W_3 = \frac{w_3}{\left(\frac{\lambda_{s_{max_{local}}} * r_{max_{local}} + \lambda_{s_{max_{global}}} * r_{max_{global}}}{\lambda_{s_{max_{local}}} + \lambda_{s_{max_{global}}}}\right)}} \quad \textbf{(3.11)}$$

$$\boldsymbol{W_4 = \frac{2 * w_6}{\lambda_{s_{max_{local}}} + \lambda_{s_{max_{global}}}}} \quad \textbf{(3.12)}$$

$$\boldsymbol{W_5 = \frac{2 * w_7}{\lambda_{s_{max_{local}}} * r_{max_{local}} + \lambda_{s_{max_{global}}} * r_{max_{global}}}} \quad \textbf{(3.13)}$$

$$\boldsymbol{W_6 = \frac{2 * w_8}{\lambda_{m_{max_{local}}} + \lambda_{m_{max_{global}}}}} \quad \textbf{(3.14)}$$

$$\boldsymbol{W_7 = \frac{2 * w_9}{\lambda_{me_{max_{local}}} + \lambda_{me_{max_{global}}}}} \quad \textbf{(3.15)}$$

$$\boldsymbol{W_8 = w_{11}} \quad \textbf{(3.16)}$$

$$\boldsymbol{W_9 = w_{12}} \quad \textbf{(3.17)}$$

Finally, the general formulation is enhanced for multiple system studies. The individual weights $w_1 \cdots w_{12}$ will be discussed in the following section.

## 3.4 Unification

In this section, the problem of assigning individual weights for each index of the IEEE Std 1366™-2003 [3] is tackled. These weights play a significant role in deciding which system is performing best. In any case, all weights should be kept constant among all systems under study, and their summation must be equal to one. The common ways for assigning these values are either by experience or relative cost (reliability worth) of each index. The following subsections discuss these methods and propose new methods for this task.

### 3.4.1 Equal Weights Method

One simple way to combine theses indices is to give each an equal weight (i.e. averaging). This approach is not practical, as indices differ in their impact on reliability, so it is beneficial to perform quick assessments, especially when weights are unknown and the systems under study have similar topology. In such cases, the effect of each index toward the unified index is the same. Thus, (3.4) will be as described in the following equation (3.18):

$$
\begin{aligned}
UI = {} & \frac{1/6 + 1/6 * \frac{N_T}{CN}}{\lambda_{s_{max_{local}}} + \lambda_{s_{max_{global}}}} SAIFI + \frac{1/3 + 1/6 * \frac{N_T}{CN}}{\lambda_{s_{max_{local}}} * r_{max_{local}} + \lambda_{s_{max_{global}}} * r_{max_{global}}} SAIDI \\
& + \frac{1}{12 * \left( \frac{\lambda_{s_{max_{local}}} * r_{max_{local}} + \lambda_{s_{max_{global}}} * r_{max_{global}}}{\lambda_{s_{max_{local}}} + \lambda_{s_{max_{global}}}} \right)} \frac{SAIDI}{SAIFI} + \frac{1}{6 * \left( \lambda_{s_{max_{local}}} + \lambda_{s_{max_{global}}} \right)} ASIFI \\
& + \frac{1}{6 * \left( \lambda_{s_{max_{local}}} * r_{max_{local}} + \lambda_{s_{max_{global}}} * r_{max_{global}} \right)} ASIDI \\
& + \frac{1}{6 * \left( \lambda_{m_{max_{local}}} + \lambda_{m_{max_{global}}} \right)} MAIFI + \frac{1}{6 * \left( \lambda_{me_{max_{local}}} + \lambda_{me_{max_{global}}} \right)} MAIFI_E + \frac{CEMI_k}{12} \\
& + \frac{CEMSMI_l}{12}
\end{aligned}
\tag{3.18}
$$

### 3.4.2 Different Weights Method

Depending on the impact each one has, different weights can be assigned for each index. The difference in weights comes from many factors. For instance, an industry type that is concerned with the duration of each interruption, rather than how many short interruptions happen, should be assigned larger weights for the duration indices. Other industries may reflect dissatisfaction with the frequency of interruptions regardless of duration, and these must be assigned different weights.

A general consensus regarding this issue is hard to achieve. However, developing curves for different weights may be achieved by changing the weights interchangeably until reaching a desired depth of curve. In a general sense, these weights depend on the authority performing such studies and will differ between one authority and another. The following figure (Figure 8) represents the change of the unified index if all weights are kept constant except for two. The selected weights are for SAIFI and SAIDI. The effect on the unified index curve of changing different weights is different. This figure clearly illustrates the effects of changing weights on the unified index.

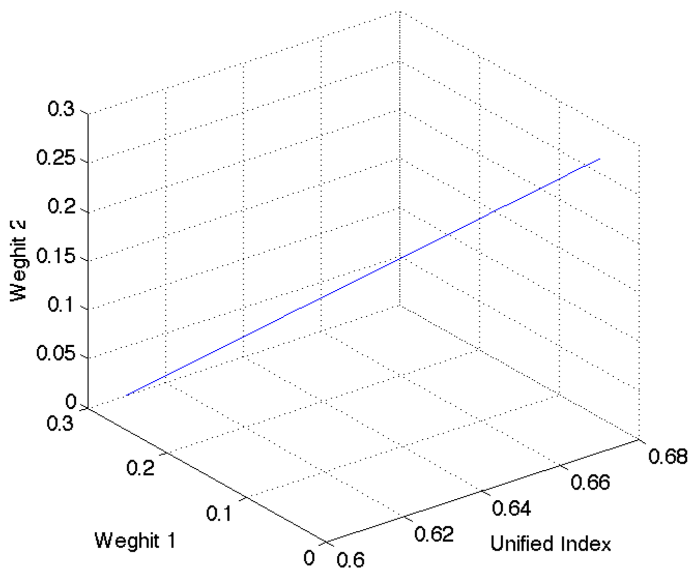


**FIGURE 8: EFFECTS OF CHANGING WEIGHTS ON THE UNIFIED INDEX**

Another approach can be taken. In this approach, an optimization issue needs to be solved in order to evaluate the weights. The optimization problem minimizes the sum of all unified indices of all systems by finding the optimum individual weights. This problem is constrained first because the sum of weights must equal one, and the value of each unified index does not equal zero and cannot exceed one. Minimum weight can also be constrained.

Equation (3.4) in a minimization of summation form can be used as an objective function. In doing so, the control variables are the individual weights, leading to a minimum sum. This sum is constrained by the fact that the sum of all weights is equal to one. In order to avoid neglecting some weights, minimum and maximum values are used as constrains. These values may differ; however, in this work, the range is taken to be plus or minus 60% of the weight when all are equal. The reasons for choosing the 60% figure are to allow more room for weights to be optimized and not to allow for smaller weights to result in a negligible index. However, choosing this number was primarily based on experience with the optimization problem. Moreover, it is easier for an expert to decide on one number rather than deciding on each single weight based on one utility, let alone multiple system studies. The following set of equations, (3.19)-(3.21), represents the mathematical formulation of the optimization problem. Starting with the objective function to the equality constraint and finally the inequality constraints respectively.

$$\boldsymbol{Obj = min \sum_{i=1}^{NS} UI_i} \tag{3.19}$$

Where;

$$UI = \frac{w_1}{SAIFI_{base}}\frac{CI}{N_T} + \frac{w_2}{SAIDI_{base}}\frac{CMI}{N_T} + \frac{w_3}{CAIDI_{base}}\frac{CMI}{CI} + \frac{w_4}{CAIFI_{base}}\frac{CI}{CN} + \frac{w_5}{CTAIDI_{base}}\frac{CMI}{CN} + \frac{w_6}{ASIFI_{base}}\frac{\sum_{i=1}^{NLP} L_i}{LT} + \frac{w_7}{ASIDI_{base}}\frac{\sum_{i=1}^{NLP} L_i * r_i}{LT} + \frac{w_8}{MAIFI_{base}}\frac{\sum_{i=1}^{NLP} IM_i * N_{mi}}{N_T} + \frac{w_9}{MAIFI_{E_{base}}}\frac{\sum_{i=1}^{NLP} IM_E * N_{mi}}{N_T} + \frac{w_{10}}{ASUI_{base}}\frac{CMI}{8760 * N_T} + \frac{w_{11}}{CEMI_{k_{base}}}\frac{CN_k}{N_T} + \frac{w_{12}}{CEMSMI_{l_{base}}}\frac{CNT_l}{N_T}$$

$NS = Number\ of\ Systems\ under\ Study$

$$\boldsymbol{\sum_{i=1}^{12} w_i = 1} \tag{3.20}$$

$$UI_i \leq 1$$
$$\frac{1}{12} - \frac{1}{12} * 60\% \leq w_i \leq \frac{1}{12} + \frac{1}{12} * 60\% \tag{3.21}$$

### 3.5 Ratios

Although this development of the unified index is adequate in multiple system studies, it does not promote standardization in its current situation. In this section, an interest of how standardization can be made on reliability assessment and practice is explored. Factors that may lead to standards in reliability assessment and practice are also discussed. These factors are dependent on current reliability measures (system and load point levels). The fundamental principle in developing such ratios and factors is to be able to compare among system and construct fair standards. Each alone is not sufficient to form a comprehensive idea of a system or to impose a standard. However, together they can lead to standardization.

#### 3.5.1 Deviations

Deviations in the sense of voltage (power quality) are not addressed in this section. Instead, the exploration is of more metaphorical deviations between two distinct reliability measures. The deviations between the average system interruption frequency and duration between SAIFI, SAIDI and ASIFI, ASIDI have provoked this factor.

It is known that all four indices (for frequency and duration) depend on the frequency of interruption in each load point; however, the interpretation is different. A system can have SAIFI and SAIDI equal to 0.3 and 4, respectively while the values of ASIFI and ASIDI are equal to 0.2 and 3. These values can be in another arrangement in another system. This is because SAIFI and SAIDI use the number of customers where ASIFI and ASIDI use load (in kVA or kW). Systems or subsystems that are majorly industrial can yield better ASIFI and ASIDI when compared with residential areas with the same other factors: frequency of interruption and time to repair.

Due to the lack of homogeneity in distribution systems, not every customer requires equal demand (kVA/customers count), which causes the variation frequency indices SAIFI and ASIFI and duration indices SAIDI and ASIDI. In a perfectly homogeneous system, frequency and duration indices will be equal to each other respectively. However, non-homogeneous systems (majority) can yield misleading results. The following table (Table 2) illustrates an example of artificial systems to highlight the idea of this factor.

**TABLE 2: DEVIATIONS EXAMPLE**

| | Industrial system | Residential system |
|---|---|---|
| λ | 0.3 and 0.4 | 0.3 and 0.4 |
| r | 3 and 4 | 3 and 4 |
| Customers | 1 and 2 | 70 and 50 |
| Load | 100 kVA and 200 kVA | 100 kVA and 200 kVA |
| SAIFI | 0.3667 | <u>0.3417</u> |
| ASIFI | 0.3667 | 0.3667 |
| SAIDI | 1.3667 | <u>1.1917</u> |
| ASIDI | 1.3667 | 1.3667 |

In the previous example, it is clear from SAIFI and SAIDI that the residential system is performing better overall; however, ASIFI and ASIDI are indicating that both systems are performing in a similar fashion. This leads to the idea of deviation from homogeneity. By factoring both SAIFI over ASIFI and SAIDI over ASIDI or the opposite, a factor of deviation will result. This factor can limit any inherited favorability of indices toward specific types of systems. The factor is defined as the absolute deviation from a homogenous (equal to one) ratio between SAIFI and ASIFI and SAIDI and ASIDI. The next equation (3.22) mathematically represents this factor.

$$devFR = \left|1 - \frac{SAIFI}{ASIFI}\right|$$

$$devDR = \left|1 - \frac{SAIDI}{ASIDI}\right| \tag{3.22}$$

Where 'devFR' and 'devDR' are the deviation factors for frequency and duration indices, respectively.

### 3.5.2 Sustained to Momentary

This factor provides a measure of how many momentary interruptions one sustains in a system. The importance of this measure is to show the strength of a system's performance in not allowing momentary interruption to become sustained. For instance, for a system with a MAIFI equal to 14 and a SAIFI equal to 7, the conclusion will be that the strength of this system indicates that, out of two momentary interruptions, one sustained interruption will result. In (3.23), a mathematical representation of this ratio is illustrated.

$$SM = \frac{SAIFI}{MAIFI} \tag{3.23}$$

### 3.5.3 Momentary Events

Momentary events cause momentary interruptions. Knowing the ratio of how many momentary interruptions per single momentary event can be useful in assessing the strength of each utility. The following equation (3.24) represents this factor.

$$MME = \frac{MAIFI_E}{MAIFI} \tag{3.24}$$

### 3.5.4 Unavailability

The availability of a system is defined by the number of hours the customers were not served in a reporting period (usually one year). The unavailability is the direct opposite of that and it is described mathematically in (3.25).

$$uA = ASUI = \frac{\sum_{j=1}^{NLP}\left(U_{L_j}^{S} * N_{L_j}\right)}{\sum_{j=1}^{NLP}\left(8760 * N_{L_j}\right)} \tag{3.25}$$

### 3.6 Standardization

In the previous section, ratios were developed with the basis of being able to use them in cross-comparisons and standard design. The following equations (3.26) and (3.27) represent the methodology of cross -comparison and standard design. The numbers used in standards are arbitrary for illustration purposes. The major point in this section is that developed ratios can be used in designing a standard for reliability performance. The major difference in using such a methodology is the independency from a special normalization methodology. However, it still needs to be normalized. On the other hand, the numbers obtained from each index can be directly compared with other systems because it reflects ratios rather than actual indices. For instance, SAIFI of two systems is not a totally fair index to use in comparison as it is because of the aforementioned reason such as system loading level and size; where devFR can be used because it is a ratio reflecting performance in per unit.

$$UI = w_1 \frac{devFR}{devFR_{base}} + w_2 \frac{devDR}{devDR_{base}} + w_3 \frac{SM}{SM_{base}} + w_4 \frac{MME}{MME_{base}} + w_5 \frac{uA}{uA_{base}} \tag{3.26}$$

$$\begin{aligned} &devFR \;\&\; devDR < 20\% \\ &SM < 25\% \\ &MME < 25\% \\ &uA < 5\% \end{aligned} \tag{3.27}$$

Chapter 4

# Verification

## 4.1 Introduction

This chapter addresses known assessments. The goal of this chapter is to verify whether or not the known assessments and ranks are achieved. In order to do so, case studies will be presented and studied. These cases have one thing in common: rank is known. First, systems which are relatively similar, and with known rank, are studied. Second, systems with relatively different topologies but approximately equal indices are analyzed. These systems are based on published Test Systems [40].

Some realistic additions or deductions of test systems parts are made to illustrate and verify the methodology described in this work. These modifications will be mentioned when systems are presented.

In [40], the two test systems provided are, first, a 38-load-point with 7 feeders system (i.e. Bus4) and, second, a 22-load-point 4-feeder system (i.e. Bus2). The reference provides comprehensive data on the two systems with regard to loading and failure rates for two cases: lines or cables. Moreover, the paper suggests different (six for every case) protection and restoration topologies. As a result, the two systems with the two cases of lines or cables and the six different topologies yield to a total number of options for each test system of 12. In this chapter, the methodology described in this work will be implemented and compared with the explicit and implicit ranking described in [40]. Not all cases will be used for the verification phase; some will be used in the next chapter (Testing and Evaluation). The following two figures (Figure 9 and Figure 10) show a simple single line diagram of the two test systems.

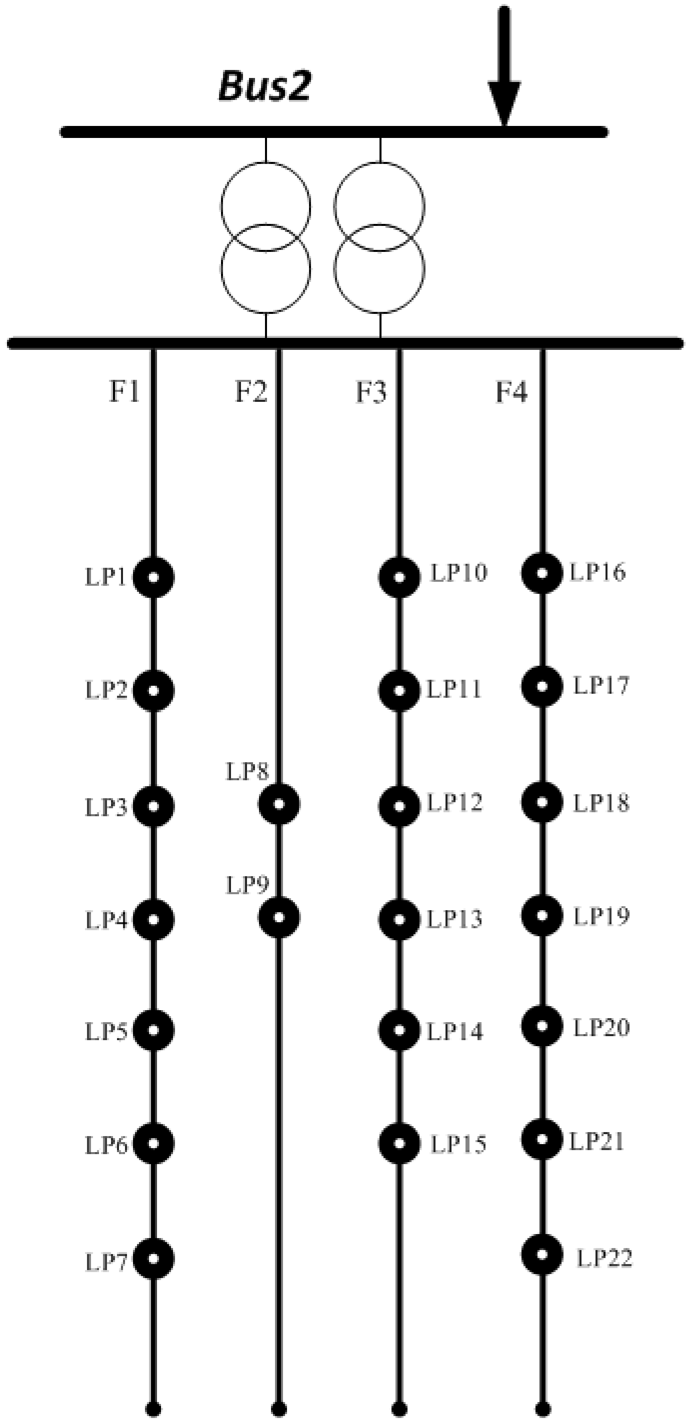


**FIGURE 9: FIRST TEST SYSTEM BUS2**

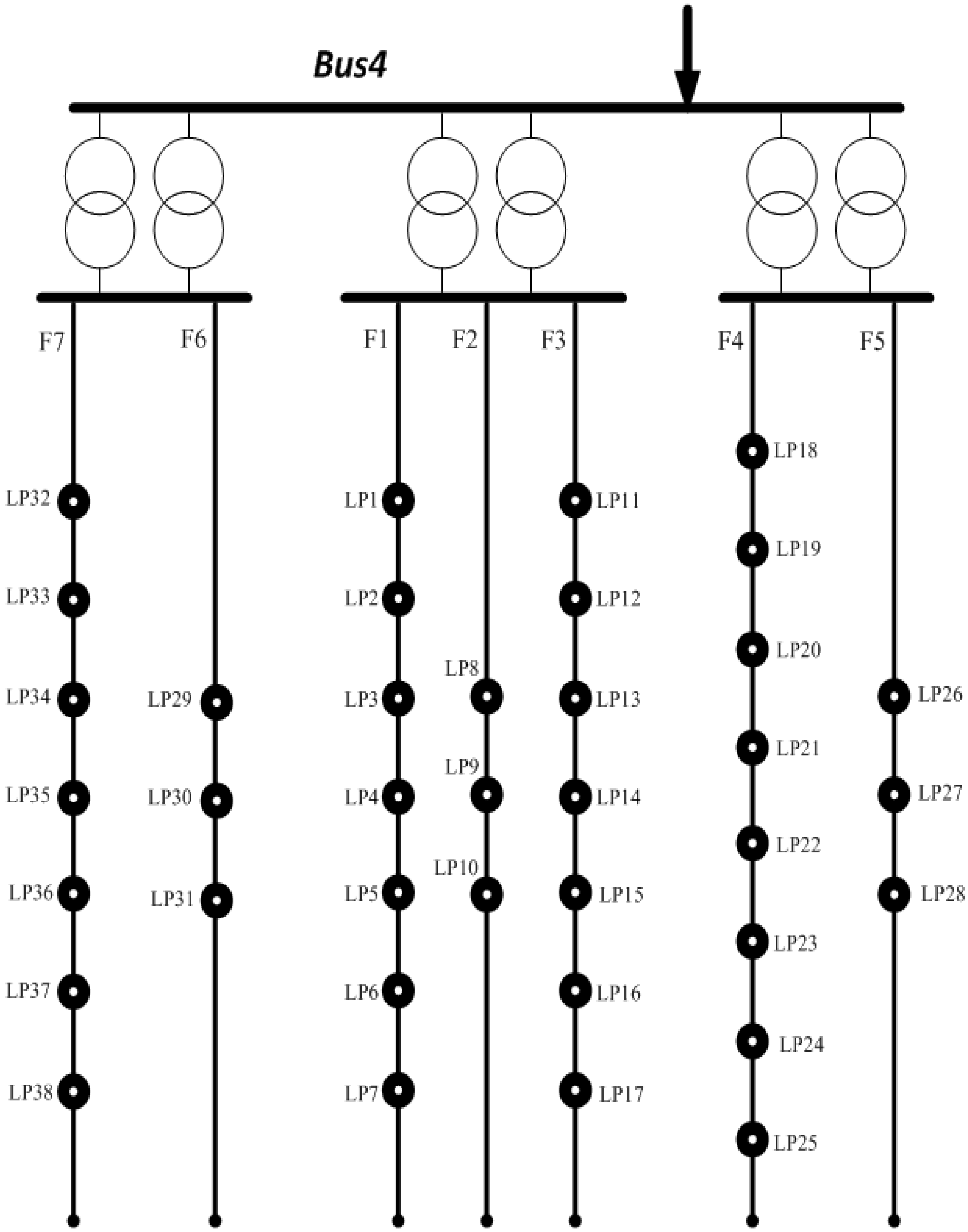


**FIGURE 10: SECOND TEST SYSTEM BUS4**

The aforementioned test systems have several topologies; these will be coded and described in the following table (Table 3). Each first letter in the code represent a topology. Description of each topology is listed in the table. The second letter code whether it is cables or lines. The number by the end of each code denotes whether it is belonging to bus 4 or bus2. In Table 4, the reliability data (system indices) is illustrated. The values are either directly quoted from [40] or calculated with accordance to [3].

**TABLE 3: TEST SYSTEMS CODES**

| | | Code | Disconnects | Fuses | Alt. supply | Repair or Replace Transformer |
|---|---|---|---|---|---|---|
| Bus4 | Cables | AC4 | Yes | Yes | Yes | Repair |
| | | BC4 | No | No | No | Repair |
| | | CC4 | No | Yes | No | Repair |
| | | DC4 | Yes | No | Yes | Repair |
| | | EC4 | Yes | Yes | Yes | Replace |
| | | FC4 | Yes | No | No | Repair |
| | Lines | AL4 | Yes | Yes | Yes | Repair |
| | | BL4 | No | No | No | Repair |
| | | CL4 | No | Yes | No | Repair |
| | | DL4 | Yes | No | Yes | Repair |
| | | EL4 | Yes | Yes | Yes | Replace |
| | | FL4 | Yes | No | No | Repair |
| Bus2 | Cables | AC2 | Yes | Yes | Yes | Repair |
| | | BC2 | No | No | No | Repair |
| | | CC2 | No | Yes | No | Repair |
| | | DC2 | Yes | No | Yes | Repair |
| | | EC2 | Yes | Yes | Yes | Replace |
| | | FC2 | Yes | No | No | Repair |
| | Lines | AL2 | Yes | Yes | Yes | Repair |
| | | BL2 | No | No | No | Repair |
| | | CL2 | No | Yes | No | Repair |
| | | DL2 | Yes | No | Yes | Repair |
| | | EL2 | Yes | Yes | Yes | Replace |
| | | FL2 | Yes | No | No | Repair |

**TABLE 4: TEST SYSTEMS DATA**

| | SAIFI | SAIDI | CAIDI | ASIFI | ASIDI | MAIFI | MAIFI-E | CEMI | CEMSMI |
|---|---|---|---|---|---|---|---|---|---|
| AL4 | 0.3 | 3.47 | 11.56 | 0.255631001 | 2.209519727 | 14.23612058 | 5.338545218 | 0.422964133 | 0.134217426 |
| BL4 | 0.682 | 24.64 | 36.13 | 0.581134475 | 15.68950031 | 62.17810783 | 23.31679044 | 0.961538462 | 0.586212061 |
| CL4 | 0.3 | 4.42 | 14.74 | 0.255631001 | 2.814431468 | 18.02404998 | 6.759018741 | 0.422964133 | 0.169929833 |
| DL4 | 0.682 | 5.44 | 7.98 | 0.581134475 | 3.463915653 | 14.5176401 | 5.444115039 | 0.961538462 | 0.136871578 |
| EL4 | 0.3 | 0.62 | 2.07 | 0.255631001 | 0.394784505 | 2.912332404 | 1.092124652 | 0.422964133 | 0.027457323 |
| FL4 | 0.682 | 12.45 | 18.25 | 0.581134475 | 7.927527552 | 31.91252962 | 11.96719861 | 0.961538462 | 0.300869718 |
| AC4 | 0.19 | 4.29 | 22.58 | 0.160477624 | 2.994538627 | 24.172013 | 9.064504875 | 0.267877284 | 0.227892518 |
| BC4 | 0.462 | 32.36 | 70.1 | 0.390214012 | 22.58817482 | 100.7203111 | 37.77011665 | 0.651364764 | 0.949586007 |
| CC4 | 0.19 | 8.25 | 43.38 | 0.160477624 | 5.758728129 | 46.1913646 | 17.32176173 | 0.267877284 | 0.435489853 |
| DC4 | 0.462 | 6.97 | 15.11 | 0.390214012 | 4.865252734 | 22.2379734 | 8.339240024 | 0.651364764 | 0.20965849 |
| EC4 | 0.19 | 1.45 | 7.62 | 0.160477624 | 1.012140095 | 8.346094176 | 3.129785316 | 0.267877284 | 0.078686554 |
| FC4 | 0.462 | 16.8 | 36.38 | 0.390214012 | 11.72686455 | 52.60726285 | 19.72772357 | 0.651364764 | 0.495978618 |
| AL2 | 0.248 | 3.61 | 14.55 | 0.231028069 | 3.072551865 | 17.36926395 | 6.51347398 | 0.34965035 | 0.163756543 |
| BL2 | 0.602 | 22.5 | 37.48 | 0.560802007 | 19.150254 | 64.23444481 | 24.0879168 | 0.848748026 | 0.605599102 |
| CL2 | 0.248 | 4.16 | 16.77 | 0.231028069 | 3.540669185 | 19.9597578 | 7.484909176 | 0.34965035 | 0.188179589 |
| DL2 | 0.602 | 6.74 | 11.19 | 0.560802007 | 5.736564977 | 19.86349359 | 7.448810095 | 0.848748026 | 0.187272015 |
| EL2 | 0.248 | 0.77 | 3.08 | 0.231028069 | 0.655364248 | 3.987513854 | 1.495317695 | 0.34965035 | 0.037594079 |
| FL2 | 0.602 | 9.93 | 16.49 | 0.560802007 | 8.451645434 | 28.82755795 | 10.81033423 | 0.848748026 | 0.271784761 |
| AC2 | 0.159 | 5.02 | 31.65 | 0.146572533 | 4.446811835 | 33.13790749 | 12.42671531 | 0.22417099 | 0.312422519 |
| BC2 | 0.409 | 29.26 | 71.52 | 0.37703249 | 25.91906659 | 101.9880793 | 38.24552972 | 0.576641101 | 0.961538462 |
| CC2 | 0.159 | 7.3 | 46.07 | 0.146572533 | 6.466479361 | 48.11364152 | 18.04261557 | 0.22417099 | 0.453612983 |
| DC2 | 0.409 | 9.04 | 22.09 | 0.37703249 | 8.007804579 | 31.93906965 | 11.97715112 | 0.576641101 | 0.301119936 |
| EC2 | 0.159 | 2.17 | 13.69 | 0.146572533 | 1.922227427 | 14.47023997 | 5.426339988 | 0.22417099 | 0.136424692 |
| FC2 | 0.409 | 13.1 | 32.03 | 0.37703249 | 11.60423009 | 46.01621006 | 17.25607877 | 0.576641101 | 0.433838505 |

In these test systems, the different weights optimization problem yielded the values listed in Table 5. Values are compared with the equal weights method to illustrate the difference. The problem was solved using Matlab, and the documentation associated with Matlab was consulted [41].

**TABLE 5: DIFFERENT WEIGHTS RESULTS**

| | Different | Equal |
|---|---|---|
| w1 | 0.033333333 | 0.083333333 |
| w2 | 0.133333333 | 0.083333333 |
| w3 | 0.133333333 | 0.083333333 |
| w4 | 0.033333333 | 0.083333333 |
| w5 | 0.033333333 | 0.083333333 |
| w6 | 0.033333333 | 0.083333333 |
| w7 | 0.133333333 | 0.083333333 |
| w8 | 0.093236763 | 0.083333333 |
| w9 | 0.073429904 | 0.083333333 |
| w10 | 0.133333333 | 0.083333333 |
| w11 | 0.033333333 | 0.083333333 |
| w12 | 0.133333333 | 0.083333333 |
| $\sum PI$ | 9.849356245 | 12.95229909 |

## 4.2 Case Study I: Similar Systems

In this case study, two systems were chosen within one case (Bus4, Bus2, Lines, and/or Cables). However, the rank of the chosen systems is known before in order to compare it with results obtained from applying new methodology. Two cases were chosen for this study. The first involves 4 systems with known rank. Two systems from each bus were chosen so that one or more indices are equal within the same bus. The following table (Table 6) summarizes the required data to be reported from each system.

**TABLE 6: CASE STUDY I DATA**

| | AL4 | AL2 | EL4 | EL2 |
|---|---|---|---|---|
| SAIFI | 0.3 | 0.248 | 0.3 | 0.248 |
| SAIDI | 3.47 | 3.61 | 0.62 | 0.77 |
| ASIFI | 0.255631001 | 0.231028069 | 0.255631001 | 0.231028069 |
| ASIDI | 2.209519727 | 3.072551865 | 0.394784505 | 0.655364248 |
| MAIFI | 14.23612058 | 17.36926395 | 2.912332404 | 3.987513854 |
| MAIFI-E | 5.338545218 | 6.51347398 | 1.092124652 | 1.495317695 |
| CEMI | 0.422964133 | 0.34965035 | 0.422964133 | 0.34965035 |
| CEMSMI | 0.134217426 | 0.163756543 | 0.027457323 | 0.037594079 |
| NT | 4779 | 1908 | 4779 | 1908 |
| FIs_max | 0.312 | 0.25792 | 0.312 | 0.25792 |
| FIm_max | 14.80556541 | 18.06403451 | 3.028825701 | 4.147014408 |
| FIme_max | 5.552087027 | 6.774012939 | 1.135809638 | 1.555130403 |
| r_max | 12.0224 | 15.132 | 2.1528 | 3.2032 |
| RANK | 3 | 4 | 1 | 2 |
| UI | 0.252475007 | 0.272309887 | 0.142405685 | 0.148323366 |
| Norm.Avg | 0.232501957 | 0.229920106 | 0.163183198 | 0.148250847 |

The results indicate that, generally, configuration ‘E’ is better than configuration ‘A’ which is consonant with the information suggested in [40] as ‘E’ is similar to ‘A’ other than the repair or replacement of transformers.

The results pose evidence that comparison on the basis of single or two indices is not sufficient. For instance, EL2 has lower SAIFI, ASIFI, and CEMI than EL4, but EL4 has an additional 9 indices that are lower than EL2. Moreover, EL4 is more than double the size of EL2. This also appears between AL4 and AL2.

On the other hand, the table shows that using simple normalized averaging may overcome some, but not all, inadequacies. For instance, simple normalized averaging detected that configuration 'E' is superior to configuration 'A'; however, it did not detect the size effects on the decision.

### 4.3 Case Study II: Same Topology

In this study, cases with identical topology (A, B, C, D, E, or F) are compared with each other but in different case (i.e. lines or cables). Lines require shorter repair time than do cables; however, cables are less susceptible to outages than are lines. In such a problem, comprehensive reliability studies need to be conducted in order to decide which is performing better than the other. This case describes two systems with identical configuration, size, loading, and number of customers with difference of cables or lines. In Table 7, it is clear that lines perform better overall with this configuration and system size; nevertheless, the normalized averaging technique shows that cables are more reliable. Except for three indices, all other reliability indices are better performing in lines than cables.

An identical case has been studied on the smaller system. The results were consistent with the methodology described in this work. The normalized average yielded the same decision as the new methodology. This discrepancy in the results of normalized averaging inherently ignores system size and the relative advancement between systems.

**TABLE 7: CASE STUDY II**

| | SAIFI | SAIDI | CAIDI | ASIFI | ASIDI | MAIFI | MAIFI-E | CEMI | CEMSMI | UI | norm.Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AC4 | 0.19 | 4.29 | 22.58 | 0.16 | 2.99 | 24.17 | 9.06 | 0.27 | 0.23 | 0.31 | 0.23 |
| AL4 | 0.30 | 3.47 | 11.56 | 0.26 | 2.21 | 14.24 | 5.34 | 0.42 | 0.13 | 0.25 | 0.23 |
| | AC4 | AL4 | AL4 | AC4 | AL4 | AL4 | AL4 | AC4 | AL4 | AL4 | AL4 |
| EC4 | 0.19 | 1.45 | 7.62 | 0.16 | 1.01 | 8.35 | 3.13 | 0.27 | 0.08 | 0.18 | 0.14 |
| EL4 | 0.30 | 0.62 | 2.07 | 0.26 | 0.39 | 2.91 | 1.09 | 0.42 | 0.03 | 0.14 | 0.16 |
| | EC4 | EL4 | EL4 | EC4 | EL4 | EL4 | EL4 | EC4 | EL4 | EL4 | EC4 |

# Chapter 5

# Testing and Evaluation

## 5.1 Introduction

In the previous chapter (Chapter 4), the methodology proved an adequate and fair comparison using the unified reliability index. This chapter puts the methodology of the developed unified index to the test in order to evaluate its performance. The main objective of the unified index is to be able to fairly and accurately compare and cross-compare systems. All test systems, cases, and configurations, will be compared using both the developed unified reliability index and the normalized averaging methodology. Analysis and discussion of the results will be conducted. Although the normalized averaging technique may result in some correct decisions, the downsides of this will be apparent when compared across all systems with the unified index methodology.

Test systems have been thoroughly described in (4.1 ). This chapter will be divided into two cases: first, Factual test systems' data, and second, Artificial systems' data. In both cases, the codes assigned in (4.1 ) will remain the same except for the artificial systems where an 'X' mark will be added to highlight that it is an artificial one. The sole purpose of these artificial yet possible and practical systems is to further evaluate the performance of both the developed unified reliability index and the normalized averaging technique.

## 5.2 Case Study I: Factual Systems

The following table illustrates results obtained from the implementation of the developed unified reliability index and the normalized averaging methodologies for comparison of systems' reliability performance. The ranking according to each methodology is highlighted in the table. However, cases where normalized averaging differs from the unified index ranking will be discussed later in this section.

**TABLE 8: FACTUAL SYSTEMS RANKING**

| UI | | Norm.Avg | |
|---|---|---|---|
| EL4 | 0.142405685 | EC4 | 0.14102603 |
| EL2 | 0.148323366 | EL2 | 0.148250847 |
| EC4 | 0.1785731 | EL4 | 0.163183198 |
| EC2 | 0.22624366 | EC2 | 0.164086043 |
| AL4 | 0.252475007 | AL2 | 0.229920106 |
| AL2 | 0.272309887 | AL4 | 0.232501957 |
| CL4 | 0.286371524 | AC4 | 0.234241776 |
| DL4 | 0.292680735 | CL2 | 0.245730906 |
| CL2 | 0.294539563 | CL4 | 0.25567768 |
| AC4 | 0.312740552 | AC2 | 0.273608941 |
| DL2 | 0.341352611 | CC2 | 0.361444008 |
| DC4 | 0.347422815 | CC4 | 0.363969741 |
| AC2 | 0.372888943 | DC4 | 0.366090105 |
| FL2 | 0.421085258 | DC2 | 0.409430086 |
| DC2 | 0.423813268 | DL4 | 0.426707646 |
| FL4 | 0.450987977 | DL2 | 0.433418296 |
| CC4 | 0.47365228 | FL2 | 0.493542257 |
| CC2 | 0.477152107 | FC2 | 0.50023937 |
| FC2 | 0.528939012 | FL4 | 0.542719791 |
| FC4 | 0.578579865 | FC4 | 0.561559041 |
| BL4 | 0.662412973 | BL2 | 0.730897527 |
| BL2 | 0.672225852 | BL4 | 0.744546164 |
| BC4 | 0.842809234 | BC2 | 0.861378134 |
| BC2 | 0.84937097 | BC4 | 0.8711834 |

The numbers in the previous table represent the performance indicator according to each methodology. Direct comparison between numbers in one method with one in the other method is not correct. However, the purpose of the table was to show rank according to each method.

For instance, EC4 and EL4 rank according to each methodology was previously discussed in the verification phase. Nevertheless, this has been performed because of the notion of superiority between them. Table 9 illustrates the values of the individual indices of CL4 and CL2. This case shows conflicting results between the two methodologies.

**TABLE 9: CASE I OF CONFLICTING RESULTS**

| | SAIFI | SAIDI | CAIDI | ASIFI | ASIDI | MAIFI | MAIFI-E | CEMI | CEMSMI | PI | norm.Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CL4 | 0.300 | 4.420 | 14.740 | 0.256 | 2.814 | 18.024 | 6.759 | 0.423 | 0.170 | 0.286 | 0.256 |
| CL2 | 0.248 | 4.160 | 16.770 | 0.231 | 3.541 | 19.960 | 7.485 | 0.350 | 0.188 | 0.295 | 0.246 |
| | CL2 | CL2 | CL4 | CL2 | CL4 | CL4 | CL4 | CL2 | CL4 | CL4 | CL2 |

These results clearly indicate the importance of incorporating other indices and using new tools because SAIFI and SAIDI alone are not sufficient metrics. Other indices, such as CAIDI and MAIFI, can significantly affect reliability of systems and customer satisfaction. Therefore, these indices are gaining popularity amongst utilities and regulators. This should not mean neglecting widely accepted indices such as SAIFI, SAIDI, ASIFI, and ASIDI.

In this case, CL2 was superior in the ‘norm.Avg’ method due to lack of knowledge in this methodology regarding size effects and customer satisfaction (CAIDI). These factors are incorporated into the unified reliability index (UI), resulting in a more accurate decision.

Another example is shown in Table 10. In this case, the two systems are of the same size but different topologies. One system ‘DL2’ is superior in every aspect of reliability except number of interruptions. SAIFI and ASIFI indicate superiority to ‘CC2’ over ‘DL2’, while SAIDI, CAIDI, MAIFI, MAIFI-E, CEMI, and CEMSMI indicate the opposite. Moreover, SAIFI and ASIFI both provide a very similar knowledge that even would be exact in homogenous systems.

**TABLE 10: CASE II OF CONFLICTING RESULTS**

| | SAIFI | SAIDI | CAIDI | ASIFI | ASIDI | MAIFI | MAIFI-E | CEMI | CEMSMI | PI | norm.Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DL2 | 0.602 | 6.740 | 11.190 | 0.561 | 5.737 | 19.863 | 7.449 | 0.849 | 0.187 | 0.341 | 0.433 |
| CC2 | 0.159 | 7.300 | 46.070 | 0.147 | 6.466 | 48.114 | 18.043 | 0.224 | 0.454 | 0.477 | 0.361 |
| | CC2 | DL2 | DL2 | CC2 | DL2 | DL2 | DL2 | CC2 | DL2 | DL2 | CC2 |

This clearly indicates the weaknesses of simple normalized averaging. The difference in customer average interruption duration index (CAIDI) is significant and alone may indicate superiority.

The following figure (Figure 11) illustrates the difference with regard to normalization. Part of the unified reliability index's role is to normalize the numbers to better compare and combine. The simple normalization to maximum, minimum, or norm would not be as comprehensive as the methodology utilized.

In addition to better normalizing capabilities, the unified reliability index incorporates system size and the ability to compare based on one index, if that is a particular interest, as each system has its own normalizing base.

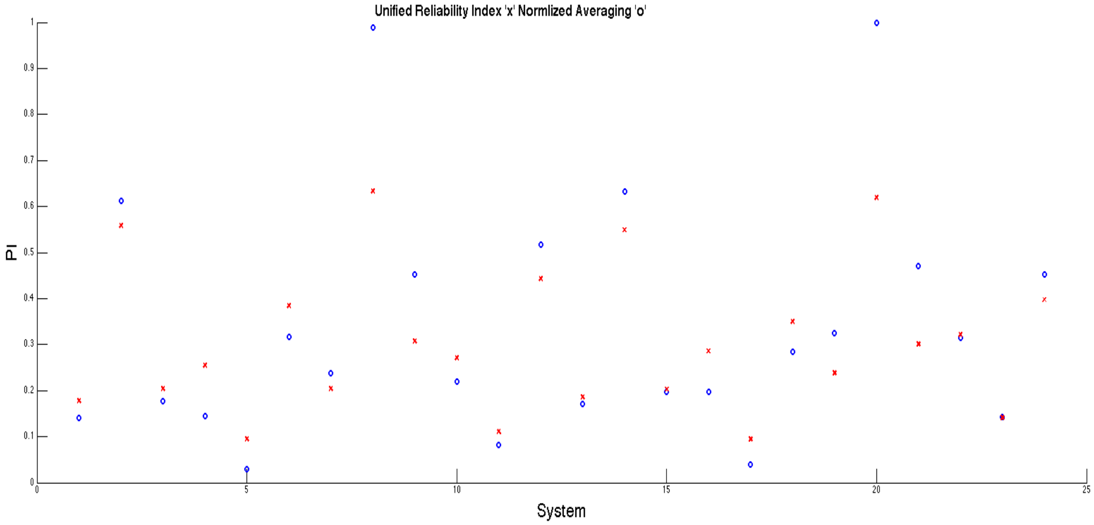


**FIGURE 11: NEW NORMALIZATION METHODOLOGY**

### 5.3 Case Study II: Artificial Systems

In this section, artificial systems will be built for highlighting other points. First, it is useful in comparing two systems sharing 12 reliability indices with a difference only in size of system. Second, it is helpful if all indices are different but the resulting average is equal.

In these two cases, the normalized averaging methodology will fail to distinguish the superior preforming system. On the other hand, the unified reliability index will succeed in determining the hidden strengths of each and will compare accordingly. Nevertheless, if the unified index yielded equal numbers for systems under study, this can only mean that they are truly equal in performance.

#### 5.3.1 Equal Indices

Table 11 illustrates two systems with equal indices and differing sizes: 'BL4' is a 38-bus system with 4779 customers to serve and 'BL2X' is a 22-bus system with 1908 customers to serve. The loading is also larger in 'BL4'. The normalized averaging and unified reliability index methodologies are implemented and compared. The unified reliability index is consistently performing accurately and yielding fair decisions. On the other hand, the normalized averaging methodology reported equal performance for both. The decision made by the unified reliability index was based upon the factor of the increased susceptibility of the larger system, yet it maintains equal indices. Moreover, a larger system contains greater number of lines or cables, transformers, and risks; therefore, for a large system to perform similar to smaller one with the imbedded greater risks and susceptibility to interruption is something that is not 'mathematically' accounted for in the normalized averaging technique. This also plays a major role for systems with close indices, where averaging may result in inaccurate decisions. Such systems can have very close indices and the negligence of system size and fair comparison basis, the results can be misleading.

**TABLE 11: EQUAL INDICES CASE STUDY**

| | SAIFI | SAIDI | CAIDI | ASIFI | ASIDI | MAIFI | MAIFI-E | CEMI | CEMSMI | NT | UI | Norm.Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BL4 | 0.682 | 24.640 | 36.130 | 0.581 | 15.690 | 62.178 | 23.317 | 0.962 | 0.5862 | 4779 | 0.6624 | 0.7445 |
| BL2X | 0.682 | 24.640 | 36.130 | 0.581 | 15.690 | 62.178 | 23.317 | 0.962 | 0.5862 | 1908 | 0.6708 | 0.7445 |

### 5.3.2 Equal Averages

This case shows confusion if resulting averages are equal while indices are not. Table 12 illustrates an example of such a case. This case describes two systems with very different indices where ‘CC4X’ is better in five indices and greater in size and loading, while ‘FC2X’ is better in four indices and inferior in size, customer count and loading. The results of both methodologies are described in the table. Nevertheless, the main point that can be concluded from this case is the weakness of the normalized averaging technique because it concluded same performance for both. On the other hand, the number of better indices, system size, customer count, and loading were considered in the decision made by the unified reliability index. Its conclusion was overall performance superiority to the larger system ‘CC4X’.

**TABLE 12: EQUAL AVERAGES CASE STUDY**

| | SAIFI | SAIDI | CAIDI | ASIFI | ASIDI | MAIFI | MAIFI-E | CEMI | CEMSMI | NT | UI | Norm.Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CC4X | 0.190 | 9.250 | 48.684 | 0.193 | 6.457 | 51.819 | 19.432 | 0.268 | 0.4885 | 4779 | 0.5213 | 0.4032 |
| FC2X | 0.375 | 11.100 | 29.628 | 0.345 | 9.833 | 41.024 | 3.130 | 0.528 | 0.3028 | 1908 | 0.4347 | 0.4032 |

Chapter 6

# Conclusion and Future Work

In this work, a novel normalization methodology has been developed. The new methodology does not require customer surveys or customer interaction. This is beneficial as service quality, from a utilities perspective, should remain unbiased and independent of customer type. Using the developed normalization methodology, single index comparison is deemed more reliable. As reporting data are routinely practiced by utilities, no major infrastructure or regulatory changes are required. The methodology uses the current available reported data with the currently recommended indices by the IEEE standard [3].

Indices which combined to form a unified reliability index were implemented. Optimization-like problems were formed in order to decide on the best weights to work with multiple systems with different indices impacts. Mathematical manipulation was conducted to relax and ease the general formulation of the unified reliability index. This yielded a decrease in the amount of reliability indices that need to be reported. Thus, the reporting routine can be also relaxed. The unified index was compared with performance of the most practical and ready methodology in order to compare and cross-compare systems (i.e. normalized averaging [16]). After verifying the validity and superiority of the unified reliability index, testing and evolution was implemented to further prove its accuracy.

First steps towards standardization of reliability performance have been taken. Since the unified reliability index in its current situation cannot be imposed as a standard but rather a comparative, planning, and operational tool. Standardization and combining with power quality indices are the next advisable steps. In doing so, a unified reliability and power quality index will be reached.

In conclusion, steps toward a comprehensive reliability and power quality standard unified index have been made. The results of these initial steps were a unified reliability index capable of fair and accurate utility quality assessment.

# Bibliography


[1] H. Saadat, *Power system analysis*. Boston: McGraw-Hill, 2002.

[2] J. D. Glover, M. S. Sarma, and T. J. Overbye, *Power system analysis and design*. Australia; Toronto, Ont.: Thomson, 2008.

[3] "IEEE Guide for Electric Power Distribution Reliability Indices," *IEEE Std 1366-2003 (Revision of IEEE Std 1366-1998),* pp. 0_1-0_1, 2004.

[4] W. Q. Meeker and M. Hamada, "Statistical tools for the rapid development and evaluation of high-reliability products," *Reliability, IEEE Transactions on,* vol. 44, pp. 187-198, 1995.

[5] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*: Springer, 1996.

[6] D. P. Gaver, F. E. Montmeat, and A. D. Patton, "Power System Reliability I-Measures of Reliability and Methods of Calculation," *Power Apparatus and Systems, IEEE Transactions on,* vol. 83, pp. 727-737, 1964.

[7] F. E. Montmeat, A. D. Patton, J. Zemkoski, and D. J. Cumming, "Power System Reliability II-Applications and a Computer Program," *Power Apparatus and Systems, IEEE Transactions on,* vol. 84, pp. 636-643, 1965.

[8] R. Billinton and K. E. Bollinger, "Transmission System Reliability Evaluation Using Markov Processes," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-87, pp. 538-547, 1968.

[9] . *Reliability of Electric Utility Distribution Systems: EPRI White Paper, EPRI, Palo Alto, CA: 2000. 1000424*.

[10] H. E. Brown and S. Suryanarayanan, "A survey seeking a definition of a smart distribution system," 2009, pp. 1-7.

[11] H. L. Willis, *Power distribution planning reference book*. New York; London: Marcel Dekker ; Taylor & Francis, distributor], 2004.

[12] R. E. Brown, "Distribution reliability assessment and reconfiguration optimization," 2001, pp. 994-999.

[13] E. Fumagalli, J. W. Black, I. Vogelsang, and M. Ilic, "Quality of Service Provision in Electric Power Distribution Systems Through Reliability Insurance," *IEEE Transactions on Power Systems,* vol. 19, pp. 1286-1293, 2004.

[14] A. Chowdhury and D. Koval, *Power distribution system reliability : practical methods and applications*. Oxford: Wiley-Blackwell, 2009.

[15] R. E. Brown and J. H. Spare, "A Survey of Reliability Reporting Practices," 2006, pp. 1212-1217.

[16] R. E. Brown, *Electric power distribution reliability* vol. 14: CRC, 2002.

[17] C. A. Warren and R. Saint, "IEEE reliability indices standards," *IEEE Industry Applications Magazine,* vol. 11, pp. 16-22, 2005/02//jan 2005.

[18] J. Fraser, "Annual Reporting of Reliability Indices (Annual Response to Directive 26 of BCUC Decision on F05/F06 RRA)," BC hydro Annual ReportingJune 6, 2012 2012.

[19] C. A. Warren, "Distribution reliability: What is it?," *Industry Applications Magazine, IEEE,* vol. 2, pp. 32-37, 1996.
[20] "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems," *IEEE Std 493-1990*, pp. 0_1-0_1, 1991.
[21] R. S. Tsai, "Reliability worth guides distribution system design," *Industry Applications, IEEE Transactions on,* pp. 368-375, 1979.
[22] R. Billinton, "Distribution system reliability performance and evaluation," *International Journal of Electrical Power & Energy Systems,* vol. 10, pp. 190-200, 1988.
[23] E. N. Dialynas, "Evaluating the approximate probability distributions of load point reliability indices in power distribution networks," *Generation, Transmission and Distribution [see also IEE Proceedings-Generation, Transmission and Distribution], IEE Proceedings,* vol. 135, pp. 450-460, 1988.
[24] R. N. Allan and M. G. Da Silva, "Evaluation of reliability indices and outage costs in distribution systems," *Power Systems, IEEE Transactions on,* vol. 10, pp. 413-419, 1995.
[25] E. Abbasi, M. Fotuhi-Firuzabad, and A. Abiri-Jahromi, "Risk based maintenance optimization of overhead distribution networks utilizing priority based dynamic programming," 2009, pp. 1-11.
[26] T. Ortmeyer, "A unified index for power distribution reliability/power quality indices," 2010, pp. 1-6.
[27] B. Lee and K. M. Kim, "Unified power quality index based on value-based methodology," 2009, pp. 1-8.
[28] B. Lee, K. M. Kim, and Y. Goh, "Unified power quality index using ideal AHP," 2008, pp. 1-5.
[29] R. E. Brown, S. Gupta, R. D. Christie, S. S. Venkata, and R. Fletcher, "Distribution system reliability assessment using hierarchical Markov modeling," *Power Delivery, IEEE Transactions on*, vol. 11, pp. 1929-1934, 1996.
[30] N. Balijepalli, S. S. Venkata, and R. D. Christie, "Modeling and Analysis of Distribution Reliability Indices," *IEEE Transactions on Power Delivery,* vol. 19, pp. 1950-1955, 2004.
[31] R. E. Brown, S. Gupta, R. D. Christie, S. S. Venkata, and R. Fletcher, "Distribution system reliability assessment: Momentary interruptions and storms," *Power Delivery, IEEE Transactions on*, vol. 12, pp. 1569-1575, 1997.
[32] G. Wacker, E. Wojczynski, and R. Billinton, "Interruption cost methodology and results-a Canadian residential Survey," *Power Apparatus and Systems, IEEE Transactions on,* pp. 3385-3392, 1983.
[33] C. A. Warren, R. Ammon, and G. Welch, "A survey of distribution reliability measurement practices in the US," *Power Delivery, IEEE Transactions on,* vol. 14, pp. 250-257, 1999.
[34] C. A. Warren, D. J. Pearson, and M. T. Sheehan, "A nationwide survey of recorded information used for calculating distribution reliability indices," *Power Delivery, IEEE Transactions on*, vol. 18, pp. 449-453, 2003.

[35] K. Alvehag and L. Söder, "Risk-based method for distribution system reliability investment decisions under performance-based regulation," *IET Generation, Transmission & Distribution,* vol. 5, pp. 1062-1062, 2011.

[36] T. H. Ortmeyer, J. A. Reeves, D. Hou, and P. McGrath, "Evaluation of Sustained and Momentary Interruption Impacts in Reliability-Based Distribution System Design," *IEEE Transactions on Power Delivery,* vol. 25, pp. 3133-3138, 2010.

[37] C. L. Benner, B. D. Russell, and A. Sundaram, "Feeder Interruptions Caused by Recurring Faults on Distribution Feeders: Faults You Don't Know About," 2008, pp. 584-590.

[38] M. F. McGranaghan, "Quantifying Reliability and Service Quality for Distribution Systems," *IEEE Transactions on Industry Applications,* vol. 43, pp. 188-195, 2007.

[39] W. Wangdee and R. Billinton, "Reliability-performance-index probability distribution analysis of bulk electricity systems," *Electrical and Computer Engineering, Canadian Journal of,* vol. 30, pp. 189-193, 2005.

[40] R. N. Allan, R. Billinton, I. Sjarief, L. Goel, and K. S. So, "A reliability test system for educational purposes-basic distribution system data and results," *IEEE Transactions on Power Systems,* vol. 6, pp. 813-820, 1991/05// 1991.

[41] "MatLab 7 Users Optimization Toolbox," ed. USA: The MathWorks, Inc., 1984-2012.."

# Appendix A
# Optimization Results

## Different Weights

### Objective

| | |
|---|---|
| PI | 9.849356245 |

### Decision

| | |
|---|---|
| w1 | 0.033333333 |
| w2 | 0.133333333 |
| w3 | 0.133333333 |
| w4 | 0.033333333 |
| w5 | 0.033333333 |
| w6 | 0.033333333 |
| w7 | 0.133333333 |
| w8 | 0.093236763 |
| w9 | 0.073429904 |
| w10 | 0.133333333 |
| w11 | 0.033333333 |
| w12 | 0.133333333 |

### Constraints

| | | |
|---|---|---|
| AL4 | 0.252475007 | 1 |
| BL4 | 0.662412973 | 1 |
| CL4 | 0.286371524 | 1 |
| DL4 | 0.292680735 | 1 |
| EL4 | 0.142405685 | 1 |
| FL4 | 0.450987977 | 1 |
| AC4 | 0.312740552 | 1 |
| BC4 | 0.842809234 | 1 |
| CC4 | 0.47365228 | 1 |
| DC4 | 0.347422815 | 1 |
| EC4 | 0.1785731 | 1 |
| FC4 | 0.578579865 | 1 |
| AL2 | 0.272309887 | 1 |

| | | |
|---|---|---|
| BL2 | 0.672225852 | 1 |
| CL2 | 0.294539563 | 1 |
| DL2 | 0.341352611 | 1 |
| EL2 | 0.148323366 | 1 |
| FL2 | 0.421085258 | 1 |
| AC2 | 0.372888943 | 1 |
| BC2 | 0.84937097 | 1 |
| CC2 | 0.477152107 | 1 |
| DC2 | 0.423813268 | 1 |
| EC2 | 0.22624366 | 1 |
| FC2 | 0.528939012 | 1 |
| total | 1 | 1 |
| AL4 | 0.252475007 | 0 |
| BL4 | 0.662412973 | 0 |
| CL4 | 0.286371524 | 0 |
| DL4 | 0.292680735 | 0 |
| EL4 | 0.142405685 | 0 |
| FL4 | 0.450987977 | 0 |
| AC4 | 0.312740552 | 0 |
| BC4 | 0.842809234 | 0 |
| CC4 | 0.47365228 | 0 |
| DC4 | 0.347422815 | 0 |
| EC4 | 0.1785731 | 0 |
| FC4 | 0.578579865 | 0 |
| AL2 | 0.272309887 | 0 |
| BL2 | 0.672225852 | 0 |
| CL2 | 0.294539563 | 0 |
| DL2 | 0.341352611 | 0 |
| EL2 | 0.148323366 | 0 |
| FL2 | 0.421085258 | 0 |
| AC2 | 0.372888943 | 0 |
| BC2 | 0.84937097 | 0 |
| CC2 | 0.477152107 | 0 |
| DC2 | 0.423813268 | 0 |
| EC2 | 0.22624366 | 0 |
| FC2 | 0.528939012 | 0 |
| w1 | 0.033333333 | 0.133333333 |
| w2 | 0.133333333 | 0.133333333 |
| w3 | 0.133333333 | 0.133333333 |
| w4 | 0.033333333 | 0.133333333 |

| | | |
|---|---|---|
| w5 | 0.033333333 | 0.133333333 |
| w6 | 0.033333333 | 0.133333333 |
| w7 | 0.133333333 | 0.133333333 |
| w8 | 0.093236763 | 0.133333333 |
| w9 | 0.073429904 | 0.133333333 |
| w10 | 0.133333333 | 0.133333333 |
| w11 | 0.033333333 | 0.133333333 |
| w12 | 0.133333333 | 0.133333333 |
| w1 | 0.033333333 | 0.033333333 |
| w2 | 0.133333333 | 0.033333333 |
| w3 | 0.133333333 | 0.033333333 |
| w4 | 0.033333333 | 0.033333333 |
| w5 | 0.033333333 | 0.033333333 |
| w6 | 0.033333333 | 0.033333333 |
| w7 | 0.133333333 | 0.033333333 |
| w8 | 0.093236763 | 0.033333333 |
| w9 | 0.073429904 | 0.033333333 |
| w10 | 0.133333333 | 0.033333333 |
| w11 | 0.033333333 | 0.033333333 |
| w12 | 0.133333333 | 0.033333333 |

# Appendix B

# Code Used in Calculation

```
%%
clc
clear all

%%
w1=0.033333333;
w2=0.133333333;
w3=0.133333333;
w4=0.033333333;
w5=0.033333333;
w6=0.033333333;
w7=0.133333333;
w8=0.093236763;
w9=0.073429904;
w10=0.133333333;
w11=0.033333333;
w12=0.133333333;
% w1=1/12;               %for equal weights
% w2=1/12;
% w3=1/12;
% w4=1/12;
% w5=1/12;
% w6=1/12;
% w7=1/12;
% w8=1/12;
% w9=1/12;
% w10=1/12;
% w11=1/12;
% w12=1/12;

%%
% SAIFI SAIDI CAIDI ASIFI ASIDI MAIFI MAIFIe CEMI CEMSMI NT LT FIs_max
% FIm_max FIme_max r_max
data=[
0.3     3.47    11.56   0.255631001 2.209519727 14.23612058 5.338545218
0.422964133 0.134217426 4779    40  0.312   14.80556541 5.552087027
12.0224;
0.682   24.64   36.13   0.581134475 15.68950031 62.17810783 23.31679044
0.961538462 0.586212061 4779    40  0.70928 64.66523214 24.24946205
37.5752;
0.3     4.42    14.74   0.255631001 2.814431468 18.02404998 6.759018741
0.422964133 0.169929833 4779    40  0.312   18.74501197 7.02937949
15.3296;
0.682   5.44    7.98    0.581134475 3.463915653 14.5176401  5.444115039
0.961538462 0.136871578 4779    40  0.70928 15.09834571 5.66187964  8.2992;
0.3     0.62    2.07    0.255631001 0.394784505 2.912332404 1.092124652
0.422964133 0.027457323 4779    40  0.312   3.028825701 1.135809638 2.1528;
0.682   12.45   18.25   0.581134475 7.927527552 31.91252962 11.96719861
0.961538462 0.300869718 4779    40  0.70928 33.18903081 12.44588655 18.98;
0.19    4.29    22.58   0.160477624 2.994538627 24.172013   9.064504875
0.267877284 0.227892518 4779    40  0.1976  25.13889352 9.42708507
23.4832;
```

```
0.462   32.36   70.1    0.390214012 22.58817482 100.7203111 37.77011665
0.651364764 0.949586007 4779    40  0.48048 104.7491235 39.28092131 72.904;
0.19    8.25    43.38   0.160477624 5.758728129 46.1913646  17.32176173
0.267877284 0.435489853 4779    40  0.1976  48.03901919 18.01463219
45.1152;
0.462   6.97    15.11   0.390214012 4.865252734 22.2379734  8.339240024
0.651364764 0.20965849  4779    40  0.48048 23.12749233 8.672809625
15.7144;
0.19    1.45    7.62    0.160477624 1.012140095 8.346094176 3.129785316
0.267877284 0.078686554 4779    40  0.1976  8.679937943 3.254976728 7.9248;
0.462   16.8    36.38   0.390214012 11.72686455 52.60726285 19.72772357
0.651364764 0.495978618 4779    40  0.48048 54.71155337 20.51683251
37.8352;
0.248   3.61    14.55   0.231028069 3.072551865 17.36926395 6.51347398
0.34965035  0.163756543 1908    20  0.25792 18.06403451 6.774012939 15.132;
0.602   22.5    37.48   0.560802007 19.150254   64.23444481 24.0879168
0.848748026 0.605599102 1908    20  0.62608 66.8038226  25.05143348
38.9792;
0.248   4.16    16.77   0.231028069 3.540669185 19.9597578  7.484909176
0.34965035  0.188179589 1908    20  0.25792 20.75814812 7.784305543
17.4408;
0.602   6.74    11.19   0.560802007 5.736564977 19.86349359 7.448810095
0.848748026 0.187272015 1908    20  0.62608 20.65803333 7.746762499
11.6376;
0.248   0.77    3.08    0.231028069 0.655364248 3.987513854 1.495317695
0.34965035  0.037594079 1908    20  0.25792 4.147014408 1.555130403 3.2032;
0.602   9.93    16.49   0.560802007 8.451645434 28.82755795 10.81033423
0.848748026 0.271784761 1908    20  0.62608 29.98066027 11.2427476
17.1496;
0.159   5.02    31.65   0.146572533 4.446811835 33.13790749 12.42671531
0.22417099  0.312422519 1908    20  0.16536 34.46342379 12.92378392 32.916;
0.409   29.26   71.52   0.37703249  25.91906659 101.9880793 38.24552972
0.576641101 0.961538462 1908    20  0.42536 106.0676024 39.77535091
74.3808;
0.159   7.3     46.07   0.146572533 6.466479361 48.11364152 18.04261557
0.22417099  0.453612983 1908    20  0.16536 50.03818718 18.76432019
47.9128;
0.409   9.04    22.09   0.37703249  8.007804579 31.93906965 11.97715112
0.576641101 0.301119936 1908    20  0.42536 33.21663244 12.45623717
22.9736;
0.159   2.17    13.69   0.146572533 1.922227427 14.47023997 5.426339988
0.22417099  0.136424692 1908    20  0.16536 15.04904957 5.643393587
14.2376;
0.409   13.1    32.03   0.37703249  11.60423009 46.01621006 17.25607877
0.576641101 0.433838505 1908    20  0.42536 47.85685846 17.94632192
33.3112;
];

SAIFI=data(:,1);
SAIDI=data(:,2);
CAIDI=data(:,3);
ASIFI=data(:,4);
ASIDI=data(:,5);
MAIFI=data(:,6);
MAIFIe=data(:,7);
CEMI=data(:,8);
CEMSMI=data(:,9);
NT=data(:,10);
LT=data(:,11);
FIs_max=data(:,12);
```

```
FIm_max=data(:,13);
FIme_max=data(:,14);
r_max=data(:,15);
CN=floor(0.9.*NT);

%%
SAIFI_base=zeros(length(data),1);
SAIDI_base=zeros(length(data),1);
MAIFI_base=zeros(length(data),1);
MAIFIe_base=zeros(length(data),1);
W1=zeros(length(data),1);
W2=zeros(length(data),1);
W3=zeros(length(data),1);
W4=zeros(length(data),1);
W5=zeros(length(data),1);
W6=zeros(length(data),1);
W7=zeros(length(data),1);
W8=zeros(length(data),1);
W9=zeros(length(data),1);
for i=1:1:length(data)
    SAIFI_base(i,1)=(data(i,12)+max(data(:,12)))/2;
    SAIDI_base(i,1)=(data(i,15)+max(data(:,15)))/2;
    MAIFI_base(i,1)=(data(i,13)+max(data(:,13)))/2;
    MAIFIe_base(i,1)=(data(i,14)+max(data(:,14)))/2;
    W1(i,1)=w1./SAIFI_base(i)+(w4.*NT(i))./(SAIFI_base(i).*CN(i));

W2(i,1)=w2./SAIDI_base(i)+w10./SAIDI_base(i)+(w5.*NT(i))./(SAIDI_base(i)*CN
(i));
    W3(i,1)=w3./(SAIDI_base(i)./SAIFI_base(i));
    W4(i,1)=w6./SAIFI_base(i);
    W5(i,1)=w7./SAIDI_base(i);
    W6(i,1)=w8./MAIFI_base(i);
    W7(i,1)=w9./MAIFIe_base(i);
    W8(i,1)=w11;
    W9(i,1)=w12;
end


UI=W1.*SAIFI+W2.*SAIDI+W3.*(SAIDI./SAIFI)+W4.*ASIFI+W5.*ASIDI+W6.*MAIFI+W7.
*MAIFIe+W8.*CEMI+W9.*CEMSMI;
%%
c=data(:,1:9);
c=c';
b=mean(c);
b=b';
AVG=b./max(b);
i=1:1:length(AVG);
%
scatter(i,AVG)
hold on
scatter(i,UI,'x','r')
% plot(i,AVG)
% plot(i,UI)
```