Power system design guidelines to enhance the reliability of cellular networks in Africa

LP Strydom

24933988

Dissertation submitted in fulfilment of the requirements for the degree *Magister in Electrical and Electronic Engineering* at the Potchefstroom Campus of the North-West University

Supervisor: Dr JF van Rensburg

April 2014

ABSTRACT

Title: Power system design guidelines to enhance the reliability of cellular networks in Africa
Author: Leon Petrus Strydom

Promoter: Dr J.F. van Rensburg
Keywords: Data Centre, Downtime, Power Distribution System, Power Quality, Reliability, Availability

Cellular networks in Africa have grown exponentially over the past 10 years and their data centres (DCs) on average consume 3 MW of electrical power. They require a reliable electrical power supply and can have a downtime loss of over a million dollars per hour. Power quality, reliability and availability have emerged as key issues for the successful operation of a data centre.

Investigations are carried out into emerging technologies and their application in data centre power distribution systems for cellular networks in Africa. Best practices are applied to develop a power distribution system (PDS) with the objective of achieving optimal reliability and availability.

Analytical techniques are applied to determine and compare the reliability and availability of various power systems. Minimal cut set simulations identify system weak points and confirm component selection. Components' inherent characteristics (CIC) and system connectivity topology (SCT) are key factors in the improvement of data centre availability.

The analysis practices can be used by engineers and managers as a basis for informed decision making in determining power system reliability and the availability of an existing or a new data centre design. Weak points in the PDS of a data centre causing downtime are identified through analysis, and accurate solutions can be determined to prevent or minimise downtime.

System connectivity topology (SCT) techniques were identified that could increase the reliability and availability of data centres for cellular networks in Africa. These techniques include multiple incomers from the utility company, redundancy levels of critical equipment and parallel distribution paths.

Two case studies were carried out on data centres for a cellular network, one in Nigeria and one in Cameroon. The reliability and availability of both data centres was improved, with substantial reduction in downtime per year.

The outcome of the case studies shows the importance of designing and implementing the power distribution system with sufficient levels of redundancy for critical equipment, and parallel distribution paths.

ACKNOWLEDGEMENTS

First and foremost, I would like to give thanks to the Lord, my God, for providing me with the opportunity and ability to further my studies.

To my promoter Dr. J. F. van Rensburg, thank you for your guidance, support and encouragement, which are deeply appreciated.

A special thanks to Prof. E. H. Mathews and Prof. M. Kleingeld for granting me the opportunity to complete my Masters degree at CRCED Pretoria.

To my colleagues and friends, a special thanks for the support, encouragement and contributions to this study.

To my wife Marlene, thank you for your support and encouragement during my studies and writing of this dissertation.

TABLE OF CONTENTS

ABBREVIATIONS

ASTS	Automatic Supply Transfer Switch
BMS	Building Management System
CBEMA	Computer and Business Equipment Manufacturers` Association
CCHP	Combined Cooling, Heat and Power
CCTV	Close Circuit Television
CIC	Component Inherent Characteristic
CRAC	Computer Room Air Conditioning
CRCED	Centre for Research and Continued Engineering Development
DC	Data Centre
EMI	Electromagnetic Interference
EPO	Emergency Power Off
ESD	Electro Static Discharge
FEMEA	Failure Modes and Effects Analysis
FLOP	Floating-point Operations Per Second
FTTH	Fibre To The Home
HD	High Definition
ICT	Information and Communication Technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IT	Information Technology
ITI	Information Technology Industry
kVA	Kilo Volt Ampere
kV	Kilo Volt
MLV	Main Low Voltage
MOV	Metal Oxide Varistor
MTBF	Mean Time Between Failures
MTPD	Maximum Tolerable Period of Disruption
MTTF	Mean Time to Failure

MTTR	Mean Time to Repair
MV	Medium Voltage
MW	Mega Watt
ONAN	Oil Natural Air Natural
PDS	Power Distribution System
PDU	Power Distribution Unit
PHCN	Power Holding Company of Nigeria
PM	Preventative Maintenance
PREP	Power Reliability Enhancement Program
PQ	Power Quality
PU	Per Unit
RCM	Reliability Centred Maintenance
RMS	Root Mean Square
SCT	System Connectivity Topology
SF6	Sulphur Hexafluoride
SLA	Service Level Agreement
SOW	Statement of Work
SPD	Surge Protection Device
SPOF	Single Point of Failure
SRG	Signal Reference Grid
STS	Static Transfer Switch
TCO	Total Cost of Ownership
TIA	Telecommunication Industry Association
TWh	Terra Watt Hours
UPS	Uninterrupted Power Supply
VAS	Value Added Services
VLA	Ventilated Lead Acid
VRLA	Valve Regulated Lead Acid
XLPE	Cross-linked Polyethylene

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 OVERVIEW OF POWER DISTRIBUTION NETWORKS IN AFRICA

The majority of countries in Sub-Saharan Africa are experiencing a serious power crisis marked by lack of generating and distribution capacity, unreliable supplies, rapid increase in electricity consumption, low energy access rates, high prices and deficiency in maintenance. The rapid increase in power consumption is the result of strong economic growth and urbanisation [1], [2], [3], [4].

The chronic power problems of Sub-Saharan Africa are deep-rooted, with the main problems being the underdevelopment of the region`s energy resources, the vulnerability to high oil prices, unreliability of power supplies and the aggravating effects of conflict and drought [1]. National and regional grids in Sub-Saharan Africa provide power quality of varying levels, with rural coverage uneven and inadequate as 80% of the people in rural areas are without access to electricity [2], [3].

Urbanisation is increasing at the rate of 3.5% a year, with electrical power consumption expected to show a yearly growth rate of 2.6%. The demand for power is growing with the expansion of the manufacturing and industrial sectors. The International Energy Agency (IEA) expects Africa`s electrical power consumption to double between 2007 and 2030 from 505 to 1012 TWh (IEA 2009) [2]. Many countries revert to power rationing or load shedding due to the lack of generating capacity [4], [5].

South Africa and North Africa produce three-quarters of the electricity of the African continent. All of the Sub-Saharan African countries combined produce a total of 68 GW, which is equivalent to a country like Spain, and this falls to a mere 28 GW without South Africa [1]. The generation capacity is insufficient to keep up with the growing demand although it has increased in Sub-Saharan Africa by an annual average of 2.9% [4].

Low power generation levels are accompanied by equally low rates of electrification, with less than 25% of the population of Sub-Saharan Africa having access to electricity compared to about 50% of South Asia and 80% in Latin America [1].

The power system reliability is normally measured in terms of the number of interruptions in transmission, frequency and duration of interruption in power distribution and unplanned capacity loss factors of generators [1].

The infrastructure is inadequate, with transmission systems having insufficient redundant lines, and is only partially functional as the systems are not well maintained. Manufacturing enterprises in Sub–Saharan Africa experience power outages of an average of 56 days per year compared to one day in ten years in the USA [1].

As a result of unreliable power and low accessibility to electricity, self-generation of electricity by consumers, from households to large businesses, has become an important power source. In-house generation by mining, manufacturing, commercial and services sectors accounts for approximately 6% of the total generating capacity in the Sub-Saharan Africa region [1], [4], [5].

The most economical option for providing services is by increasing access to the national electricity grids. Decentralised power, which is often based on renewable energy sources, will probably be an important component of any notable increase in electricity access, especially remote and rural areas [2], [6].

African governments have not been able to raise the required funds to invest in new generation capacity and maintenance of existing networks. Africa`s power sector requires investment of an estimated US $40.8 billion per year, with 65.5% for capital expenditure and 34.5% for operations and maintenance [4].

Optimal generation planning, improved grid operation, demand management, efficiency improvements and increased electrical trade are important factors in limiting the investment required [2].

Utilities are centralised and poorly managed, lack technical skills, and apply inappropriate tariffs and revenue collection. Regulations are inadequate with the lack of general harmonisation of standards, specifications and technical codes, and regulatory bodies are seldom effective or independent [1], [3], [4].

The use of cell phones has grown exponentially world-wide, with Africa following at a rate of nearly 20% per year for the past five years and having reached 649 million connections [7]. This has created a major investment market for cellular network companies in Africa. Power quality is an important requirement for the successful operation of cellular networks.

1.2 DATA CENTRE DOWNTIME

The growth of the internet and e-commerce has changed the meaning and tactics of the business model. E-commerce provides services such as real-time online banking and purchasing [8]. Information is growing at an exponential rate as depicted in Figure 1-1 [11].

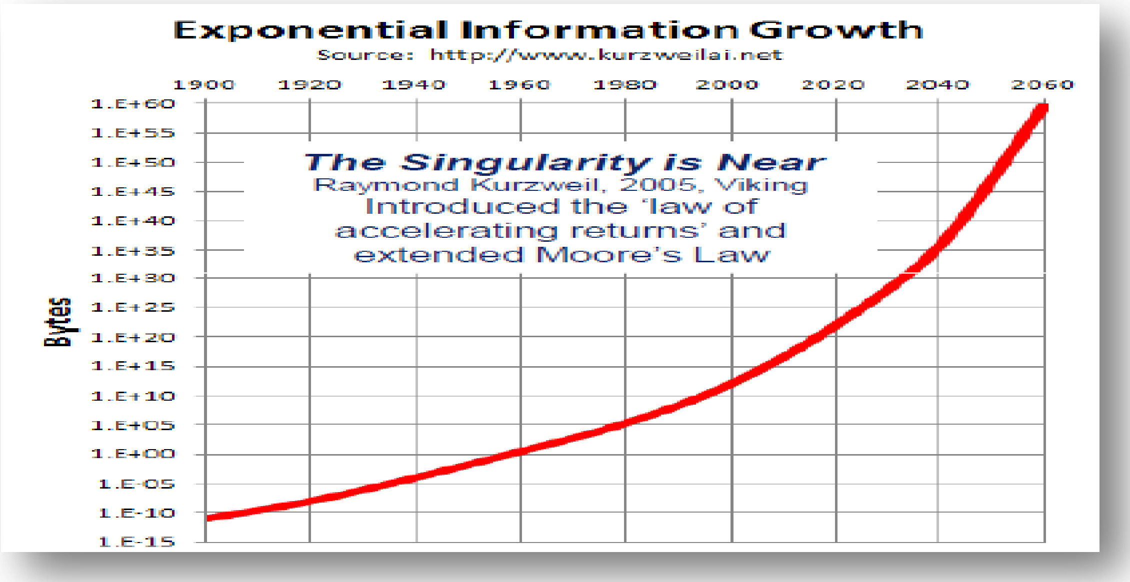

Figure 1-1: Exponential information growth [11]

More than 30 years ago Moore's law was written which predicted the doubling of the number of transistors on a microprocessor every two years and this held true ever since. This law also applies to doubling of computing capacity, halving the Watts/FLOP (FLOP being a measure of computer performance) and halving kWh of compute load [11].

The above graph in Figure 1-1 by Raymond Kurzweil clearly shows how the information growth is accelerating [11]. The complexity and criticality of the information is increasing as data centres experience a steady growth in capacity and density, and this is straining resources and increasing the consequences of poor performance. The availability of information technology (IT) is normally the most important metric against which data centres are measured [9].

Data centres are facilities hosting a large number of servers dedicated to massive computation and storage, which have become essential to nearly every sector of the global economy. A typical cellular network data centre consumes on average 3 MW of electrical power, with computing 52 % and power and cooling equipment 48% the major users.

The following adverse effects can occur due to data centre outages [13]:

- Mission critical data can be damaged
- Impact on organisational productivity
- Equipment and asset damage
- Costs of detection and remedial work to systems and core business processes
- Legal and regulatory impact, including litigation cost
- Confidence and trust diminishment among key stakeholders
- Marketplace brand and reputation loss due to erosion of customer confidence

A typical data centre layout for a cellular network in Africa, also referred to as white space, is shown in Figure 1-2 below.

Figure 1-2: Typical data centre [16]

Data centres for cellular networks control the hub of the network and consist of multi-million dollar servers which control the telecommunications and worldwide web data flow.

Dependence on IT systems by enterprises has created an even stronger link between data centre availability and the total cost of ownership (TCO). IT services are becoming more commoditised with co-location, disaster recovery and cloud computing services. Infrastructure vulnerabilities and misperception with regard to frequency and the cost of IT failures increase the risk of downtime, with serious financial consequences [10], [12].

The compound annual growth rate (CAGR) of data is compared to the energy efficiency of data equipment in Figure 1-3.

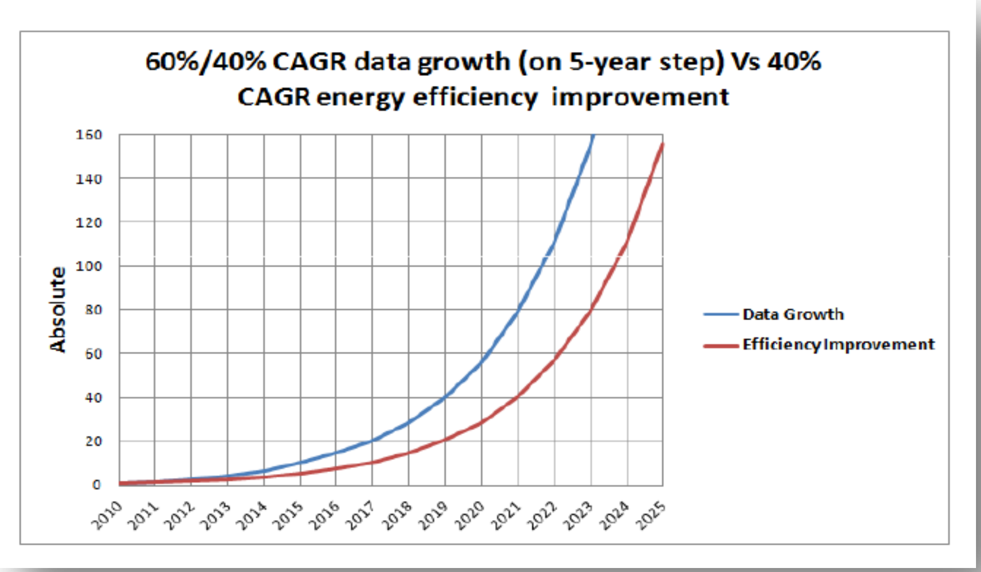

Figure 1-3: Compound annual growth rate (CAGR) [11]

Moore’s Law predicts the doubling of the number of transistors on a microprocessor every two years. The compound annual growth rate in Figure 1-3 shows that data growth outstrips Moore`s Law [11].

Downtime adversely affects costs, opportunity losses, company reputation and customer confidence. The consequences of data centre downtime can have serious financial implications for a company and can range from a few thousand to over a million dollars per outage [12], [13]. All employees of an organisation must have a thorough understanding of the actual financial implications of data centre downtime [10].

The Meta Group did a study showing that there is a 50% probability that a company experiencing downtime of key information technology systems for more than 10 days, will be put out of business within three to five years [14], [15].

Research done by the Ponemon Institute, computed from 41 benchmarked data centres, shows that indirect costs are the largest component, followed by direct and opportunity loss costs [10], [13].

The main cost structure for unplanned outages in a data centre is shown in Figure 1-4 and consists of the following categories [13]:

- *Direct cost* which includes failure detection and repair or replacement of equipment or assets
- *Indirect cost which* covers the impact on organisational productivity and litigation cost
- *Opportunity loss cost* which includes marketplace brand and reputation loss

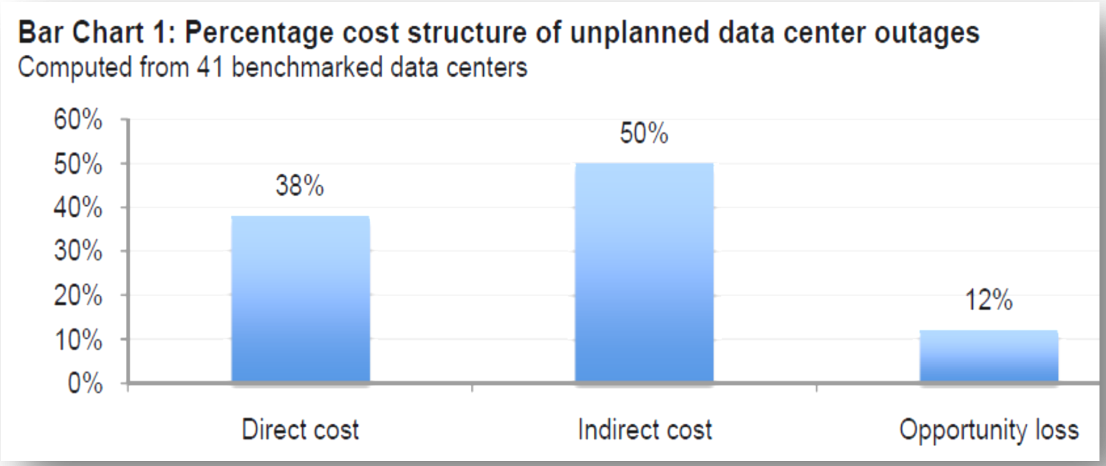

Figure 1-4: Cost structures of unplanned outages [13]

Table 1-1 below gives an overview of the activity-based costs plus related cost consequences.

Table 1-1: Activity-based costs and related cost consequences [13]

Activity-based cost loadings by activity center and related cost consequences				
Cost activities and cost consequences	Direct cost	Indirect cost	Opportunity cost	Total
Detection cost	52%	48%	0%	100%
Equipment cost	60%	40%	0%	100%
IT productivity loss	23%	77%	0%	100%
User productivity loss	22%	78%	0%	100%
Third-party loss	35%	41%	24%	100%
Recovery cost	22%	78%	0%	100%
Ex-post response costs	53%	47%	0%	100%
Customer turnover	55%	31%	14%	100%
Lost revenue	33%	26%	41%	100%
Reputation and brand loss	24%	30%	45%	100%
Overall contribution	38%	50%	12%	100%

The costs of the various activities in Table 1-1 are split into the three main categories and allocated a percentage for direct, indirect and opportunity costs. Indirect costs are the greatest contributor to downtime costs, with IT productivity loss, user productivity loss and recovery cost also impacting severely on this category.

Power vulnerabilities are costly for data centres due to the fact that a failure in the power system could result in a catastrophic unplanned outage. Data centre power systems require technologies such as redundancy and parallel distribution paths to isolate a power system failure [10]. Primary root causes of data centre downtime are shown in Figure 1-5 [13], [17]:

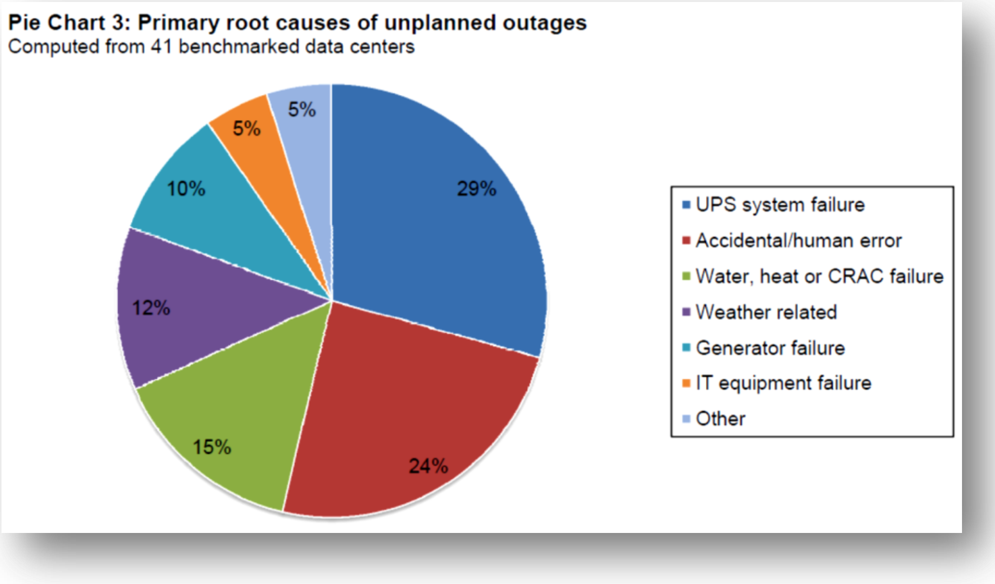

Figure 1-5: Primary root causes of unplanned outages [13]

The root causes of unplanned outages:

- UPS system failure, with the capacity being exceeded, battery system failure, and equipment failure the most common problems
- Accidental/human error
- Water, heat or computer room air conditioning (CRAC) failure
- Generator failure
- IT equipment failure

Key industry drivers that influence availability and cause downtime of a data centre [13], [17]:

- *Increasing data centre capacity:*
  Demand for IT applications grows and thus more servers and storage are added, and therefore the supporting IT infrastructure has to follow the growth trend. Exceeding data centre capacity leads to UPS capacity being exceeded, IT equipment failure due to thermal events, and power distribution units (PDU) or circuit breaker failure.
- *Higher rack densities*:
  A typical blade server rack can contain over 10kW of IT equipment which requires precision cooling due to high heat densities. Certain types of cooling utilise water,

which could cause water incursion with heat-related or CRAC failure, and IT equipment failure causes downtime.

- *Data centre efficiency*:
  Data centres consume a large amount of electricity. Efficiency gains should not be at the expense of availability.
- *Need for infrastructure management and control:*
  Increased efficiency, improved availability, increased density, capacity planning and monitoring mission critical equipment can be achieved with infrastructure management and control.

Inadequate data centre infrastructure will cause recurring downtime events with serious financial losses and damage to the company`s reputation; it is therefore important to identify and address these vulnerabilities [10]. Infrastructure must be able to adjust on a continuous basis to cope with capacity and demand changes.

Generally, equipment failures, data centre mishaps and lack of resources exacerbate the frequency and duration of unplanned outages. Systems should be implemented that increase availability and enhance the performance of mission critical applications [16].

1.3 POWER QUALITY REQUIREMENTS FOR IMPROVED RELIABILITY

Power quality is the degree to which the utilisation and delivery of electrical power affects the performance of electrical equipment. Poor power quality impairs the power handling of equipment. Power quality (PQ) disturbances are causes of electronic component failures, resets, short lifetimes and cascading failures to a whole data centre [17].

Studies done on power distribution systems have shown that reliability of power quality is only 99,75%, which means that downtime per year is equal to 21,97 hours [19], [20]. This differs from location to location and from country to country, especially when comparing between developing and developed countries.

Electricity is generated to very high standards and norms, the waveform being a pure sinusoid and the voltage regulated at the generator. During the transmission and distribution of electricity to the end-user, a number of phenomena can degrade the power and affect other customers on the network [21].

The IEEE 1159–1995 defined power quality disturbances in seven categories based on wave/shape [23]:

- Transients
- Interruptions
- Sag / Under voltage
- Swell / Over voltage
- Wave Form Distortion
- Voltage Fluctuations
- Frequency Variations

The majority of power problems originate in the power grid, where transmission and distribution are mainly carried out via overhead lines which are exposed to an unpredictably changing hostile environment.

Factors influencing this environment are veld and bush fires, fast growing vegetation, lightning, salt mist in coastal areas and sabotage. These factors cause transient and permanent faults on the overhead lines [21].

Surge voltages and voltage sags are two major concerns, with relatively little known about surge levels at application voltages. Proper network design, grounding and surge suppression provide protection against surge voltages. Voltage sags present the most harmful impacts to end-users. The control of sags in a network is complex and the most costly PQ phenomenon [21].

The IEEE defines voltage sag as a decrease in the RMS voltage magnitude at the power frequency for a duration from 0.5 cycles to 1 minute, with typical values between 0.1 to 0.9 per unit (PU) [23], [24].

Equipment connected to the power distribution network can fail or malfunction during a voltage sag event, and this could affect the safety and production of facility-related equipment [24]. The voltage wave shape is influenced by the current flowing through the system impedance, and when the current wave shape passing through the system impedance deviates significantly, the quality of the voltage is impacted.

Voltage sags on utility networks are caused by transient and permanent faults. Breakdown of insulation due to overvoltage is the main cause of electrical faults on overhead lines. The most frequent cause of overvoltage is a direct or nearby lightning strike. Large connected end users' loads and equipment with large inrush currents can also cause voltage sags.

Networks incorrectly designed and operated have problems with voltage regulation and unbalance. Voltage depressions are caused by abnormally large currents that flow through the power distribution system impedance. Transient and permanent faults, correctly isolated, result in voltage sags and power outages under certain conditions [21]. Transients can be caused by lightning, switching of inductive loads, electrostatic discharge (ESD) and poor grounding [22].

Long transmission lines in Africa escalate the issue of voltage regulation, which adversely influences the cost of power distribution. Shunt reactors and capacitors are installed to improve regulation, but resonance problems at harmonic frequencies could be introduced. Asymmetry in the supply network and unbalanced connected loads cause voltage unbalance.

The IEEE states that an interruption occurs when the load current or supply voltage decreases to less than 0.1 per unit (PU) for a period of time that does not exceed one minute. Interruptions can be the result of power system faults, control malfunctions and equipment failures [23].

The ITI (CBEMA) curve in Figure 1-6 that follows, published by the Information Technology Industry Council (ITI), indicates the AC input voltage envelope which can typically be tolerated by most information technology equipment (ITE) [25].

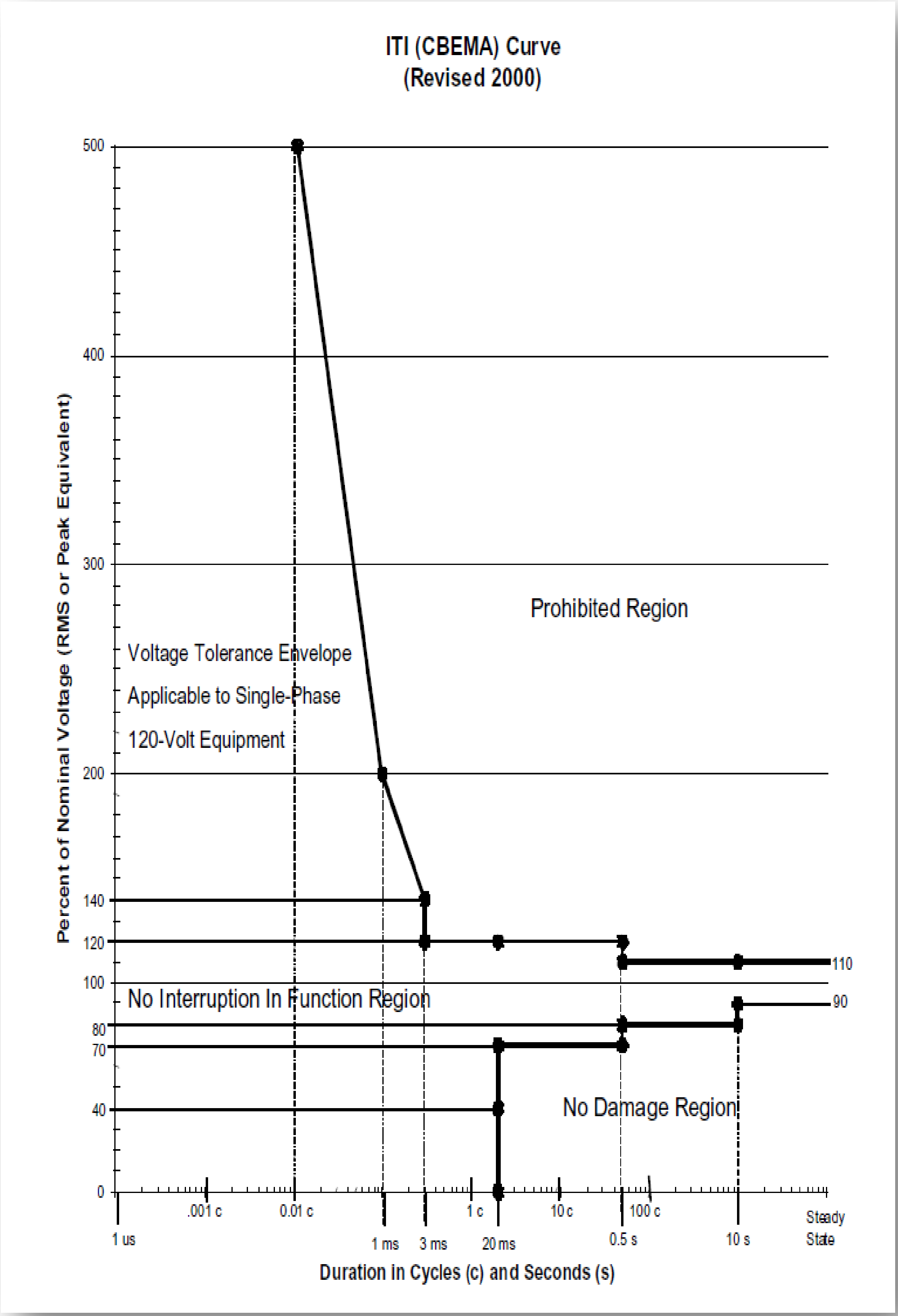

Figure 1-6: Information Technology Industry Council (ITI) curves [25]

Various conditions considered in the ITI curve [25]:

- *Steady-state tolerances* range is ± 10% from the nominal voltage for an indefinite period and are a function of the normal load and losses in the power distribution system (PDS).
- *Line voltage swell* has an amplitude up to 120% of the RMS nominal voltage for a duration up to 0.5 seconds.
- *Low-frequency decaying ring wave* transient and the frequency may range from 200Hz to 5KHz with the amplitude varying from 140% for the former to 200% for the latter, with linear increase in amplitude with increasing frequency. The transient is expressed as a percentage of the peak nominal voltage.
- *High-frequency impulse and ring wave* describes transients which occur as a result of lightning strikes. The curve deals with energy amplitude and duration and intent is to provide a minimum transient immunity of 80 Joule.
- *Voltage sags (RMS)* transients result from large loads, as well as fault conditions with a maximum deviation of 20% up to 10 seconds and 30% up to 0.5 seconds.
- *Dropout* includes both severe RMS voltage sags and a total interruption of the applied voltage, immediately followed by a re-application of the nominal voltage with the interruption lasting up to 20 milliseconds.
- *No damage region* includes sag and dropout events that are more severe than specified in the preceding paragraphs, with the continuous applied voltages less than the lower limit of the steady-state tolerance range, but no damage to the ITE should occur.
- *Prohibited region* includes any surge or swell that might exceed the upper limit of the envelope, and should ITE be subjected to these conditions, damage to the information technology might occur.

Non-linear loads such as computer power supplies, electronic equipment, variable speed drives and rectifiers distort the wave form. The non-sinusoidal currents produced by these loads give rise to harmonic voltage problems and cause serious resonance and overheating in non-linear network components. Resonance at harmonic frequencies may also result in nuisance tripping of circuits.

The impact of harmonics can be reduced by the following [21]:

- Tuned filters
- Blocking filters
- Harmonic isolation
- Network restructuring
- Line reactors
- Oversizing of neutral conductors
- Harmonic isolation

The power distribution systems in Africa are unreliable and of poor quality. Therefore it is critical that power quality be managed efficiently and effectively as it can adversely affect the data centre in many ways and result in catastrophic power outages. The proper design of power distribution systems is very important and is a major contributor to good power quality of the system.

1.4 GOALS OF THE STUDY

The objective of this study is to propose power system design guidelines to increase the reliability of power distribution systems of cellular networks in Africa. The study will address techniques and technologies which will include the following:

- Eliminating single point of failure
- Redundancy
- Tier classification
- System topology
- Preventative maintenance
- Infrastructure monitoring and measurement
- Training

A reliability model will be implemented, which a data centre manager or engineer can utilise to determine the reliability and availability of a data centre power distribution network. The improved design will be applied in two case studies and reliability verified.

1.5 OUTLINE OF DISSERTATION

Chapter 1 provides a brief background on the power distribution networks in Africa. The problem statement and need for the study is motivated.

Chapter 2 addresses the literature review for this study. The data centre power distribution system (PDS) is discussed. Reliability and availability are reviewed along with factors that impact on them.

Chapter 3 deals with techniques to improve system reliability and the methodology to develop a mathematical model to determine system reliability. In addition to this, assumptions, criteria, limitations and constraints are defined.

Chapter 4 applies an improved design to case studies of data centres. This leads to discussion on the application and benefits of improved design.

Chapter 5 concludes the outcome of the dissertation and provides recommendations for further studies.

CHAPTER 2 CELLULAR NETWORK DATA CENTRE POWER DISTRIBUTION SYSTEM

2.1 PREAMBLE

Chapter 1 mentions the exponential data growth, with the internet and e-commerce changing business models. Data centres for cellular networks host equipment dedicated to the computation and storage of large amounts of data, with the result that downtime can have serious adverse effects and financial consequences [12]. Tier classification is an important technique to evaluate and manage the system connectivity topology (SCT) of data centres for cellular networks.

2.2 TIER CLASSIFICATION

Tier classification and performance standards are an objective basis for comparing capacities, functionality and the relative cost of one infrastructure design topology against another.

A typical power distribution system (PDS) with no redundancy is shown in Figure 2-1 [32].

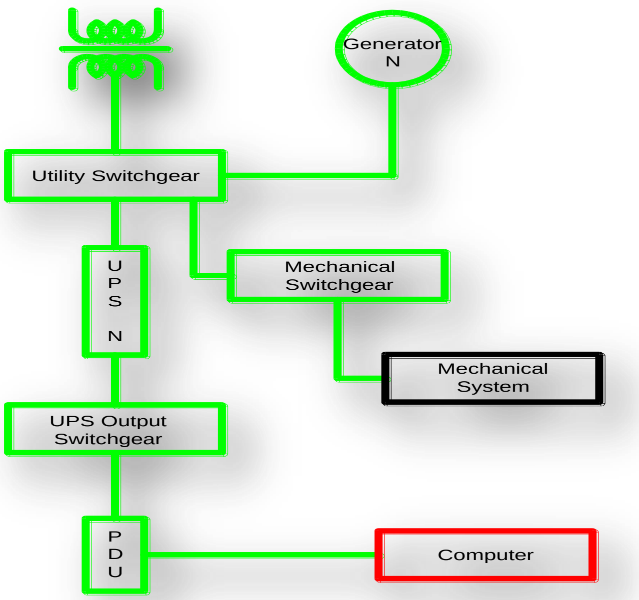

Figure 2-1: Typical power distribution system with no redundancy [32]

Where:

- Gen N : Required amount of generators
- UPS N : Required amount of uninterruptable power supplies
- PDU : Power distribution unit

The power distribution system typically consists of a medium voltage feeder with a step down transformer, a backup power generator, a main low voltage (MLV) panel interfacing all equipment and a power distribution unit (PDU).

This basic type of power distribution system is employed where reliability is not a prime requirement and capital investment a constraining factor.

Data centres rely upon the integrated operation of several separate infrastructure sub-systems, of which the number is dependent upon the individual technologies (e.g. power generation, uninterruptible power sources, refrigeration, etc.) selected to sustain the operation [32].

Tier classifications are designed to consistently describe the site-level requirements to sustain data centre operation. The Uptime Institute and the Telecommunications Industry Association (TIA), define a resilient four Tier rating system that addresses data centre infrastructure [33].

Design topology can utilise Tier performance standards as a basis to compare capabilities of various system configurations [32], [34], [35]. The four Tier systems have outcome based requirements presented by actual site availability performance that is a combination of design topology and operational sustainability [33].

A Tier I data centre has a single power distribution system with no redundancy and consists of a single module uninterruptable power supply (UPS) and generator system which has many single points of failure [8], [32].

Table 2-1 provides a summary of requirements for the different Tier levels.

Table 2-1: Tier requirements summary [32]

	Tier 1	Tier II	Tier III	Tier IV
Active Capacity Components to Support the IT Load	N	N+1	N+1	N After any Failure
Distribution Paths	1	1	1 Active and 1 Alternate	2 Simultaneously Active
Concurrently Maintainable	No	No	Yes	Yes
Fault Tolerance	No	No	No	Yes
Compartmentalization	No	No	No	Yes
Continuous Cooling	Load Density Dependent	Load Density Dependent	Load Density Dependent	Class A

Five requirement categories are listed in the above table indicating the compliance requirement of each Tier level.

Tiers represent site infrastructure topology categories which address increasingly sophisticated operating philosophies that provide increased availability, with Tier IV being the most resilient. The correct Tier level must be maintained as the data centre load increases over time.

The data centre standards, Uptime Institute and TIA, list and describe the different criteria to distinguish between the four distinctive Tier levels based on increasing levels of distribution paths and redundancy as to describe the site level infrastructure to sustain data centre operation.

Table 2-2 provides an overview of the attributes for the various TIER levels.

Table 2-2: Typical tier attributes [33]

Typical Tier Attributes

	Tier 1	Tier II	Tier III	Tier IV
Building Type	Tenant	Tenant	Stand-alone	Stand-alone
Staffing	None	1 Shift	1+Shifts	"24 by Forever"
Useable for Critical Load	100% N	100% N	90% N	90% N
Initial Build-out Gross Watts per Square Foot (W/ft^2) (typical)	20-30	40-50	40-60	50-80
Ultimate Gross W/ft^2 (typical)	20-30	40-50	100-150[1,2,3]	150+[1,2]
Class A Uninterruptible Cooling	No	No	Maybe	Yes
Support Space to Raised Floor Ratio	20%	30%	80-90+%[2]	100+%
Raised Floor Height (typical)	12"	18"	30-36"[2]	30-36"[2]
Floor Loading lbs/ft^2 (typical)	85	100	150	150+
Utility Voltage (typical)	208, 480	208, 480	12-15 kV[2]	12-15 kV[2]
Single Points-of-Failure	Many + human error	Many + human error	Some + human error	None + fire and EPO
Annual Site Caused IT Downtime (actual field data)	28.8 hours	22.0 hours	1.6 hours	0.8 hours
Representative Site Availability	99.67%	99.75%	99.98%	99.99%
Typical Months to Implement	3	3-6	15-20	15-20
Year first deployed	1965	1970	1985	1995
Construction Cost (+ 30%)[1,2,3,4,5] Raised Floor Useable UPS Output	 $220/ft² $10,000/kW	 $220/ft² $11,000/kW	 $220/ft² $20,000/kW	 $220/ft² $22,000/kW

Typical Tier attributes are listed which act as guidelines for achieving required tier levels, representative site availability being one of the key attributes [33].

Uptime Institute classification defines outcome based infrastructure performance [33] [36]:

- *Tier I:* Basic site with no redundancy where the distribution path or component failure will impact on computer systems and scheduled work will require a shutdown of the computer systems.
- *Tier II:* A site with redundant capacity components and a single non-redundant distribution path where component failure may impact the computer equipment and distribution path failure cause equipment shutdown.
- *Tier III:* A data centre that is concurrently maintainable with redundant components and multiple distribution paths where unplanned events may result in system failure. Normal maintenance activities may elevate the risk of data centre operation disruption.
- *Tier IV:* Fault tolerant system with redundancy capacity systems and multiple distribution paths simultaneously providing power to computer equipment, that are dual-corded.
    - In the event of a single worst-case failure of component, a system or distribution element will not affect operation.
    - Each component and element of the distribution path may be removed for planned maintenance without requiring a shutdown.
    - Complementary systems and distribution paths must be compartmentalised to prevent any single event affecting both systems simultaneously.

Compartmentalisation of the primary and secondary distribution paths, physically separated, provides major advantages in the event of an arch flash or electrical fire. Compartments will allow the data centre to rapidly recover on a power route through a different area from where the fire occurred [33].

Every system and subsystem integrated into the data centre infrastructure must consistently be employed with the object to satisfy Tier requirements. Outcome based confirmation tests and operational impacts are used to measure compliance of each Tier, and differ from a prescriptive design approach or checklist [32].

Tier rating for a data centre is determined by the rating of the weakest sub-system that affects the DC operation and no fractional or partial Tier rating can be obtained. The mechanical and electrical systems must both comply with the requirements for a specific Tier category [33].

Generator plants in a Tier III and IV application are the primary power supply source for a data centre, with the supply authority the alternative supply. These generators, distribution paths and supporting elements must be concurrently maintainable and fault tolerant. The engines of the generators are of the continuous running type [33].

Tier topology is achieved through a review and recommendation process utilising other recognised standards [32]. The four Tier categories address system configuration or topology instead of a prescribed list of components, to obtain the required operational outcome. Tier selection must be based on data centre availability objectives required to sustain defined business processes [33].

Rigorous availability requirements and long term viability are normally satisfied by strategic solutions provided by Tier III and Tier IV site infrastructure which allows the data centre manager to make strategic business decisions [32].

2.3 SYSTEM CONNECTIVITY TOPOLOGY

A power distribution system (PDS) is the most sensitive element that causes data centre downtime. System connectivity topology (SCT) determines the level of power quality and reliability of a power distribution system.

Appropriate system architecture is required to satisfy the growing system load under concepts of safety, reliability, dependability, optimisation, utilisation, efficiency and regulations. Continuous operation is supported by generators and uninterruptable power supplies (UPSs) that provide backup power for mission critical equipment [27], [28]. Primary distribution equipment is [14]:

- Utility service
- Transformers
- Cables
- Generators
- UPS

The requirement to guarantee electrical service continuity through source reliability and power system integrity converts the traditional vertically operated power system to a horizontally operated system [28].

Power system design must be based on equipment steady state and transient characteristic parameters, as this is vital for the functional requirements of the PDS, safety factors and tolerances. Operational data obtained during the life cycle of a system provides valuable information to adjust and improve the performance of the power system [28]. The system design should also allow surplus capacity in the core power infrastructure, including the cable trenches [46].

Figure 2-2 shows the percentage power consumption of the various key components of a data centre with computing equipment 52% and power and cooling 48%. Cooling forms a very large component, 38%, of the latter.

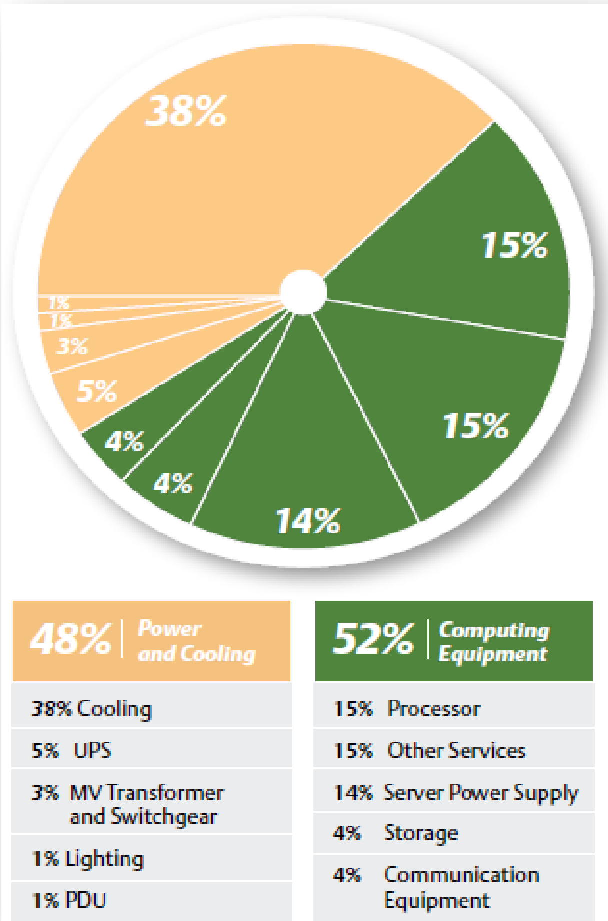

Figure 2-2: Typical data centre power consumption [9]

The PDS architecture must guarantee operational performance while the system allows maintenance, flexibility and expansion. The implementation of an applicable Tier classification standard will increase the reliability of the power distribution system.

A more reliable, fault tolerant PDS is required as technology becomes more complex, with the goal an almost fault-free system of 99.9999% [12]. The elimination of single point of failure (SPOF) is a very successful method to improve system reliability. This can be achieved by incorporating a 2N redundancy design into critical equipment such as generators, UPSs, switchgear and distribution paths [27].

Topology utilising series-parallel systems reduces reliability, while it is enhanced through parallel systems [30]. Zero downtime is the main purpose of data centre operation and thus the objective of a fault tolerant PDS design is to eliminate any SPOF [66].

A system with redundancy and SPOF, where common mode events could cause system failure, must be eliminated. Typical examples of this are a UPS system where a static bypass switch, output circuit breaker or controls are common components [27].

Fault-tolerant IT power equipment can receive two different AC power supplies. Full functionality must be maintained when operating from either supply A or supply B alone or operating from both supplies. The equipment shares the load between the two power supplies within a 10 % average [27], [29].

A 2N configuration provides a complete second PDS and transferring the load from one system to the other without loss of power to the load is critical. Two methods are commonly applied to achieve this, using an automatic supply transfer switch (ASTS) or IT equipment with two built-in power supplies referred to as dual-corded loads [27].

The static transfer switch (STS) provides a break before make switching between the A & B power supplies for uninterrupted power to critical equipment [29].

2.4 KEY COMPONENTS OF SYSTEM CONNECTIVITY TOPOLOGY

MV switchgear & transformers

The design topology of the primary distribution must allow for ease of maintenance without total power disruption. Compact or metal clad MV modular switchgear with electronic relays, vacuum or sulphur hexafluoride (SF6) type with adequate fault level withstand capacity are utilised for the primary distribution.

Step-down medium voltage oil cooled or dry type (cast resin) transformers are used to provide secondary power distribution. Oil-type distribution transformers have a long service life where the oil is used as an insulation and cooling medium.

A dry type distribution transformer is shown Figure 2-3. A special cast resin which is non-flammable is used for outer insulation.

Figure 2-3: Dry type transformers

The cast resin used in the dry type transformers has outstanding mechanical strength and very low calorific energy compared to transformer oil. Forced ventilation is used, allowing the transformer to operate safely within the designed boundaries. These transformers are non-flammable and maintenance free.

Power generators

Cellular network data centres have a large and nearly constant electrical load that requires a high degree of reliability and are thus well suited for self-generation. Diesel power generation and tri-generation, with the latter being a new trend in the data centre industry, are used for delivering reliable power to the data centre infrastructure.

Generation systems can be sized and designed to be the primary power source, while utilizing the grid for backup, thereby eliminating the need for emergency backup generators. Surplus and redundant self-generation capacity can be sold to the grid, recapturing a portion of the generation plant capital cost [49].
Base load type generation, as defined by ISO 8528, must sustain power for long term outages with a minimum fuel capacity of 96 hours.

The energy ratios produced by tri-generation are shown in Figure 2-4 [47]. Heat and electricity produced are 68% and 30% respectively.

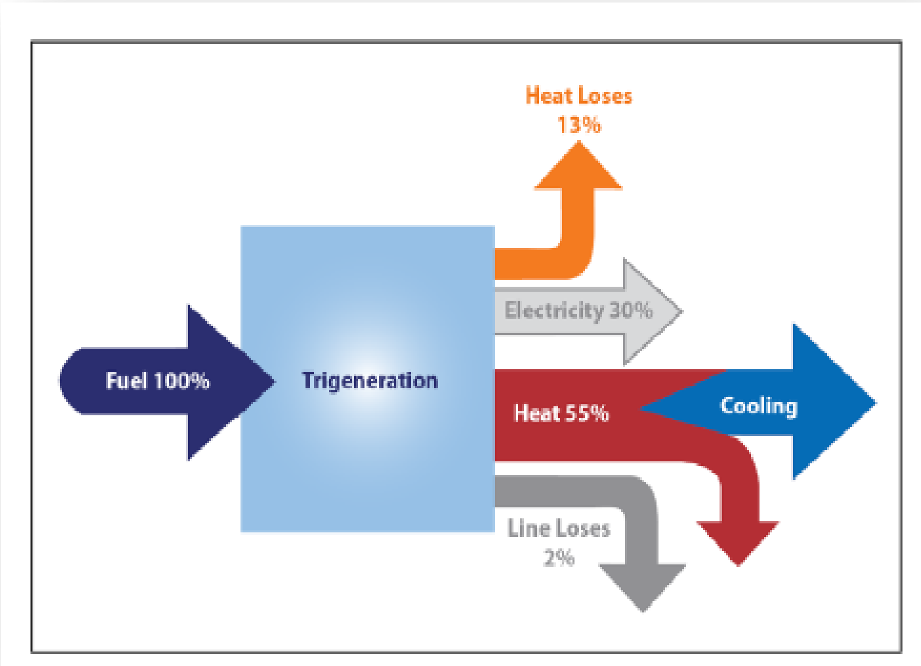

Figure 2-4: Tri-generation energy ratios [47]

Tri-generation uses natural gas to produce combined cooling, heat and power (CCHP) and is the simultaneous generation of electrical or mechanical and thermal energy. Cogeneration converts up to 80% of the fuel`s energy into useable energy, see figure 2-4 depicting the energy ratios [47], [48].

The IT equipment normally has a constant power demand which converts into a heat load, and thus results into a constant cooling load which allows ease of matching of plant selection and power load. Reliability will be increased by running the plant embedded with the grid network.

CCHP generation has a number of advantages including the reduction of the greenhouse gas emissions, CO_2 and SO_2, therefore lowering the carbon footprint.
A schematic representation of the key elements plus the operation of a tri-generation system are shown in Figure 2-5 [48]. A gas fired generator set delivers heat and electricity with the absorption chiller utilising the heat to deliver chilled water.

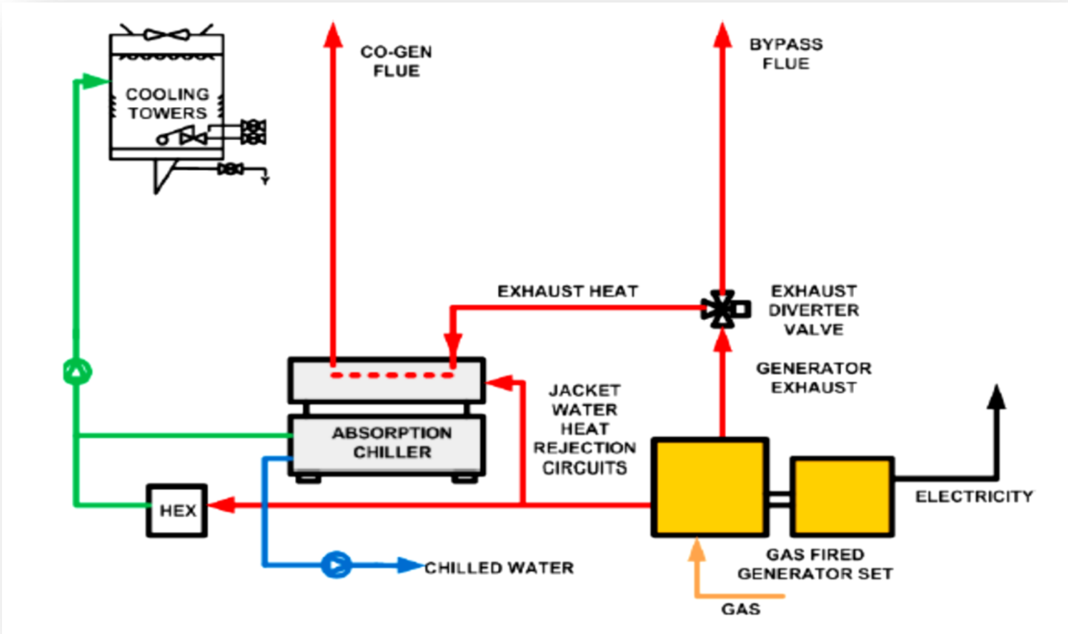

Figure 2-5: Schematic diagram of tri-generation system [48]

One of the major advantages of this type of generation is a large fuel saving of approximately 25% compared with conventional electricity generation. Further advantages are the emission reduction in atmospheric pollution and economic benefits due to the lower energy costs of tri-generation compared with those of conventional units.

Disadvantages:
(a) Risks are introduced, which include fire and explosion and which require mitigating strategies. (b) Gas engines are not good at accepting step loads as large as diesel engines

can, the latter having good step load capacity. (c) Engines consume lubrication oil and require a storage tank and pumping system. (d) They require high capital investment. (e) Complex system to maintain due to many moving parts and sophisticated control interfaces.

Generator system design must take account of harmonic currents imposed by the UPS system. Diesel and maintenance contracts are key issues of onsite generation and have to be implemented.
The correct selection of generators and uninterruptible power supplies is vital for providing reliable backup and primary power to mission critical equipment. Reliability, maintainability constraints, and costs influence the selection of the UPS-generator configuration [28].

Generators are classified by the International Organisation for Standardisation (ISO) Standard 8528-1 into various categories based on application, ratings, and performance. The principle classifications used are emergency standby, prime and continuous ratings. Only continuous rating generators comply with Tier III and IV requirements [28].

Main low voltage (MLV) panel

The MLV panel is one of the most important elements in the system configuration as integrator of all the key elements. Design and modular functional units of a Type Tested panel ensure reliability with optimal safety for personnel.

Type Tested panels are manufactured in increasing equipment separation categories ranging from Form 2 to Form 4, the highest level of separation of functional units and thus providing the highest reliability. Distribution paths and complementary systems are compartmentalised, preventing a fault condition simultaneously affecting both paths and systems [32].

The circuit breakers are draw-out or plug-in type, which allow the equipment to be hot swappable. The incomers and feeders with ratings of 800 Amp or larger, are air circuit breakers with Micrologic electronic control units. Moulded case circuit breakers with electronic overloads are for feeders smaller than 800 Amp.

Air circuit breakers are robust, maintainable and of the utilisation category B, that is with an adjustable short-time delay that provides selectivity under fault conditions with respect to other circuit breakers that are connected in series on the load side. All protection is coordinated selectivity, allowing the fault to be isolated and ensuring service continuity of the power system.

Moulded case circuit breakers with fault current limitation are used, which have, as the air circuit breakers, incorporated advanced monitoring and communication functions. The equipment has a monitoring unit to control energy consumption and power, and provides real time data.

The monitoring units provide maximum demand and instantaneous values, kilowatt-hour data, harmonic distortion rates, alarm notifications event logs and tables. They further provide communication on (a) device status: on/off and trip indication (b) commands: open, close, and reset (c) measurements.

Where several circuit breakers are connected in series, discrimination between the downstream devices is achieved and this trips the device nearest to the fault. Current limiting circuit breakers reduce the thermal and electro dynamic stresses of fault conditions on the equipment, thereby extending their service life.

Multi-pole modular combined lightning current and surge arresters of the class 1 type are fitted to the A and B sections of the panel. These units have a discharge capacity of 100kA at a 10/350µs wave form and a clamping time of ≤ 100ns.

Uninterruptable power supply (UPS)

The UPS system provides reliable conditioned power to critical equipment. Rotary machines, static double conversion type with a battery bank, or other type technologies can be utilised to deliver uninterrupted power to critical server equipment.

UPS systems are static, rotary or hybrid type and system selection based on UPS system kW rating with allowance for peak load and future expansion. Each module must have a separate battery system with a minimum backup capacity of 5 to 30 minutes. A battery monitoring system must be implemented that is capable of logging and trending battery cell voltages and resistances [31].

Parallel redundant configurations allow for the failure of a single UPS module without the need for the critical load to be transferred to a generator or utility power. An N+1 system has multiple units, identical in capacity and model type, paralleled onto a common output bus with the spare capacity equal to one unit.

The output of the modules is synchronised and in certain cases the paralleling function also controls the current output between the modules. There is a maximum number of modules that can be parallel on the output bus, which differs between the various manufacturers.

The UPS modules in the redundancy configuration share the critical load evenly under normal operating conditions, and this characteristic allows a module to be removed for maintenance without impacting on the critical load.

Increased UPS efficiency is achieved by minimising losses through improving the load factor to 0.9 as shown in Figure 2-6 [51].

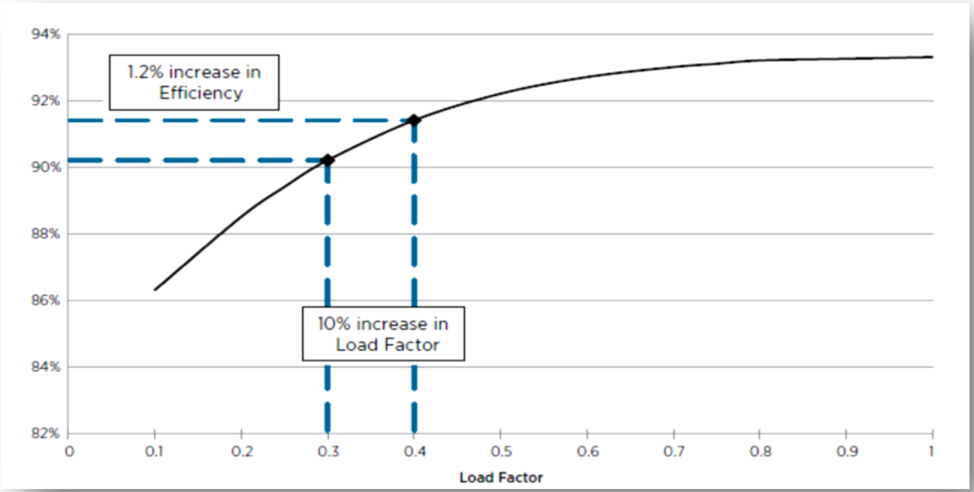

Figure 2-6: Typical UPS efficiency curve for a 100 kVA unit [51]

Efficiency is improved by the following [25]:

- De-activate certain UPS models when redundancy exceeds (N+1) or (2N)
- Switch load between UPS models to achieve the best load factor
- Use scalable/modular UPS
- Install UPS that closely fits the current load capacity
- Double conversion with isolation transformer for galvanic isolation
- A maintenance manual bypass switch

- The Delta static UPS and Rotary UPS have the highest efficiencies

A static UPS should have a static bypass switch, an electronic switch which will operate in less than 12 milliseconds and shunt power around the UPS during the loss of inverter output.

Parallel UPS modules must use intelligent control to divide and manage the load between multiple modules and deactivate units that are not required to provide power to the load, while redundancy is not compromised. Data centres require a UPS configuration that provides a very high level of availability, for example an 2(N+1) system. The system configuration must have the capacity to grow as the load grows.

Battery system

The IEEE defines two types of batteries to be used for UPS systems, wet or flooded cells called vented lead acid (VLA) and valve regulated lead acid (VRLA). VLA batteries require higher investment costs, more floor space, a vigorous maintenance plan and ventilation, but provide higher reliability [32].

Battery failure is one of the main causes of UPS system failure and best practice is to install a dedicated battery monitoring system which records and performs trending of battery cell resistance and voltage [52].

Power distribution units (PDUs)

Multiple PDUs with built-in power monitoring provide redundancy and are used for distribution of conditioned reliable power to critical equipment, servers, networking equipment and other electronic devices.

The PDUs are strategically placed on the perimeter of the space, relatively close to the equipment, which results in shorter cables with less power losses. Two types, field-wired and modular factory configured, are built into server cabinet to customer requirements with circuit breakers and pre-cut and terminated cables.

Modular PDUs with the equipment wired to terminals provide more reliability and flexibility, and improve the efficiency with greater ease of system management.

Integrated branch circuit monitoring reports the current and alarm conditions of the various circuit breakers. Concurrent maintainability is provided, which means that any component of the PDS can be repaired, replaced or serviced without disrupting the service [53].

Power distribution units (PDUs) are located in the same room as servers, fed with A and B supplies, and provide the final distribution to the servers. The PDUs must allow load balancing and service continuity.

The circuit protective devices must be able to handle the inrush current produced by the electronic equipment. Discrimination between devices is an important characteristic, as a fault condition is cleared by the protective device immediately upstream of the fault.

Grounding and surge protection

Electrical continuity throughout server racks and cabinets is established for electrostatic discharge (ESD) and safety protection through proper grounding and bonding of all metallic components in the data centre [16], [54]. High relative humidity of 40% in data centres deters static charges from forming.

The data centre has a lightning protection level 1 which provides a system efficiency system of 98% as defined by the IEC 62305 standards for protection against lightning. The down conductors are linked to the earth electrode copper strip, which establishes a common potential level.

Ground reference is very important with respect to SPDs as all voltage and signal levels are referenced to ground. The surge protection devices use ground wires and cables to discharge the excess voltage during transients.

A network of surge protection devices (SPD) with remote monitoring capabilities is installed to attenuate the damaging effects of transient voltages on equipment. The SPD are cascaded, with the first units in the main low voltage panel and the others in the sub-distribution and critical server room panels.

Metal oxide varistors (MOV) are installed in the class 1 and 2 areas which require high energy devices, while silicon avalanche diode surge arrestors are installed in the server room (class 3) of the data centre. This type of surge arrestor clamps the voltage transients in less than 5 Nano seconds.

2.5 RELIABILITY – SYSTEM FAILURE LIFE CYCLE

The term reliability covers various topics including availability, durability and quality. Reliability is defined as the probability that a component will perform its required function under given conditions for a specific period of time [50]. The application of a proper design, utilising correct components, and a comprehensive understanding of failure mechanisms, leads to achievement of reliability [37], [38], [67].

Reliability of a data centre power distribution system depends on numerous electronic parts, systems and component inherent characteristics (CICs). Product reliability confirms the robustness of the design and the integrity of the quality [39]. Redundancy represents a possible approach to enhancing power system reliability [8].

Redundancy systems used in power distribution systems are:

Active redundancy:

- Load sharing
- Distribution path diversity
- Frequency diversity
- Space diversity

Standby redundancy is not operational until a sensing device records a failure in system A and switches automatically or manually to system B.

System reliability is compromised by six main components [14]:

- Lack of or poor system monitoring
- Inadequate system protection
- Inadequate surge protection
- Poor wiring and grounding
- Insufficient system maintenance
- Poor system design and availability

Availability can be improved through reliability-centred maintenance (RCM). A maintenance programme that is efficient and effective maximises resources and availability. Reliability-centred maintenance is based on the concept of developing an effective and efficient maintenance programme utilising reliability characteristics of the components and sub-systems, economics and safety [37], [40].

RCM consists of a logical, structured framework for determining the optimum combination of applicable and effective maintenance activities required to sustain operational reliability of equipment and systems while ensuring their support, safe and economical operation.

Figure 2-7 illustrates how system reliability changes with time and refers to the mean up and down times.

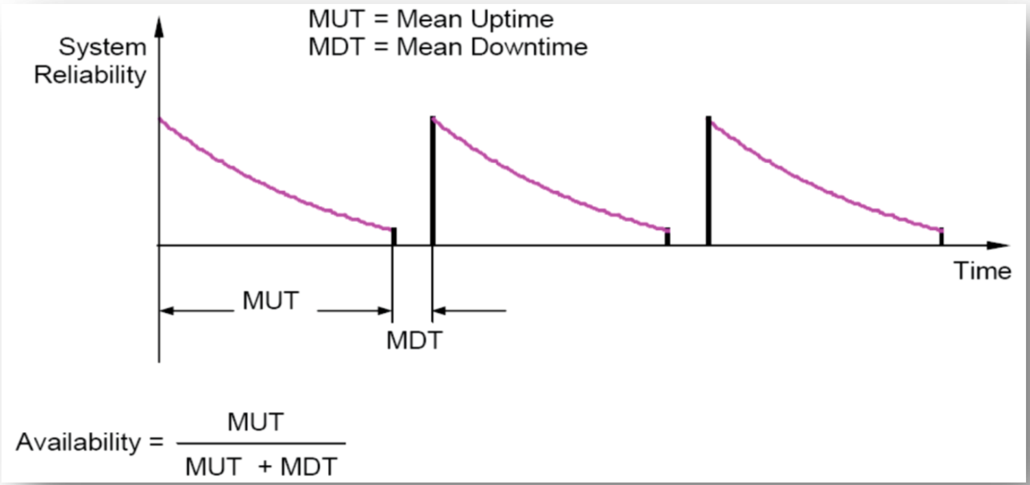

Figure 2-7: Illustration of system reliability changes with time [41]

The reliability-centred maintenance method is based on the following factors [53]:

- Aim to preserve equipment or system function
- Maintaining end system function more important than individual component function
- Reliability is used as basis for decision making with the requirement that the failure characteristics of a component or system in question are understood to determine the efficacy of the preventative maintenance (PM)
- Safety is the first consideration and then economics

- Design limitations must be acknowledged, as inherent reliability is dictated by design
- RCM must be treated as an ongoing process with the actual and perceived design life and failure characteristics addressed through investigation

Systems are becoming more complex and hence the importance of employing methods to specify and analyse systems and sub-systems. The need to assess the availability, reliability and maintainability of the PDS is becoming very important as data centre managers understand the effects of failures and downtime [37].

The reliability of a system is defined by five interrelated metrics [42]:

- Mean time between failures (MTBF)
- Mean time to repair (MTTR)
- Availability (A)
- Reliability (R)
- Time

The "language" of reliability is the mathematics based on the theory of probability and statistics [37], [41]. Reliability modelling provides a valuable and effective tool that involves a large portion of statistics and is used to compare various system designs. Modelling allows for evaluation, prediction and control required for design, an effective maintenance system, and operation [37], [67].

Important factors that are considered in the analysis are: reliability data such as failure rates of components, repair times, interruption definitions and reliability equations [22]. The following definitions apply [20], [24], [26], [42], [67], [70]:

- *Failure* is the transition event that occurs when the provided service deviates from the correct state to the unwanted delivered service state
- *Failure rate* (λ) is the rate that a failure per unit of time occurs in an interval, provided that no failure has occurred prior to the start of the interval
- *Dependability* is the ability to deliver service that can justifiably be relied on
- *Mean time between failures* (MTBF) is the mean exposure time between consecutive failures of a component and for a case of a constant failure rate: MTBF = $1/\lambda$

- *Mean time to repair* is the mean time to repair or replace a failed component, while the logistics time associated with the repair are not included
- *Availability* is the ability of a system or component to perform its required function at a stated average fraction of time or over a stated period and mathematically defined as the mean time between failures divided by the mean time between failures plus the mean time to repair:

$$A = MTBF/ (MTBF + MTTR)$$

- *Error* is a deviation from the correct service state of a sub-system or system
- *Maintainability* is the probability that a device or system that has failed will be restored to operational effectiveness within a given time period

$$M(t) = 1 - e^{-\mu t}$$

Where μ is the repair (restoration) rate = 1/MTTR

Figure 2-8 shows the reliability bathtub curve which indicates the three distinct phases in the life cycle of equipment and components: infant mortality, useful life and wear out.

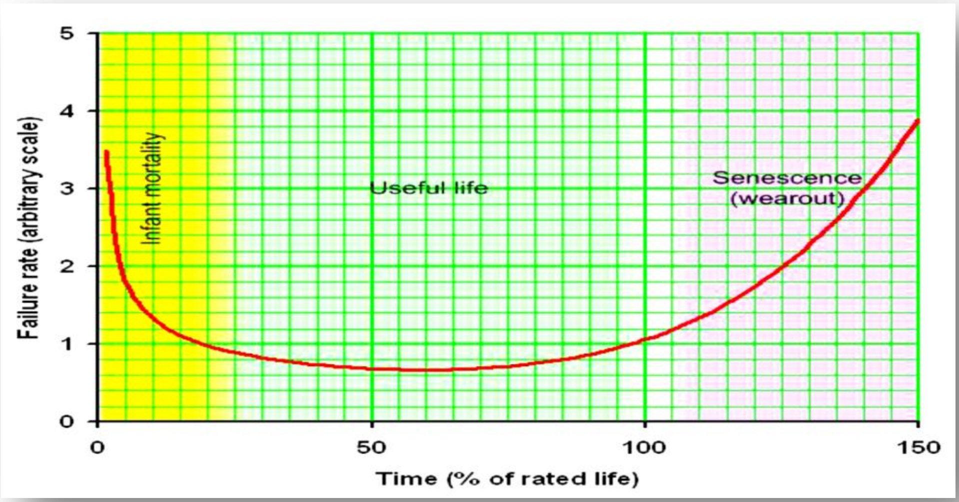

Figure 2-8: Reliability Bathtub Curve [26], [43]

Electronic and many other types of equipment have a relatively constant failure rate over a great part of their useful life and follow an exponential statistical distribution with reliability as a function of time (t):

$$R(t) = e^{-\lambda t}$$

The life of a component or system can be divided into three definite periods: the infant mortality period, normal life, and the end of life wear-out [39]. Figure 2-8 is based on the *cumulative distribution function,* probability theory and statistics, and may be analysed using a Weibull chart which models the exponential distribution.

Calculations and analysis tools are important in optimising system reliability [36]. The analysis tools can provide forecasting of system reliability, classify power disturbances and trace the causes in real-time.

The steps in performing reliability analysis are [37]:

- Define the problem and objectives
- Model building: Description of system`s entities and their interaction
- Quantify probability distributions for system`s entities
- Calculate the various indices
- Experimental design: Determine initial conditions, simulation period and number of runs
- Document reliability study to verify that problem definition objectives are achieved

Figure 2-9 shows the exponential distribution curve for the equation $R(t) = e^{-\lambda t}$, relating reliability and time when the failure rate is constant. In probability theory and statistics exponential distribution is family of continuous probability distributions.

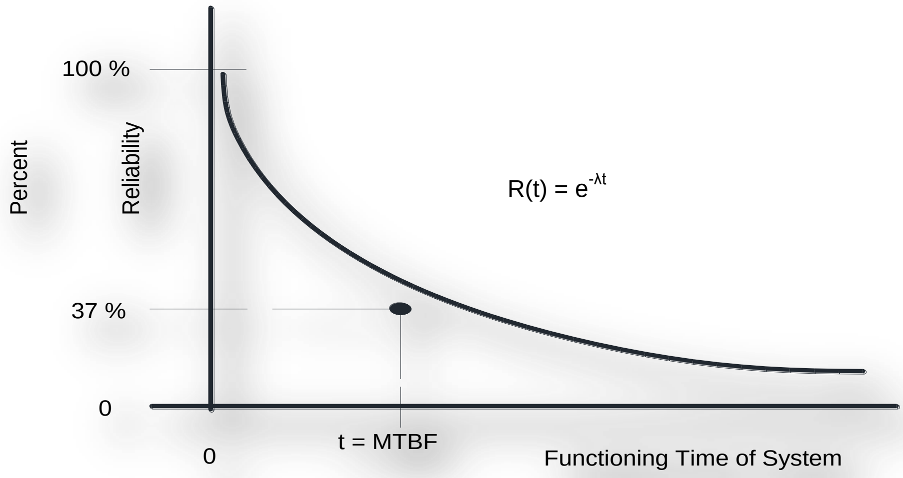

Figure 2-9: Exponential curve relating reliability and time [37]

The mean is not "50-50" point as for normal distribution, but approximately the 37-63 point. This is when the time of operation equals the MTBF and the reliability is 37%. In other words, if the MTBF of equipment is 100 hours, only 37% of the equipment will be operational after 100 hours of operation [37].

Systems are evaluated using analytical methods based on a variety of logical and mathematical principles. Certain simulations use algebraic formulas to determine an exact solution to a model of a system, while other methods use simulation processing to empirically determine model solutions. Simple systems can be calculated with pen and paper, but this becomes cumbersome as the system grows linearly [37], [44].

Various techniques and algorithms that can be used for calculating reliability of larger systems [27], [37], [68], [69]:

- *Cut-set* method can be applied to simple or complex systems and is a highly suitable technique analysis of power distribution systems. A cut-set is defined as a set of components whose failure alone will cause failure of the system.
- *Network reduction* methodology successively reduces series and parallel structures by replacing them with equivalent components.
- *Boolean algebra and block diagrams* are one of the most useful evaluation methods. The use of software to perform these analyses is a definite requirement as the logic and algebra becomes immense as systems grow larger. The GO algorithm, a success-oriented system analysis technique, is one such method.
- *State space* method is based on a mathematical concept called Markov Chains which uses a modelling technique to describe a system by the possible states it can possess, that is state space. A power distribution system is basically in two distinct states: up or down.
- *Monte Carlo simulation* methodology can be used in many forms, from simple spread sheet models to complex programming language models. This simulation is an iterative process which considers possible scenarios that could occur in the future. These scenarios are dependent on the failure characteristics of the system components. The average of all the iterations provides the expected system availability.

Analysis results are very sensitive to the following [37]:

- Assumptions
- Calculation techniques
- Databases such as the IEEE 493 Gold Book standard [27] and Power Reliability Enhancement Program (PREP) of the US Army Corps of Engineers [67] are two well-known and recognised databases

Rigorous reliability analysis results are powerful tools when used correctly to compare alternative designs. The use of the results of an analysis to guarantee availability of a particular system over a period of time can lead to over-optimistic results [41].

Data centres are dynamic systems in which reliability can be maximised through the recognition of the following factors [41]:

- Over-emphasis on availability analysis figures
- Failure rate complexities
- Importance of commissioning and maintenance
- Implementation of emergency procedures
- Employing trained maintenance staff

2.6 SUMMARY

The power distribution system of a data centre is complex and consists of medium voltage switchgear, step down distribution transformers, main low voltage panel (MLV), power distribution units (PDUs), power generators, uninterruptable power supply (UPS) system, cable management system, lightning and surge protection systems, and monitoring and measurement systems.

The power distribution system (PDS) is the element that impacts the most on data centre downtime and could have serious financial consequences for a company. System connectivity topology (SCT) plays a vital role in the PDS reliability and it is therefore important to select the correct configuration for a specific application.

Topics such as availability, durability and power quality are covered by the term reliability. Redundancy, reliability-centred maintenance and system topology design are possible approaches to enhance reliability.

Reliability modelling and analysis is a valuable and effective tool which allows system evaluation, reliability and availability prediction and the implementation of effective maintenance and operational systems.

CHAPTER 3 RELIABLE POWER SYSTEM DESIGN FOR A CELLULAR NETWORK IN AFRICA

3.1 PREAMBLE

This chapter serves as discussion and development of methodologies to improve system reliability. A recognised methodology is used to determine the reliability of the power system. In addition to this, assumptions, criteria, limitations and constraints are defined to design a reliable power system.

3.2 TECHNIQUES TO IMPROVE POWER SYSTEM RELIABILITY

African countries are experiencing a serious power crisis marked by unreliable supplies and lack of distribution capacity. This adversely affects the reliability of a power distribution system of a cellular network. The majority of African countries have weak infrastructure and the reason for this appears to be the difficult environment in which to develop infrastructure [74].

The majority of the existing cellular network data centres in Africa have multiple single points of failure with insufficient redundancy and no Tier level certification. This was evident during the author`s 15 years of experience in power distribution system design for cellular networks in Africa. The reliability of the distribution system must be improved and maintained to be compliant with international data centre standards for information and communication technology (ICT).

Certain electrical power failures at data centres can be catastrophic, causing downtime that amounts to thousands in lost profits [14]. Reliability of the power distribution system (PDS) is one of the critical issues and depends on numerous electronic parts, systems and component inherent characteristics (CIC).

The following methodologies have been identified to improve the reliability of the PDS for data centres in Africa:

- Eliminate single point of failure (SPOF)
- Provide adequate redundancy

- Optimise system connectivity topology (SCT)
- Provide adequate system and component maintenance
- Provide in-depth training to all staff

These methodologies are discussed in the following sections.

3.2.1 ELIMINATING SINGLE POINT OF FAILURE

Single point of failure (SPOF), as the name implies, represents positions in the PDS in which the failure of a single piece of equipment causes the system to fail [27]. This increases the vulnerability of the system and is one of the major factors resulting in a power outage during a fault condition in the system.

Figure 3-1 illustrates a typical (N+1) system which only requires one out of two generators and two out of three UPS modules to support the critical single corded loads [27].

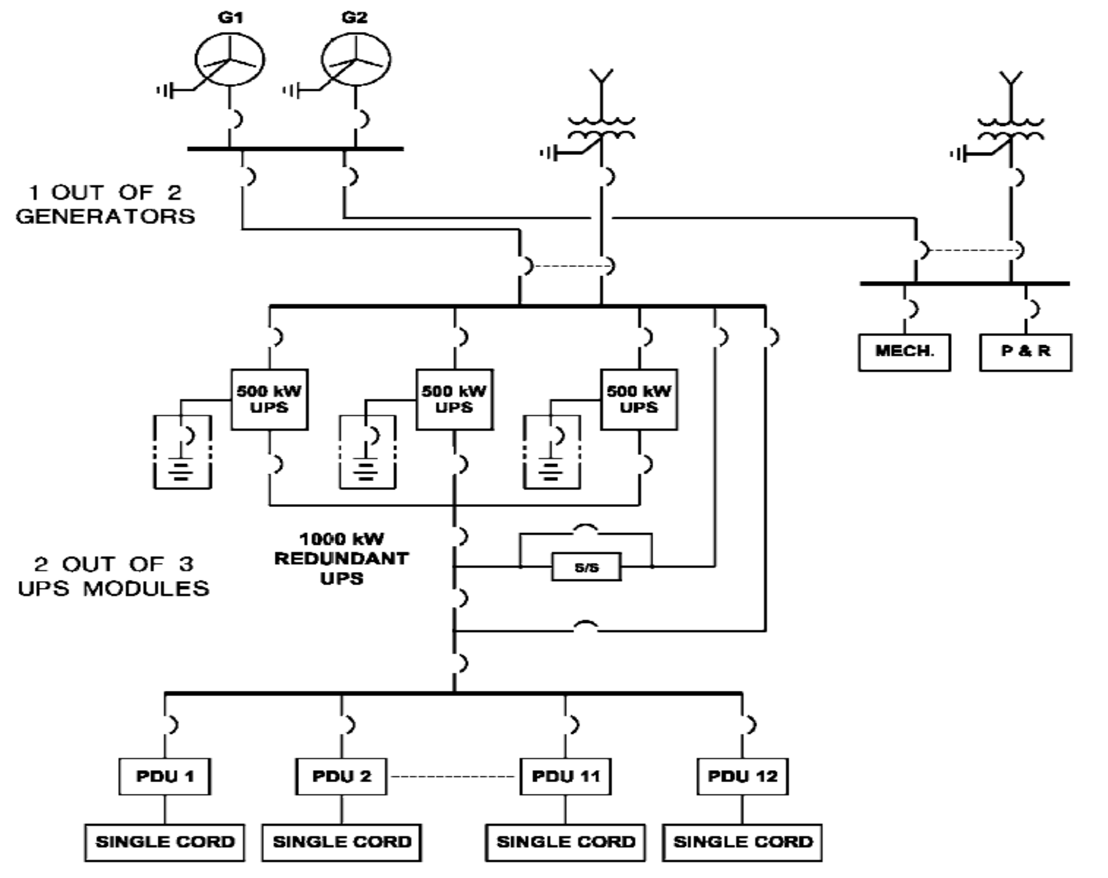

Figure 3-1: (N+1) generators and UPS modules [27]

In Figure 3-1 the switchboard supplying power to the UPS modules and the panel below the UPS modules supplying power to the PDUs, are both SPOFs. A failure that takes longer to repair than the battery backup time will result in all of the critical loads losing power.

Therefore a fault on the distribution panel itself would take down the data centre facility. The quick location and isolation of the main breaker tripping on a feeder fault might not take down the data centre.

Figure 3-2 shows a PDS with two parallel distribution paths with automatic static transfer switches (ASTSs) providing power to single corded loads [27].

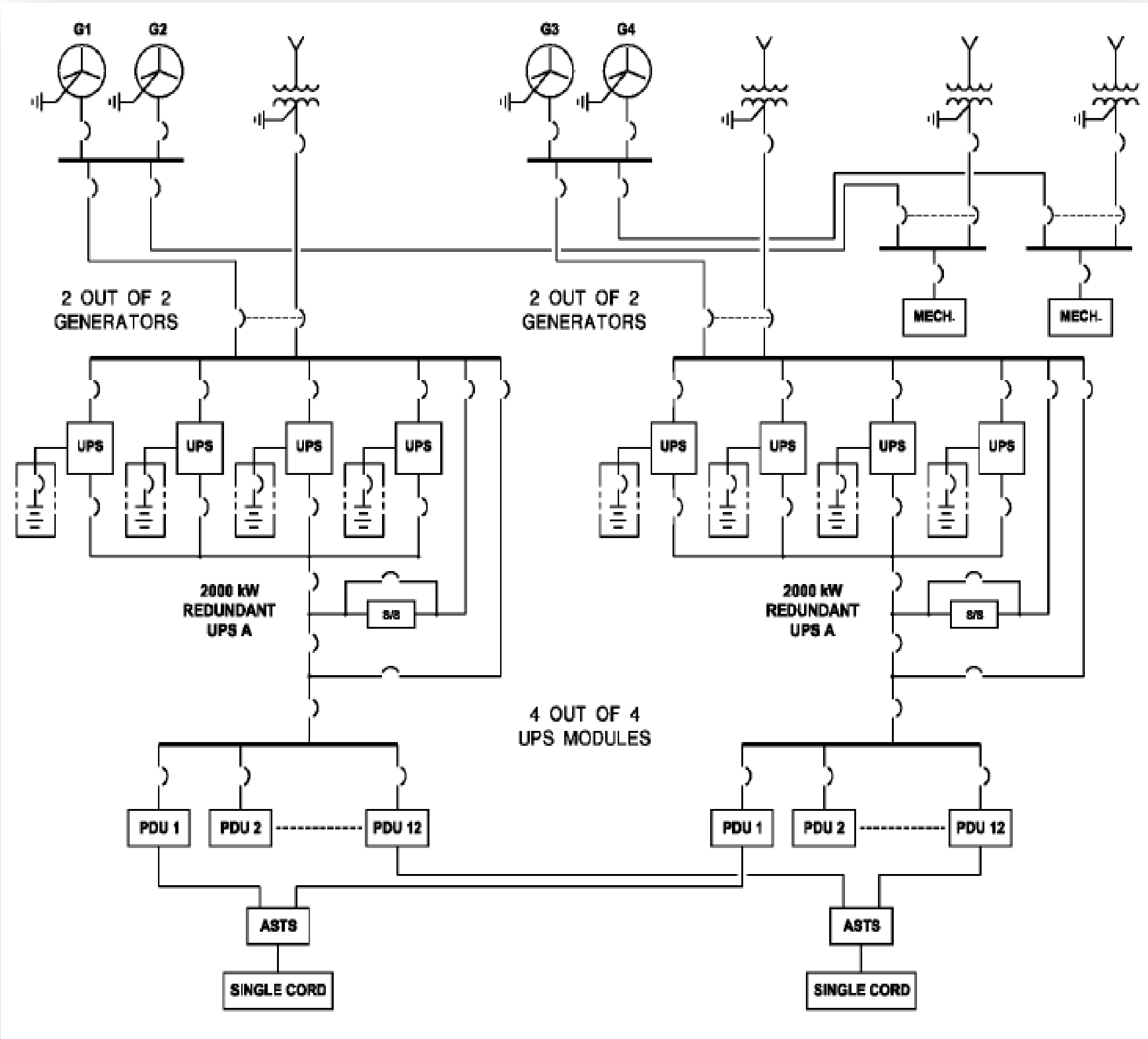

Figure 3-2: 2N power distribution system to single corded loads [27]

Eliminating a SPOF in a distribution system increases the reliability of the system. Each component in a distribution path provides a single point of failure which can cause the system to go down. A typical example is that when the feeder cable of a bank of UPS modules supplying a critical load develops a fault, the entire system fails.

Introducing parallel distribution paths, 2N configuration which is a duplicate second path, eliminates SPOF. However, to utilise the second system, we require a method of transferring the load from one system to the other without disrupting the operation of the load [27].

Two commonly used methods to accomplish this are:

- Automatic static transfer switches (ASTSs) transferring power to PDU, distribution panels, or racks as shown in Figure 3-2.
- Utilising IT equipment that has two power supplies built into it, either of which is capable of providing power to the entire load.

The second option is referred to as *dual-cord loads,* as there are two power cords (one for each power supply). Dual-cord loads require each cord to be powered from a different system as to gain the benefit of the redundant system.

Reliability is enhanced by system design as shown in Figures 3-1 and 3-2. The following should be considered when designing to eliminate SPOF in the PDS for data centres of cellular networks in Africa:

- Power quality
- Parallel paths
- Redundancy
- Component inherent characteristic (CIC) of individual components in the critical path
- System monitoring and coordination of protective devices
- Grounding, surge and lightning protection

Single point of failure is the most influential factor in the design of power distribution systems for data centres of cellular networks.

3.2.2 REDUNDANCY

Redundancy is a key aspect of critical distribution systems and represents a possible approach to improving system reliability and availability. A requirement for redundancy is that any of the parallel power systems must have adequate capacity to support the entire load [8], [27].

System redundancy is not limited to simply having a duplicate system. The required equipment to achieve an operational system is defined as N, while 2N would, in turn, imply that there is double the capacity, i.e., 1 of 2 is required to operate the system successfully.

In certain facilities where there is a full 2N philosophy for redundancy, the PDS will often have an additional piece of equipment on each side so that if one of the N pieces of equipment is down for maintenance, the facility remains 2N redundant. This configuration would be 2(N+1) [27].

Levels of redundancy where *"N"* is the number of units:

- *N* - Satisfy base load requirements with no redundancy and where N>1, the reliability is rapidly diminished.
- *N+1* - Provides one additional unit/path/module; stoppage of a single unit will not affect operations and if this system runs at partial load, it can become N+2.
- *N+2* - Provides the opportunity to carry out maintenance without degrading resilience.
- *2N* - Two dedicated units/paths/modules for every base load system, and failure of one complete system will not disrupt operations for dual-fed loads.
- *2(N+1)* - Two complete (N+1) units/paths/modules, and failure of a system leaves an additional system with resilient components for dual-fed loads.

Table 3-1 shows the impact that various levels of redundancy have on the availability of a distribution system [27] [72].

Table 3-1: Redundancy comparison [27]

Number of Paths	Redundancy	Requirement	Availability
1	N	1 of 1	0.99
2	N + 1	1 of 2	0.9999
3	N + 2	1 of 3	0.999999

With regard to availability, Table 3-1 represents the availability of a system that requires 500 kVA of power, assuming that each has an availability of 0.99.

The reliability of above redundant system in Table 3-1 can easily be calculated by finding the probability of failure (1– *R*(*t*)) for each parallel path, multiplying the probabilities of failure (which gives the probability of both paths failing), and then subtracting the result from 1. See below a typical example of how to perform the calculations.

A reliability block diagram of a distribution system with redundant components is shown in Figure 3-3 [27]. The redundant system has two paths and with either of them intact the system can operate. The values above blocks A and B are the failure rates per year and below are the reliability values of each block.

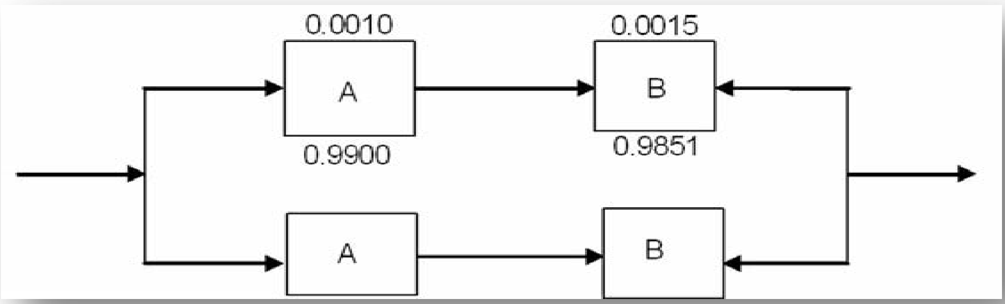

Figure 3-3: Reliability block diagram of system with redundant components [27]

The reliability and probability of each path and of the complete parallel system are determined by utilising Equations 3-1 and 3-2.

The reliability of each path can be calculated where the failure rate is the sum of the failure rates of A and B:

Failure rate per year (A+B) = (0.001+0.0015) = 0.0025

The reliability of one path:

$$R(t) = e^{-\lambda t} \quad (3\text{-}1)$$

$$R(t) = e^{-0.0025x10} = 0.9753$$

Where: t = 10 *million hours*

λ = *failure rate per year*

The probability of a path failing is then found by subtracting its reliability from 1. Thus, the probability of either path failing:

$$Probability\ of\ failure = (1\text{-}R(t)) \qquad (3\text{-}2)$$

$$= (1 - 0.9753) = 0.0247$$

The probability that both paths will fail:

$$Probability = (0.0247 \times 0.0247) = 0.0006$$

Finally, the reliability of the system in Figure 3-3:

$$R(t) = (1 - 0.0006) = 0.9994$$

The last-mentioned shows a significant improvement over the series-configured system, (A + B), which had a reliability of 0.9753.

The above methodology is now applied using Equations 3-1 and 3-2 to calculate the availability of the various redundancy levels in Table 3-1:

The availability (A) of one path (given):

$$A = 0.99$$

Probability of one path failing:

$$(1\text{-}A) = (1 - 0.99) = 0.01$$

The probability that both paths (N+1) will fail:

$$(0.01 \times 0.01) = 0.0001$$

And thus the (N+1) availability:

$$A = (1 - 0.0001) = 0.9999$$

The availability for redundancy level (N+2) in Table 3-1 can be calculated using the above method. The table clearly demonstrates that as the redundancy increases, the availability increases.

Component redundancy is utilised to obtain a higher level of reliability. Generators and UPSs are critical distribution equipment that has to be provided with sufficient redundancy to achieve the required reliability levels. A UPS redundancy system provides the highest level of reliability. Redundancy increases reliability and availability, but the trade-offs are an increase in capital and life cycle costs [27].

Table 3-2 indicates the critical distribution systems' availability and probability of failure (5 years) for the various redundancy configurations.

Table 3-2: Critical distribution systems reliability and availability [27]

Name	Description of critical distribution system	MTBF (h)	MTTR (h)	Inherent Availability (Ai)	Probability of failure (5 years) (%)
N + 1	Gen (1-2), UPS (2-3) 6 ASTS/single-cord loads	67 759.1	4.48	0.9999340	39.95
2N	2X (Gen (1-2), UPS (2-4)) 12 ASTS/ single-cord loads	106 799.6	5.44	0.9999490	29.80
2N	2X (Gen (1-2), UPS (2-4)) 12 dual-cord loads	188 654.5	1.64	0.9999913	16.61
2(N + 1)	Gen (2-3), 2X (UPS (2-5)) 12 ASTS/ single-cord loads	111 264.2	5.63	0.9999494	28.07
2(N + 1)	Gen (2-3)< 2X (UPS (2-5)) 12 dual-cord loads	203 269.3	1.74	0.9999914	16.49
DR (2-3)	Gen (2-3), DR(2-3) X (UPS 2-3), 12 ASTS/single-cord loads	95 476.9	4.90	0.9999487	28.84
DR (2-3)	Gen (2-3), DR (2-3)X (UPS 2-3), 12 dual-cord loads	156 564.7	1.38	0.9999912	17.05

The 2(N+1) configuration with two out of three generators, 2 x (2 out of 5 UPS) and with twelve dual-cord loads provides the best availability and probability of failure results, 0.9999914 and 16.49% respectively [27].

Table 3-2 confirms the increase of system reliability with the application of various configurations of redundancy to critical equipment.

3.2.3 SYSTEM CONNECTIVITY TOPOLOGY (SCT)

Data centre design should provide flexibility to meet the business needs, scalability and high power density capacity, and take cognisance of new technologies. Furthermore, it should have the right level of availability and redundancy to meet service level agreements (SLAs) [16], [45].

The power system architecture must guarantee operational performance with a high reliability level, while the system allows for maintenance, flexibility and expansion. This can be achieved by implementing a Tier IV classification standard that provides the required reliability.

The impact of actual operating loads is considered when selecting power supplies to achieve the best efficiency for the most frequently operated load level. Multiple feeders are installed from the supply authority, and power generators and uninterruptable power supply (UPS) with redundancy provide backup power to critical equipment during long term outages.

Figure 3-4 shows typical examples of parallel medium voltage distribution paths [11]. The right-hand option provides a higher reliability due to a higher connection voltage resulting in fewer shared connections and two parallel feeds connected to the data centre.

Mission critical configuration must address technology choices that provide resiliency for cellular network data centres. Tier IV topology allows a fault tolerant infrastructure with independent A and B distribution paths, two transformers, two generators, and two (N+1) UPS systems with the last point of redundancy inside the server equipment.

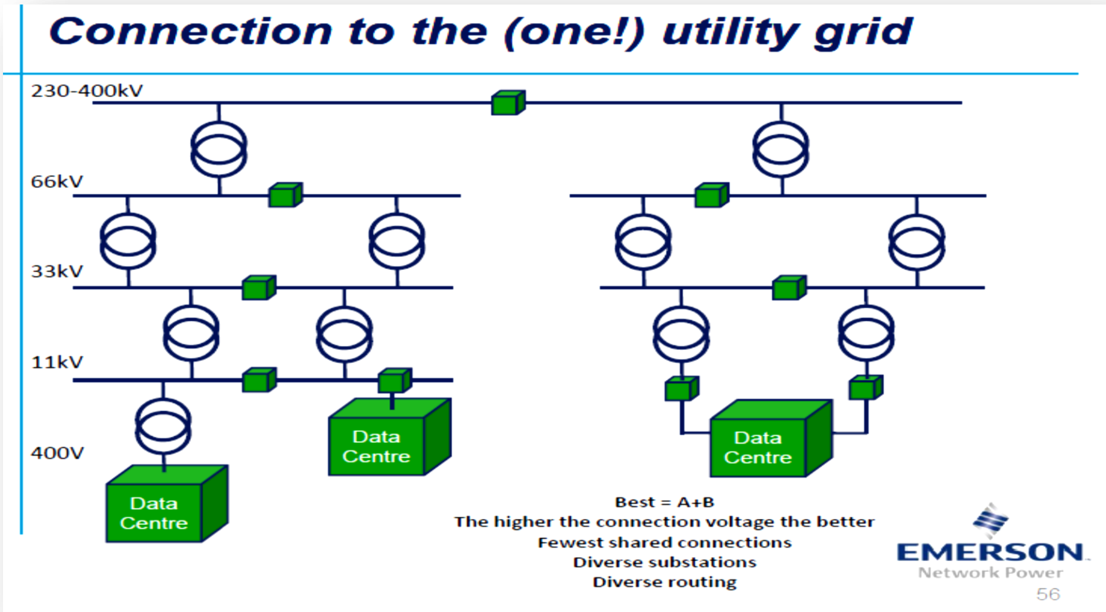

Figure 3-4: Utility power supply configuration [11]

Zero downtime is the main objective of data centre operation and implementing a fault tolerant system as recommended by international standards TIA-492, IEEE-493, IEC-620040-3 eliminates a single point of failure (SPOF), which assists in working towards this goal [29], [34].

The power system design must allow surplus capacity in the core power infrastructure including the cable trenches [46].

Figure 3-5 shows a typical Tier IV parallel redundant power distribution system for a data centre [32].

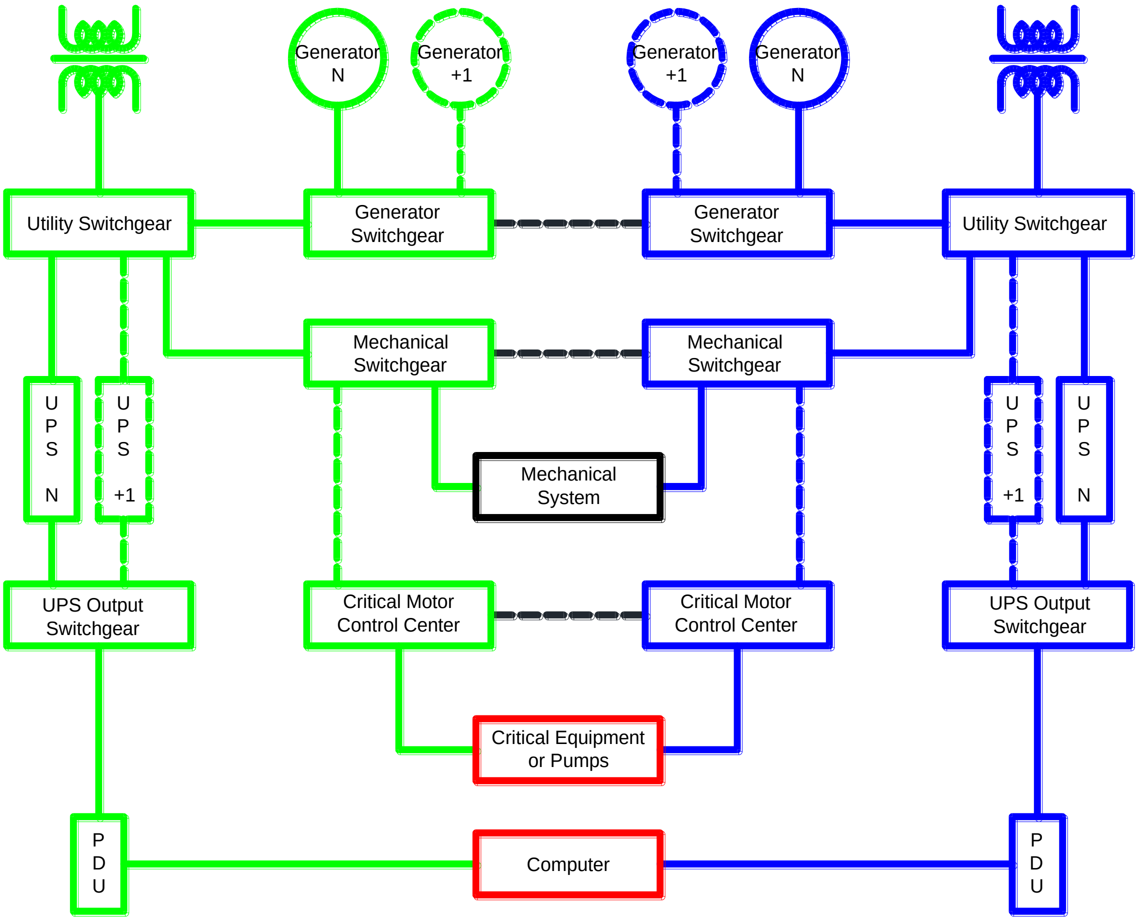

Figure 3-5: Typical Tier IV power distribution system [32]

It is important that a Tier IV system as shown in Figure 3-5 be implemented to achieve and maintain the reliability requirements. The PDS is a 2N system and can be expanded to a 2(N+1) system with dual-cord equipment to achieve the high reliability levels as shown in Table 3-2.

The distribution systems that are installed must be fault tolerant and concurrent maintainable with two utility supplies, redundant generators and UPSs, 2N critical switchgear and power distribution units (PDUs).

An accredited institution has to carry out Tier level certification once the installation has been completed, confirming the design implementation. The major advantage of certification is that it emphasises areas or equipment that do not comply and may result in downtime of the data centre.

3.2.4 DESIGN GUIDELINES FOR KEY COMPONENTS OF SYSTEM CONNECTIVITY TOPOLOGY

The type of component used in the design of the system connectivity topology must be rigorously evaluated.

The block diagram in Figure 3-6 indicates the key components of SCT found in a data centre. The block diagram further illustrates the interfacing of the components.

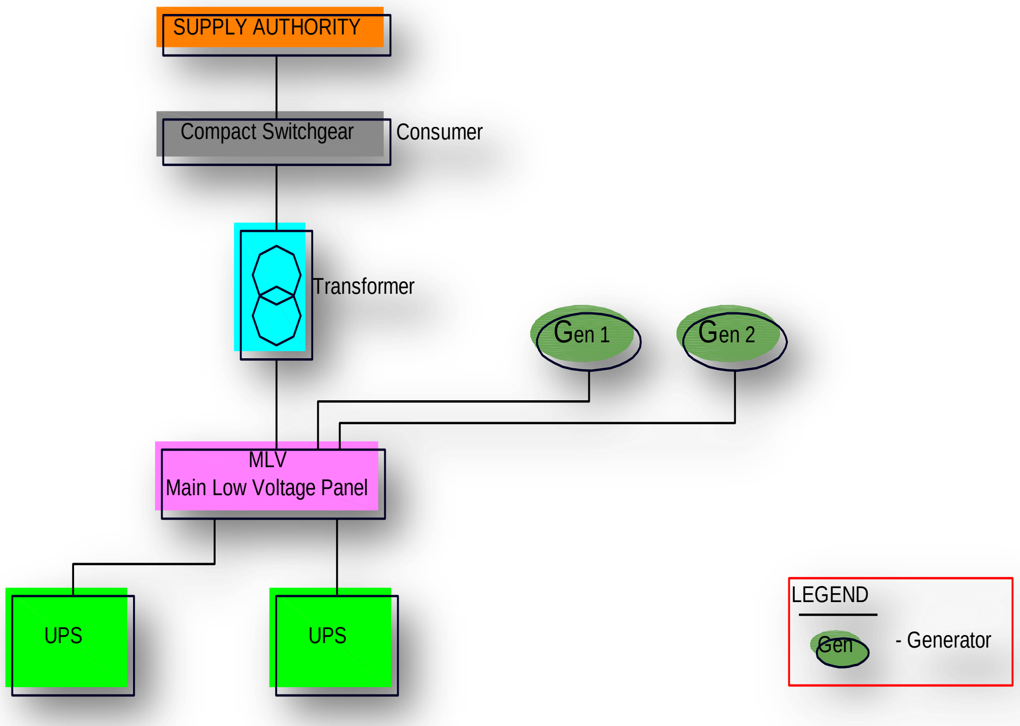

Figure 3-6: Block diagram of key SCT components

A few key components that require special attention during the design are:

- Medium voltage (MV) switchgear and transformers
- Power generators
- Main low voltage (MLV) panel

- Uninterruptable power supply (UPS) system
- Power distribution unit (PDU)
- Grounding and surge protection
- Cable management system

MV switchgear & transformers

Metal clad switchgear with adequate fault level capacity allowing discrimination with the network should be used. Redundancy must be provided by two parallel paths utilising vacuum draw out type circuit breakers fitted with electronic relays having integrated protection, communication, monitoring and measurement functions.

Dry type cast resin distribution transformers in IP 21 enclosures with forced ventilation are to be used to step down from medium voltage. Parallel path A or B has the capacity to carry the total load and the two paths are linked via a bus coupler which is normally in the open position. The major advantage of cast resin transformers is that they are maintenance free and non-flammable.

Power generators

On-site generation by 2(N+1) diesel power generators rated at base load, provide the primary power supply source, while the supply authority acts as backup supply. The generation system must have a fuel capacity to run continuously at full load for a minimum of 96 hours. Diesel supply and maintenance contracts to be negotiated with reputable vendors. The generators are to be linked to an advance remote monitoring system that collects data on the capacity loading, status and system alarms.

Main low voltage (MLV) panel

The main low voltage (MLV) panel is a vital component in the PDS which interfaces all the key elements, and must be designed with spare capacity, load balancing and be maintained without loss of service continuity. Protection must be coordinated as to isolate the fault and continue supply of power [29].

The MLV panel to be installed must be type tested with Form 4 partitioning, which provides physical separation of the bus bars and functional units, with the latter separated from the covered terminals for the external conductors.

The panel is to be fault tolerant and provide redundant distribution equipment which is hot replaceable. Monitoring and measuring equipment with capabilities providing energy, power, voltage and current characteristics at system level.

The main low voltage panel should be a modular type tested Form 4B, with parallel redundant paths A and B, and integrate all the key elements of the power distribution system. Glass doors should be installed on all the sections of the MLV panel to prevent the tripping of circuit breakers by accidentally bumping against them.

Large air and moulded case circuit breakers should be draw-out type with the smaller ones being plug-in type which allows the equipment to be hot replaceable. Circuit breakers with electronic and microprocessor overload protection should be used. This will allow coordinated selectivity that enhances discrimination between series equipment isolating the fault and ensuring service continuity of the power system.

Multi-pole modular combined lightning current and surge arrester of the class 1 type is to be fitted to the A and B sections of the panel. These units to have a discharge capacity of 100kA at a 10/350μs wave form and a clamping time of ≤ 100ns. These units are capable of discharging large energy surges caused by lightning and thus preventing damage to the distribution equipment.

An advanced metering system should be installed in the MLV panel which provides maximum and instantaneous power unit values and status of the incomers and feeders, and which forms part of the remote monitoring and management system.

Uninterruptable power supply (UPS)

Mission critical equipment requires clean uninterrupted power to avoid downtime and data processing errors caused by utility power. The uninterruptible power supply (UPS) configuration selected and implemented directly impacts the availability of the critical equipment.

These units should be installed in a dedicated room and system sized to energise all information technology (IT) equipment, peak load and fault overload conditions.

A double conversion, high efficient 2(N+1) UPS system isolates the mission critical electronic equipment from the upstream supply and removes a wide range of disturbances. The system utilises isolation transformers for galvanic isolation to prevent fault currents from entering and damaging the server equipment.

Scalable static UPSs are to be used which require substantially less capital investment than rotary UPSs, to provide flexibility for long term growth and which do not require complex maintenance. Highly skilled technicians have to carry out two or more preventative maintenance visits a year to increase the reliability of the UPS system.

Parallel UPS modules must use intelligent control to divide and manage the load between multiple modules and deactivate units that are not required to provide power to the load, while redundancy is not compromised. The system configuration must have the capacity to grow as the load grows.

Intelligent digital control should be used, which automatically calibrates the UPS system and monitors the load, power factor and ambient temperature, and utilises the collected data to make adjustments to achieve optimal performance [50].

The UPSs and batteries must have a management and monitoring system and be installed in a dedicated access controlled and air-conditioned room. The battery monitoring system must be capable of logging and trending battery cell voltages and resistances. The state of the batteries is determined by measuring the internal resistance of the cells.

Power distribution units (PDUs)

Field wired modular PDUs are to be placed at both ends of a row or future rows of servers, at one end an A and the other end a B power distribution unit, which provides concurrent maintainability. Glass doors are fitted to the floor standing PDU units to prevent accidental tripping of circuits and also enhance visual monitoring.

Uninterruptable power supply systems which have branch current monitoring and alarm status notification must provide power to the PDUs. Flexibility must be further increased by wiring all equipment to terminals.

Grounding and surge protection

A well designed and installed grounding and bonding system is essential for the protection of personnel and equipment, and will minimise the detrimental effects of surges and transient voltages.

Grounding systems must create a low impedance path to earth ground for surges and transient voltages caused by lightning, fault currents, electrostatic discharge and circuit switching. Surges that are not dissipated by the system will introduce electrical noise on the data cables, resulting in the loss of data and reduction of network efficiency [19].

Figure 3-7 shows the general grounding arrangement in the white space area of a data centre.

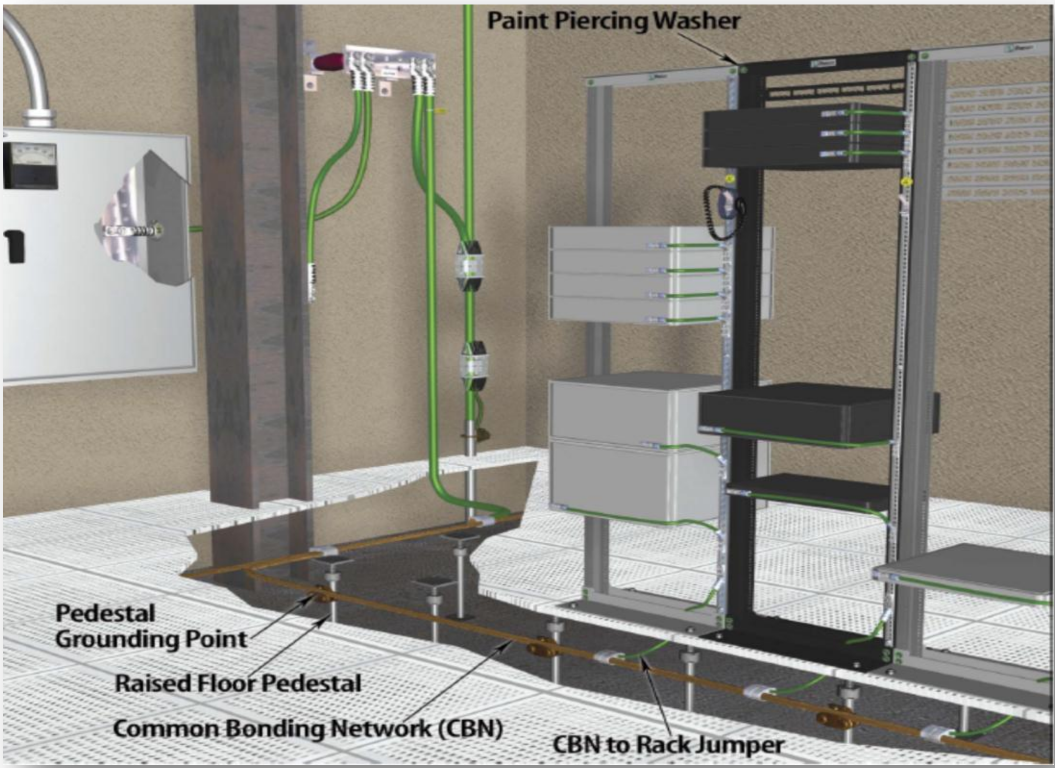

Figure 3-7: Data centre grounding infrastructure at server room level [16]

A common flat bonding bar is run between the rows of servers to which all equipment and pedestals of the raised floor are bonded. The bonding flat bar is to be linked to earth bars fitted to each of the four walls. These earth bars are then linked to each other and to the main earth bar in the main UPS panel. All the grounding conductors must be insulated copper conductors.

A solidly-grounded system must be implemented with an earth electrode having a value of less than one ohm (Ω) installed. The system consists of a flat copper strip with copper earth spikes that are exothermically welded to the copper strip and installed in a trench that runs around the buildings [19]. The electrode must be connected to the main earth bar from where all the grounding of the data centre is to be carried out.

A signal reference grid (SRG) that reduces high frequency impedance is to be installed in the floor void of the server room area, also known as the white space, with further measures implemented to prevent electromagnetic interference (EMI) [46], [51].

This type of system is very effective in reducing the possibility of line-to-ground transients and provides the most stable phase to ground voltage characteristics [73]. The electrode is to be connected to the main insulated earth bar, to which all equipment is connected and bonded via the various earth conductors of the various distribution paths.

High frequency noise voltages produced by data processing equipment are reduced through the signal reference grid (SRG) under the raised floor of the server room [14]. All server room equipment and metal work in this area is bonded to the SRG.

A lightning protection system with a protection level 1 installed will provide an efficiency of 98% against lightning strikes and associated induced voltages and currents. Surge protection fitted to all distribution boards discharges high currents, and clamps voltages that exceed pre-determined values.

Multi-level surge protection devices with remote monitoring capabilities are used, to mitigate the damaging effects of transient currents and voltages. Metal oxide varistor (MOV) must be used for class 1 and 2 areas with silicon avalanche diode type in the class 3 area for the critical loads.

Cable management system

Increasing server density and higher networking speed result in an increasing heat load. Obstructions interfere with the distribution of cooling air and can adversely affect the air distribution.

Poor cable assembly management makes maintenance difficult and reduces system performance, which could result in unscheduled downtime. Planning is a key factor to achieve flexibility and scalability in the cabling infrastructure, and a structured approach is used to design several horizontal cable rack routes [51].

Cable congestion in computer raised floor voids can substantially reduce the volume of airflow and limit the flow through the perforated tiles in the cold aisles. Separate data and power cable trays must be installed and, where possible, the cables routed in the floor void under the hot aisles so as to avoid blocking the cold aisle perforated tiles [16].

A cable management strategy implemented, minimises air flow obstructions caused by power cables and wiring. Other benefits are the reduction of signal interference and increase in cooling efficiency, which results in lower power consumption and provides ease of serviceability [51], [55].

The power and data cable management in the floor void of the data centre is shown in Figure 3-8 [55].

Figure 3-8: Mesh trays for better airflow [55]

The power and data wire mesh trays are to be installed at different levels in the floor void. Galvanised mesh cable trays should be used which provide better air flow than enclosed wire ways and conduits. All cable and other openings in the floor or ceiling must be sealed to maintain the correct static pressure so as to provide optimum airflow.

An effective cable management system should be of sufficient size to accommodate changes and additions, while service time is minimised.

3.2.5 COMPONENT AND SYSTEM MAINTENANCE

Data centres of cellular networks in Africa are dynamic environments which require trained staff that are familiar with system operation. This is a very challenging requirement as highly trained technicians are not freely available.

Maintaining power system components keeps them to their normal, nearly constant failure rates. Facility managers can increase network uptime with an understanding of preventative maintenance best practices.

Preventative maintenance (PM) is the systematic inspection and detection of potential failures before they occur and involves various approaches [27], [56]. Condition based (predictive) maintenance is, for example, a system that estimates and projects equipment condition over time, using probability formulas to determine the risks of downtime.

Any of the following outcomes can be obtained during preventative maintenance [57]:

- A potential issue is identified which requires immediate action to prevent equipment failing in the future.
- The identifying of a new or active issue and scheduling appropriate repair action. Proper documentation to be kept to allow the performance of trend analysis and comparison of current and past incidents.
- Unplanned downtime due to an attempted repair of an identified defect.
- No issues are identified and no equipment failures are reported up to the next scheduled PM.

Procedures should be developed to accomplish four basic PM functions: keep equipment clean and dry, sealed and minimizing friction.

Infrastructure management software can be used to support an integrated PM system, which can use self-diagnosis to obtain operational hours and flag warnings when equipment is operating above its temperature limits. Temperature is one of the root causes of component failure [57]. Studies conducted by researchers at Los Alamos National Laboratory have shown that for every rise of 10ºC, the failure rate doubles [52].

Thermal scanning, infrared thermography is an excellent tool to be utilized by qualified maintenance personnel; the infra-red readings obtained over a period can be compared to identify problems and trends.

A detailed statement of work (SOW) should be issued to the PM team and data centre manager and must contain the following:

- Scheduling and method of execution
- List of parts to be replaced
- Outcome report

Condition based maintenance, also called reliability centred maintenance, uses statistics and data to predict which components are most likely to be in an acceptable condition without requiring maintenance [72]. Equipment age, operating and environmental history, and operating characteristics data assist in estimating and projecting equipment condition over time [56], [57].

Inadequate maintenance reduces equipment life. More than 10% of all downtime experienced is due to premature failures as a result of component degradation [27]. Maintenance assists in identifying abnormal sources of component deterioration such as changing voltage conditions and capacity overloading.

- Emergency contingency procedures are required, which are vital to allow resolution of PDS issues while minimizing the impact on critical loads.
- Additional infrastructure to support the DC is system documentation which must be maintained.

3.2.6 TRAINING

Accidental emergency power-off (EPO) and human error are two main factors for data centre outages and present serious threats to availability of the data centre. These factors have the least financial implications to address and management needs to implement rules and training to mitigate the impact [17].

Personnel training to be provided on a regular basis is a key factor to negate EPO and human error, of which the following are included [59]:

- A well-documented works-orientated maintenance programme to be used which indicates a step-by-step procedure including alternative plans for unforeseen events.
- Follow consistent operating procedures that do not allow short cuts, which could erroneously shut down the wrong equipment.
- Site specific operating processes including capacity planning and basic equipment knowledge to prevent a shutdown by mistake.
- Access control policies that require sign-in and escorting of all visitors and external contractors.
- Environmental issues that include strict foods and drinks policies. Contaminants such as dust particles must be avoided in the server area.

3.3 METHODOLOGY TO DETERMINE RELIABILITY AND AVAILABILITY

African cellular network data centre operational managers can use reliability assessments to optimise their PDS. The assessment will also allow them to schedule maintenance events and take appropriate action to improve the data centre uptime.

Research done on existing cellular network data centres in Africa has shown that no PDS reliability data is available, nor any method of assessment employed by the data centre managers.

The most accurate reliability results were obtained, using probability and statistical mathematics. Quantitative evaluation of the power system allows consistent, unbiased and reliability assessments [27], [60], [69].

Interruption frequency and expected interruption duration were two indices that were used to calculate total expected interruption time per year and availability at the load point.
Steps taken to determine the system reliability indices were: (a) creating a system level reliability model, based on system design and behaviour [36], and (b) analysing the model.

A mathematical model was used to determine the reliability of a radial distribution system that has no redundancy depicted in Figure 3-10. All calculations were implemented using Microsoft Excel to perform reliability analysis.

The first step of analysis was defining a failure, and this analysis used the IEEE 493-2007 standard definition. This states that a failure constitutes a loss of power to a UPS distribution panel or a PDU [52].

Analysis was done using the minimal cut set method which is systematic and easy to use. This is one of the recommended methods by the IEEE 493-2007 standard [52]. System weaknesses were numerically and non-numerically determined and thus alternative choices could be considered.

Assumptions made:

- Failure rates are constant with age
- Exponential distribution of outage time after failure
- A failure event is independent of other failure events
- Component uptimes are much larger than downtimes

The following reliability analysis methodology was applied:

Component-level reliability

The random variable X is defined as the time in years, between failures of component "A". Probability density value of a random variable for a certain time (t), is the probability that the random variable is equal to that number and written as P(X=t). Where (t) is the actual number of years until the component fails [24], [41]:

Exponential probability density:

$$P(X = t) = \lambda e^{-\lambda t} \tag{3-3}$$

Associated *exponential probability distribution:*

$$P(X \leq t) = 1 - e^{-\lambda t} \tag{3-4}$$

Where:

$P(X \leq t)$ = *Q(t)* = *unreliability*

The term λ in (1) and (2) is a simple number and is known as the failure rate of the component A. The above two equations are related through calculus.

The average (mean) value of X is a constant and where X = 1/λ represents the Mean Time Between Failures (MTBF) [27], [30].

System-level reliability

Method of minimal cut sets is used to calculate the reliability indices and allows easy analysis. A minimal cut-set is a set with no sub-sets and in a PDS could be considered as the portion which, if removed from the power path, will cause a power failure of the system [69]. There may be many parallel paths in a sub-set [44].

Assume that a component has a constant MTBF and mean time to repair (MTTR), and then the probability of the component (jth) failure can be determined as:

$$P_j = \frac{\text{Average Downtime of Component j}}{\text{Total Time Period Considered}} = \frac{\text{MTTR}_j}{\text{MTTR}_j + \text{MTBF}_j} = \frac{r_j}{r_j + d_j} \tag{3-5}$$

The system consists of a number of cut-sets and the (ith) cut-set to be considered where i = 1,2,3, . . . , n. Assuming component independence, the probability that the entire (ith) cut-set fails, $C_{i,}$ can be calculated as the product of all the probabilities of failure of the components:

$$C_i = P_1 \text{ x } P_2 \text{ x } P_3 \text{ x } . . . \text{ x } P_n \tag{3-6}$$

Thus for a given cut-set where the probability of failure C_i has been calculated, this can be seen as in terms of cut-set failure MTBF (d_i) and MTTR (r_i):

$$C_i = \frac{\text{Average Downtime of Cut-set i}}{\text{Total Time Period Considered}} = \frac{r_i}{r_i + d_i} \quad (3\text{-}7)$$

The reciprocal of (d_i) is the *repair rate* and thus repair rate of a cut-set would be the sum of the repair rates for each cut-set component and mathematically stated and MTTR (r_i) is solved:

$$\frac{1}{r_i} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \ldots \frac{1}{r_m} \Rightarrow r_i = \frac{1}{\frac{1}{r_i} + \frac{1}{r_2} + \frac{1}{r_3} + \frac{1}{r_m}} \quad (3\text{-}8)$$

Solving MTBF (d_i) using formula (3-7):

$$\text{MTBF } (d_i) = r_i \left(\frac{1 - C_i}{C_i}\right) \quad (3\text{-}9)$$

The order of minimal cut-set is dependent on the amount of components, e.g. one component is first order and two a second order. The complete PDS can be seen as the total number (n) of minimal cut-sets connected in series.

Failure Mode and Effects Analysis (FMEA) is used for the identification of minimal cut-sets. Higher-order minimal cut-sets maybe ignored for approximation as the probability of their occurrence is low.

The system consists of *n* minimal cut-sets in series, each with an associated, probability of failure (C_i), MTTR (r_i) and MTBF (d_i). Probability of system failure is the probability that any of the minimal cut-sets fails, which is the sum of all of the individual cut-set probabilities, minus the sum of the probabilities of any one combination of simultaneous cut-set failures. Should the probabilities of simultaneous cut-set failures be low, the probability of system failure, S:

$$S = C_1 + C_2 + C_3 + \ldots C_n \quad (3\text{-}10)$$

The probability of system failure (S) can be seen as a function of the system MTBF (d) and MTTR (r):

$$S = \frac{r}{d+r} \quad (3\text{-}11)$$

The *system failure rate* is the reciprocal of the MTBF and thus the sum of individual cut-set failure rates is equal to the system failure rate for a series combination of cut-sets [27]:

$$\frac{1}{d} = \frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3} + \ldots \frac{1}{d_n} \Rightarrow d = \frac{1}{\frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{dr_3} + \frac{1}{d_m}} \quad (3\text{-}12)$$

System MTBF :

$$r = d\left(\frac{S}{1-S}\right) \quad (3\text{-}13)$$

System reliability indices are:

Inherent Availability: $Ai = 1 - S$ (3-14)

And

Repair Downtime: $Rdt = r$ (3-15)

Careful consideration must be given to what constitutes a failure when performing computer analysis, as this will impact on the values of the component MTBF`s [27], [41], [61].

The mathematical model is used to calculate the reliability indexes for 'm' out 'n' units:

$$R_{m;n}(t) = \sum_{i=0}^{n-m} \binom{n}{i} (R(t))^{(n-i)} (1 - R(t))^{i} \quad (3\text{-}16)$$

Where:

$R_{m;n}(t)$ = the reliability of system that contains m of n parallel modules

R(t) = the reliability of the modules at time t

$\binom{n}{i} = \frac{n!}{(n-i)!i}$ = the binomial operator

Series system reliability

The example in Figure 3-9 demonstrates series system reliability calculations. Components A and B in are said to be in series, which means all must operate for the system to operate. The number below each block is the reliability calculated using the equation, R(t) = $e^{-\lambda t}$, with *t* = 10 million hours.

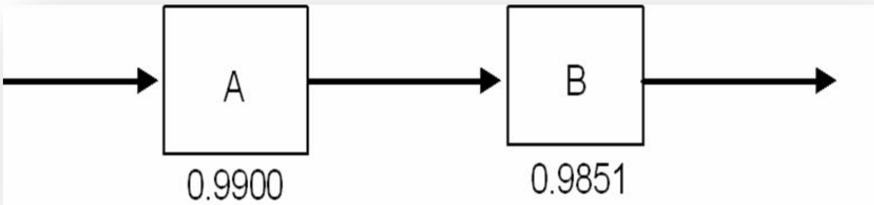

Figure 3-9: Example of reliability block diagram [27]

The components are in series and the system reliability can be found by adding together the failure rates of the components. The system failure rate provided as an example is:
0.001000 + 0.001500 = 0.002500 [27].

Thus reliability using equation (3-1):

$$R(t) = e^{-0.0025x10} = 0.9753$$

Figure 3-10 below shows a typical PDS with no redundancy for small cellular network data centre in Africa.

The distribution system has one 15kV feeder from the supply authority. The service transformer supplies a 2000A, 400V bus that is referred to as the MLV panel.

A single 1000 kVA base load diesel generator and a UPS are linked to the bus with the critical load being served through the UPS. The services and critical load below the main bus have not been included in the model below.

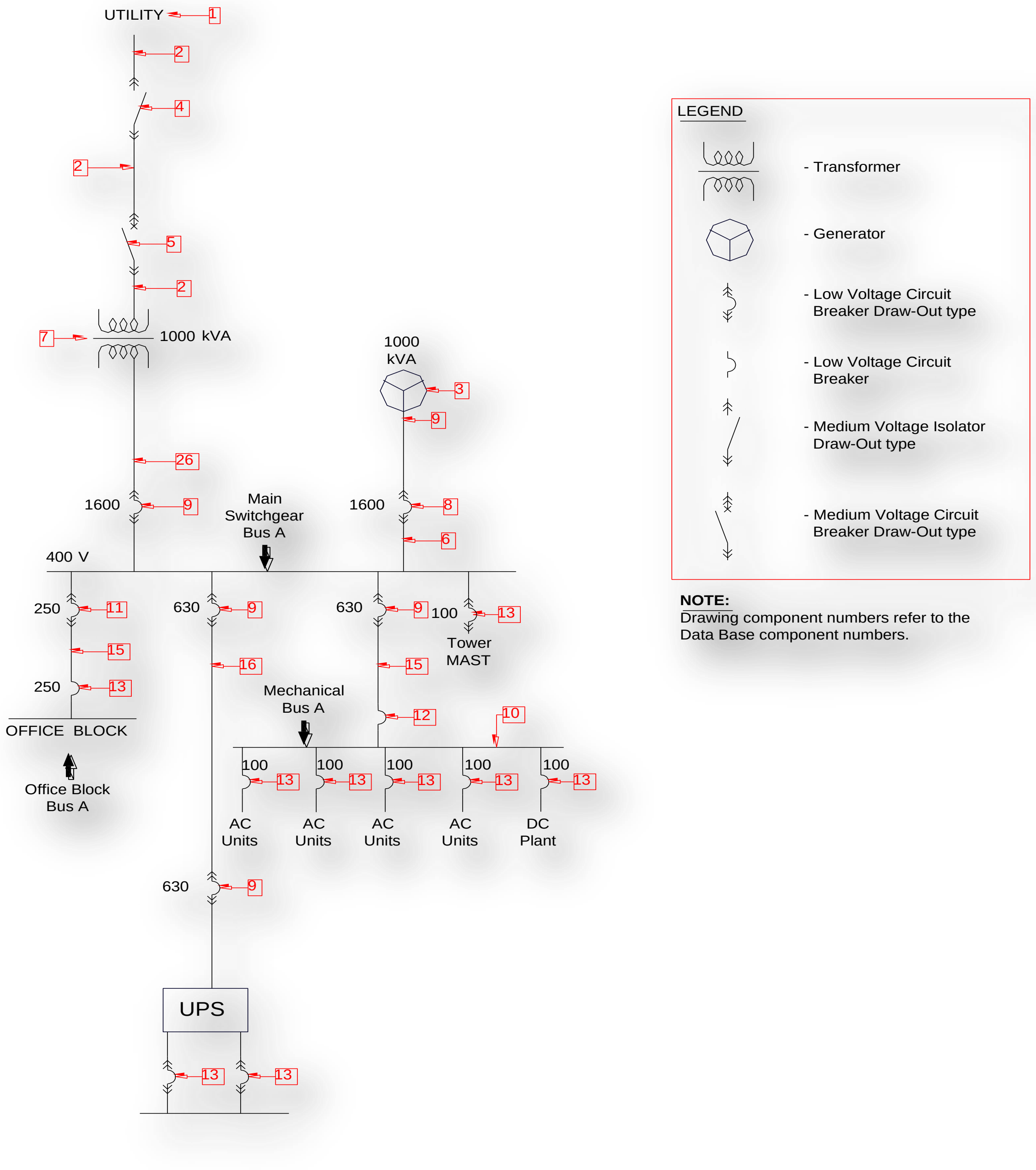

Figure 3-10: Typical small data centre radial distribution system

The logic diagram in Figure 3-11 is derived from the single line diagram in Figure 3-10 in which a power outage at the main bus B is represented by the true condition of the last logic gate.

Failure states of the individual components are the initial inputs to the logic gates. The representation is simplified by combining all series elements in a path into a single failure event. Every failure event is assigned a number and each logic gate a letter.

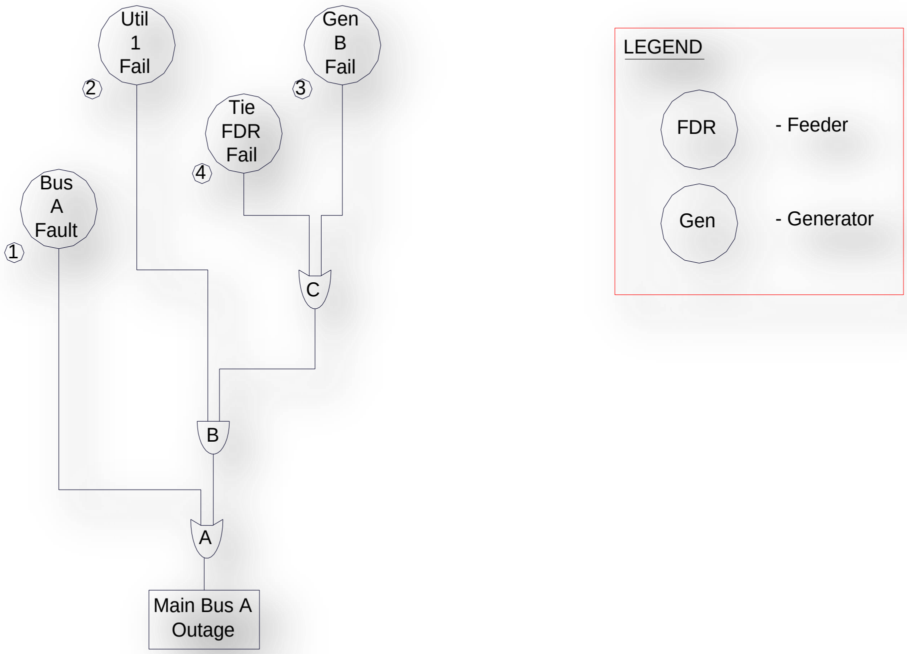

Figure 3-11: Logic diagram for the small data centre PDS

Table 3.3 is developed; working from the logic gate output back to the input, each gate is replaced with the logical permutation of its inputs. An AND gate is replaced by a horizontal arrangement of inputs in the table, increasing the order of the cut-set, while an OR gate is replaced by a vertical arrangement of inputs in the table, which increases the number of cut-sets. Duplicate or super sets are eliminated from the table. Item 5 in Table 3-3 provides the final amount of cut-sets.

Table 3-3 has been developed from the logic diagram in Figure 3-11 to obtain the cut-sets.

Table 3-3: Development of cut-sets

Step	Description				
		Cut-sets			
1	Start	A			
2	Replace A	1			
		B			
3	Replace B	1			
		2	C		
4	Replace C	1			
		2	3		
		2	4		
5	Eliminate Duplicates	1			
		2	3		
		2	4		

Component reliability, mean time to repair (MTTR) and failure rate per year indices, from the IEEE 493 database, used in the system reliability calculations are listed in Table E-1 from Appendix E.

The calculated reliability indices at the various outputs for the distribution system shown in Figure 3-11 are listed in Table 3-4.

Table 3-4: Calculated reliability indices at output buses

Ref #	Output Location	Failure Rate per year	Failure Duration, Hr	Downtime, Hr/Yr	Inherent Availability
1	Main Switchgear Bus	0.01579216	4.94334593	0.07806611	0.99999108
2	Generation Bus	0.1235	18.28	2.25758	0.99996704
3	Mechanical Switchgear Bus	0.02384088	9.90447584	0.23613142	0.99997304

The indices indicate an availability of 0.99999108 at the main switchgear bus with a failure duration of 4.94334593 hours, with the mechanical switchgear bus having an availability of 0.99997304 and 9.9 hours downtime per event. These indices compare well with Tier I requirements as listed in Table 3-5 below, but are only a guideline as the system is very small and therefore not an accurate comparison.

The downtime and inherent availability indices for the various Tier levels as defined by the Uptime Institute are shown Table 3-5 [17].

Table 3-5: Tier level downtime and availability indices [17]

Ref #	Description	Downtime, Hr/Yr	Inherent Availability
1	Tier I	28.8	0.9967
2	Tier II	22	0.9975
3	Tier III	1.6	0.9998
4	Tier IV	0.8	0.9999

Reliability of data centres for cellular networks in Africa becomes a major factor due to lack of trained skilled staff, inadequate maintenance and logistics. The PDS design should thus aim to achieve reliability taking into account the capital expenditure available. A parallel redundant system is considered and the reliability determined.

A typical power distribution system with redundancy is shown in Figure 3-12 below.

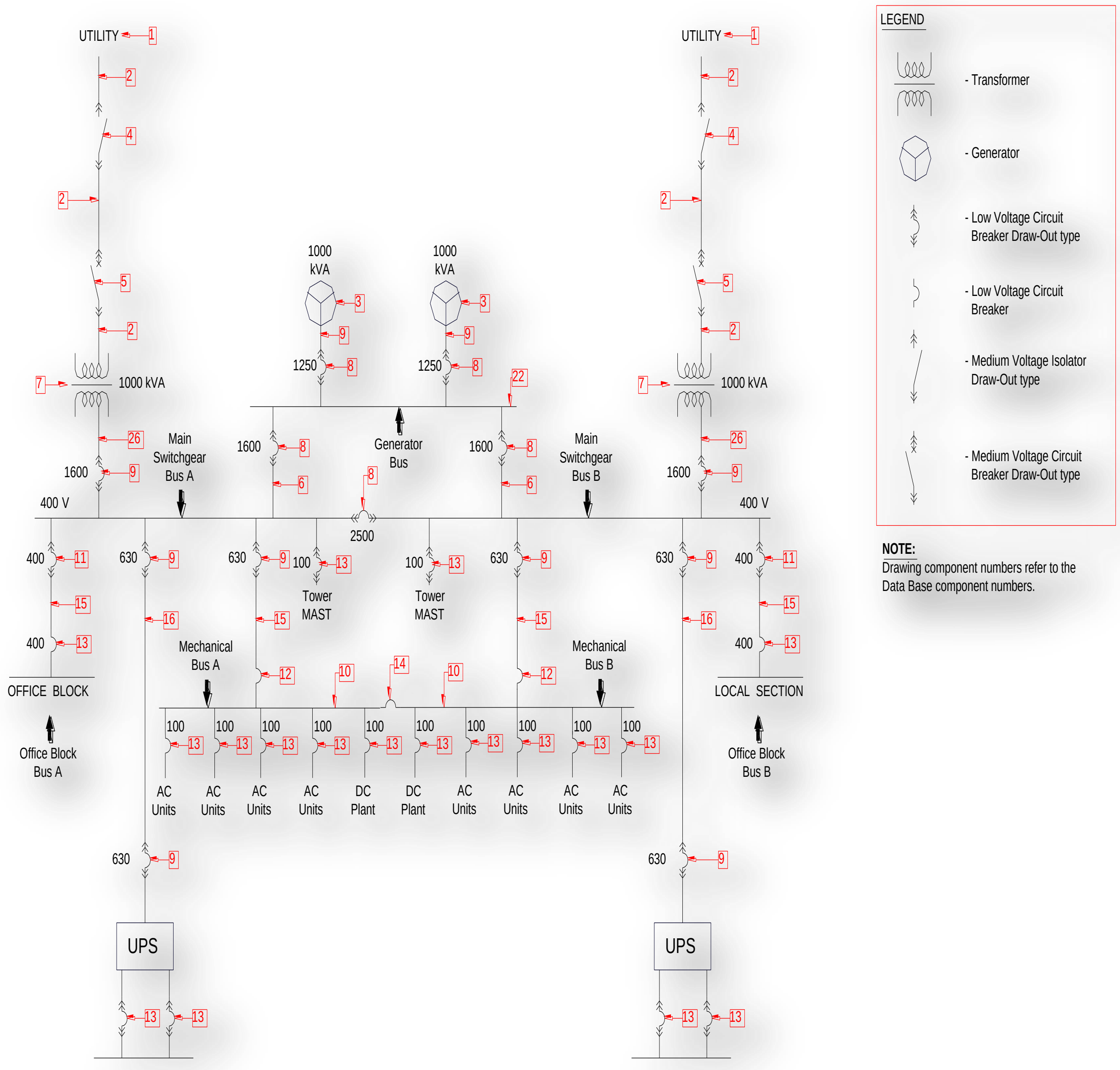

Figure 3-12: Typical small data centre distribution system with redundancy

The PDS in Figure 3-12 demonstrates a 2N redundant system and is used to draw a comparison with the radial distribution system shown in Figure 3-10. The distribution system has two 15 kV feeders from the supply authority with parallel redundant distribution paths as shown in above single line diagram.

The results clearly indicate that the radial system produces low reliability indices that are non-compliant with cellular network data centre Tier IV standards.

The calculated indices for the various buses of the parallel redundant 2N system are shown in Table 3-6 below.

Table 3-6: Calculated indices at output buses of 2N systems

Ref #	Output Location	Failure Rate per year	Failure Duration, Hr	Downtime, Hr/Yr	Inherent Availability
1	Main Switchgear Bus A	0.0178961	4.5977112	0.0822810	0.9999906
2	Main Switchgear Bus B	0.0178961	4.5977112	0.0822810	0.9999906
3	Generation Bus	0.01276	2.0532915	0.02620	0.999999772
4	Mechanical Switchgear Bus A	0.0239415	9.4844111	0.2260123	0.999986261
5	Mechanical Switchgear Bus B	0.0239415	9.4844111	0.2260123	0.999986261

The indices in the above table show 4.5977112 hours per downtime event at the main bus A with an inherent availability of 0.9999906. This is an improvement from 4.94334593 hours per downtime event and an availability of 0.99997304 for the radial distribution system in Figure 3-10. It must be noted that both systems are very small and therefore impact on the figures.

A 2N parallel redundant power distribution system should be implemented for data centres of cellular networks in Africa. This type of distribution system reduces the risk of downtime as it provides a high level of reliability and availability.

The capital investment for a 2N distribution system is nearly double that of a radial system with no redundancy, but the trade-off is a data centre with a high reliability which is an essential requirement for cellular networks in Africa.

3.4 POWER SUPPLY OPTIMISATION MONITORING AND MEASUREMENT SYSTEM

Data centre managers must collect, consolidate and analyse data to assist them in decision making and acting upon their decisions. Monitoring can help to (a) maximise data centre capacity and accommodate growth, (b) maximise availability and continuity of business, and (c) reduce total cost of ownership (TCO) [58], [71].

Cellular network data centres in Africa should employ an effective monitoring system that uses advanced devices and software to improve uptime, as problems must be detected before outages occur. This system should provide maximum demand values, energy consumption and power quality data. Alarm notifications and event logs that are generated should be used for control and maintenance planning.

A monitoring and measurement system should have the following attributes [58]:

- Ability to collect real time data from the various devices
- Integrate data across devices and time scales
- Be able to integrate with control devices
- Perform trending and analysis
- Adapt with ease to new measurement requirements
- Detect and flag problems

The system must also provide the following:

- Power quality problems which include transients, harmonics, and sags and swells
- Early warning of overloads and mechanical conditions leading to downtime
- Verify and manage energy consumption and available capacity
- Status of critical equipment such as transformers, switchgear, generators, UPS systems and PDUs
- Physical threats, e.g. leaks, humidity, smoke and fire
- Historical reports, graphical trends and charts
- Multiple alarm levels

Remote monitoring must be implemented which has an advantage of utilising infrastructure specialists to systematically analyse the data and provide a quick response to resolve potential problems. Telemetry-based monitoring should be used to remotely control systems which have been authorised by data centre management [50].

The system must have monitoring and alerting capabilities for critical equipment such as an uninterruptible power supply (UPS) system, computer room air conditioner (CRAC), and fire suppression systems. The surrounding environment has to be monitored for threats that include water leaks, excessive air intake temperatures at the servers, and unauthorised access or malicious actions [26], [53].

High end metering and monitoring equipment is shown in Figure 3-13.

Figure 3-13: High end metering and monitoring equipment

A continuous site monitoring and performance measurement system should have a high bandwidth data capturing capability. The accuracy class of the measuring equipment must be specified and power meters should read true root mean square (RMS) values [51].

The monitoring system must utilise high-end digital meters that provide historical trending, event and alarm notifications, power quality monitoring and real-time control. Branch circuits have to be monitored, which will provide valuable capacity data that assists in planning future loading.

3.5 SUMMARY

Different technologies were discussed for data centre critical elements which will improve reliability and availability. These technologies include system topology, preventative maintenance and personnel training.

A substantial improvement in reliability can be achieved by implementing capacity planning, redundancy, and the elimination of single point of failure (SPOF) through the provision of parallel distribution paths. Component inherent characteristics (CIC) are also an important factor when determining the reliability of equipment and a system.

Data centre managers require a reliable, fault tolerant power distribution system that is concurrently maintainable with ease. A simple and quick mathematical model can be used to determine the reliability of the power system configuration.

An integrated preventative maintenance system is utilised, supported by infrastructure monitoring and management software. Self-diagnosis provides operational hours and flags warnings when equipment is operated beyond its design limits.

Training on a regular basis is a key factor in negating the risk of human error in the causes of data centre downtime.

In the next chapter the design and implementation of these methodologies plus the problems experienced on data centres will be reviewed.

CHAPTER 4 EVALUATION AND RESULTS

4.1 PREAMBLE

This chapter describes the application of the technologies and techniques discussed in Chapter 3. No budget constraints were imposed on the design due to the fact that system failure can result in catastrophic unplanned power outages. A single 33kV incomer, parallel distribution paths and redundancy were implemented at a Nigerian data centre (DC). The reliability is evaluated and discussed in Case Study 1. The impact that multiple incomers and distribution paths have on the reliability of a DC in Cameroon is addressed in Case Study 2.

4.2 CASE STUDY 1: SINGLE INCOMER, PARALLEL PATHS

4.2.1 INTRODUCTION

The data centre is situated in the city of Ibadan, capital city of the Oyo state, and forms part of the backbone of a cellular network company in Nigeria. The city is the second largest metropolitan area and is located in south-western Nigeria, 128km north-east of Lagos. Nigeria is an oil rich country with 36 states and has a population of 174,507,539, as estimated in 2013 [62].

A multi-level building facilitates the data centre, offices for the value added services (VAS) and an energy centre located on the ground floor. The energy centre consists of medium voltage switchgear and transformer rooms, a roofed area for the power generators and a main low voltage room with a UPS section.

The site is enclosed with a two metre high steel palisade fence which has closed circuit television (CCTV) monitoring the perimeter and various secure areas in the building. The data centre complex employs a sophisticated access control system with security personnel enforcing a strict access control policy.

4.2.2 OVERVIEW OF DATA CENTRE POWER DISTRIBUTION SYSTEM DESIGN

The supply authority, Power Holding Company of Nigeria (PHCN), delivers power to the data centre complex via a single feeder from a nearby 33 kV overhead line that forms part of its distribution network. Several power outages per day lasting for long periods, and the fact that the network is not well maintained, render the supply authority distribution network unreliable [5], [63].

The client provided the following design requirements and parameters:

- 33 kV incomer from the supply authority
- Design load of 1400 kVA with 0.72 diversity factor
- (N+1) Generator and UPS redundancy
- A and B distribution systems
- Capital investment constraints

A block diagram in Figure 4-1 depicts the data centre PDS of the cellular network in Nigeria.

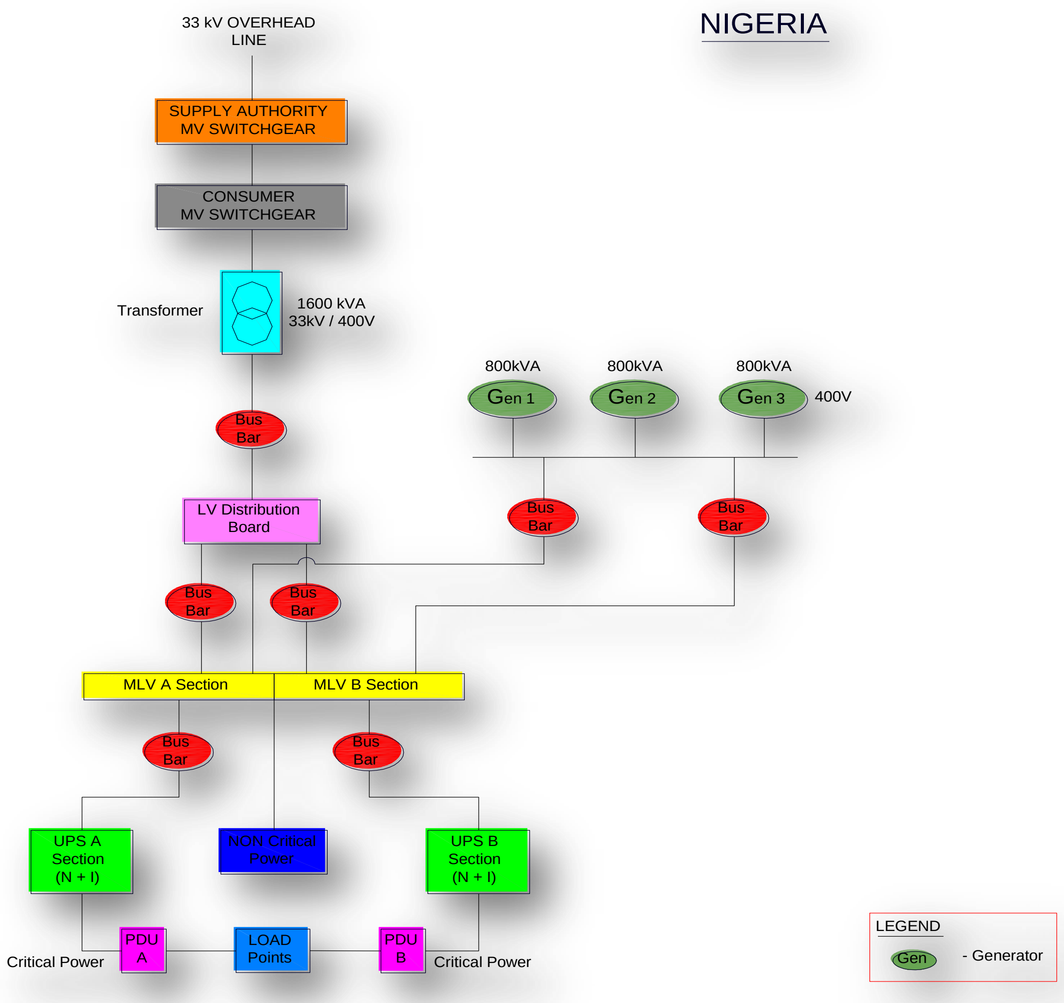

Figure 4-1: Nigeria data centre power distribution block diagram

The PDS in Figure 4-1 shows the general arrangement of the equipment for the data centre power distribution system. The system consists of a single incomer, a step down transformer, a main low voltage (MLV) panel with an A and B section, a (N+1) power generator and UPS configuration and power distribution units (PDUs).

4.2.3 DETAIL DESIGN OF A FAULT TOLERANT POWER SYSTEM

The power distribution system is the main cause of downtime in a data centre. Electrical distribution architecture has a major influence on reliability performance of a data centre throughout its lifecycle.

The data centre complex will have a connected load of 1400 kVA with a diversity factor of 0.72 (i.e. operates at 72% of the connected load). The load is constant, with the bulk of the load provided by servers and air-conditioning equipment.

Data centre standards are used that provide definitions of site infrastructure, with Tier IV topology the most reliable as it provides a concurrently maintainable and fault tolerant system. These standards are non-prescriptive, but outcome based.

The power system is modular with spare capacity for future load growth and concurrent maintainable. Compartmentalisation of the power train allows maintenance on specific equipment without affecting system performance and in the case of an event preventing both paths being impacted. Preference is given to equipment that offers lower probability of failures and least mean time to repair (MTTR).

A single 33 kV incoming feeder terminates in the supply authority MV room that provides power to an adjacent room, the consumer section. The consumer section delivers power to a single 1600 kVA transformer.

Metal clad 33 kV modular switchgear with SF6 insulated draw out type circuit breakers equipped with electronic protection relays are installed in a dedicated medium voltage room. The equipment is fitted with communication modules that are linked to the building management system (BMS).

A 1600kVA 33kV step down distribution transformer of the oil natural, air natural (ONAN) cooling type was installed. These transformers have an external oil reservoir, the conservator, and are fitted with a Buchholz protection relay which is sensitive to dielectric failure inside the equipment. The selection of oil type transformers was based on expertise and equipment being locally available.

A single line diagram in Figure 4-2 shows the PDS of the Nigerian cellular network data centre.

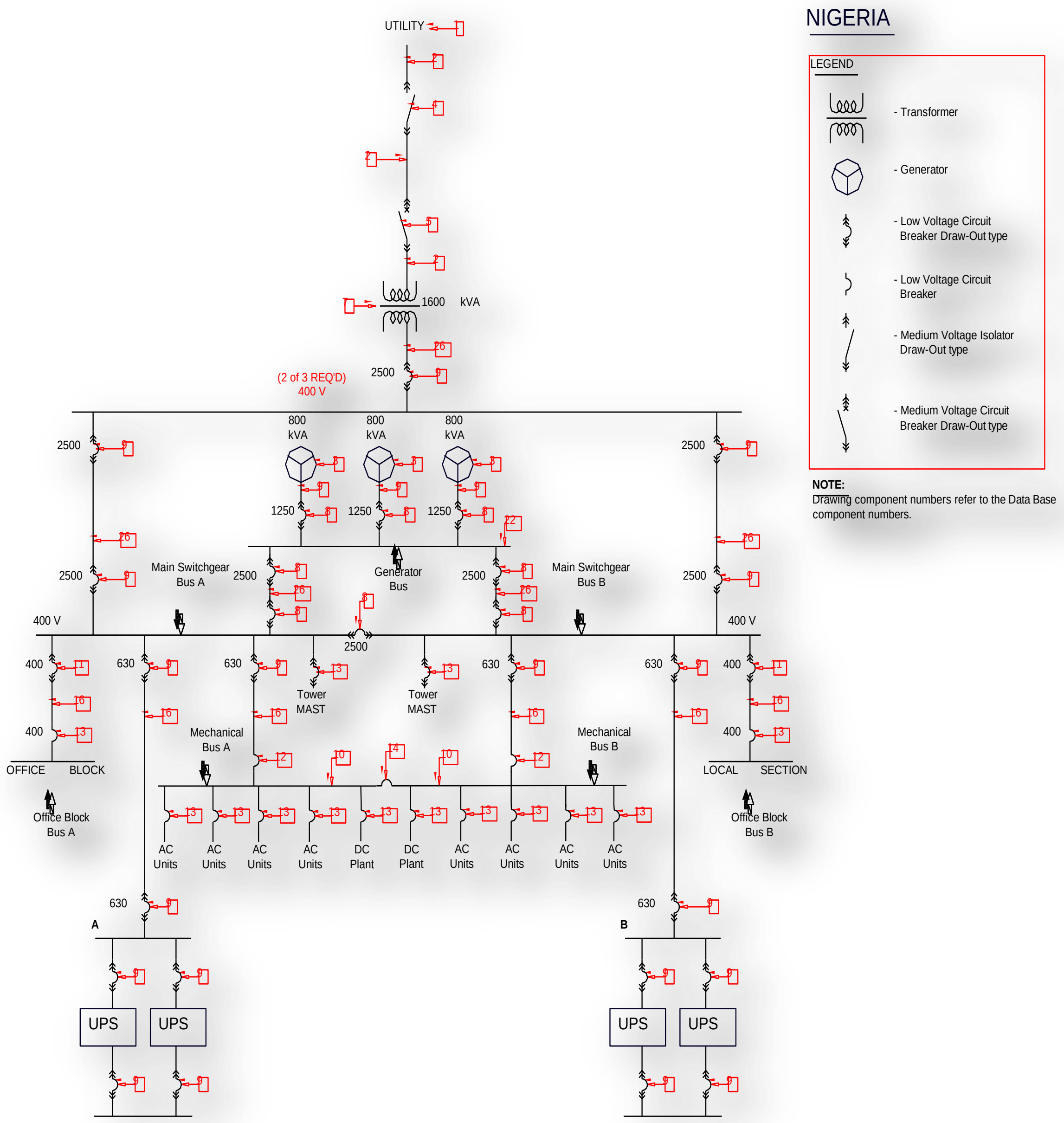

Figure 4-2: Nigeria single line diagram

The system then branches into two parallel independent power distribution systems which eliminate single point of failure (SPOF). Redundancy is provided by the main low voltage panel (MLV), generator and UPS systems. Metal enclosed busbar and cables will link all the distribution equipment with the panels.

Base load type diesel power generators were selected and installed in a covered area with open front and back sides. The generators feed onto a common bus and have one redundant set as indicated in Figure 4-2. These generators are used as the primary power supply with the supply authority providing the backup supply. Bulk diesel tanks have the capacity to provide fuel for ninety six (96) hours continuous power generation. The diesel fill point for delivery by large trucks is provided on the site boundary.

The main low voltage (MLV) panel is a modular type tested Form 4B type with all equipment compartmentalised. Parallel redundant distribution paths, an A and B section, are provided by the MLV panel. All other distribution boards and PDUs are modular type tested units. Power metering of the incomers and feeders of the panels and distribution boards is done, and is linked to the building management system (BMS).

All circuit breakers are of the draw-out or plug-in type and wired to terminal strips. Air circuit breakers, category B, are used for incomers and feeders that are larger than 800 ampere (A). Enhanced discrimination methodology is applied to series circuit breakers, which allows isolation of the fault at the closest circuit breaker. Non-critical equipment is fed directly from the MLV panel. An advanced monitoring system as discussed in section 3.2.4 is implemented, which provides the equipment status, on-off or trip condition.

Power integrity and power quality are assured through the parallel redundant uninterruptable power supply (UPS) system that delivers power to all critical server equipment. The system includes 20-minute power backup batteries with a 10-year life cycle and has a battery monitoring and management system linked to the BMS. The system should be housed in a separate room with access control and the temperature regulated at a constant 20°C.

The data centre uses dual corded IT equipment which has two built-in power supplies. Floor standing power distribution units (PDUs) are placed at the ends of each row of servers and two power supplies are provided for every server unit. They are equipped with power metering and status monitoring, and are interfaced with the building management system (BMS).

A galvanised cable management system will be installed in the void of the 650mm raised computer floor. Power and data trays will be installed at different levels to distribute the power and data cables to the servers.

4.2.4 RESULTS OF SYSTEM RELIABILITY EVALUATION

Probability calculations are used to obtain a statistical view and predict an event happening that might cause a failure that could result in data centre downtime.

Two databases, IEEE Gold book and Power Reliability Enhancement Program (PREP) managed by the U.S. Army Corps of Engineers, provide the required indices to analyse the reliability and availability of the power distribution system. The reliability data of equipment corresponding to each labelled component in Figure 4-2 are shown in Table 4-1.

This analysis uses the definition of failure as defined in section 3.4, and the meaning of 'repaired' will be the restoration of power to the load and not normal data centre operation. IT processes normally take a few hours to be fully restored.

The following assumptions apply to the data centre PDS [68]:

- Failure rates and repair times are exponentially distributed
- Cable failure rates are determined per actual cable length
- The generators are (N+1) redundant
- Manual switching operations require 15 minutes
- Automatic starting and paralleling of generators
- Automatic source transfer
- The UPSs are 2(N+1) redundant
- Low voltage switchgear, busbars and automatic transfer switches (ATS) are redundant
- There are two paths of power distribution
- Circuit breaker failure modes are 50% open and 50% closed (shorted)

A common assumption for the analysis is made that the power distribution system falls within the statistical distribution where failures are random and at a constant failure rate which is typical for electronic systems.

Table 4-1 provides component reliability indices from the IEEE 493 and the Power Reliability Enhancement Program (PREP) databases [27], [67].

Table 4-1: Nigeria component reliability indices

Ref #	Item Description	Failure Rate Symbol	Failure Rate (Failures/ Year)	MTTR Symbol	MTTR (Hour/ Failure)	Availability Symbol	Inherent Availability
1	Single Circuit Supply, 1.78 failures/unit years, A=0.999705 Gold Book – p. 107	λ1	0.956	r1	1.32	P1	0.998705
2	Cable Areal, ≥ 15 kV, per mile	λ2	0.00411	r2	2.54	P2	0.999998806
3	Diesel Engines Generator, Packaged, Standby, 1500 kW	λ3	0.12350	r3	18.28	P3	0.999742312
4	Manual Disconnect Switch	λ4	0.00174	r4	1.00	P4	0.999999801
5	Vacuum 33kV Circuit Breaker, Normally Closed, ≤ 600 Amp *	λ5	0.00283	r5	8.00	P5	0.999973208
6	Cable Below Ground in conduit, ≤ 600 V, per 1000 ft	λ6	0.00201	r6	11.22	P6	0.999997428
7	Transformer, Liquid, Non Forced Air, 3000 kVA	λ7	0.00111	r7	5.00	P7	0.999999367
8	Circuit Breaker, 600 V, Drawout, Normally Open, > 600 Amp	λ8	0.00553	r8	2.00	P8	0.999998738
9	Circuit Breaker, 600 V, Drawout, Normally Closed, > 600 Amp	λ9	0.00185	r9	0.50	P9	0.999999894
10	Switchgear, Bare Bus, 600 V	λ10	0.00949	r10	7.29	P10	0.999992098
11	Circuit Breaker, 600 V, Drawout, Normally Closed, > 600 Amp	λ11	0.00021	r11	6.00	P11	0.999999858
12	Circuit Breaker, 600 V, Normally Closed, > 600 Amp Gold Book p. 40	λ12	0.0096	r12	9.60	P12	0.999989479
13	Circuit Breaker, 3 Phase Fixed, Normally Open, ≤ 600 Amp Gold Book p. 40	λ13	0.0052	r13	5.80	P13	0.999996557
14	Circuit Breaker, 3 Phase Fixed, Normally Open, > 600 Amp	λ14	0.00343	r14	37.50	P14	0.999985320
15	Cable, Above Ground, Trays, ≤ 600 V, per 1000 ft	λ15	0.00012	r15	2.50	P15	0.999998866
16	Cable, Above Ground, Trays, ≤ 600 V, per 1000 ft Gold Book p. 105	λ16	0.00141	r16	10.50	P16	0.99999831
17	Battery, Lead Acid, Strings	λ17	0.00746	r17	32.13	P17	0.999972627
18	Fuse, 0 ~ 5kV	λ18	0.00137	r18	0.00	P18	1.000000000
19	Inverter	λ19	0.00482	r19	26.00	P19	0.999985691
20	Rectifier	λ20	0.00447	r20	16.00	P20	0.999991837
21	Static Switch, 0 ~ 600 Amp	λ21	0.0061	r21	3.60	P21	0.999997493
22	Switchgear, Insulated bus, ≤ 600 V	λ22	0.0017	r22	2.40	P22	0.999999534
23	Transformer, Dry, Isolation, < 600 V	λ23	0.00284	r23	21.26	P23	0.999993113
24	Circuit Breaker, 3 Phased Fixed, Normally Open	λ24	0.00011	r24	18.67	P24	0.999999760
25	Cable, Above Ground, In Conduit, ≤ 600 V, per 1000 ft	λ25	0.00007	r25	8.00	P25	0.999999838
26	Bus Duct, Gold Book p.206	λ26	0.000125	r26	12.90	P26	0.999999826
27	Cable underground, ≤ 15 kV, per 305 m	λ27	0.02017	R27	5.13	P27	0.999988193

The reference numbers in Table 4-1 refer to the numbered components and equipment in the single line diagram in Figure 4-2. The 33 kV switchgear data of item 5 is not available and therefore 15 kV switchgear data is used for calculations.

The logic diagram in Figure 4-3 is derived from the single line diagram shown in Figure 4-2 for an outage on the main bus A.

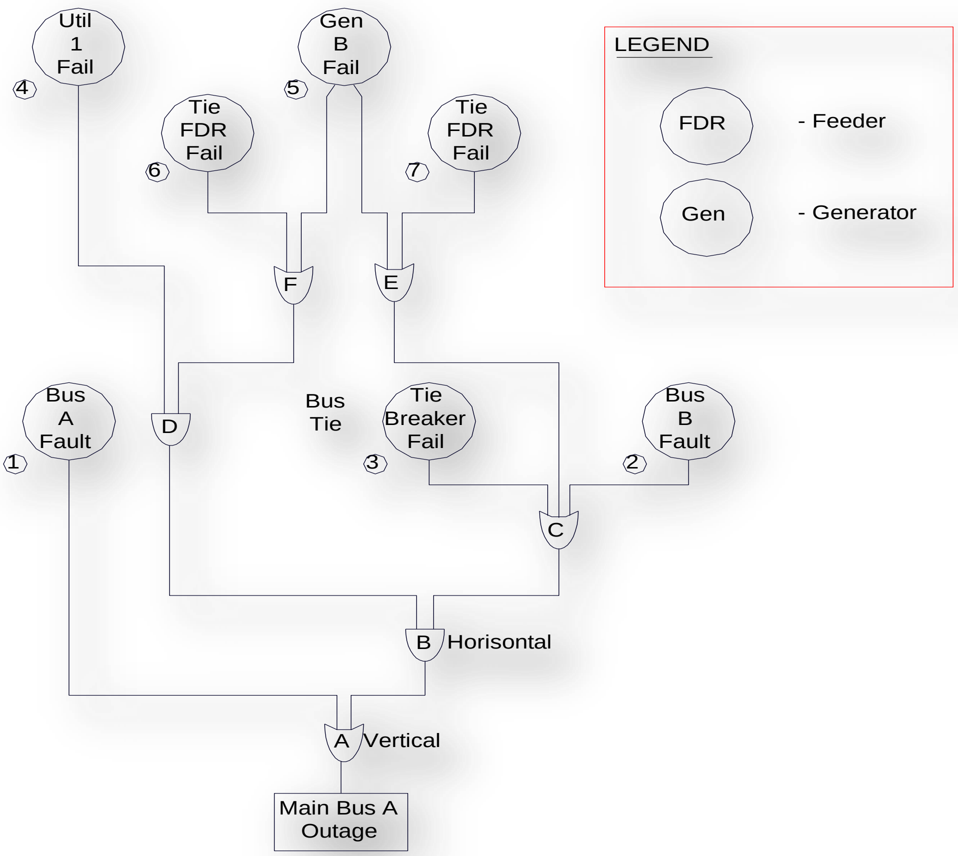

Figure 4-3: Logic diagram for Nigeria

The power outage at the main bus A is represented by the true condition of the last logic gate. Combining all series elements in a path into a single failure event simplifies the representation. Every failure event is assigned a number and each logic gate a letter.

Failure states of the individual components are the initial inputs to the logic gates. The representation is simplified by combining all series elements in a path into a single failure event. Every failure event is assigned a number and each logic gate a letter.

An outage at main A will occur in the following conditions:

- A fault on main bus A, or
- The utility and generator feeders fail, or
- The utility fails and tie breaker fails, or bus B fails, or generator feeder fails

Table 4-2 is used to develop cut-sets based on the logic diagram in Figure 4-3.

Table 4-2: Nigeria – Development of cut-sets

Step	Description	Cut-sets			
1	Start	A			
2	Replace A	1			
		B			
3	Replace B	1			
		C	D		
4	Replace C	1			
		2	D		
		3	D		
		E	D		
5	Replace D	1			
		2	4	F	
		3	4	F	
		E	4	F	
6	Replace E	1			
		2	4	F	
		3	4	F	
		5	4	F	
		7	4	F	
.7	Replace F	1			
		2	4	5	
		2	4	6	
		3	4	5	
		3	4	6	
		5	4	5	
		5	6	6	
		7	4	5	
		7	4	6	
8	Eliminate Duplicates	1			
		4	5		
		2	4	5	
		2	4	6	
		3	4	5	
		3	4	6	
		7	4	5	
		7	4	6	
9	Eliminate Supersets	1			
		4	5		
		2	4	6	
		3	4	6	
		7	4	6	

A top-down method of generation was used to develop cut-sets. The AND gates in the table are replaced by horizontal arrangements of inputs, increasing the order of the cut-set, while the OR gates are replaced by vertical arrangements of inputs in the table, which increase the number of cut-sets. Duplicate or super sets are eliminated from the table.

Table A-1 shown in Appendix A, is an Excel spreadsheet that has been used to calculate the cut-set event indices. The failure rate per year, failure duration (hours) and downtime hours/year are indices calculated for the following events:

- 1,2 - Indices for switchgear bus fault
- 3 - Indices for the tie breaker failure
- 4,5 - Indices for each utility service to the switchgear bus
- 6 - Indices for generator bus
- 7,8 - Indices for generator-switchgear tie circuits
- 10,11 - Indices for mechanical switchgear bus fault
- 12 - Indices for mechanical switchgear tie breaker failure
- 13,14 - Indices for feeder main switchgear to mechanical switchgear failure

Table B-1 shown in Appendix B, is an Excel spreadsheet using the indices that have been calculated in Table A-1, to determine the indices of the various cut-sets for an outage at the main switchgear bus A.

The mechanical switchgear bus A outage cut-set indices have been determined in Table C-1 shown in Appendix C, using an Excel spreadsheet and the event indices calculated in Table A-1.

Table D-1 shown in Appendix D, is an Excel spreadsheet that has been used to determine the load bus indices of the various cut-sets for an outage at the main switchgear of the office bus and main switchgear of the non-critical bus utilising the calculated event indices from Table A-1.

An Excel spreadsheet has been used (Table 4-3 shown below) to calculate reliability indices at the various output buses.

Table 4-3: Nigeria – Calculated reliability indices at output buses

Ref #	Output Location	Failure Rate per year	Failure Duration, Hr	Downtime, Hr/Yr	Inherent Availability
1	Main Switchgear Bus A	0.53023544	0.156287	0.0828703	0.99999054
2	Main Switchgear Bus B	0.53023544	0.156287	0.0828703	0.99999054
3	Generation Bus	0.01276	2.0532915	0.02620	0.999999772
4	Mechanical Switchgear Bus A	0.023847089	9.4823666	0.2261268	0.999974187
5	Mechanical Switchgear Bus B	0.023847089	9.4823666	0.2261268	0.999974187
6	Office Bus	0.03481	7.0853203	0.2466496	0.999971846
7	UPS Bus	0.033955	6.8285848	0.2318646	0.999973532

The failure rate per year, failure duration (hours) and downtime hours/year indices are obtained from the tables in the appendices. These indices are used to calculate the inherent availability at each bus as listed.

The indices in Table 4-3 above show 1.32 hours downtime per year at the main bus A with an inherent availability of 0.999960715. This distribution system provides good reliability and availability and compares well with a Tier III type data centre. The risk of downtime is considerably reduced compared to that of a Tier I system which is 28.8 hours per year, thus increasing the reliability and availability of the data centre.

The design of the power distribution system does not exceed the capital constraints provided by the client.

4.3 CASE STUDY 2: MULTIPLE INCOMERS AND DISTRIBUTION PATHS

4.3.1 INTRODUCTION

Douala is the largest city in Cameroon, the capital of the Littoral Region, with an estimated population of 2,446,945 located on the coast with a large port and international airport. The city houses the main data centre of a cellular network backbone [65].

Cameroon has experienced 8 337 power cuts across the country from August 2012 to March 2013. This equates to an average of nearly 38 outages per day for the country. Severe over-voltages are experienced when the power returns, which damages or destroys appliances and equipment [64].

The site is located near the city centre, totally enclosed with secure access control and closed circuit television monitoring. The data centre shares a new multi-level building with hosting facilities and value added services (VAS) offices. An energy centre on the ground floor facilitates the medium and low voltage switchgear, static UPSs and power generators.

4.3.2 DESIGN OVERVIEW OF DATA CENTRE POWER DISTRIBUTION SYSTEM

Power is provided to the site by the supply authority, AES-Sonel, from a nearby distribution substation via two dedicated underground 15 kV cables. The supply authority network is unreliable and the power delivered of poor quality [64].

Figure 4-4 provides a block diagram depicting the PDS of data centre for a cellular network in Cameroon.

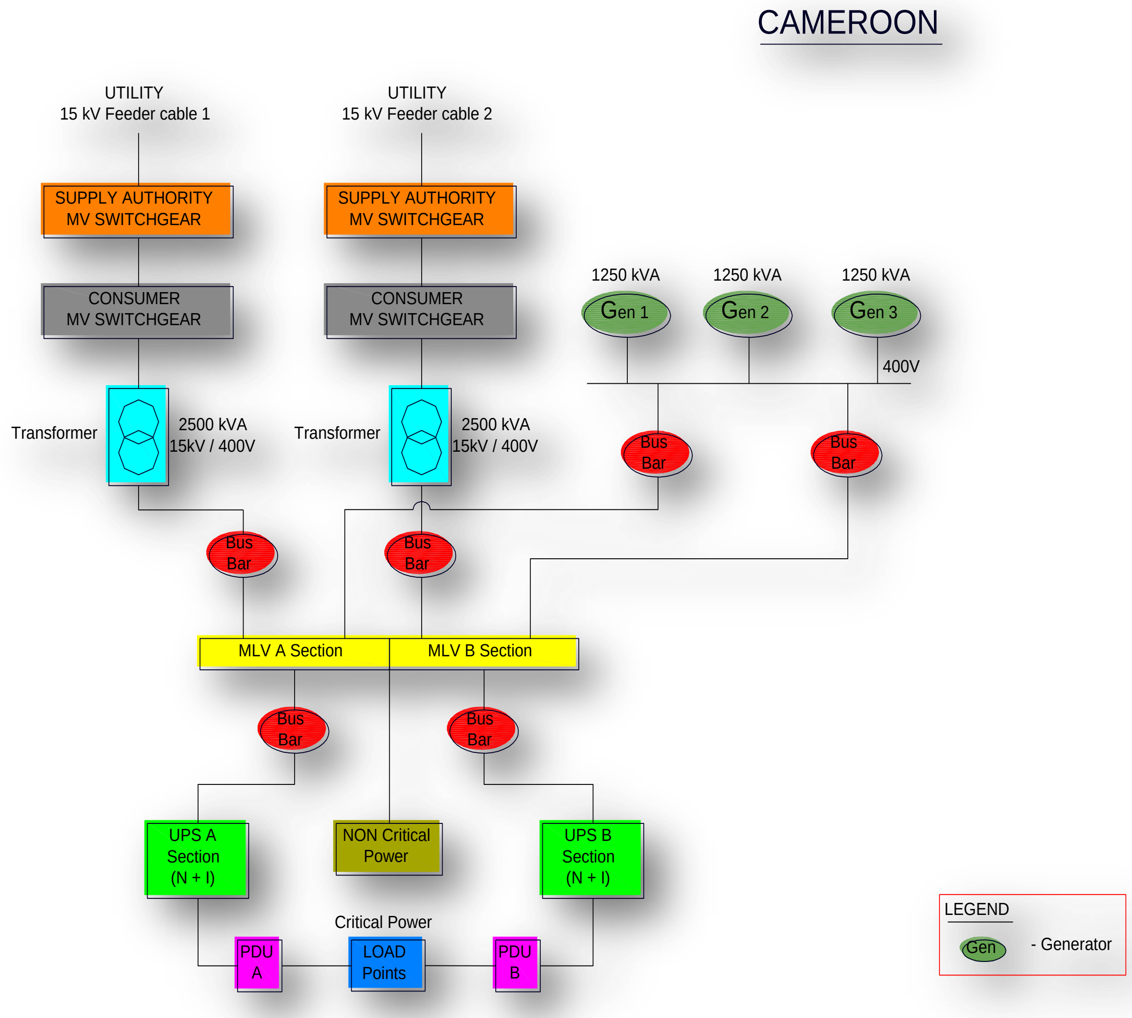

Figure 4-4: Cameroon power distribution block diagram

The following design parameters and requirements were provided:

- Two 15 kV incomers from the supply authority
- Design load of 1782 kVA with 0.79 diversity factor
- (N+1) Generator and 2(N+1) UPS redundancy
- A and B distribution systems

The power distribution system in Figure 4-4 illustrates the general arrangement of all key power distribution equipment for the data centre. The system consists of two incomers, two step-down down transformers, (N+1) generator and 2(N+1) UPS system configuration, MLV panel with A & B sections and power distribution units.

4.3.3 DESIGN OF A FAULT TOLERANT POWER SYSTEM

Case Study 2 entails the reliability evaluation of the data centre that is Tier IV compliant, thus eliminating SPOF, providing redundancy and allowing concurrent maintenance. Equipment considered comprised active capacity components to support the IT load after failure, and equipment in the two simultaneous active distribution paths. Dual corded IT equipment is used, which has two built-in power supplies.

The data centre complex was designed for a constant connected load of 1782 kVA with a 0.79 diversity factor (i.e. operates at 79% of the connected load). Parallel distribution paths with redundancy are provided, thus meeting Tier IV data centre requirements.

Two dedicated 15kV incomers are provided via parallel XLPE underground armoured cables from a nearby supply authority distribution substation. Each of these supply cables carries the total connected load with 60% spare capacity for future load growth.

The energy centre has a supply authority and consumer section which houses the respective medium voltage switchgear. Enclosed parallel busbar feeders link the transformers and the main low voltage (MLV) panel sections.

SF6 insulated metal clad modular type switchgear with draw-out vacuum circuit breakers is installed in a dedicated medium voltage room. The switchgear is equipped with high level electronic protection relays which have data logging and communication capabilities.

Figure 4-5 shows a single line diagram of the PDS for the data centre of the cellular network in Cameroon. The detail power distribution design in Figure 4-5 shows a parallel redundant system which has A and B sections for the main bus, UPS bus, mechanical bus and office bus.

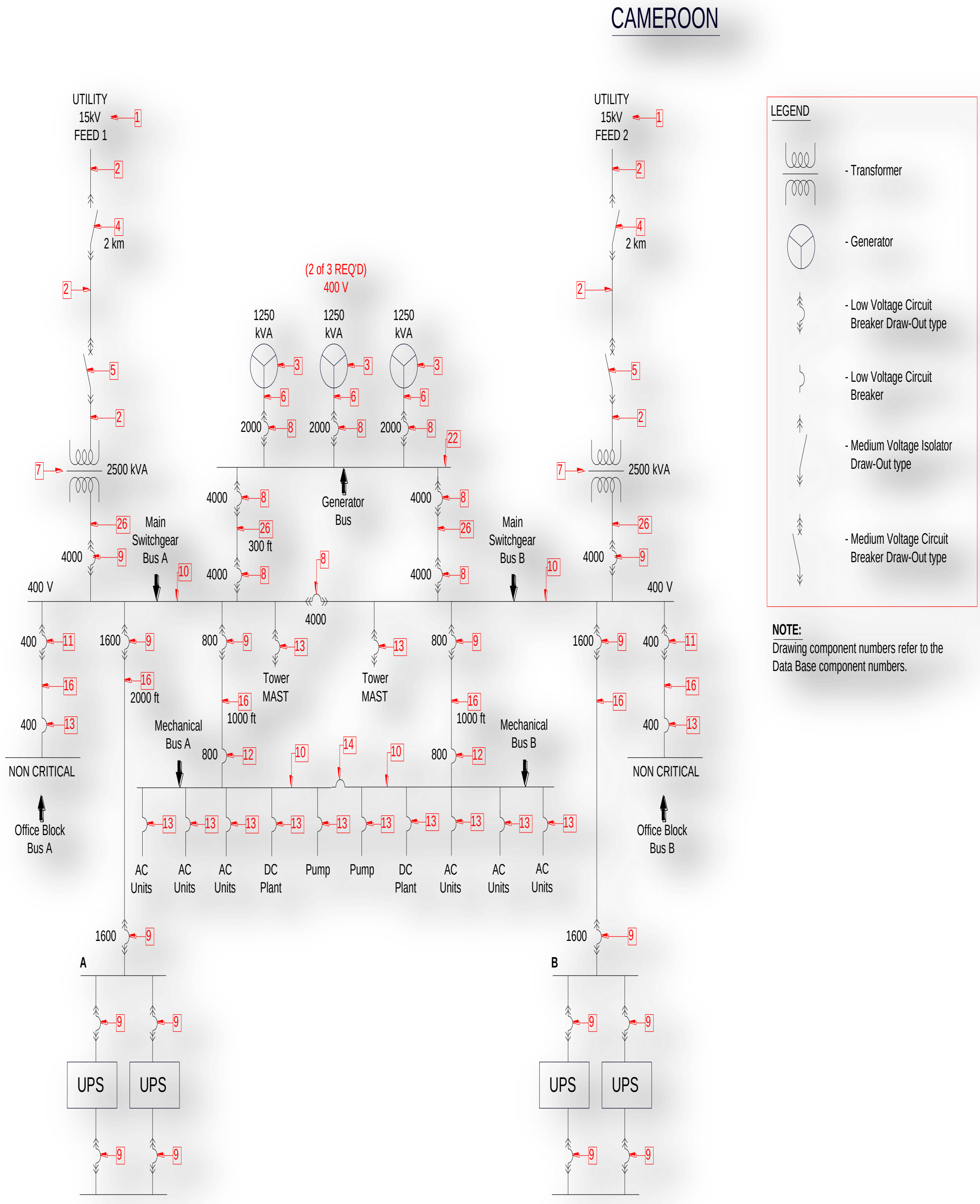

Figure 4-5: Cameroon single line diagram

Two 2500 kVA 15 kV step-down distribution transformers of the oil natural, air natural (ONAN) cooling type, fitted with a Buchholz protection relay, should be installed in a dedicated transformer room with capacity for a future third transformer.

Primary power supply is provided by three 1250 kVA base load (continuous running) diesel power generators which have redundancy and are connected to a common bus. Bulk diesel tanks provide fuel for ninety six (96) hours continuous power generation. The generators have a (N+1) and the static UPS system provides a 2(N+1) redundancy system.

Low loss metal enclosed copper busbar and cross-linked polyethylene (XLPE) insulated copper cables are used to link all distribution equipment, panels and distribution boards.

The MLV panel, distribution boards and PDUs are modular type tested units with advanced metering and monitoring capabilities linked to the management system. All equipment is compartmentalised, draw-out or plug-in type wired to terminal strips.

Incomers and feeders utilise air circuit breakers, category B, when equal or larger than 800A and moulded case type when smaller. Enhanced discrimination methodology is applied to series circuit breakers allowing isolation of the circuit breaker nearest to the fault.

Four 500kVA parallel redundant static UPSs, two for A and B sections respectively (N+1), provide filtered power to mission critical equipment. A and B battery banks consist of 10-year life cycle batteries to provide 20-minute power backup. Valve regulated lead acid (VRLA) flood type batteries are used with one battery string per module. An advanced battery monitoring and management system is employed and linked to the BMS.

Computer raised floors with 900mm floor voids are provided for services and cooling. A galvanised cable management system providing power and data trays installed at various levels in the floor void. The floor supporting structure and cable trays are connected at various points to the insulated earth bars located in the floor void.

PDUs should be placed at the end of each row of servers and be equipped with power metering and status monitoring and interfaced with the BMS. Dual corded IT equipment should be used that has two built-in power supplies

4.3.4 RESULTS OF SYSTEM RELIABILITY EVALUATION

The IEEE Gold book and PREP databases are used for probability calculations to obtain a statistical view and prediction of an event happening that might cause a failure which results in data centre downtime. The reliability data of equipment corresponding to each labelled component in Figure 4-5 are shown in Table 4-4.

Table 4-4: Cameroon – Indices

Ref #	Item Description	Failure Rate Symbol	Failure Rate (Failures/ Year)	MTTR Symbol	MTTR (Hour/ Failure)	Availability Symbol	Inherent Availability
1	Single Circuit Supply, 1.78 failures/unit years, A=0.999705 Gold Book – p. 107	λ1	0.956	r1	1.32	P1	0.999705
2	Cable Areal, ≤ 15 kV, per mile	λ2	0.04717	r2	1.82	P2	0.999991118
3	Diesel Engines Generator, Packaged, Standby, 1500 kW	λ3	0.12350	r3	18.28	P3	0.999742312
4	Manual Disconnect Switch	λ4	0.00174	r4	1.00	P4	0.999999801
5	Vacuum 33kV Circuit Breaker, Normally Closed, ≤ 600 Amp *	λ5	0.00283	r5	8.00	P5	0.999973208
6	Cable Below Ground in conduit, ≤ 600 V, per 1000 ft	λ6	0.00201	r6	11.22	P6	0.999996428
7	Transformer, Liquid, Non Forced Air, 3000 kVA	λ7	0.00111	r7	5.00	P7	0.999999367
8	Circuit Breaker, 600 V, Drawout, Normally Open, > 600 Amp	λ8	0.00553	r8	2.00	P8	0.999998738
9	Circuit Breaker, 600 V, Drawout, Normally Closed, > 600 Amp	λ9	0.00185	r9	0.50	P9	0.999999894
10	Switchgear, Bare Bus, 600 V	λ10	0.00949	r10	7.29	P10	0.999992098
11	Circuit Breaker, 600 V, Drawout, Normally Closed, > 600 Amp	λ11	0.00021	r11	6.00	P11	0.999999858
12	Circuit Breaker, 600 V, Normally Closed, > 600 Amp Gold Book p. 40	λ12	0.0096	r12	9.60	P12	0.999989479
13	Circuit Breaker, 3 Phase Fixed, Normally Open, ≤ 600 Amp Gold Book p. 40	λ13	0.0052	r13	5.80	P13	0.999996557
14	Circuit Breaker, 3 Phase Fixed, Normally Open, > 600 Amp	λ14	0.00343	r14	37.50	P14	0.999985320
15	Cable, Above Ground, Trays, ≤ 600 V, per 1000 ft	λ15	0.00012	r15	2.50	P15	0.999999866
16	Cable, Above Ground, Trays, ≤ 600 V, per 1000 ft Gold Book p. 105	λ16	0.00141	r16	10.50	P16	0.99999831
17	Battery, Lead Acid, Strings	λ17	0.00746	r17	32.13	P17	0.999972627
18	Fuse, 0 ~ 5kV	λ18	0.00137	r18	0.00	P18	1.000000000
19	Inverter	λ19	0.00482	r19	26.00	P19	0.999985691
20	Rectifier	λ20	0.00447	r20	16.00	P20	0.999991837
21	Static Switch, 0 ~ 600 Amp	λ21	0.0061	r21	3.60	P21	0.999997493
22	Switchgear, Insulated bus, ≤ 600 V	λ22	0.0017	r22	2.40	P22	0.999999534
23	Transformer, Dry, Isolation, < 600 V	λ23	0.00284	r23	21.26	P23	0.999993113
24	Circuit Breaker, 3 Phased Fixed, Normally Open	λ24	0.00011	r24	18.67	P24	0.999999760
25	Cable, Above Ground, In Conduit, ≤ 600 V, per 1000 ft	λ25	0.00007	r25	8.00	P25	0.999999838
26	Bus Duct, Gold Book p.206	λ26	0.000125	r26	12.90	P26	0.999999816
27	Cable underground, ≤ 15 kV, per 305 m	λ27	0.02017	R27	5.13	P27	0.999988193

Table 4-4 provides component reliability indices from the IEEE 493 and the Power Reliability Enhancement Program (PREP) databases [27], [67].

The fundamental assumptions below apply to the power distribution system:

- Failure rates and repair times are exponentially distributed
- There are two paths of power distribution
- Cable failure rates are determined per actual cable length
- The generators are (N+1) redundant
- The UPSs are 2(N+1) redundant
- Manual switching operations require 15 minutes
- Automatic starting and paralleling of generators
- Automatic source transfer
- Low voltage switchgear, busbars and automatic transfer switches (ATS) are redundant
- Circuit breaker failure modes are 50% open and 50% closed (shorted)

The reference numbers in Table 4-4 refer to the numbered components and equipment in the single line diagram in Figure 4-5.

The logic diagrams in Figure 4-6 and Figure 4-7 are derived from the single line diagram shown in Figure 4-5.

Main Bus A

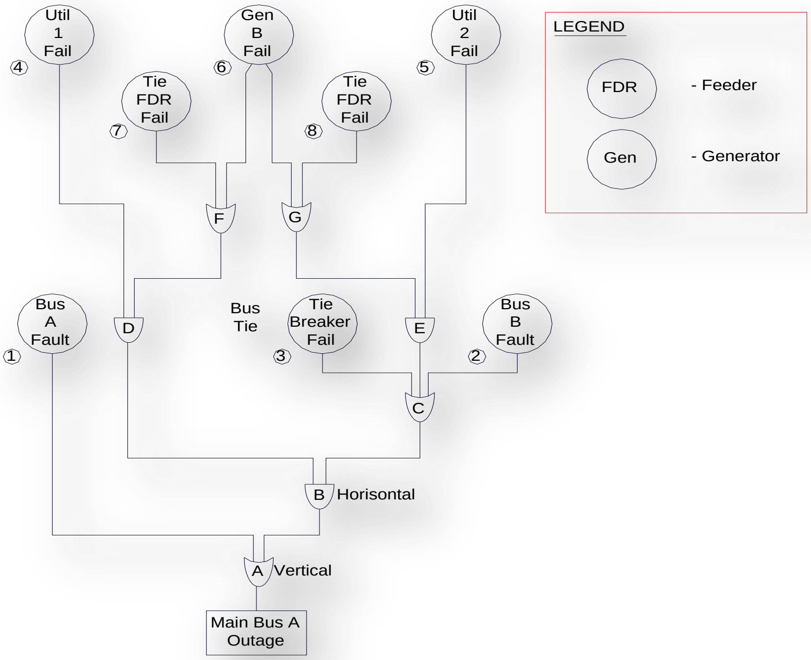

Figure 4-6: Logic diagrams for Cameroon – Main Bus A

Mechanical Bus A

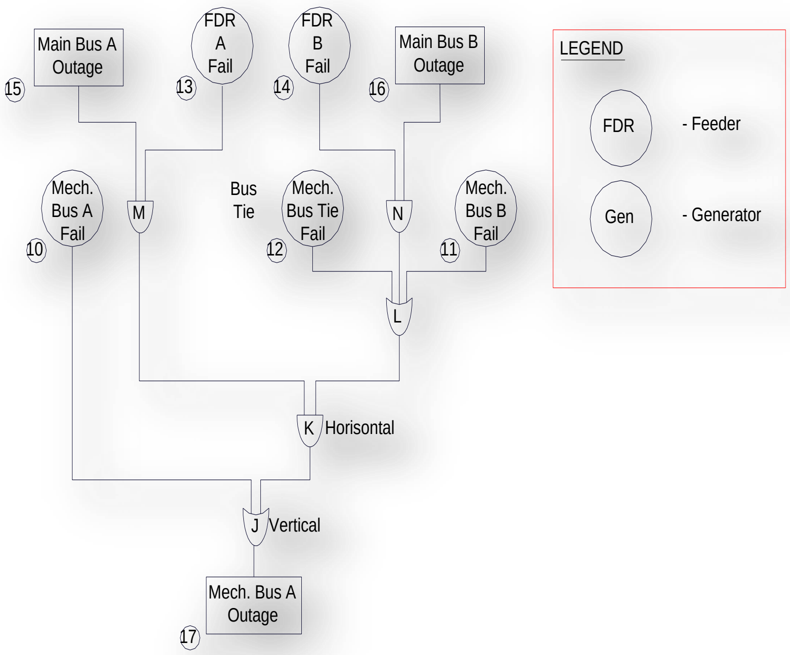

Figure 4-7: Logic diagrams for Cameroon – Mechanical Bus A

A further assumption is made that the power distribution system falls within the statistical distribution where failures are random and at a constant failure rate which is typical for electronic systems.

Logic diagrams are designed from the single line drawing in Figure 4-5, with an outage at a particular bus represented by a true condition of the last logic gate. Each logic gate and failure event is assigned a letter and number respectively. The failure state of each component is the initial input to the logic gates.

The minimal cut-set method is used which estimates the frequency and duration load point interruptions [68]. Combining all series elements in a path into a single failure event simplifies the representation. Failure rate, failure duration and inherent availability are reliability indices calculated from the single line diagram, see Figure 4-5.

An outage at main A will occur in the following conditions:

- A bus fault on main bus A, or
- Utility 1 and generator feeder fail plus bus B fault, or
- Utility 1 and generator feeder fail plus tie breaker fail, or
- Utility 1 and generator feeders fail plus Utility 2 fail

Table 4-5 is used to develop cut-sets for an outage at the main bus A based on the logic diagrams in Figure 4-6 and Figure 4-7.

Table 4-5: Cameroon – Development of cut-sets

Step	Description	Cut-sets			
1	Start	A			
2	Replace A	1			
		B			
3	Replace B	1			
		C	D		
4	Replace C	1			
		2	D		
		3	D		
		E	D		
5	Replace D	1			
		2	4	F	
		3	4	F	
		E	4	F	

Step	Description	Cut-sets			
6	Replace E	1			
		2	4	F	
		3	4	F	
		5	G	4	F
7	Replace F	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	G	4	6
		5	G	4	7
8	Replace G	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	6	4	6
		5	8	4	6
		5	6	4	7
		5	8	4	7
9	Eliminate Duplicates	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	4	6	
		5	8	4	6
		5	6	4	7
		5	8	4	7
10	Eliminate Supersets	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	4	6	
		5	8	4	7

Cut-sets are developed using the top-down method of generation. Calculated results for selected output buses are shown in Table 4.6. The AND logic gates in the table are replaced by horizontal arrangements of inputs, increasing the order of the cut-set, while OR gates are replaced with vertical arrangements of inputs, thus increasing the number of cut-sets. Duplicate or super sets are eliminated from the table.

Table A-2 listed in Appendix A provides an Excel spreadsheet that has been used to calculate the cut-set event indices. Failure rate per year, failure duration (hours) and downtime hours/year are indices calculated for events that follow:

- 1,2 - Indices for switchgear bus fault
- 3 - Indices for the tie breaker failure
- 4,5 - Indices for each utility service to the switchgear bus
- 6 - Indices for generator bus
- 7,8 - Indices for generator-switchgear tie circuits
- 10,11 - Indices for mechanical switchgear bus fault
- 12 - Indices for mechanical switchgear tie breaker failure
- 13,14 - Indices for feeder main switchgear to mechanical switchgear failure

Table B-2 listed in Appendix B provides an Excel spreadsheet using the indices that have been calculated in Table A-2, determining the indices for the various cut-sets for an outage at the main switchgear bus A.

Mechanical switchgear cut-set indices for an outage at bus A are calculated and listed in Table C-2 shown in Appendix C, using an Excel spreadsheet and the event indices calculated in Table A-2.

An Excel spreadsheet has been used to determine the load bus indices of the various cut-sets for an outage at the office switchgear bus and the non-critical bus utilising the calculated event indices from Table A-2 and listed in Table D-2 shown in Appendix D.

Table 4-6 below used a spreadsheet to calculate reliability indices at the various output buses. The failure rate per year, failure duration (hours) and downtime hours/year indices are obtained from the tables in the appendixes. These indices are used to calculate the inherent availability at each bus as listed in Table 4-6.

Table 4-6: Cameroon – Calculated reliability indices at output buses

Ref #	Output Location	Failure Rate per year	Failure Duration, Hr	Downtime, Hr/Yr	Inherent Availability
1	Main Switchgear Bus A	0.018005005	4.60000	0.082823023	0.999990545
2	Main Switchgear Bus B	0.018005005	4.60000	0.082823023	0.999990545
3	Generation Bus	0.01276	2.053291536	0.0262	0.999997009
4	Mechanical Switchgear Bus A	2.38E-02	9.501127773	0.226126841	0.999974187
5	Mechanical Switchgear Bus B	2.38E-02	9.501127773	0.226126841	0.999974187
6	Office Bus	0.03481	7.08532031	0.2466496	0.999971846
7	UPS Bus	0.033955	6.82858489	0.2318646	0.999973532

The calculated indices for inherent availability are high and for the main and generator buses in excess of “five nines” while slightly less for the other buses. The downtime per year is nearly 50% less than the PDS in Case Study 1. The availability indices compare well with Tier IV Uptime Institute standards.

A Tier IV data centre provides an average downtime of 0.8 hours per year and availability of 99.99% compared to 1.6 hours downtime per year and 99.98% availability for a Tier III data centre. The designed power distribution system compares favourably with these indices and the system is concurrently maintainable. The goal of data centres of cellular networks is to have zero down time.

4.4 SUMMARY

Two case studies are presented to reveal the frequency and duration of interruptions for selected load points on the respective networks, with each case study having a unique operating system topology.

In Case Study 1 the utility company provided a 33 kV supply and one step-down distribution transformer with (N+1) generator and UPS redundancy. Reliability indices were calculated for a typical data centre which has a single incomer with parallel distribution paths. The reliability of this topology, which is commonly used due to financial constraints, compares well with the availability indices of a Tier III topology.

The risk of downtime is considerably higher than a Tier IV topology. It takes a data centre four hours or more to be operational after a downtime incident.

In Case Study 2, two 15kV incomers and step down transformers were provided with parallel distribution paths and (N+1) redundant generators and UPS systems. The downtime for case study 2 is nearly 50% less than for case study 1. The reliability and availability indices were determined to be higher than in Case Study 1.

The two case studies confirm the impact that component inherent characteristics (CIC) and system connectivity topology (SCT) have on the reliability of a data centre.

Reliable data sources are the key to accurate analysis and provide the necessary data to perform an analysis. Simple spreadsheet calculations can be used with the implementation of minimal cut-set methodology for standard networks such as mission-critical installations.

The reliability analysis provides the ability to identify and assess risks and allows the comparison of functions and values of the various items of equipment. The evaluation of reliability analysis is used to optimise the PDS in order to reduce the number and duration of failures, improve the targeting of maintenance requirements and enhance system efficiency.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Data centres for cellular networks host large number of servers dedicated to massive computation and storage which is essential to almost every sector of the global economy. The growth of the internet, e-commerce and social media has changed the definition and tactics of the business model. E-commerce provides services such as online trading, real-time online banking and purchasing.

Data is growing at an exponential rate, with growth in emerging markets faster than mature regions. An average Japanese home with fibre to the home downloads data at a rate of more than 500 MB per day, dominated by high definition (HD) Video. The social media are another major source of data growth, with more video content being uploaded to YouTube every month than a TV station can broadcast in 300 years [11]. Africa is the world`s fastest growing cell phone market and has reached 649 million connections [7].

Complexity and criticality are increasing as data centres experience a steady growth in capacity and density resources and increasing consequences of poor performance. The availability of information technology (IT) is the most important metric against which data centres are evaluated [9].

Vulnerabilities in the power distribution system can lead to a system failure resulting in catastrophic unplanned power outages with serious financial consequences. Power systems technologies, redundancy and parallel distribution paths are employed to isolate data centre power system failures.

Enterprise dependence on IT systems has created an even stronger link between data centre availability and total cost of ownership (TCO). IT services are becoming more commoditised with co-location, disaster recovery and cloud computing services. Misperception with regard to the frequency and costs of IT failures and infrastructure vulnerabilities increases the risk of downtime with serious financial consequences.

The consequences of data centre downtime can have serious financial implications for a company and can range from a few thousand to a few million dollars per outage. Downtime adversely affects costs, opportunity losses, company reputation and customer confidence [12], [13].

Poor grid quality is one of major causes of power distribution system downtime. Nearly all the countries in Sub-Saharan Africa are experiencing a serious power crisis emphasised by lack of generating and distribution capacity, unreliable supplies, steep rate of increase in electricity consumption, low energy access rates, high electricity costs and lack of maintenance.

From the literature study it was determined that data centres for cellular networks in Africa require a reliable power distribution system and a simple methodology to evaluate the reliability of various distribution systems. The study focused on optimising the design of power distribution systems to achieve the required reliability and availability. The design of two data centres was not limited by budget constraints, due to the fact that system failure could result in catastrophic unplanned power outages with serious financial consequences.

The requirement to guarantee electrical service continuity through source reliability and power system integrity was addressed through techniques and technologies discussed in Chapter 3. They include system topology, preventative maintenance, infrastructure monitoring and measurement and personnel training. These technologies and techniques were implemented in the power distribution systems of two cellular data centres in Nigeria and Cameroon respectively.

Parallel distribution paths were provided for both data centres, but due to financial constraints only the Cameroon data centre had a Tier IV fault tolerant and concurrent maintainable system installed. The calculated results have shown that the reliability and availability indices of the Cameroon data centre are considerably higher than those of the Nigerian data centre.

The static double conversion parallel redundant UPS system that has been installed provides higher tolerance of poor power quality and voltage surges passed on to the critical IT loads.

Both case studies utilise diesel generators providing the primary source of supply have a poor reliability factor of 0.005, meaning that 5 out of a 1000 attempts the engine fails to start. The system was enhanced by installing continuous rated generator units in parallel on a common bus with a redundant unit.

Resilient Tier classification and performance standards were used as an objective basis for the design of infrastructure topology. The power systems installed comply with the Tier outcome based requirements presented by actual site availability performance, through being a combination of design topology and operational sustainability.

The power distribution system design was based on equipment steady state and transient characteristic parameters, as this is vital for the functional requirements of the PDS, safety factors and tolerances. This study shows that the power systems became more complex with the increase in reliability achieved through the elimination of single point of failure and the provision of redundancy into critical equipment.

Several separate infrastructure sub-systems are integrated, of which the number is dependent upon the individual technologies (e.g. power generation, uninterruptible power sources, cooling, etc.) selected to sustain the data centre operation.

Chapter 3 discusses a simplified probability and statistical mathematical model to determine the reliability and availability of a power distribution system. This model was then used to carry out quantitative evaluations of the power systems, allowing consistent, unbiased, and defendable reliability assessments. System weaknesses can thus be numerically and non-numerically determined and alternative choices considered.

Important factors that are considered in the analysis are reliability data such as failure rates of components, repair times, interruption definitions and reliability equations. Utilising spreadsheets with mathematical calculations allows for evaluation, prediction and control which is required for design, and an effective maintenance system and operation [37].

The IEEE 493 Gold Book standard and Power Reliability Enhancement Program (PREP) of the US Army Corps of Engineers are two well-known and recognised databases that were used for the analysis of the two case studies. The analysis has shown that rigorous reliability analysis results are powerful tools when used correctly to compare alternative designs.

An integrated reliability centred maintenance system, also called condition based maintenance, was implemented and supported by infrastructure monitoring and management software. The system uses estimation and projection of equipment condition over time, utilising probability theory. Self-diagnosis provides operational hours and flags warnings when equipment is operated beyond its design limits.

An authorised third party was appointed to carry out the preventative maintenance (PM), utilising onsite trained expert maintenance staff. The maintenance company is responsible for scheduling, risk management and execution of PM programmes.

A comprehensive infrastructure management and monitoring system, which is a web based automated system, was installed in the data centres. The monitoring system continuously collects data on power quality, loading and power system quantities, equipment status and temperature of critical equipment.

High-end digital meters are used that provide historical trending, event and alarm notifications, power quality monitoring and real-time control. Branch circuits are monitored and provide valuable capacity data, which assists in planning future loading. Analyses of the collected data are carried out by expert technical staff and appropriate action is taken, preventing equipment failure and data centre downtime.

It was shown during this study that system connectivity topology and component inherent characteristics have a significant influence on the power quality and thus the reliability of the power distribution system as confirmed by the two case studies. The PDS architecture implemented in Case Study 2 guarantees operational performance, while the system also allows maintenance, flexibility and expansion.

Consider Case Study 1, which uses only one supply incomer with a step-down transformer, parallel distribution paths, (N+1) generator and 2(N+1) UPS redundancy. This topology is a combination of the Tier III and Tier IV standard. The reliability and availability indices are considerably lower than for a Tier IV standard, with downtime per year double than that of a Tier IV system.

The failure rate in Case Study 1 is not ideal as a data centre takes four hours or more to be back online after a downtime event. The PDS used is a good alternative when budget constraints are a limiting factor in the design of the system due to relative low downtime per year and high availability indices.

Case Study 2 employs a power distribution system which has two supply incomers with two step-down transformers, parallel distribution paths, (N+1) generator and 2(N+1) UPS redundancy. This system compares well to Tier IV standards and provides very good downtime and availability indices.

Poor power quality delivered by distribution networks in Africa, logistics, lack of trained staff and the catastrophic financial consequences of downtime are major factors to be considered when designing a PDS for a data centre of a cellular network in Africa. Taking the investment costs into account, the PDS should be compliant to Tier IV standards or beyond.

5.2 RECOMMENDATIONS FOR FURTHER WORK

During this study, four additional cellular data centres were investigated, three in Nigeria and one in Cameroon. These are existing data centres which require further investigation into the reliability of their power distribution systems.

Spreadsheets with mathematical calculations can be used to carry out quantitative evaluations of the power distribution systems, which will allow consistent reliability assessments. System weaknesses can be determined and alternative upgrading options considered. Further investigations can be conducted into the methodology for upgrading the existing power distribution systems without resulting in data centre downtime.

During this study, the reliability of the data centres was improved through the elimination of single point of failure as illustrated in Case Study 2 and a mathematical model was used to determine the PDS reliability. It is recommended that the actual operational data be analysed and compared with the reliability model data.

Making use of the reliability model, it is recommended that every data centre in the cellular network in the African countries be evaluated so as to obtain an overall picture. By utilising the norms presented in the model, statistical data can be retrieved from which the reliability of the various data centres can be analysed. This will indicate, as a whole, where urgent attention should be paid and what PDS upgrades need to be implemented. These could be operational and/or managerial amendments.

The statistical data obtained from a complete audit as described above will provide valuable data with regard to the reliability of the data centres. Once benchmarks have been established, the power distribution systems for current and future data centres can be optimised by using these figures, which will go a long way toward improving the reliability of data centres as a whole.

The spreadsheet calculations conclusively confirm the relationship between system connectivity topology, component inherent characteristics and data centre reliability. The influence that increased reliability has on the energy efficiency has not been included in this study and should be investigated and confirmed in future work.

It is recommended as further work to investigate the extent to which smart grids will impact on the reliability, power quality and efficiency of the data centre power distribution system. A smart grid system can provide a dynamic, reliable, interactive, real time information and efficient utility distribution system.

REFERENCES

[1] A. Eberhard, et al, *"Africa Infrastructure Country Diagnostic – Underpowered: The State of the Power Sector in the Sub-Saharan Africa"*, Report produced by the World Bank May 2008.

[2] M. Bazilian, M. Welsch, et al, *"Smart and Just Grids: Opportunities for sub-Saharan Africa",* Imperial College London 2011.

[3] Dr. X Mkhwanazi, National Energy Regulator SA, *"Power Sector Development in Africa",* June 2003, Workshop for African Energy Experts.

[4] Dambudzo Muzenda, *"Increasing Private Investment in African Energy Infrastructure",* Secretariat of the NEPAD-OECD Africa Investment Initiative, November 2009.

[5] V. Foster, J Steinbuks, *"Paying the Price for Unreliable Power Supplies: In-House Generation of Electricity by Firms in Africa"* Policy Research Working Paper for the World Bank, 2009.

[6] U.Deichmann, G. Meisner, Siobhan Murray, D.Wheeler, *"The Economics of Renewable Energy Expansion in Rural Sub-Saharan Africa",* Policy Research Working Paper for the World Bank, 2010.

[7] Donna Bryson, *"Africa the world`s fastest growing cellphone market",* Mail & Guardian, 9 November 2011, mg.co.za/article/2011-11-09-africa-is-fastest-growing-cellphone-market.

[8] Montri Wiboonrat, *"Data Center Design of Optimal Reliable Systems"* The College of Graduate Study in Management, Khon Kaen University, Bangkok, IEEE Publication 2011.

[9] Emerson Network Power, "*Seven Best Practices for Increasing Energy Efficiency, Availability and Capacity: The enterprise Data Center Design Guide",* White Paper by Liebert Corporation 2012.

[10] Emerson Network Power, "*Understanding the Cost of Data Center Downtime: An Analysis of the Financial Impact on the Infrastructure Vulnerability"*, White Paper by Liebert Corporation 2011*.*

[11] I. Bitterlin, Visiting Professor, School of Mechanical Engineering, University of Leeds, *"The Future of Data-Centers?",* Emerson Road Show 2013.

[12] Montri Wiboonrat, *"An Optimal Data Center Availability and Investment Trade-offs",* Graduate School of Information Technology, Assumption University, Bangkok, Ninth ACIS International Conference on Software Engineering, Networking, and Parallel/distributed computing, IEEE 2008.

[13] Ponemon Institute Research Report, *"Calculating the Cost of Data Center Outages"*, February 2011.

[14] T.J. Dionise, Carolyn L. Cooper, *"Identifying Issues That Adversely Affect Data Center Reliability Through Electrical System Audits"* Eaton Electrical Group, Power Systems Engineering, Dallas, Texas, IEEE Publication 2010.

[15] Reichle & De-Massari, *"R & M Data Center Handbook",* 2011.

[16] K.G. Brill, *"Measuring data centre energy flow," Forbes*, Jan 28, 2009.

[17] Ponemon Institute Research Report, "*National Survey on Data Center Outages"*, http://www.Ponemon.org, February 2010.

[18] Montri Wiboonrat, *"Next Generation Data Center Design Under Smart Grid"* The College of Graduate Study in Management, Khon Kaen University, Bangkok, IEEE Publication 2012.

[19] IEEE Green Book, Standard 1100-2005 – *"Recommendation Practice for Powering and Grounding Electronic Equipment",* Emerald book.

[20] Montri Wiboonrat, *"An Empirical Study on Data Center System Failure Diagnosis"* Graduate School of Information Technology, Assumption University, Bangkok, IEEE Publication 2008.

[21] R.G. Coney, "*The Impact Of Power Quality on the Industry in Africa",* IEEE 1996.

[22] Joseph Seymour *"The Seven Types of Power Problems"*, APC White Paper, Lead Claim Analyst at Schneider Electric in West Kingston, Rhode Island, 2011.

[23] IEEE 1159-1995, Standard 1159-1995, *"Recommended Practice for Monitoring Electric Power Quality",* published in 1995.

[24] C.J. Melhorn, T.D. Davis, and G.E.Beam, *"Voltage Sags: Their Impact on the Utility and Industrial Customers"*, IEEE 1998.

[25] Information Technology Industry Council (ITI), *"ITI (CBEMA) Curve Application Note"*, ITI Publication 2000.

[26] Montri Wiboonrat, *"Transformation of System Failure Life Cycle"* Graduate School of Information Technology, Assumption University, Bangkok, International Journal of Management Science and Engineering Management 2009.

[27] IEEE Gold Book, Standard 493-2007, *"IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems".*

[28] S. Siu, J. Lopopolo, Critical Facilities Services, Hewlett-Packard Company, *"Compatibility, Sizing, and Design Considerations for Generators and UPSs in Tier I, II, III, and IV Topologies,* IEEE 2011.

[29] G. Parise, L. Parise, *"Electrical Distribution for A Reliable Data Center",* Electrical Engineering Dept. Engineering Faculty, Sapienza University, Rome Italy, IEEE 2012.

[30] Montri Wiboonrat, *"System Reliability of Fault Tolerant Data Center",* College of Graduate Study in Management, Khon Kaen University, Bangkok, Fifth International Conference on Communication Theory, Reliability, and Quality of service.

[31] ABB Power and Productivity, "*Increasing safety, reliability and efficiency for today's data centers",* ABB segment brochure.

[32] Uptime Institute, "Data Center Site Infrastructure Tier Standard: Topology", 2010.

[33] Turner P.W, Seader J.H, Brill K.G, *"Tier Classifications Define Site Infrastructure Performance, 2006",* Uptime Institute.

[34] TIA Standard-942-2005, *"Telecommunications Infrastructure Standard for Data Centers",* Telecommunications Industry Association.

[35] Netmagic Whitepaper, *"Data center outages impact, causes, costs, and how to mitigate",* 2012.

[36] J.F. Christin et al, *"Designing Fault-Tolerant Power Infrastructure"*, 9th International Conference, Electrical Power Quality and Utilisation, October 2007.

[37] Technical Manual TM 5-698-1, *"Reliability/Availability of Electrical & Mechanical Systems for Command, Control, Communications, Computor, Intelligence, Surveillance and Reconnaissance (CF4ISR) Facilities",* Headquarters, Department of the Army, Washington DC, 19 January 2007.

[38] W. Wang, J.M. Loman, R. Arno, P. Vassiliou, E. Furlong, D. Ogden, *"Reliability Block Diagram Simulation Techniques Applied to IEEE Std. 493 Standard network",* IEEE May 2004.

[39] S. Speaks, *" Reliability and MTBF Overview",* Vicor Reliability Engineering, 2002.

[40] P.S. Hale, Jr., Power Reliability Enhancement Program (Prep), and R. Arno from Reliability Analysis Centre (RAC), *"Survey of Reliability and Availability Information for Power Distribution, and HVAC Components for Commercial, Industrial, and Utility Installations",* IEEE 2000.

[41] B Brown, *"Data Center Power System Reliability Beyond the 9`s: A Practical Approach"*, 2007.

[42] R. Arno from Alion Science and Technology, P. Gross and R. Schuerger from EYP Mission Critical Facilities Inc., *"What Five 9`s Really Means and Managing Expectations",* IEEE 2006.

[43] E. H. Jamaluddin, et al, "*Method Of Predicting, Estimating And Improving Mean Time Between Failures In Reducing Reactive Work In Maintenance Organization",* Faculty of Mechanical Engineering, University Malaysia Pahang, Malaysia, 2009.

[44] B. Roczen & R. Arno from Reliability Analysis Center (RAC), P.S. Hale,Jr. from Power Reliability Enhancement Program (PREP), *"Reliability Block Diagram Methodology Applied to Gold Book Standard Network",* IEEE 2004.

[45] I. Stewart et al*:"Data Centre operation efficiency best practices",* IBM research paper prepared by International Data Corporation (IDC) 2012.

[46] M.A. Bell, "*Use Best Practices to Design Data Centre Facilities"*, ID Number G00127434, Gartner Research, 2005.

[47] Mohammed Shehata, *"The Auspices of Tri-generation in the Data Centre",* PTS Consulting.

[48] M. Mcphee and B. Lacey, *"Tri-Generation for Data Centres; Lessons Learnt from a recent installation",* Ecolibrium Magazine April 2011.

[49] Pacific Gas and Electric Company, *" High Performance Data Center: A Design Guidelines Source Book", January 2006.*

[50] Emerson Network Power, *"Ten Steps to Increasing Data Center Effiency and availability through infrastructure Monitoring",* White Paper from Experts in Business-Critical Continuity™, February 2011, Mission Critical Magazine

[51] J. Bruschi, et al, Rumsey Engineers for National Renewable Energy Laboratory (NREL), U.S. Department of Energy, *"Best Practices Guide for Energy-Efficient Data Center Design",* March 2011.

[52] R.Arno, A. Friedl, P. Gross, R. Schuerger, HP Critical Facility Services, *"Reliability of Example Data Center Designs Selected By Tier Classification",* IEEE 2010.

[53] C. Cowan, C. Gaskins, *"Monitoring Physical Threads in the Data Center",* American Power Conversion, WP102 Rev.3.

[54] C. Robertson and J. Romm, Centre for Energy & Climate Solutions, *"Data Centers, Power, and Pollution Prevention",* June 2002.

[55] L.R Larsen and L.A. Huff, *"Proper Cable Management Aids Data Center Cooling",* www.cablingbusiness.com, April 2008.

[56] F. Vitucci, B. Olsen, B. Schaner, *"Predictive Maintenance in a Mission Critical Environment",* Emerson Process Management, White Paper March 2009.

[57] T. Bayle, *"Preventative Maintenance Strategy for Data Centers",* American Power Conversion, WP 124, 2007.

[58] John Stanley, Jonathan Koomey, *"The Science of Measurement: Improving Data Center Performance with Continues Monitoring and Measurement of Site Infrastructure"* Lawrence Berkeley National Laboratory and Stanford University, Analytics Press, October 2009.

[59] Emerson Network Power, *"Addressing the Leading Root Causes of Downtime: Technology Investments and Best Practices for assuring Data Center Availability",* White Paper January 2011.

[60] E.J. Williams, *"Downtime Data – Its Collection, Analysis, and Importance",* Proceedings of the 1994 Winter Simulation Conference.

[61] D.O. Koval, X. Zhang, J. Propst, T. Coyle, R. Arno, R.S. Hale JR, *"Reliability Methodologies Applied to The IEEE Gold Book Standard Network",* 2003.

[62] Library of congress – Federal Research Division, *"Country Profile: Nigeria",* July 2008

[63] http://oilprice.com/Energy/Energy-General/Not-Darkest-Africa-but-Darkest-Nigeria-120-Million-Without-Electricity.html, *" Not Darkest Africa, but Darkest Nigeria – 120 Million Without Electricity",* 24 June 2013.

[64] Journalism ++, "*Power cuts in Cameroon",* www.jplusplus.github.io/camcuts/, current daily recordings.

[65] http://en.wikipedia.org/wiki/Cameroon, *"Cameroon",* The Wikipedia Encyclopedia.

[66] Montri Wiboonrat, "*Risk Anatomy of Data Center Power Distribution Systems"* Assumption University, Bangkok, IEEE Publication 2008.

[67] Technical Manual TM 5-698-5, *"Survey of Reliability and Availability Information for Power Distribution, Power Generation, and Heating Ventilating and Air Conditioning (HVAC) Components for Commercial, Industrial, and Utility Installations",* Headquarters, Department of the Army, Washington DC, 22 July 2006.

[68] T. Coyle, R. Arno (RAC), P.S.Hale, Jr. (PREP), *"Application of Minimal Cut Set Reliability Analysis Methodology To Gold Book Standard Network",* IEEE 2000.

[69] P.S. Hale, Jr., R. Arno, Dr. D.O. Koval, *"Analysis Techniques for Electrical and Mechanical Power Systems",* IEEE 2001.

[70] S. Roy, *“Reliability Considerations for Data Centers Power Architectures”* Emerson Energy Systems – North America, Canada, Interlec Conference 2001, IEE 2001.

[71] J. Tessier, ED Spears, Eaton Electrical Power Quality Division, *“Power Monitoring 101: Supervisory, connectivity and protection options that add an umbrella of protection over your entire IT infrastructure”,* White paper July 2009.

[72] B.S. Dhillon, Department of Mechanical Engineering, University of Ottawa, Canada, *“Design Reliability: Fundamentals and Applications”.*

[73] F. Waterer, B. Brown, Square D Critical Power Competency Center, *“System Grounding and Ground-fault Protectionfor Data Centers”,* 2008.

[74] T Yepes, J Pierce and V Foster, *“Making Sense of Africa`s Infrastructure Endowment: A Benchmarking Approach”,* Africa Infrastructure Country Diagnostic, 2008.

APPENDIX A

Table A-1: Case Study 1 – Event indices

Event #	Item	Description	Failure Rate per Year	Failure Duration Hr	Downtime, Hr/Yr
1, 2		**Indices for Switchgear Bus Fault**			
	10	Switchgear , Bare Bus, 600V	0.00949	7.29	0.0691821
	9	600 V Drawout Circuit Breaker, NCx50% quantity 3	0.002775	0.5	0.0013875
	8	600 V Drawout Circuit Breaker, NOx50% quantity 2	0.00553	2	0.01106
	11	600 V Drawout Circuit Breaker, NCx50% quantity 2	0.00021	6	0.00126
		Totals for Main Switchgear Bus	0.018005	4.603698973	0.0828896
3		**Indices for Tie Breaker Failure**			
	8	600 V Drawout Circuit Breaker, NOx50%	0.002765	2	0.00553
4		**Indices for Utility Service to Switchgear Bus**			
	1	Single circuit Utility Supply	1.956	1.32	2.58192
	2	1.6 km aerial cable, 33 kV	0.00411	2.54	0.0104394
	4	33 kV Disconnect	0.00174	1	0.00174
	5	Vacuum circuit breaker, 33 kV	0.00283	8	0.02264
	2	60 m aerial cable, 33 kV	0.0002	2.54	0.000508
	7	Transformer, Liquid, OA	0.00111	5	0.00555
	26	30 m Bus duct, 600 V	0.00001230	12.9	0.00015867
	9	600 V Drawout Circuit Breaker, NCx50% quantity 3	0.0028	0.5	0.0014
		Totals for Utility to Switchgear Bus	1.9688023	1.332970847	2.62435607
5		**Indices for Generator Bus**			
		A. Reliability of Each Generator to Gen Bus			
	3	Packaged Engine generator Set	0.1235	18.28	2.25758
	8	600 V Drawout Circuit Breaker, NOx50%	0.002765	2	0.00553
	26	33 m Bus duct, 600 V	0.00001353	12.9	0.000174537
			0.12627853	17.922956	2.263284537
		Calculated values for each Generator to Gen Bus			
		B. Calculated values at Generator Bus			
		1st Order Cut Set			
	22	Switchgear Insulated Bus, ≤ 600 V	0.0017	2.4	0.00408
	8	600 V Drawout Circuit Breaker, NOx50% quantity 4	0.01106	2	0.02212
		2nd Order Cut Set			
		G_2, G_3, Fail	2.90546E-09	9.14	2.65559E-08
		G_1, G_3, Fail	2.90546E-09	9.14	2.65559E-08
		G_1, G_2, Fail	2.90546E-09	9.14	2.65559E-08
		3rd Order Cut Set: None			
		Calculated values at Gen Bus	0.01276	2.053291536	0.02620

Event#	Item	Description	Failure Rate, per year	Failure Duration, Hr	Downtime, Hr/Yr
6,7	**Indices for Generator Switchgear Tie Circuits**				
	8	600 V Drawout Circuit Breaker, NO x 50%, quantity 2	0.00553	2	0.01106
	26	30 m Bus duct, 600 V	0.00001230	12.9	0.00015867
			0.0055423	2.024190318	0.01121867
10,11	**Indices for Mechanical Switchgear bus Fault**				
	10	Switchgear, Bare Bus, 600 V	0.00949	7.29	0.0691821
	12	600 V Circuit Breaker, NC x 50%, quantity 1	0.0048	9.6	0.04608
	13	600 V Circuit Breaker, NC < 400 x 50%, quantity 5	0.0130	5.8	0.0754
	14	600 V Fixed Circuit Breaker, NO x 50%, quantity 1	0.00175	37.5	0.065625
		Totals for Main Switchgear Bus	0.02904	8.825313361	0.2562871
12	**Indices for Mechanical Switchgear Tie Breaker Failure**				
	14	Circuit Breaker, 3-Phase Fixed, NO, > 600 A, x 50%	0.001715	37.5	0.0643125
13,14	**Indices for Feeder Main Switchgear to Mechanical Switchgear Failure**				
	9	Circuit Breaker, 600 V Drawout, NC, > 600A, x 50%	0.000925	0.5	0.0004625
	16	Cable, Above Ground, No Conduit, 600 V per 152 m	0.0141	10.5	0.14805
	12	Circuit Breaker, 600 V NC, > 600 A, x 50%	0.0048	9.6	0.04608
		Calculated Value for Feeder Failure	0.019825	9.815510719	0.1945925

Table A-2: Case Study 2 – Event indices

Event #	Item	Description	Failure Rate per Year	Failure Duration Hr	Downtime, Hr/Yr
1, 2		**Indices for Switchgear Bus Fault**			
	10	Switchgear , Bare Bus, 600V	0.00949	7.29	0.0691821
	9	600 V Drawout Circuit Breaker, NCx50% quantity 3	0.002775	0.5	0.0013875
	8	600 V Drawout Circuit Breaker, NOx50% quantity 2	0.00553	2	0.01106
	11	600 V Drawout Circuit Breaker, NCx50% quantity 1	0.00021	6	0.0006
		Totals for Main Switchgear Bus	0.018005	4.603698973	0.0828896
3		**Indices for Tie Breaker Failure**			
	8	600 V Drawout Circuit Breaker, NOx50%	0.002765	2	0.00553
4,5		**Indices for Each Utility Service to Switchgear Bus**			
	1	Single circuit Utility Supply	1.956	1.32	2.58192
	27	Cable underground, ≤ 15 kV, 305 m	0.02017	5.13	0.1034721
	4	15 kV Disconnect	0.00174	1	0.00174
	5	Vacuum circuit breaker, 15 kV	0.00283	8	0.02264
	27	Cable underground, ≤ 15 kV, 60 m	0.0039679	5.13	0.02035517
	7	Transformer, Liquid, OA	0.00111	5	0.00555
	26	30 m Bus duct, 600 V	0.000125	12.9	0.0016125
	9	600 V Drawout Circuit Breaker, NCx50% quantity 3	0.000925	0.5	0.0004625
		Totals for Utility to Switchgear Bus	1.9868679	1.377923651	2.73775227
6		**Indices for Generator Bus**			
		A. Reliability of Each Generator to Gen Bus			
	3	Packaged Engine generator Set	0.1235	18.28	2.25758
	8	600 V Drawout Circuit Breaker, NOx50%	0.002765	2	0.00553
	26	33 m Bus duct, 600 V	0.00001353	12.9	0.000174537
		Calculated values for each Generator to Gen Bus	0.12627853	17.922956	2.263284537
		B. Calculated values at Generator Bus			
		1st Order Cut Set			
	22	Switchgear Insulated Bus, ≤ 600 V	0.0017	2.4	0.00408
	8	600 V Drawout Circuit Breaker, NOx50% quantity 4	0.01106	2	0.02212
		2nd Order Cut Set	None		
		3rd Order Cut Set			
		G_2, G_3, G_4 Fail	1.10632E-15	0.8	8.850599E-16
		G_1, G_3, G_4 Fail	1.10632E-15	0.8	8.850599E-16
		G_1, G_2, G_3 Fail	1.10632E-15	0.8	8.850599E-16
		Calculated values at Gen Bus	0.01276	2.053291536	0.0262

Event#	Item	Description	Failure Rate, per year	Failure Duration, Hr	Downtime, Hr/Yr
7,8	Indices for Generator-Switchgear Tie Circuits				
	8	600 V Drawout Circuit Breaker, NO x 50%	0.002765	2	0.00553
	26	30 m Bus duct, 600 V	0.00001230	12.9	0.00015867
	8	600 V Drawout Circuit Breaker, NO x 50%	0.002765	2	0.00553
		Calculated Values for Generator feed to Switchgear	0.0055423	2.024190318	0.01121867
10.11	Indices for Generator-Switchgear Bus Fault				
	10	Switchgear, Bare Bus, 600 V	0.00949	7.29	0.0691821
	12	600 V Circuit Breaker, NC x 50%, quantity 1	0.0048	9.6	0.04608
	13	600 V Circuit Breaker, NC < 400 x 50%, quantity 3	0.0078	5.8	0.04524
	14	600 V Drawood Circuit Breaker, NO x 50%, quantity 1	0.00175	37.5	0.065625
		Totals for Main Switchgear Bus	0.02384	9.485197148	0.2261271
12	Indices for Mechanical-Switchgear Tie Breaker Failure				
	14	Circuit Breaker, 3-Phase Fixed, NO, > 600 A, x 50%	0.001715	37.5	0.0643125
13,14	Indices for Feeder Main-Switchgear to Mechanical Switchgear Failure				
	9	Circuit Breaker, 600 V Drawout, NC, > 600A, x 50%	0.000925	0.5	0.0004625
	16	Cable, Above Ground, No Conduit, 600 V per 152 m	0.0141	10.5	0.14805
	12	Circuit Breaker, 600 V NC, > 600 A, x 50%	0.0048	9.6	0.04608
		Calculated Value for Feeder Failure	0.019825	9.815510719	0.1945925

APPENDIX B

Table B-1: Case Study 1 – Main switchgear calculations

Line#	Event	Event Description	Component Indices: Failure Rate per Year	Component Indices: Failure Duration, Hr	Component Indices: Downtime, Hr/Yr	Calculated Cut Set Indices: Failure Rate per Year	Calculated Cut Set Indices: Failure Duration, Hr	Calculated Cut Set Indices: Downtime, Hr/Yr
	1	Switchgear A Bus Fault	0.018005	4.603698973	0.0828896	0.018005	4.60369897	0.0828896
	4	Utility 1 Failure	1.9688023	1.332970847	2.62435607			
	5	Generation Failure	0.01276	2.053291536	0.02620			
		Calculated 3rd Order Cut Set Indices				9.70818E-06	0.80825921	7.84673E-06
	2	Switchgear B Bus Fault	0.018005	4.603698973	0.0.0828896			
	4	Utility 1 Failure	1.9688023	1.332970847	2.62435607			
	6	Generation Feed to SWGR A Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				2.07229E-11	0.68425415	1.41797E-11
	3	Switchgear Tie Breaker Failure	0.002765	2	0.00553			
	4	Utility 1 Failure	1.9688023	1.332970847	2.62435607			
	6	Generation Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				3.70521E-12	0.57331933	2.12427E-12
	4	Switchgear Tie Breaker Failure	1.9688023	1.332970847	0.00553			
	6	Utility 1 Failure	0.0055423	2.024190318	0.01121867			
	7	Generation Feed to Swgr A Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				7.47962E-12	0.57529014	4.30295E-12
16								
		Indices for Switchgear Bus A Outage				**0.530235441**	**0.15628978**	**0.08287038**

Table B-2: Case Study 2 – Main switchgear calculations

Line#	Event	Event Description	Component Indices			Calculated Cut Set Indices		
			Failure Rate per Year	Failure Duration, Hr	Downtime, Hr/Yr	Failure Rate per Year	Failure Duration, Hr	Downtime, Hr/Yr
	1	Switchgear A Bus Fault	0.018005	4.603698973	0.0828896	0.018005	4.603698973	0.0828896
	2	Switchgear B Bus Fault	0.018005	4.603698973	0.0822296			
	4	Utility 1 Failure	1.9868679	1.377923651	2.737752278			
	6	Generation Failure	0.01276	2.053291536	0.0262			
		Calculated 3rd Order Cut Set Indices				1.11E-10	0.699315786	7.76241E-11
	2	Switchgear B Bus Fault	0.0180052	4.603698973	0.0828896			
	4	Utility 1 Failure	1.9868679	1.377923651	2.737752278			
	7	Generation Feed to SWGR A Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				4.76585E-11	0.695908296	3.31659E-11
	3	Switchgear Tie Breaker Failure	0.002765	2	0.00553			
	4	Utility 1 Failure	1.9868679	1.377923651	2.737752278			
	6	Generation Failure	0.01276	2.053291536	0.0262			
		Calculated 3rd Order Cut Set Indices				8.85054E-12	0.583855514	5.16744E-12
	3	Switchgear Tie Breaker Failure	0.002765	2	0.00553			
	4	Utility 1 Failure	1.9868679	1.377923651	2.737752278			
	7	Generation Feed to Swgr A Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				3.80524E-12	0.58147841	2.21266E-12
	4	Utility 1 Failure	1.9868679	1.377923651	2.737752278			
	5	Utility 2 Failure	1.9868679	1.377923651	2.737752278			
16	6	Generation Failure	0.01276	2.053291536	0.0262			
		Calculated 3rd Order Cut Set Indices				4.95759E-09	0.515867536	2.55746E-09
		Indices for Switchgear Bus A Outage				0.018005005	4.60000	0.082823023

APPENDIX C

Table C-1: Case Study 1 – Mechanical switchgear A calculations

Line#	Event#	Event Description	Component Indices			Calculated Cut Set Indices		
			Failure Rate per Year	Failure Duration, Hr	Downtime, Hr/Yr	Failure Rate per Year	Failure Duration, Hr	Downtime, Hr/Yr
	10	Mechanical A Bus Fault	0.02904	8.825313361	0.2562871	0.02384	9.485197148	0.2361271
	12	Mechanical Swgr Tie Breaker Failure	0.001715	37.5	0.0643125			
	13	Main Swgr to Mech Swgr Feeder Fail	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				2.48324E-06	0.575290136	1.42858E-06
	2	Main Swgr Bus B Fault	0.0180050	4.603698973	0.0828896			
	13	Main Swgr to March Swgr Feeder Fail	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				5.87531E-07	3.133851132	1.84123E-06
	14	Main Swgr B to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
	13	Main Swgr A to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				8.80739E-07	4.90775536	4.32245E-06
	11	Mechanical Swgr Bus B Fault	0.02904	8.825313361	0.2562871			
	13	Main Swgr to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				1.23766E-06	4.647056242	5.75148E-06
	12	Mechanical Swgr to Breaker Failure	0.001715	37.5	0.0643125			
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0828896			
		Calculated 2nd Order Cut Set Indices				1.48411E-07	4.100321722	6.08533E-07
	14	Main Swgr B to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0828896			
		Calculated 2nd Order Cut Set Indices				5.87531E-07	3.133851132	1.84123E-06
	11	Mechanical Swgr Bus B Fault	0.02904	8.825313361	0.2562871			
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0828896			
		Calculated 2nd Order Cut Set Indices				8.20696E-07	3.025470902	2.48299E-06
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0828896			
	5	Generation Failure	0.01276	2.053291536	0.02620			
		Calculated 2nd Order Cut Set Indices				1.74587E-07	1.4199714	2.47909E-07
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0828896			
	7	Generation Feed to Swgr B Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				7.55005E-08	1.405992538	1.06153E-07
	4	Utility 1 Failure	1.9688023	1.332970847	2.62435607			
	5	Generation Failure	0.01276	2.053291536	0.02620			
		Calculated 2rd Order Cut Set Indices				9.29602E-08	0.80825921	7.51359E-08
	2	Main Swgr Bus B Fault	0.018005	4.603698973	0.0.0828896			
	4	Utility Failure	1.9688023	1.332970847	2.62435607			
	6	Generation Feed to Swgr A Failure	0.0055423	2.024190318	0.01121867			
17		**Calculated 3rd Order Cut Set Indices**				1.33508E-11	0.68425415	1.41797E-11
		Indices for Mech Switchgear Bus A Outage				**0.023847089**	**9.482366631**	**0.226126841**

Table C-2: Case Study 2 – Mechanical switchgear A calculations

Line#	Event#	Event Description	Component Indices			Calculated Cut Set Indices		
			Failure Rate per Year	Failure Duration, Hr	Downtime, Hr/Yr	Failure Rate per Year	Failure Duration, Hr	Downtime, Hr/Yr
	10	Mechanical A Bus Fault	0.02384	9.485197148	0.2261271	0.02384	9.485197148	0.2461271
	12	Mechanical Swgr Tie Breaker Failure	0.001715	37.5	0.0643125			
	13	Main Swgr to Mach Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				1.84E-07	7.779302101	1.43139E-06
	2	Main Swgr Bus B Fault	0.0180050	4.603698973	0.0822296			
	13	Main Swgr to March Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				5.88E-07	3.133851132	1.8427E-06
	14	Main Swgr B to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
	13	Main Swgr A to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				8.81E-07	4.90775536	4.32373E-06
	11	Mechanical Swgr Bus B Fault	0.02384	9.485197148	0.2261271			
	13	Main Swgr to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
		Calculated 2nd Order Cut Set Indices				1.04E-06	4.823763715	5.01671E-06
	12	Mechanical Swgr to Breaker Failure	0.001715	37.5	0.0643125			
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0822296			
		Calculated 2nd Order Cut Set Indices				1.48E-07	4.100321722	6.06848E-07
	14	Main Swgr B to Mech Swgr Feeder Failure	0.019825	9.815510719	0.1945925			
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0822296			
		Calculated 2nd Order Cut Set Indices				5.88E-07	3.133851132	1.8427E-06
	11	Mechanical Swgr Bus B Fault	0.02384	9.485197148	0.2261271			
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0822296			
		Calculated 2nd Order Cut Set Indices				6.83E-07	3.133851132	2.14042E-06
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0822296			
	5	Utility 2 Failure	1.9688023	1.332970847	2.737752278			
	6	Generation Failure	0.01276	2.053291536	0.0262			
		Calculated 3rd Order Cut Set Indices				1.08E-10	0.687548198	7.42552E-11
	1	Main Swgr A Bus Fault	0.018005	4.603698973	0.0822296			
	5	Utility 2 Failure	1.9688023	1.332970847	2.737752278			
	8	Generation Feed to Swgr B Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				4.65E-11	0.684254151	3.18178E-11
	2	Main Swgr Bus B Fault	0.0180050	4.603698973	0.0822296			
	4	Utility 1 Failure	1.9688023	1.332970847	2.737752278			
	6	Generation Failure	0.01276	2.053291536	0.03174			
		Calculated 3rd Order Cut Set Indices			0.0262	1.08E-10	0.687548198	7.42552E-11
	2	Main Swgr Bus B Fault	0.0180050	4.603698973	0.0822296			
	4	Utility 1 Failure	1.9688023	1.332970847	2.737752278			
17	7	Generation Feed to Swgr A Failure	0.0055423	2.024190318	0.01121867			
		Calculated 3rd Order Cut Set Indices				4.65E-11	0.684254151	3.18178E-11
		Indices for Mech Switchgear Bus A Outage				**2.38E-02**	**9.501127773**	**0.226126841**

APPENDIX D

Table D-1: Case Study 1 – Load bus calculations

Event#	Item	Description	Failure Rate, per year	Failure Duration, Hr	Downtime, Hr/Yr
16		Main Switchgear Bus A Outage	0.018005	4.603698973	0.0828896
	11	Circuit Breaker, 600V, Drawout, NC, <600 A, x 50%	0.000105	6	0.00063
	16	305m Cable, Above Ground, No Conduit, 600V	0.0141	10.5	0.14805
	13	Circuit Breaker, 3 Phase Fixed, N.C, <600 A, x 50%	0.0026	5.8	0.01508
		Total Indices to Office A Bus:	0.03481	7.08532031	0.2466496
17		Main Switchgear Bus B Outage	0.018005	4.603698973	0.0828896
	9	600 V Drawout Circuit Breaker, NCx50% quantity	0.000925	0.5	0.0004625
	16	Cable, Above Ground, No Conduit, 600 V, 305 m	0.0141	10.5	0.14805
	9	Circuit Breaker, 3 Phase Fixed, N.C, <600 A, x 50%	0.000925	0.5	0.0004625
		Total Indices to UPS Bus:	0.033955	6.82858489	0.2318646

Table D-2: Case Study 2 – Load bus calculations

Event#	Item	Description	Failure Rate, per year	Failure Duration, Hr	Downtime, Hr/Yr
16		Main Switchgear Bus A Outage	0.018005	4.603698973	0.0828896
	11	Circuit Breaker, 600V, Drawout, NC, <600 A, x 50%	0.000105	6	0.00063
	16	305m Cable, Above Ground, No Conduit, 600V	0.0141	10.5	0.14805
	13	Circuit Breaker, 3 Phase Fixed, N.C, <600 A, x 50%	0.0026	5.8	0.01508
		Total Indices to Office A Bus:	0.03481	7.08532031	0.2466496
17		Main Switchgear Bus B Outage	0.018005	4.603698973	0.0828896
	9	600 V Drawout Circuit Breaker, NCx50% quantity	0.000925	0.5	0.0004625
	16	Cable, Above Ground, No Conduit, 600 V, 305 m	0.0141	10.5	0.14805
	9	Circuit Breaker, 3 Phase Fixed, N.C, <600 A, x 50%	0.000925	0.5	0.0004625
		Total Indices to UPS Bus:	0.033955	6.82858489	0.2318646

APPENDIX E

Table E-1: Component indices from IEEE 493 and PREP

Ref #	Item Description	Failure Rate Symbol	Failure Rate (Failures/ Year)	MTTR Symbol	MTTR (Hour/ Failure)	Availability Symbol	Inherent Availability
1	Single Circuit Supply, 1.78 failures/unit years, A=0.999705 Gold Book – p. 107	λ1	0.956	r1	1.32	P1	0.998705
2	Cable Areal, ≤ 15 kV, per mile	λ2	0.04717	r2	1.82	P2	0.999990448
3	Diesel Engines Generator, Packaged, Standby, 1500 kW	λ3	0.12350	r3	18.28	P3	0.999742312
4	Manual Disconnect Switch	λ4	0.00174	r4	1.00	P4	0.999999801
5	Fuse, 15kV	λ5	0.10154	r5	4.00	P5	0.999953634
6	Cable Below Ground in conduit, ≤ 600 V, per 1000 ft	λ6	0.00201	r6	11.22	P6	0.999997428
7	Transformer, Liquid, Non Forced Air, 3000 kVA	λ7	0.00111	r7	5.00	P7	0.999999367
8	Circuit Breaker, 600 V, Drawout, Normally Open, > 600 Amp	λ8	0.00553	r8	2.00	P8	0.999998738
9	Circuit Breaker, 600 V, Drawout, Normally Closed, > 600 Amp	λ9	0.00185	r9	0.50	P9	0.999999894
10	Switchgear, Bare Bus, 600 V	λ10	0.00949	r10	7.29	P10	0.999992098
11	Circuit Breaker, 600 V, Drawout, Normally Closed, > 600 Amp	λ11	0.00021	r11	6.00	P11	0.999999858
12	Circuit Breaker, 600 V, Normally Closed, > 600 Amp Gold Book p. 40	λ12	0.0096	r12	9.60	P12	0.999989479
13	Circuit Breaker, 3 Phase Fixed, Normally Open, ≤ 600 Amp Gold Book p. 40	λ13	0.0052	r13	5.80	P13	0.999996557
14	Circuit Breaker, 3 Phase Fixed, Normally Open, > 600 Amp	λ14	0.00343	r14	37.50	P14	0.999985320
15	Cable, Above Ground, Trays, ≤ 600 V, per 1000 ft	λ15	0.00012	r15	2.50	P15	0.999998866
16	Cable, Above Ground, Trays, ≤ 600 V, per 1000 ft Gold Book p. 105	λ16	0.00141	r16	10.50	P16	0.99999831
17	Battery, Lead Acid, Strings	λ17	0.00746	r17	32.13	P17	0.999972627
18	Fuse, 0 ~ 5kV	λ18	0.00137	r18	0.00	P18	1.000000000
19	Inverter	λ19	0.00482	r19	26.00	P19	0.999985691
20	Rectifier	λ20	0.00447	r20	16.00	P20	0.999991837
21	Static Switch, 0 ~ 600 Amp	λ21	0.0061	r21	3.60	P21	0.999997493
22	Switchgear, Insulated bus, ≤ 600 V	λ22	0.0017	r22	2.40	P22	0.999999534
23	Transformer, Dry, Isolation, < 600 V	λ23	0.00284	r23	21.26	P23	0.999993113
24	Circuit Breaker, 3 Phased Fixed, Normally Open	λ24	0.00011	r24	18.67	P24	0.999999760
25	Cable, Above Ground, In Conduit, ≤ 600 V, per 1000 ft	λ25	0.00007	r25	8.00	P25	0.999999838
26	Bus Duct, Gold Book p.206	λ26	0.000125	r26	12.90	P26	0.999999826
27	Cable underground, ≤ 15 kV, per 305 m	λ27	0.02017	R27	5.13	P27	0.999988193