DEVELOPMENT OF A GENARALIZED METHODOLOGY FOR BLACKOUT RESTORATION: A CASE STUDY OF SRI LANKAN POWER SYSTEM

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DECLARATION

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Dr. W. D. Prasad **Eng. Rienzie Fernando** Date:

DEDICATION

This work is dedicated to my beloved parents, Sanath Sirisena and Menaka Sirisena and my darling wife, Dimuthu Wasana.

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I would like to sincerely thank my internal supervisor, Dr. W.D. Prasad (Department of Electrical Engineering, University of Moratuwa) and Eng. Rienzie Fernando (Managing Director, Amithi Power Consultants Pvt. Ltd) for their continuous support, encouragement and expertise in the field to make this Masters Research thesis a success.

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My heartfelt gratitude shall go for my dearest parents and wife who had been caring, supporting and facilitating me throughout the time.

Abstract

Blackouts are been reported throughout the history worldwide and nowadays, a moment without electricity causes a greater loss of lives and economy. On the other hand, restoration of a blacked-out power system requires expertise of experienced engineers which is not completely reliable under certain system complexities. Generally, it turns out to be a trial and error approach under the guidance of experts. This paper proposes a generalized aiding methodology for solving the restoration problem by assessing the next system state for a given decisions of the system operator. With adequate system information (pre-outage data, equipment availability etc.), this proposed decision support methodology could mitigate unexpected cascaded tripping events which occur owing to lack of confidence in next state during restoration. The case study considers restoring of a crucial subsystem of Sri Lankan power system, Colombo – Kelanitissa system along with Laxapana System. Successful attempts shall fulfil load flow while maintaining system parameters and stability during switching operations. The results compare and depict the success in solving the restoration problem with proposed real-time, offline methodology against trial and error approach. Further it suggests the requirement of parallel computer based simulations on restoration of other sub systems and synchronizing events during actual implementation.

Keywords: Blackout Restoration, Decision Support, Steady State, Transient Stability, Sri Lankan Power System

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List of Abbreviations

Abbreviation	Description
BS	Black-start
CEB	Ceylon Electricity Board
DG	Diesel Generator
EG	Embedded Generation
EHV	Extra High Voltage
HV	High Voltage
GT	Gas Turbine
NBS	Non Black-start
PS	Power System
PV	Photovoltaic
RE	Renewable Energy
RoCoF	Rate of Change of Frequency
SCADA	Supervisory control and data acquisition
SCC	System Control Centre
ST	Steam Turbine

1 INTRODUCTION

1.1 Power System (PS) Blackouts

With the growth of needs in society, the world’s dependency on electricity is escalating daily. Therefore, the necessity of maintaining a healthy and secure power supply throughout the day has become more significant than yesterday. Nowadays, any disruption in the electrical system is powerful enough to cause a confusion in human life.

On the other hand, Power **Blackouts** and regional outages are intolerable due to its adverse impacts. Health sector, food storages, thermal comfort, transportation, commercial tasks, manufacturing industry, etc are highly affected by such unfortunate events. The utilities worldwide take all the efforts to rectify the system back to normal operation. Hence, Blackout Restoration has become an evolving study area, contributed by many interested academic and industrial personnel.

The condition of a PS at a given instance, designated by Equality (E) and Inequality (I) constraints may vary under different contingencies.

The Fink-Carlson model shown in Figure 1 illustrates five states a PS may endure [1]. A disturbance may push the system to an 'Alert State' and then towards an 'Emergency State' and ultimately to an 'In-Extremis State.' Sometimes, it would collapse directly from an 'Alert State' to an 'In-Extremis State.' In the meantime, Control action would be able to survive the system from an Emergency state back to a healthy nature. But once the system has fallen in an 'In-Extremis' condition, restorative procedures would be necessary to start from the blacked out stage.

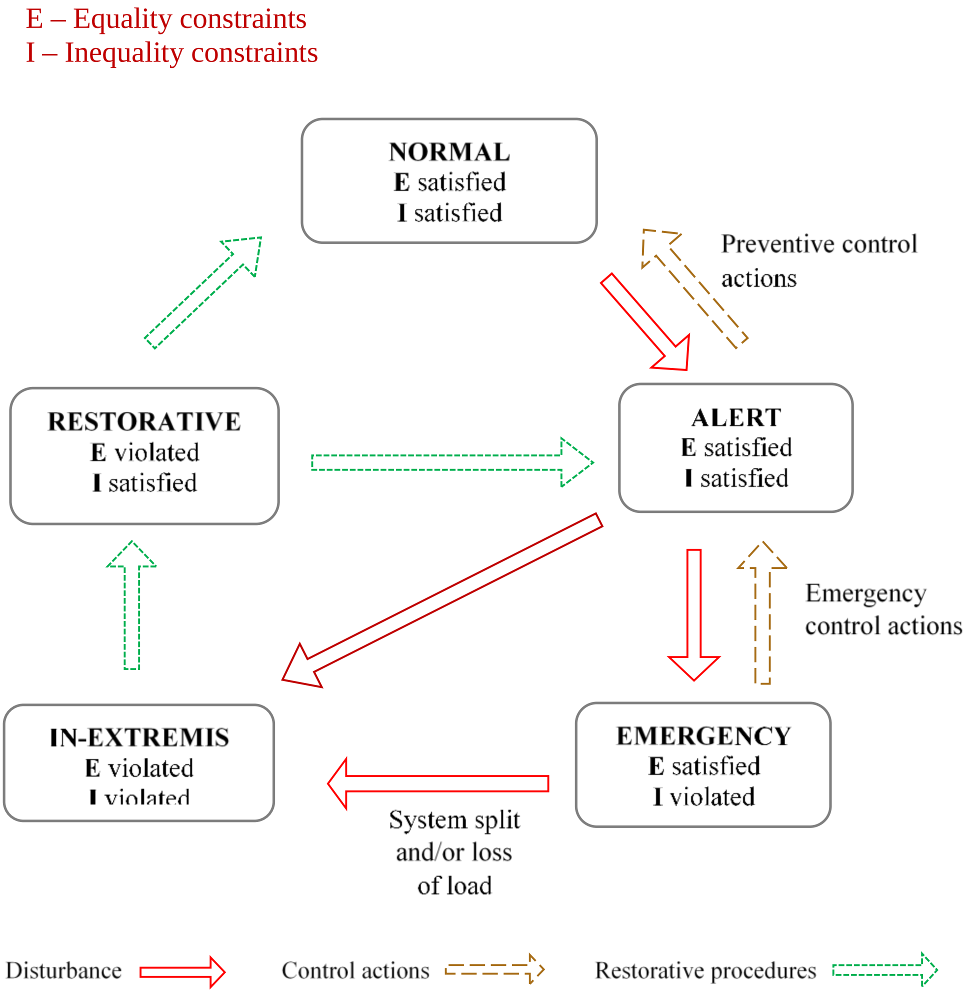

Figure 1 – States of Power System [1]

Equality constraints (E):

$$\sum_{i=1}^{G} P_{gen} = \sum_{j=1}^{L} P_{load} + P_{loss} \qquad \dots (1)$$

Inequality constraints (I):

$$V_{min} < V_{bus} < V_{max} \qquad \ldots (2)$$

$$f_{min} < f_{bus} < f_{max} \qquad \ldots (3)$$

$$I_{branch} < I_{max} \qquad \ldots (4)$$

Where P_{gen} : Active Power dispatched from generating stations

P_{load} : Loads connected to the network

P_{loss} : Total Active Power loss in the system

V_{min} : Admissible minimum bus voltage

V_{bus} : Bus voltage at a given instance

V_{max} : Admissible maximum bus voltage

f_{min} : Admissible minimum bus frequency

f_{bus} : Bus frequency at a given instance

f_{max} : Admissible maximum bus frequency

I_{bus} : Transmission line current loading at a given instance

I_{max} : Maximum current carrying capacity of a Transmission line

Under Normal operating state, a PS operates satisfactory meeting the demand while satisfying the equality and inequality constraints. Disturbance may shift the healthy system from ‘Normal’ state to an ‘Alert’ state in which still the constraints are fulfilled and the demand is met. However, the security level of the system has now dropped from the required level. Further propagation or intensity of the disturbance would shift the system to an ‘Emergency’ state and/or an ‘In-Extremis’ state. At early stages, control actions can refrain the system from shifting towards the ‘In-Extremis’ condition.

A Blackout of the system is said to occur when an entire PS collapses, transforming its state to ‘In-extremis’ condition. Investigated reasons behind the historical blackouts are, failure of equipment (generator/transformer), loss of transmission line, lightning, malfunction of protective devices and wrong decisions on Emergency Control Actions. In reality, avoiding the occurrence of blackouts completely will not be possible but it can be mitigated. During inclement weather conditions such as typhoons, certain portions of transmission and distribution systems fail physically making a great challenge for restoring the rest of the system without a pre-knowledge or consequences of unprecedented restorative decisions.

In contrast, if the PS could not be saved from an imminent outage, the post-blackout action plan becomes vital to restore the system within the shortest possible time. Hence, countries carryout studies for preparing restoration plans and they are documented for future reference. Nevertheless, system control operators prefer the ‘experience based trial and error’ approach rather than following a developed restoration plan during a blackout restoration. However, with the availability of data acquisition technologies, PS simulation software and extended capabilities in computer programming, more comprehensive analytical decisions could be drawn which are useful in system restoration.

1.2 Sri Lankan Power System

Sri Lankan PS was evolving since 1885 and is currently serving a 2.4 GW night peak daily demand. It comprises of 4043 MW generation capacity with a mix of Hydro (16%), Thermal (CEB Thermal and Coal - 58%, IPP Thermal – 19%) and NCRE (7%). The AC transmission system is branched throughout the country with 601 km of 220 kV lines and nearly 2310 km of 132 kV lines, feeding approximately 60 grid substations. The 33 kV and 11 kV distribution system is spanned for 32,863 km electrifying 99.7% of the nation. [2] Ceylon Electricity Board (CEB) has the authority of SL's Transmission System and therefore, the CEB's System Control Centre (SCC) regulate the network within safe limits. SCC used to have only the monitoring facility and now (2018), it is equipped with supervisory control.

Looking back at the history, Sri Lanka had faced its longest blackout in May 1996 which extended for 4 days.[3] In the recent past, there were frequent blackouts compared to the past decade.

In the year of 2015, there had been two blackouts which took more than 5 hours to restore the whole system, leaving a 3 x 300 MW Coal Power Plant shut for another few days. On 25th Feb 2016, an island-wide blackout occurred persisting for **3 hours** and before a month elapsed, the second blackout disrupted island-wide electricity on 13th March 2016 for more than 7 hours.[4][5]

Beyond the past records in Sri Lanka, highly populated and energy intensive countries have faced more complicated problems with blackout restoration. On 14 August 2003, several areas in North America faced a blackout affecting approximately 50 million residents, initiated from a Line to Ground Fault of 345kV transmission lines coinciding with a malfunction in alarm system.[6]

Since the dawn of distributed electricity, countries around the world have been facing blackouts. As a result, the necessity of an analytical approach for future blackout restoration is emphasized in post-incident investigation studies.

1.3 Objectives of the study

The main goal of the study is to introduce an analytical methodology to be followed during the attempts of blackout restoration by parametric assessment of the restorative decisions. The key objectives setup to achieve the goal are:

1. To investigate the problems associated with blackout restoration
2. To study the approaches proposed for optimizing restoration process
3. To develop a generalized decision support algorithm for verifying each decision before execution
4. Applying the proposed methodology to Sri Lankan PS in order to validate the proposed algorithm with justifications for its eligibility as a case study

1.4 Thesis outline

In order to achieve the objectives mentioned in Section 1.3 above, the rest of the thesis is organized as follows:

Chapter 2 provides a comprehensive review on literature related to PS restoration after major blackouts. Furthermore, the drawbacks of the current trial and error method practiced by the Sri Lankan utility are also highlighted here.

Chapter 3 presents the analytic methodology proposed in this thesis to restore Sri Lankan PS subsequent to a blackout.

Chapter 4 presents a results based detailed analysis on the proposed methodology and highlights that the drawbacks of the presently practiced trial and error approach can be overcome by following an analytic approach.

Chapter 5 presents the conclusions and future directions of the study.

Chapter Summary

The present chapter (Chapter 1) discussed about the possible states of a power system, its diversions from healthy condition with examples on blackouts occurred in Sri Lanka. This Thesis is structured to accomplish the set objectives of the study.

Next chapter will discuss the concerns during restoration and approaches proposed in literature.

2 LITERATURE REVIEW

This chapter presents a comprehensive review on the literature related to the subject area of blackout restoration.

2.1 Blackout causes

Restoration of a PS subsequent a major blackout is one of the most challenging tasks of system operators owing to its complexity and uniqueness.[7] The reasons behind the blackouts differ from event to event depending on several natural and unforeseen factors. **Table 1** lists selected blackouts recorded in history with their initiating causes and duration for restoration.

Table 1 - Extract of blackouts in history [8]

Year	Region	Reason	Restoration Time
1978 March	Thailand	Generator Failure	> 9 hrs.
2001 Jan.	India	Substation Failure	12 hrs.
2002 Jan.	Brazil	Design/Application Error	4.5 hrs.
2003 Aug.	North-eastern USA/Canada	Design/Application Error; Primary and Secondary Equipment Failure; Communication Failure; Operator Error; Inadequate Diagnostic Support	> 30 hrs.
2005 Aug.	Java & Bali, Indonesia	Failure of 500kV transmission line ; High Demand.	11 hrs.
2006 Nov.	Europe	Design/Application Error; Communication Failure; Operator Error	1.5 hrs.
2008 Jan.-Feb.	Central Chinese city, China	Winter Storm	14 days
2008 May	United Kingdom	Lack Of Co-Ordination	40 min.
2009 Dec.	Portugal	Storm	132 hrs.
2009 Feb.	Australia	Bush Fire ; Operator Error; Lack Of Load Forecast For Extreme Weather;	4 hrs.
2009 Jan.	France and Spain	Cyclone	5 days
2009 Nov.	Brazil	Natural Phenomena	237 min.
2010 March	Northern Ireland	Snow/Ice Storm	18 hrs.
2010 March	Downtown Toronto, Canada	Primary Equipment Failure	215 min.
2011 Feb.	Brazilian North-	Design/Application Error;	194 min.

Year	Region	Reason	Restoration Time
	east	Secondary Equipment Failure	
2011 March	East Japan	Natural Phenomena	17 days
2011 Sept.	Southwest USA	Communication Failure; Operator Error; Inadequate Investment	900 min.
2012 April	Argentina's western area	Natural Phenomena	14 days
2012 July	India (22 states)	Electric crematorium; Overloading: Human Errors	-

The causes behind a blackout could be due to a natural phenomenon, by human intervention or due to lack of regular maintenance and inspections. As a result, the generators, transformers and loads are withdrawn from the system as per the coordination of protection scheme.

2.2 Problems associated with restoration

Over the past decades, power system restoration has been highly valued among power system engineers due to the grave risks and impacts of system blackouts. The concerns during the restoration shall be correctly addressed to avoid cascading failures during the process itself. Issues that are probable to occur during the restoration period had been identified in a Task Force Report with the number of occurrences over five years from 1979 to 1983.[9] Table 2 is a summary of identified problems.

Table 2 - Restoration Problems encountered in 1979-1983

Restoration Problem	No. of occurrences
I. Reactive Power Balance	
• Sustained over voltage	5
• Sustained under voltage	3
• Generator under excitation	1
• Switched capacitor/reactors	1
II. Load and Generator Balance	
• Response/Sudden increase load	3
• Underfrequency load shedding	1
III. Load and generator coordination	
• Black-start capability	1
• Steam unit start-up coordination	2
• Switching operation	8

Restoration Problem	**No. of occurrences**
• Overloads during restoration	2
• Dispatch office coordination	7
IV. Monitoring and control	
• Inadequate communication	1
• Inadequate SCADA	7
• Inadequate Displays	1
• System status determination	6
V. Protective system	
• Interlocking schemes	1
• Synchronization	5
• Standing angles	3
VI. Energy storage	3
VII. System restoration plan	
• No procedure	4
• Procedure not followed	2
• Procedure outdated	7
• No training	2

Items I, II, III and V require the sense about imminent system states after the particular decisions are executed.

Reactive Power Balance (I):

As system voltages shall be maintained at safe limits during the early stages of restoration, is maintained by energizing fewer number of HV lines, switching OFF shunt capacitors, switching ON shunt reactors, maintaining generator voltages at minimum offset ranges and adjusting transformer taps to suitable positions. Also, Minimum Excitation Level relays of BS units shall be set at lowest allowable settings during this particular period.

Load and Generator Balance (II):

During these initial stages, system frequency is maintained with little confidence as the load additions could lead to a frequency decline and consequently towards a recurring outage. Hence, the current practice is to add loads with little increments which cause prolonged restoration time.

Load and generator coordination (III):

During this initial period, power islands are preferred to be formed to manage the generation and demand. Supply required for NBS units within the subsystems are prioritized. The formation of islands is limited by the BS unit availability and the number of resource management teams. Larger generator unit start-ups shall be coordinated according their critical time intervals. For example considering the minimum time to leave in idle before restarting.

Protective system (V):

The protective interlocks and mechanisms set during the station design phases could prevent the system controllers from executing certain actions. Ex: closing generator breaker with a dead bus, synchronization at locations with no controlling of frequency, voltage and phase angle. Lack of room to reduce the standing phase angle during interconnection of subsystems via tie lines could cause the system fall back into square one. Hence, information about these constraints must be retrieved by the SCC prior to execution of restorative decisions.

As the concepts and operational principles of PS in 1980’s are still valid for today, above problems can be expected to occur at present and in future as well.

2.3 Restoration planning

In order to minimize the duration and complexity of restoration problems, the exercise of ‘Restoration Planning’ is carried out worldwide. These are based on the lessons learned in the past and on the results of the simulations performed for predicted system plans. For instance in Sri Lanka, CEB has prepared an Emergency Action Memorandum to confront such power failures indicating restoration path options at different contingencies. Certain overseas countries hire internationally recognized professionals to carry out these studies.

2.4 Requirements of expert systems

In the present context, the restoration process is dealt with experience and previous knowledge without decision support tools being incorporated during the process.[1] In the year 1994, M.M. Adibi, R.J. Kafka and D.P. Milanicz had presented the goals and requirements of such expert systems to achieve a successfully restored stable system.[10]

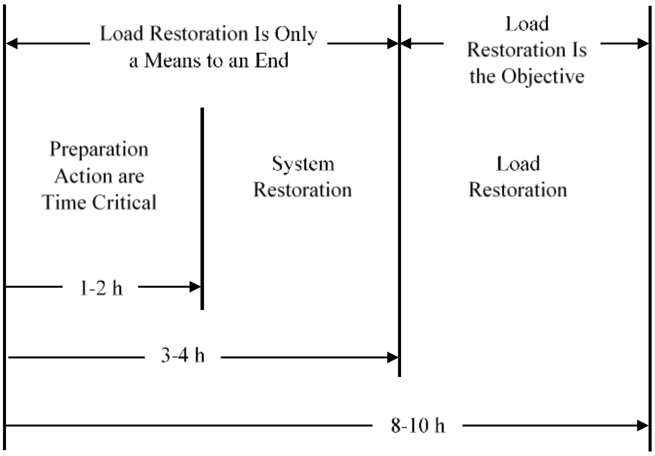

Figure 2 - Typical restoration stages [11]

As shown in Figure 2, system restoration comprises of 3 stages; Preparation Stage, Network Configuration Stage and Load Restoration Stage.

STAGE 1 : First Restoration Period – formation of subsystems with initial power sources

- Also known as 'Black-Start' and 'Restart'
- Sources of power: Hydro units, Combustion Turbines, ST, adjacent power systems linked with tie-lines
- Critical power requirements: Drum type units, pumping plants for pipe-type cables, transmission and distribution stations
- Restoring certain industrial loads

As the optimum formation of sub systems decides the speed and direction of the restoration problem solution, an algorithm for dividing subsytems had been developed based on community structure of BS units applied to network theory.[12]

During the study of Blackout Restoration Planning, consideration on initial sources demands a critical importance. Generating units with Black-start (BS) feature which can start on their own without requiring power from grid shall initiate the restoration process in each subsystem. Also the cranking power required for the Non Black start (NBS) generator units are catered by these BS units.[13] Following generator types can comprise the BS capability owing to their properties.

- Hydroelectric Generators :
  Both run-of-the river hydro units and low head pumped storage hydro units are included.[10] Requires small initial power to open the dam gates and energize the control system (with an onsite backup diesel generator).

Considered as the ideal BS units because of their reliable performance, fast ramping characteristics and low standby costs.

- Diesel Generators (DG) :
  Requires battery power to start up the engine. Maintenance of battery bank at good condition must be ensured to deploy DG sets during restorations.

- Gas Turbine Generators (GT):
  Aero-derivate GTs can be started with local battery power. Onsite DG sets are required to energize the auxiliary equipment before GTs are started.

On the other hand, Steam Generators (ST) are considered as NBS units as they require a larger amount of cranking power from outside. For instance, a 300 MW coal powered ST at Lakvijaya Power Station (Puttalam, Sri Lanka) consumes approximately 30 MW as its house load. When equipped with DGs or GTs, STs can also serve as BS units.

These BS units shall be dispatched optimally considering their capacity, ramping rate, critical maximum interval, start-up power, unit state and number of switch operations.[10][13] Herein, the importance of generator start up strategies becomes vibrant as the number of BS and NBS units will be increasing over decades. A mixed integer linear programming model was developed by Wei Sun, Chen-Ching Liu and Li Zhang considering the distances among NBS unit from BS units, system equipment outage (reflecting real life scenario) and generator power dispatch capability variation over time.[16] Also, a BS decision support system with graphical user interface had been developed based on graph algorithm and swarm intelligence.[17]

A study had been carried out to show that correct selection of BS sources integrated with restoration plans at planning stages would help the utility to produce a procurement plan with minimal cost.[18]

STAGE 2 : Second Restoration Period – synchronization of subsystems

- Also known as ‘Reintegration’, ‘Network Reconfiguration’
- Syncing large generating units after hot/cold restarts
- Interconnections through analytically proven line stretches causing minimal over-voltages due by line charging. Prior to synchronization, it was proposed to conduct studies on transient stability and voltage stability.
- Majority of loads (including residential) are attempted to restore
- Critical loads : Restoring hospital loads, national security related loads, transportation related loads

When loads are set as nodes, their importance has been assessed with node contraction methodology. To optimize the efficiency of restoration, discrete particle swarm is associated to determine the optimal skeleton networks.[19] Also, dynamic optimization strategies had been proposed to PS skeleton restoration.[20]

STAGE 3 : Third Restoration Period – Integration of large thermal units and longer lines

- Also known as ‘Load Restoration’
- Scheduling large thermal units (nuclear units)
- Strengthening network with more sources and by energizing long HV and EHV transmission lines
- Minimizing unserved load
- Establishing tie lines with other power systems

As pointed out in the systematic guidelines, decision support tools could be advantageous for operators to evaluate the practicability of restorative decisions (attempts) applying on actual system conditions.[15] During all three stages, voltages at respective buses shall be controlled against sustained power frequency overvoltages, switching transients, and harmonic resonance.[11]

Although several methodologies have been proposed to solve specific sub-problems of blackout restoration, no decision support system is yet practically deployed for the coordinated restoration of large interconnected power grids.[1]

Chapter Summary

This chapter discussed the variety of blackouts, the concerns during restoration and involvement of expert systems for restoration process. With the learnings from the previous studies and upon the requirement of decision support systems, next chapter will introduce a software-based analytical methodology for blackout restoration.

3 PROPOSED METHODOLOGY FOR BLACKOUT RESTORATION

This Chapter presents the proposed decision support methodology to be used in restoring a PS subsequent to a blackout.

This study proposes the approach of using a software based decision support methodology for the system operators to predict the next system state likely to occur from their individual decision. The proposed computer aided decision support tool architecture is shown in Figure 3.

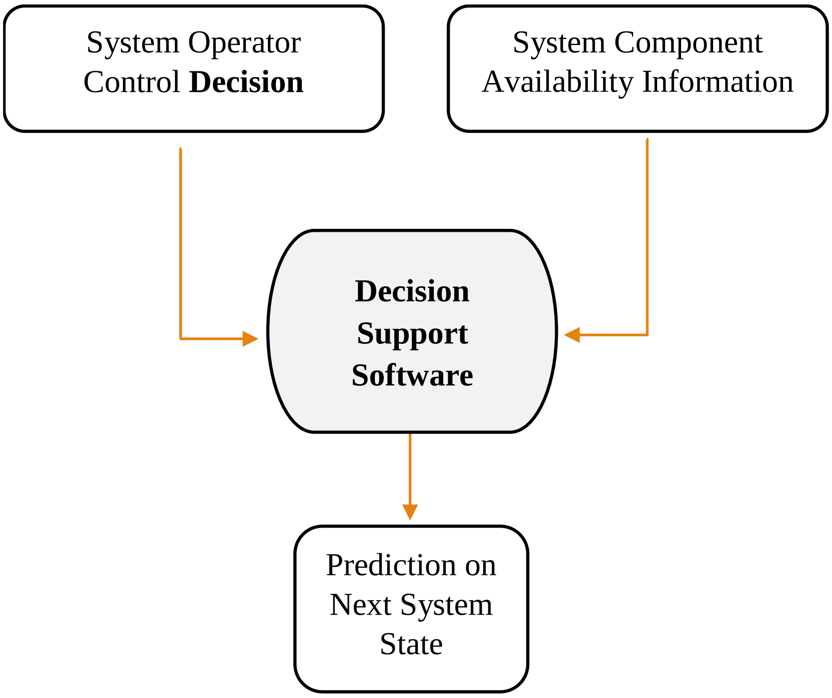

Figure 3 - Proposed approach for Blackout Restoration

The methodology is not specific to a certain country/region and hence can be universally applied for the use of system restoration regardless of extent. Thus, this approach can be identified as a generalized methodology.

Assumptions:

- Loads do not drastically vary during a single cycle of decision evaluation
- Decision support tool fetches updated system information and predicted loads at respective instances

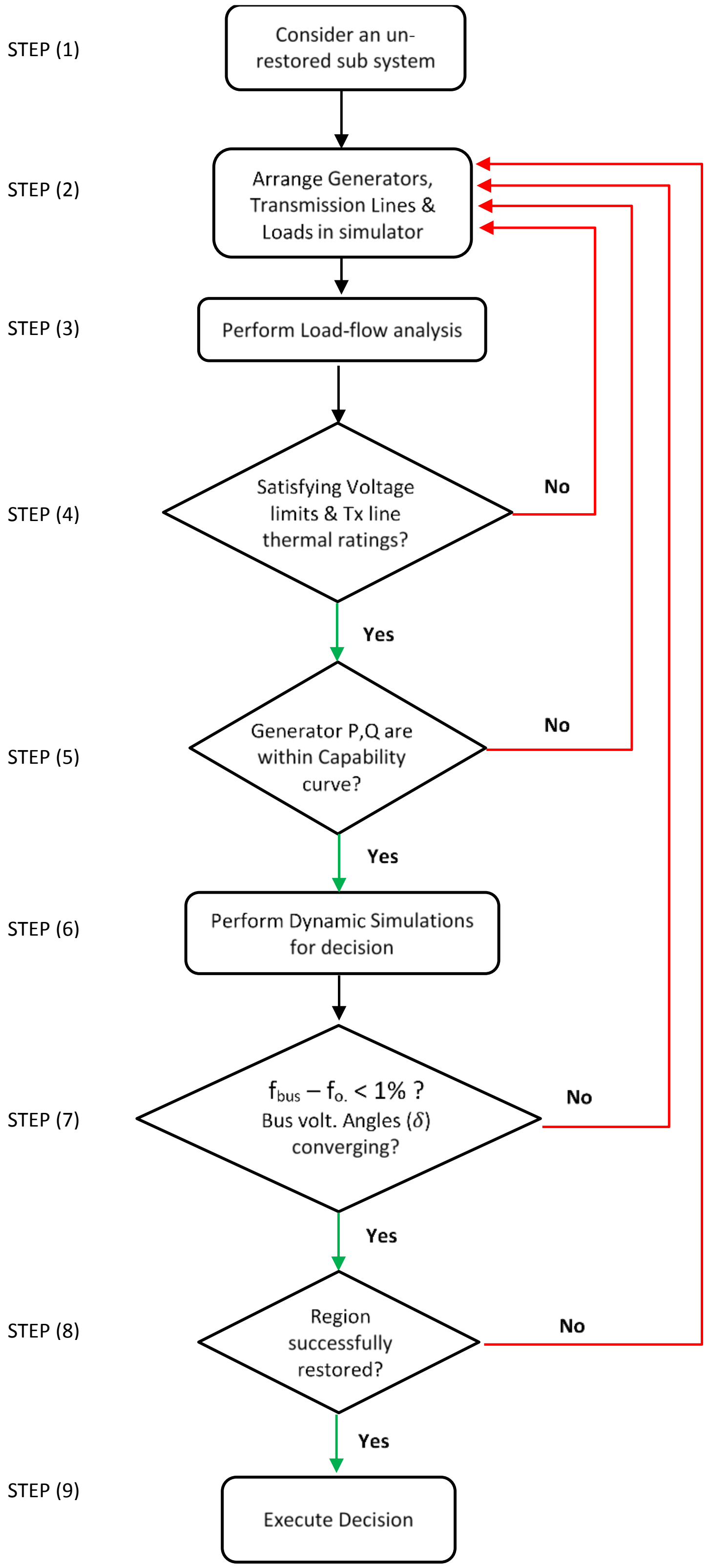

Figure 4 - Proposed Decision Support Methodology

Each step of the aforementioned methodology are explained in detail below:

STEP (1) Consider an unrestored subsystem

Identification of optimal subsystems within a PS is a crucial and effective approach to minimize the time required for restoration. This can also be defined as a ‘target system’.[11]

In Sri Lanka, there are 4 subsystems identified by CEB on their restoration plan: Colombo-Kelanitissa System, Southern System, Mahaweli Complex and Kotmale Complex.[21] These are setup only as guidelines since the actual and probable restoration path depends on system configuration, extent of the break down, plant availability and system demand.

The selection of subsystem would be unique to the restoration problem. However, each subsystem shall be equipped with BS generators and adequate loads. Grouping of sources and loads shall be optimized concurrently to minimize the restoration period. Studies have proposed optimal solutions for this sub-problem of sectionalization. Two-step partitioning strategy would group the BS generators with NBS clusters while forming the subsystems afar from each, covering the whole system.[22]

STEP (2) Arranging Generators, Transmission Lines and Loads

A particular decision involves switching on transmission line(s), adding a generator bus bar and/or switching on medium voltage load feeders. This specific decision will need to be evaluated against the given criteria before execution. A frequency controlling swing bus shall be nominated based on availability and capability. Usually, critical loads such as hospital feeders and generating stations requiring cranking power are prioritized. Attention must be paid for the regions where oil pumped underground cables are used as well.

STEP (3) Performing Load Flow analysis

With the use of PS simulation software, load flow analysis shall be performed to calculate the solution for each network configuration. The solution shall express the generator active/reactive power dispatch, bus voltages and branch currents.

STEP (4) Verifying inequality constraints

Once load flow analysis is performed, software outputs with regard to the particular decision are assessed for conformity with following specified constraints.

- Bus voltages (V_{bus}) shall be within permissible ranges following Eq(2)

  220 kV buses : $0.90 < V_{bus}$ (pu) < 1.10

  132 kV buses : $0.90 < V_{bus}$ (pu) < 1.10

  33 kV buses : $0.98 < V_{bus}$ (pu) < 1.02

- Transmission line loading shall remain below their thermal limits – Eq(4)

STEP (5) Verification of Generator performance points on their reactive capability curves

Every generator has its own performance limits for Active Power (P) and Reactive Power (Q) i.e. Rotor heat limit, Stator heat limit, Prime mover power limit and Stator end iron heating limit. These are plotted experimentally and known as Reactive Capability Curves or "D" curves.

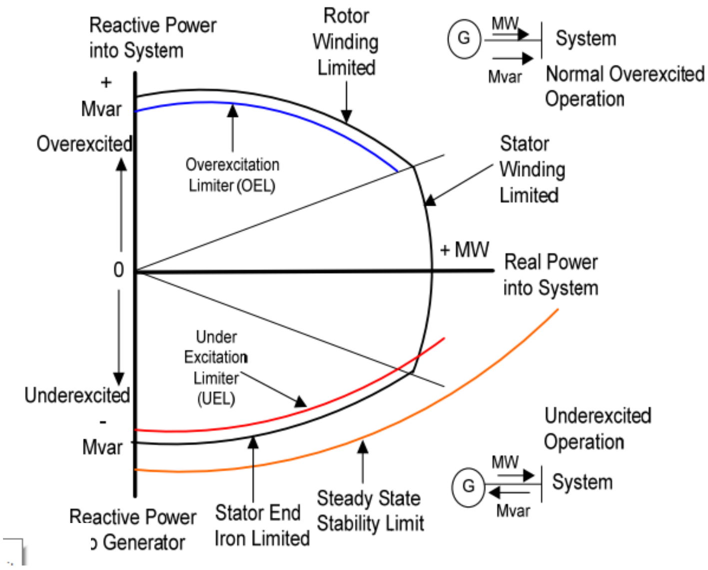

Figure 5 - Reactive Capability Curve (D-Curve) of a generator [23]

Any attempt to load the generator beyond these limits would cause it to trip by protection relays (under/over excitation etc.) as a safety measure.

Reactive Capability Curves ("D" curves) of each grid connected generator shall be numerically fed as piecewise function.

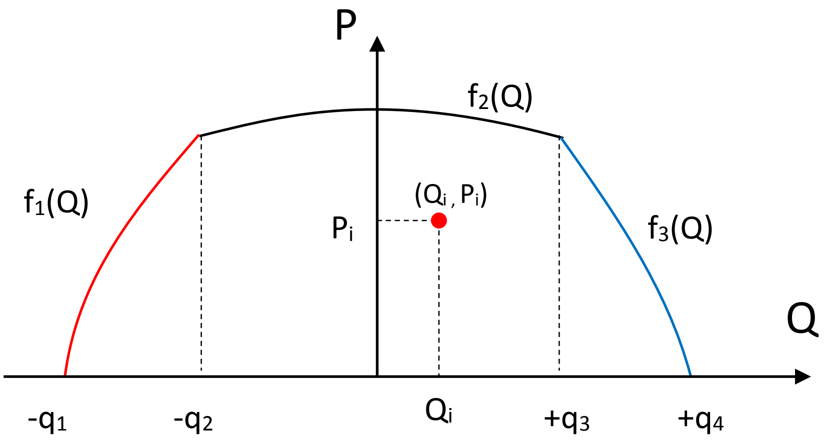

Figure 6 - Mathematical interpretation of Generator Reactive Capability Curve

$$P = \begin{cases} f_1(\mathrm{Q}), -q_2 < \mathrm{Q} < -q_1 \\ f_2(\mathrm{Q}), -q_1 < \mathrm{Q} < q_3 \\ f_3(\mathrm{Q}), \quad q_3 < \mathrm{Q} < q_4 \end{cases}$$

Operating point of each generator on D-curve, G(Qi,Pi) obtained from the computed Active and reactive power shall be evaluated for its operating point, on the D-curve. Performance of all connected generators shall be reviewed for each restorative decision.

STEP (6) Assessment of Dynamic behaviour with Transient Stability studies

During blackout restorations, the sub systems are synchronized after restoration of individual to increase the stiffness of the system. But sometimes this execution fails as the system power swings cause the generators to increase their speeds and run out of step. This phenomena further leads to voltage, angle and frequency fluctuations in the connected buses.

When overhead high voltage transmission lines are energized over a longer distance, the receiving end voltage are prone to rise as a result of the capacitance with the ground, which is explained by Ferranti effect. When those lines are lightly loaded, sustained power frequency overvoltages could overexcite transformers and cause overheating while generating harmonic distortions.[11] Therefore, the behaviour of PS during area switching actions shall be observed beyond the steady state results.

Dynamic data of all the associated network elements must be explored to carryout simulations. Variation of following properties over time shall be monitored.

- Electrical Angle (θ)
- Bus Frequency (f)
- Bus Voltage (V)
- Rate of Change of Frequency

They shall converge to a stable state after fluctuations within permissible ranges. Frequency shall be varied within ±1%. Also, the maximum magnitude of Rate of Change of Frequency (RoCoF) shall be predicted to take precautions before establishing the tie-line connection (elevate the RoCoF setting if convergence is ensured OR reject the decision.)

$$0.99\ f_o < f < 1.01\ f_o$$

$$\text{RoCoF} > -0.85$$

Transient stability studies are supportive to determine whether a system will remain in synchronism following major disturbances such as slow clearing transmission line fault. Transitions among Power-Angle curves (Figure 7) decide the capability of the system to recover from sped up generators by excess mechanical energy.

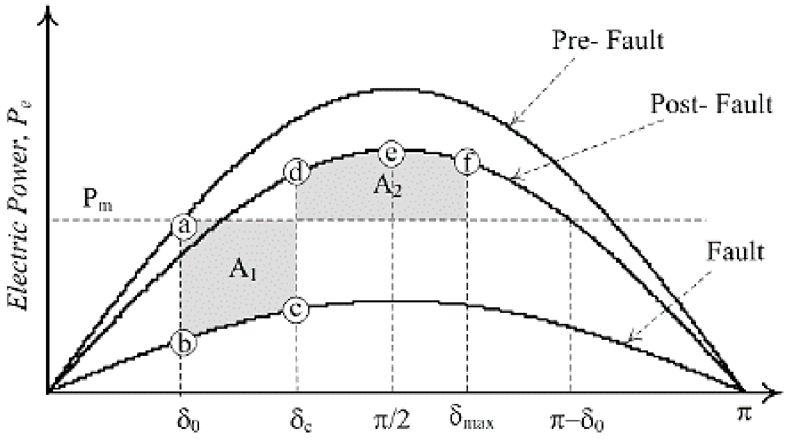

Figure 7 - Power Angle Curve

Inability to match the areas (A1 and A2) denotes the generators falling out of synchronism.

The study of blackout restoration has less concern about line faults since the probability of fault occurrence in the restored portion is inconsiderable. However, the system operators shall be aware of critical fault clearing angles (δ_c) of restored stretches in order to prevent any imminent post-restoration fault.

If the system behaviour is not foreseen during the restoration period, overvoltage conditions could damage system components:

- Power transformers - by exceeding their Basic Insulation Level (BIL), by overexcitation, harmonic generation and thus by excessive heating.
- Surge arrestor operation and resealing could be prevented
- Circuit Breakers – Risks by flash over, higher transient recovery voltage and restriking

Failures in healthy system members would lead to extended outage period.

Chapter Summary

This chapter proposed a generalized decision support methodology to be adopted during restoration subsequent to a power system blackout. In the next chapter, this methodology will be applied to restore the Sri Lankan PS.

4 CASE STUDY ON RESTORING SRI LANKAN POWER SYSTEM

This chapter defines the case study conducted with and without the involvement of suggested decision support methodology.

The proposed methodology has been implemented on a set of SCC operator decisions for achieving individual restoration of Colombo-Kelanitissa system and secondly for synchronization with partially restored Laxapana system. A fault in Biyagama 132 kV/ 220 kV/ 33 kV transformers (2 nos) are considered as the root cause of the blackout and hence not associated for restoration process.

Four 'attempts' are considered for restoration of Colombo loads. Each attempt consists of several 'decisions' which depicts either an addition of a machine/group of machines or a load with switching ON respective inter-bus transmission lines.

PSS®E software is used for PS load flow and dynamic simulations. The PS model used for the case study is 'Year 2017 Sri Lanka Transmission Network - Night Peak – Hydro Maximum' scenario composed by Ceylon Electricity Board in 2013.

Considered generator-load mix of Colombo-Kelanitissa system and Laxapana System are illustrated respectively in Table 3 and Table 4 .

Table 3 - Associated Loads and Generators from Colombo Kelanitissa System

	BUS ID	**NAME**	**MW**	**Mvar**
Loads	3301	KELAN-3A 33.000	16	6.4
	4920	SUB C-11 11.000	21.4	8.7
	4760	COL_F-11 11.000	23.5	8.2
	4430	COL_I_11 11.000	34.5	14.7
	3302	KELAN-3B 33.000	16	6.4
	3551	KOLON-3B 33.000	37.3	23.1
	4750	COL_E-11 11.000	34	11.2
	4435	COL_A_11 11.000	35	11.7
Generators	**BUS ID**	**NAME**	**Max MW**	**Max Mvar**
	4302	KCCP ST 11.500	54	33
	2222	BARGE-2	60	37
	4310	SAPUG-P 11.000	72	45
	4301	KCCP GT 15.000	109	68
	4300	GT 07	115	71

Table 4 - Associated Loads and Generators from Laxapana System

	BUS ID	NAME	MW	Mvar
Generators	4100	LAX GEN123 11.000	28.5	18
	4101	LAX GEN4 11.000	12.5	8
	4102	LAX GEN5 11.000	12.5	8
	4110	NLAX-1 12.500	50	31
	4111	NLAX-2 12.500	50	31
Loads	**BUS ID**	**NAME**	**Max MW**	**Max Mvar**
	3120	WIMAL-3 33.000	14.6	1.8
	3121	WIMAL-3B 33.000	7.3	0.9
	3510	SITHA-33 33.000	30.3	13.5
	3520	NUWAR-3 33.000	42.2	10.1
	3630	BALAN-3 33.000	29.6	6.3

This study is conducted with two assumptions.

- Load data are available throughout the restoration process
- Loads remain constant during all the decisions of a given attempt

Integration of load forecasting expert systems based on fuzzy logic to this restoration decision support could enhance its accuracy.[24]

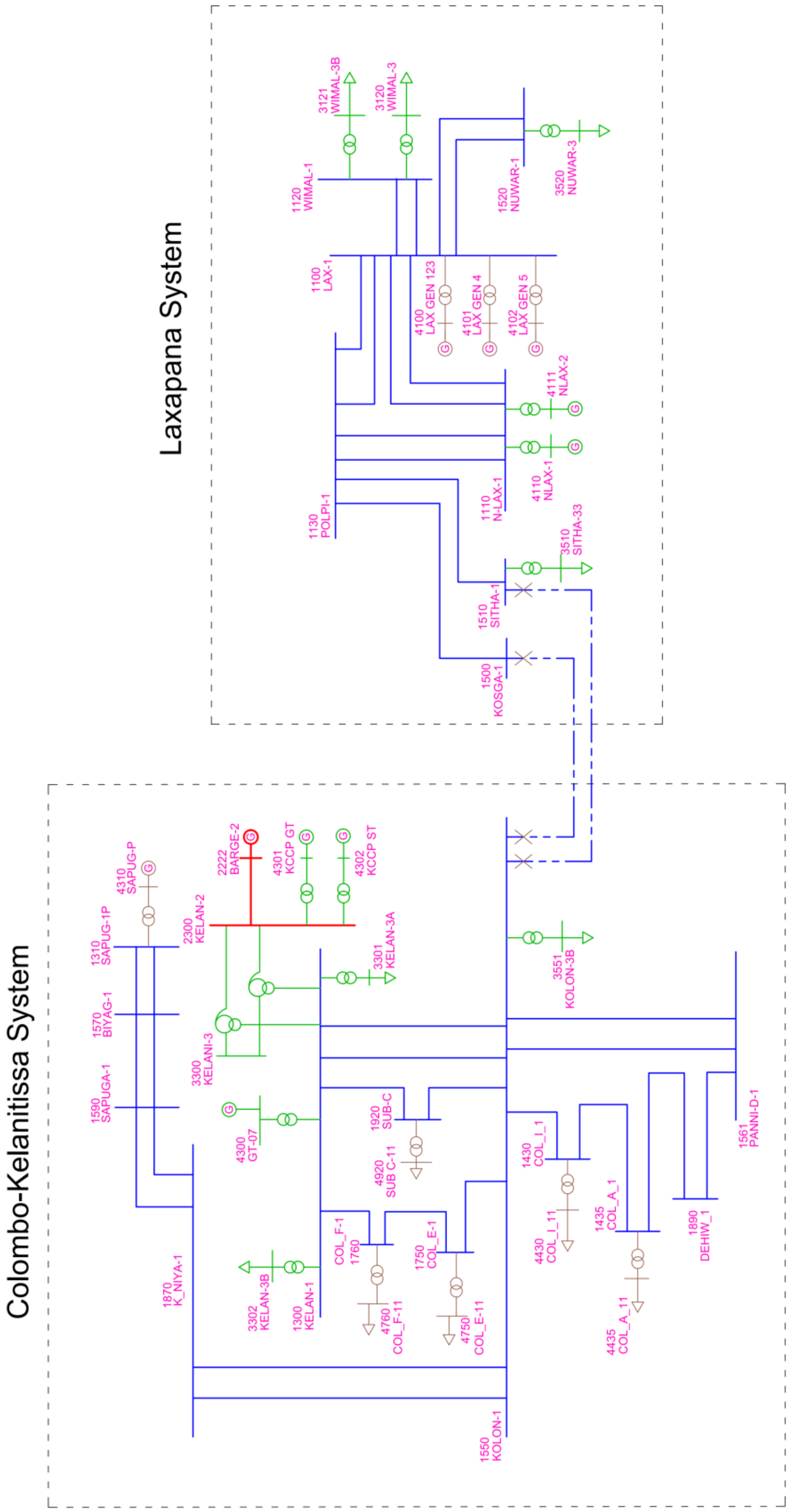

Figure 8 - Restoration problem: Colombo-Kelanitissa and Laxapana subsystems of Sri Lankan PS (PSSE model for year 2017 – Night Hydro Peak)

4.1 Restoration Attempt 1

Decisions (D) of Attempt 1 do not involve the proposed decision-support methodology. This is the conventional practice and a casual approach to restore the Colombo-Kelanitissa System, merely considering the past experience with balance between generation and demand. A list of decisions is formulated without performing an analysis for each decision beforehand (Table 5).

The listed decisions are simulated on PSSE model to evaluate the load flow results and to assess the criteria suggested in the proposed methodology.

Table 5 - List of decisions in Attempt 1

Attempt A	Decision D	ID	Added Lines	Added plant				Added Load			
				Plant Bus	Pmax MW	Qmax Mvar	Total MW	Load Bus	P MW	Q Mvar	Total Load MW
1	1	A1D1	2222-2300	**2222**	60	37	60		0	0	0
1	2	A1D2	1300-1920		0	0	60	**4920**	21.4	8.7	21.4
1	3	A1D3			0	0	60	**3301**	16.0	6.4	37.4
1	4	A1D4		**4301**	109	68	169		0	0	37.4
1	5	A1D5			0	0	169	**3302**	16.0	6.4	53.4
1	6	A1D6	1300-1760		0	0	169	**4760**	23.5	8.2	76.9
1	7	A1D7	1300-1550 (2)		0	0	169		0	0	76.9
1	8	A1D8	1750-1650		0	0	169	**4750**	34.0	11.2	110.9

4.2 Restoration Attempt 2

Decision making in Attempt 2 (Table 6) involves steady state analysis (Figure 4: Step 3-5) while restoring the Colombo loads. Each decision is assessed for voltage and generator capability criteria before laid out on attempt schedule for actual implementation.

Table 6 - List of decisions in Attempt 2

Attempt A	Decision D	ID	Added Lines	Added plant				Added Load			
				Plant Bus	Pmax MW	Qmax Mvar	Total MW	Load Bus	P MW	Q Mvar	Total Load MW
2	1	A2D1	2222-2300	**2222**	60	37	60		0	0	0
2	2	A2D2	1300-1920		0	0	60	**4920**	21.4	8.7	21.4
2	3	A2D3			0	0	60	**3301**	16.0	6.4	37.4
2	4	A2D4		**4301**	109	68	169		0	0	37.4
2	5	A2D5			0	0	169	**3302**	16.0	6.4	53.4
2	6	A2D6	1300-1760		0	0	169	**4760**	23.5	8.2	76.9
2	7	A2D7	1300-1550 (2) 1920-1550		0	0	169		0	0	76.9
2	8	A2D8		**4300**	115	71	284		0	0	76.9
2	9	A2D9	1750-1550 1780-1750		0	0	284	**4750**	34.0	11.2	110.9
2	10	A2D10					284	**3551**	37.3	23.1	148.2
2	11	A2D11		**4302**	54	33	338		0	0	148.2
2	12	A2D12	1550-1430				338	**4430**	34.5	14.7	182.7

4.3 Restoration Attempt 3

Third attempt is also allied with the proposed methodology and hence avoids all disparities with the given criteria in order to successfully restore all the Colombo loads. The decisions A3D1 – A3D15 are listed in Table 7.

Table 7 - List of decisions in Attempt 3

Attempt A	Decision D	ID	Added Lines	Added plant				Added Load			
				Plant Bus	Pmax MW	Qmax Mvar	Total MW	Load Bus	P MW	Q Mvar	Total Load MW
3	1	A3D1	2222-2300	**2222**	60	37	60		0	0	0
3	2	A3D2	1300-1920		0	0	60	**4920**	21.4	8.7	21.4
3	3	A3D3			0	0	60	**3301**	16	6.4	37.4
3	4	A3D4		**4301**	109	68	169		0	0	37.4
3	5	A3D5			0	0	169	**3302**	16	6.4	53.4
3	6	A3D6	1300-1760		0	0	169	**4760**	23.5	8.2	76.9
3	7	A3D7	1300-1550 (2) 1920-1550		0	0	169		0	0	76.9
3	8	A3D8		**4300**	115	71	284		0	0	76.9
3	9	A3D9	1750-1550 1780-1750		0	0	284	**4750**	34	11.2	110.9
3	10	A3D10			0	0	284	**3551**	37.3	23.1	148.2
3	11	A3D11		**4302**	54	33	338		0	0	148.2
3	12	A3D12	(-) 1760-1750		0	0	338		0	0	148.2
3	13	A3D13	1550-1870 (2) 1870-1590 (2) 1590-1570 (2) 1570-1310 (2) 1550-1430 1430-1435		0	0	338	**4430**	34.5	14.7	182.7
3	14	A3D14		**4310**	72	45	410		0	0	182.7
3	15	A3D15			0	0	410	**4435**	35	11.7	217.7

The 8th decision in Attempt 3 (A3D8) has been adjusted to avoid the foreseen failures in Attempt 2.

4.4 Restoration Attempt 4

After restoration of Colombo-Kelanitissa subsystem, the decision on interconnection with restored Laxapana system will be assessed with dynamic studies. The associated bus voltages, frequencies and Rate of Change of Frequencies (RoCoF) will be visualized with simulation outputs.
The summary of restoration attempts is listed on **Table 8**.

Table 8- Summary of Restoration Attempts

Attempt	Restoration Problem	Use of decision support system
1	Colombo – Kelanitissa System	NO
2	Colombo – Kelanitissa System	YES - Partially
3	Colombo – Kelanitissa System	YES - Partially
4	Synchronizing 2 subsystems (Col-Kel + Laxapana)	YES

As per the scenario layout described in the chapter, the results obtained from the simulations and the decision support tool will be analysed.

Chapter Summary

This chapter lays out the proceedings of the case study which comprises of four attempts. First three attempts are oriented to highlight the restore the Colombo-Kelanitissa system while the fourth attempt is focused on the scenario of interconnecting two subsystems. Next chapter will carry out an analysis on the results of the case study.

5 RESULTS AND ANALYSIS

Chapter 5 presents a detailed analysis on the proposed methodology based on the results of the case study, highlighting the drawbacks of the presently practiced trial and error approach which can be eliminated by following an analytic approach.

During all the restoration attempts, 4 x 16MW BARGE power station (Bus-2222) was appointed as the frequency controlling machines in the Colombo-Kelanitissa system owing to its BS capability. In the Laxapana system, 58MW New Laxapana 1 machine (N-Lax1: Bus4110) having the BS capability was appointed for frequency controlling.

The swing bus voltages were set at 1.03 pu.

5.1 Attempt 1

The arbitrary decisions listed out in Attempt 1 were simulated and reviewed. The maximum bus voltage was 1.0644 pu while the minimum was 0.9754 pu. They are well within the specified ranges.

Table 9 - Bus voltages during Attempt 1

BUS		Base kV	A1D1	A1D2	A1D3	A1D4	A1D5	A1D6	A1D7	A1D8
1300	KELAN-1	**132**	1.0644	1.007	1.0032	1.0032	0.9996	0.9778	0.981	0.9889
1430	COL_I_1	**132**								0.9875
1550	KOLON-1	**132**							0.981	0.9884
1760	COL_F-1	**132**						0.9754	0.9787	0.9866
1920	SUB-C	**132**		1.006	1.0029	1.0028	0.9993	0.9774	0.9808	0.9886
2222	BARGE-2	**220**	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
2300	KELAN-2	**220**	1.03	1.03	1.0299	1.0299	1.0298	1.0299	1.0299	1.0298
3300	KELANI-3	**33**	1.03	1.023	1.0193	1.0193	1.0154	0.9912	0.9949	0.9854
3301	KELAN-3A	**33**		1.026	1.0259	1.0259	1.0221	0.9857	1.0025	1.0108
3302	KELAN-3B	**33**					1.022	0.9856	1.0023	1.0107
4301	KCCP GT	15				1.0407	1.0407	0.9964	1.0182	1.0175
4430	COL_I_11	11								1.0093
4760	COL_F-11	11						0.998	1.0026	1.0136
4920	SUB C-11	11		1.013	1.0094	1.0094	1.0053	0.9802	0.9841	1.0114

Generator capability studies have shown failures in implementation. Although first 7 decisions are safe to operate, the swing bus BARGE (2222) is predicted to exceed its stator winding current limits during A1D8 (**Figure 9**).

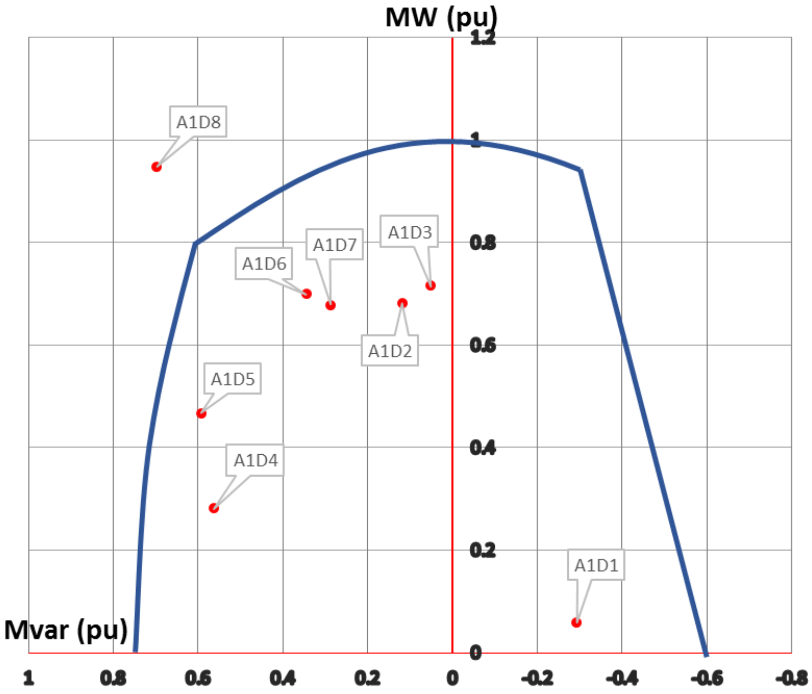

Figure 9 - BARGE (2222) performance during Attempt 1

However, KCCP GT (4301) synchronized at A1D4 can be expected to perform safely throughout the period (Figure 10).

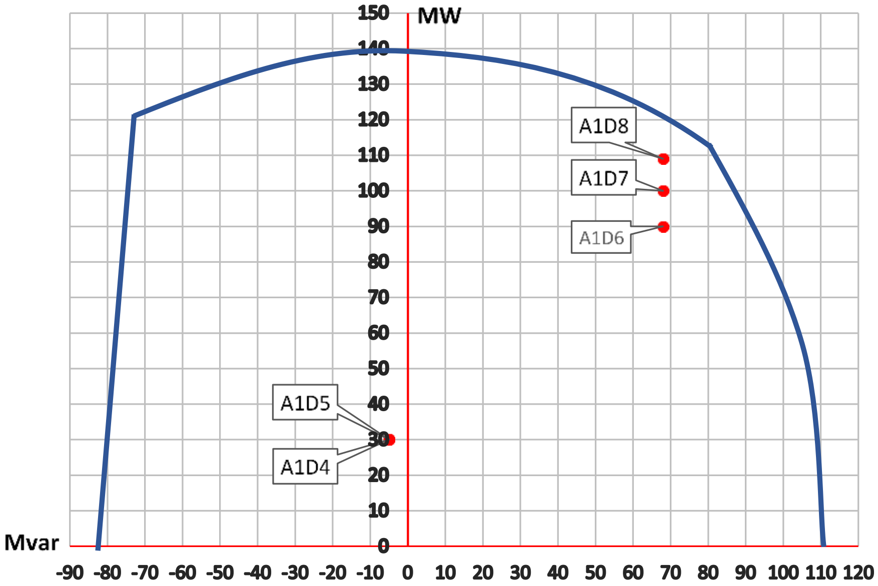

Figure 10 – KCCP GT (4301) performance during Attempt 1

If this decision sequence was attempted during a real restoration process, the frequency controlling generator could trip, jeopardizing the partially restored Colombo network.

5.2 Attempt 2

With the awareness about the suspected failure, changing of decision A2D8 improved the capability to restore further stretch of the network.

Table 10 - Bus voltages during Attempt 2

BUS		Base kV	A2D1	A2D2	A2D3	A2D4	A2D5	A2D6	A2D7	A2D8	A2D9	A2D10	A2D11	A2D12
1300	KELAN-1	132	1.0644	1.0066	1.0032	1.0032	0.9996	0.9778	0.981	1.0064	0.9962	0.9886	0.9886	0.9823
1430	COL_I_1	132								0.9875	0.9875	0.9899	0.9796	0.9796
1550	KOLON-1	132							0.981	1.0064	0.9953	0.9873	0.9873	0.9805
1750	COL_E-1	132									0.9933	0.9857	0.9857	0.9791
1760	COL_F-1	132						0.9754	0.9787	1.0041	0.9939	0.986	0.986	0.9794
1920	SUB-C	132		1.0063	1.0029	1.0028	0.9993	0.9774	0.9808	1.0061	0.9958	0.9881	0.9881	0.9817
2222	BARGE-2	220	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
2300	KELAN-2	220	1.03	1.0299	1.0299	1.0299	1.0298	1.0299	1.0299	1.0301	1.0299	1.03	1.03	1.0299
2570	BIYAG-2	220								1.0302	1.0302	1.0302	1.0302	1.0302
3300	KELANI-3	33	1.03	1.0231	1.0193	1.0193	1.0154	0.9912	0.9949	1.0042	0.9932	0.9851	0.9851	0.9782
3301	KELAN-3A	33		1.0259	1.0259	1.0259	1.0221	0.9857	1.0025	1.0292	1.0185	1.0105	1.0105	1.0038
3302	KELAN-3B	33					1.022	0.9856	1.0023	1.0291	1.0184	1.0104	1.0104	1.0037
3551	KOLON-3B	33										1.0145	1.0145	1.0069
4300	GT 07	15								1.04	1.04	1.04	1.04	1.04
4301	KCCP GT	15				1.0407	1.0407	0.9964	1.0182	1.0203	1.0193	1.0193	1.0193	1.0187
4302	KCCP ST	11.5								1.0123	1.0123	1.0125	1.0125	1.0121
4430	COL_I_11	11								1.0093	1.0093	1.0122	0.9996	0.9996
4750	COL_E-11	11									1.0262	1.0163	1.0163	1.0076
4760	COL_F-11	11						0.998	1.0026	1.0377	1.0238	1.0128	1.0128	1.0037
4920	SUB C-11	11		1.0134	1.0094	1.0094	1.0053	0.9802	0.9841	1.0318	1.0198	1.0109	1.0109	1.0034

Bus voltages remained within safe limits (Table 10): Max: 1.0644 pu, Min: 0.9754 pu.

The 2222 Barge generator could deliver the expected active power without leading to a tripping issue (**Figure *11***).

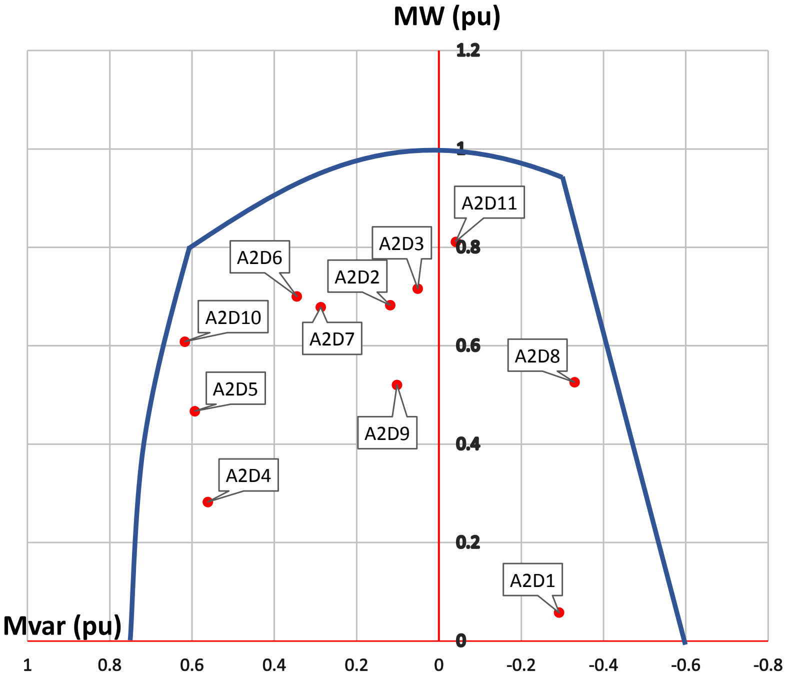

Figure 11 - BARGE (2222) performance during Attempt 2

In the meantime, KCCP GT (4301) could pump dedicated active power without exceeding its safe limits (**Figure *12***).

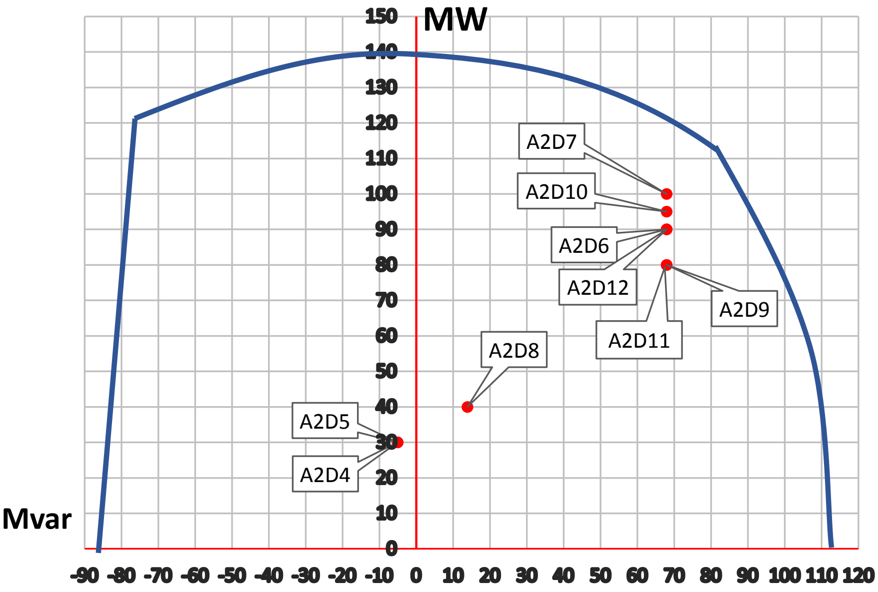

Figure 12 - KCCP GT (4301) performance during Attempt 2

Although the generator capabilities have been successfully secured, the thermal loading of 1760-1300 transmission line /branch indicated an imminent overload of 124% during 12th decision (A2D12). This scenario highlights the importance of verifying branch currents against their thermal limits (‘Step 4’ of Figure 4).

5.3 Attempt 3

With the learnings from Attempt 2, the branch bridging Col-F-1 (bus 1760) and Col-E-1 (bus 1750) had been switched off as the next Attempt’s decision (A3D12).

All the loads of Colombo area were restored whist monitoring bus bar voltages, line currents and generator performances in Attempt 3.

With the expected generation and load mix, voltages at active buses could be maintained within safe limits (Table 11). – Max: 1.06 pu, Min: 0.9716 pu.

Table 11 - Bus voltages during Attempt 3

BUS		Base kV	A3D1	A3D2	A3D3	A3D4	A3D5	A3D6	A3D7	A3D8	A3D9	A3D10	A3D11	A3D12	A3D13	A3D14	A3D15
1300	KELAN-1	132	1.0644	1.0066	1.0032	1.0032	0.9996	0.9778	0.981	1.0064	0.9962	0.9886	0.9886	0.9869	0.9833	0.9969	0.9817
1310	SAPUG-1P	132												0.9903	0.9815	1.0051	0.989
1430	COL_I_1	132								0.9875	0.9875	0.9899	0.9796	0.9918	0.9807	0.9953	0.9772
1435	COL_A_1	132											0.9716	0.992	0.9809	0.9955	0.9745
1550	KOLON-1	132							0.981	1.0064	0.9953	0.9873	0.9873	0.9853	0.9814	0.996	0.9798
1570	BIYAG-1	132								1.0989	1.0989	1.0989	1.0989	0.9903	0.9815	1.0041	0.9879
1590	SAPUGA-1	132												0.9902	0.9815	1.0019	0.9857
1750	COL_E-1	132									0.9933	0.9857	0.9857	0.9832	0.9792	0.9939	0.9776
1760	COL_F-1	132						0.9754	0.9787	1.0041	0.9939	0.986	0.986	0.9846	0.9809	0.9945	0.9794
1870	K_NIYA-1	132												0.9902	0.9815	0.9994	0.9833
1890	DEHIW_1	132											0.9867				
1920	SUB-C	132		1.0063	1.0029	1.0028	0.9993	0.9774	0.9808	1.0061	0.9958	0.9881	0.9881	0.9864	0.9827	0.9965	0.9811
2222	BARGE-2	220	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
2300	KELAN-2	220	1.03	1.0299	1.0299	1.0299	1.0298	1.0299	1.0299	1.0301	1.0299	1.03	1.03	1.0299	1.0299	1.0301	1.0299
2570	BIYAG-2	220								1.0302	1.0302	1.0302	1.0302				
3300	KELANI-3	33	1.03	1.0231	1.0193	1.0193	1.0154	0.9912	0.9949	1.0042	0.9932	0.9851	0.9851	0.9832	0.9793	0.994	0.9776
3301	KELAN-3A	33		1.0259	1.0259	1.0259	1.0221	0.9857	1.0025	1.0292	1.0185	1.0105	1.0105	1.0087	1.0048	1.0192	1.0032
3302	KELAN-3B	33					1.022	0.9856	1.0023	1.0291	1.0184	1.0104	1.0104	1.0085	1.0047	1.0191	1.0031
3551	KOLON-3B	33										1.0145	1.0145	1.0123	1.0079	1.0241	1.0061
3890	DEHIW_3	33											1.0331				
4300	GT 07	15								1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
4301	KCCP GT	15				1.0407	1.0407	0.9964	1.0182	1.0203	1.0193	1.0193	1.0193	1.0193	1.0184	1.0194	1.0188
4302	KCCP ST	11.5								1.0123	1.0123	1.0125	1.0125	1.0125	1.0117	1.0126	1.0119
4310	SAPUG-P	11												1.0027	1.0027	0.9961	0.98
4430	COL_I_11	11								1.0093	1.0093	1.0122	0.9996	1.0001	1.001	1.0188	0.9968
4435	COL_A_11	11											0.9788				0.9828
4750	COL_E-11	11									1.0262	1.0163	1.0163	1.0131	1.0078	1.027	1.0057
4760	COL_F-11	11						0.998	1.0026	1.0377	1.0238	1.0128	1.0128	1.0108	1.0057	1.0246	1.0036
4920	SUB C-11	11		1.0134	1.0094	1.0094	1.0053	0.9802	0.9841	1.0318	1.0198	1.0109	1.0109	1.0088	1.0045	1.0206	1.0027

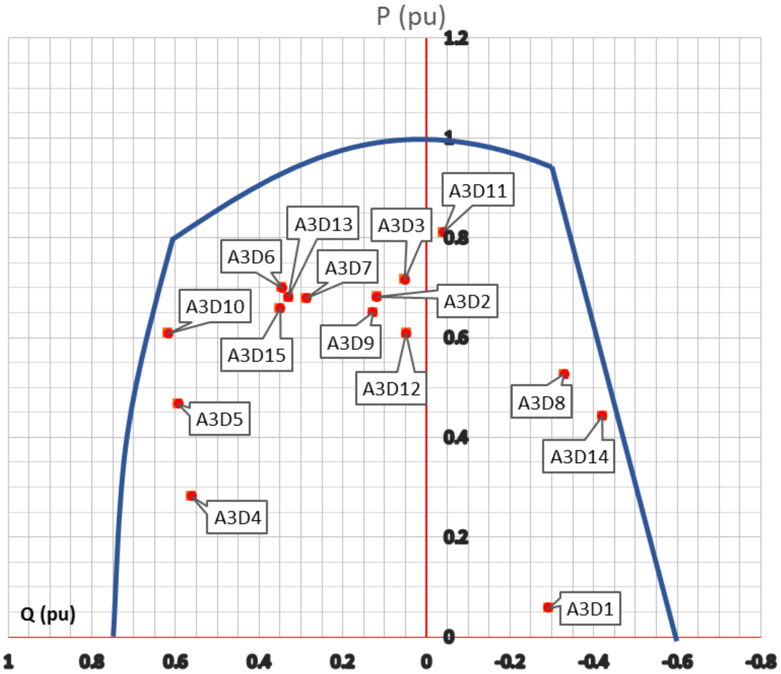

Figure 13 - BARGE (2222) performance during Attempt 3

5.4 Attempt 4

The scenario of synchronizing individually stable subsystems with medium-long transmission lines is a substantial step during blackout restorations. The SCC operator's decision to interconnect two networks in Attempt 4 is scheduled at two instants (**Table** *12*). Each bridging line is 32km and 42km long.

Table 12 - Sequence of operations during Attempt 4

Time (s)	Operation	Decision ID
0	Col & Lax - Ready	A4D0
0.2	Close 1550-1500	A4D1
5	Close 1550-1510	A4D2

According to the steady state analysis, all bus voltages were settled within safe limits (Table 13).

Table 13 - Bus voltages during Attempt 4

BUS		Base kV	A4D0	A4D1	A4D2
1100	LAX-1	132	1.02	1.02	1.01
1110	N-LAX-1	132	1.02	1.02	1.01
1120	WIMAL-1	132	1.02	1.02	1.01
1130	POLPI-1	132	1.02	1.02	1.01
1300	KELAN-1	132	0.99	0.99	1.00
1310	SAPUG-1P	132	1.00	1.00	1.00
1430	COL_I_1	132	0.99	0.99	0.99
1435	COL_A_1	132	0.98	0.98	0.99
1500	KOSGA-1	132	1.02	1.02	1.00
1510	SITHA-1	132	1.01	1.01	1.00
1520	NUWAR-1	132	1.01	1.01	1.00
1550	KOLON-1	132	0.99	0.99	0.99
1560	PANNI-1	132	1.08	1.08	1.08
1561	PANNI-D-1	132	0.99	0.99	0.99
1570	BIYAG-1	132	1.00	1.00	1.00
1590	SAPUGA-1	132	0.99	0.99	1.00
1630	BALAN-1	132	1.03	1.03	1.03
1750	COL_E-1	132	0.99	0.99	0.99
1760	COL_F-1	132	0.99	0.99	0.99
1820	ATURU-1	132	0.99	0.99	0.99
1840	JPURA_1	132	0.97	0.97	0.97
1870	K_NIYA-1	132	0.99	0.99	1.00
1890	DEHIW_1	132	0.99	0.99	0.99
1920	SUB-C	132	0.99	0.99	0.99
2220	KOTMA-2	220	1.03	1.03	1.03
2222	BARGE-2	220	1.03	1.03	1.03
2300	KELAN-2	220	1.03	1.03	1.03
2305	KERAWALA_	220	1.04	1.04	1.04
2560	PANNI-2	220	1.01	1.01	1.01
2561	PANNI-D-2	220	1.01	1.01	1.01
2570	BIYAG-2	220	1.03	1.03	1.03
2580	KOTUG-2	220	1.03	1.03	1.03
3300	KELANI-3	33	0.99	0.99	0.99
3301	KELAN-3A	33	1.01	1.01	1.02
3302	KELAN-3B	33	1.01	1.01	1.02
3510	SITHA-33	33	1.02	1.02	1.01
3520	NUWAR-3	33	1.00	1.00	0.99
3551	KOLON-3B	33	1.01	1.01	1.02
3565	PANNI-C	33	0.93	0.93	0.93
3566	PANNI-D-C	33	0.93	0.93	0.93
3570	BIYAG-3	33	1.04	1.04	1.04
3890	DEHIW_3	33	1.03	1.03	1.03
4110	NLAX-1	12.5	1.02	1.02	1.02
4111	NLAX-2	12.5	1.02	1.02	1.02
4130	POL GEN1	12.5	1.02	1.02	1.02
4131	POL GEN2	12.5	1.02	1.02	1.02
4220	KOTH GEN1	13.8	1.04	1.04	1.04
4221	KOTH GEN2	13.8	1.04	1.04	1.04
4300	GT 07	15	1.04	1.04	1.04
4301	KCCP GT	15	1.02	1.02	1.02
4302	KCCP ST	11.5	1.01	1.01	1.01
4306	KERAWALA-	14.5	1.09	1.09	1.09
4310	SAPUG-P	11	0.99	0.99	0.99
4430	COL_I_11	11	1.01	1.01	1.02
4435	COL_A_11	11	1.00	1.00	1.01
4750	COL_E-11	11	1.02	1.02	1.02
4760	COL_F-11	11	1.01	1.01	1.02
4920	SUB C-11	11	1.01	1.01	1.02
5521	NUWAR-T1	132	1.01	1.01	1.00
5522	NUWAR-T2	132	1.01	1.01	1.00
5840	JAPURA_T1	132	0.99	0.99	0.99
5841	JAPURA_T2	132	0.99	0.99	0.99

The restored Laxapana subsystem was analysed for its compliance with criteria in proposed methodology i.e. the operating points of 3x9.6MW Old Laxapana 1, 2 and 3 generators are within safe region (**Figure *14***).

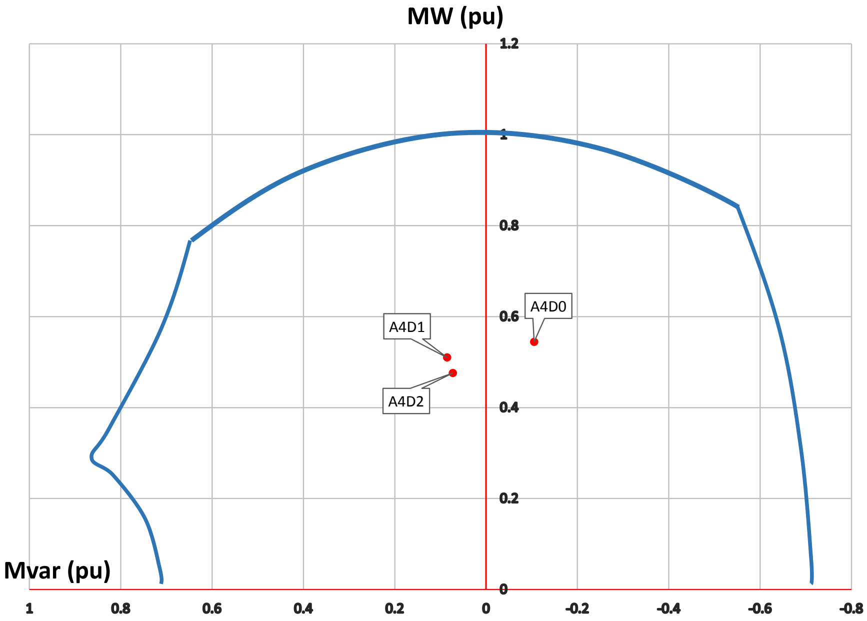

Figure 14 - Old Laxapana (4100) performance during Attempt 4

The dynamic simulations run during the switching actions can predict the voltage variation of concerned buses. As illustrated in **Figure 15**, all the voltages remain within the ±10% (0.90pu–1.1pu) Emergency safe region without leading to a tripping state.

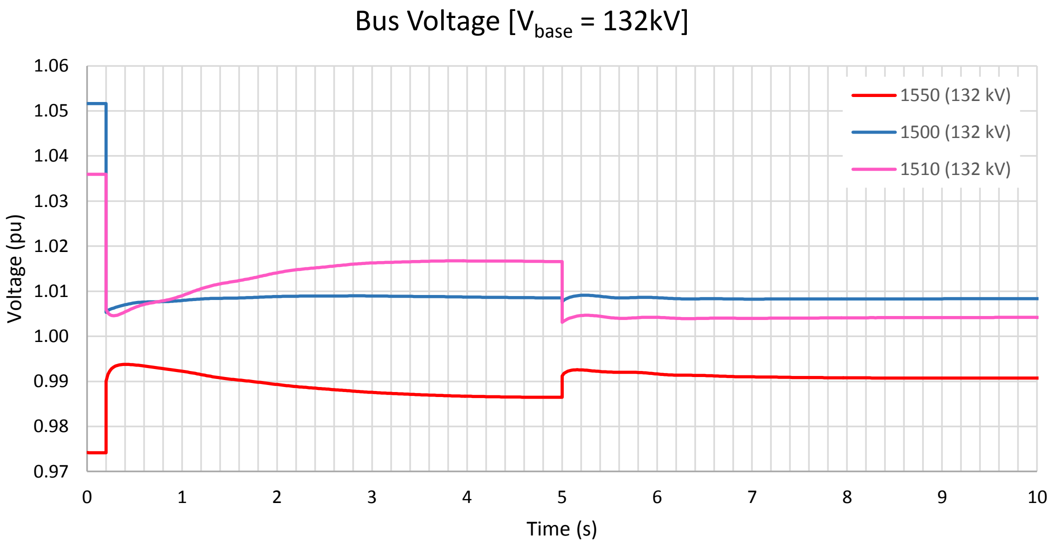

Figure 15 – Bus voltage behaviour during interconnection of Col. and Lax. Sub-systems

Study on voltage angle variation during the switching operations assessed the stability of buses and machines involved with feeding two regions as shown in **Figure 16** and **Figure 17**. Angles of the bus 1550 and bus 1500 were measured relative to their swing buses.

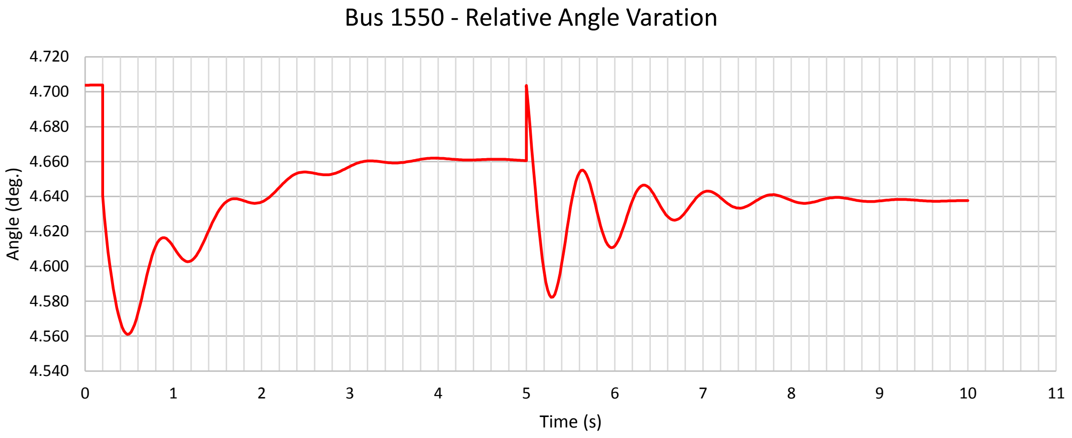

Figure 16 - Load Angle variation of Bus 1550 [Kolonnawa 132 kV]

The voltage angle of the bus 1550 shifted from approx. 4.7^{o} to 4.66 ^{o} after switching ON the first line. Thereafter, it further dropped to 4.64 ^{o} and stabilized.

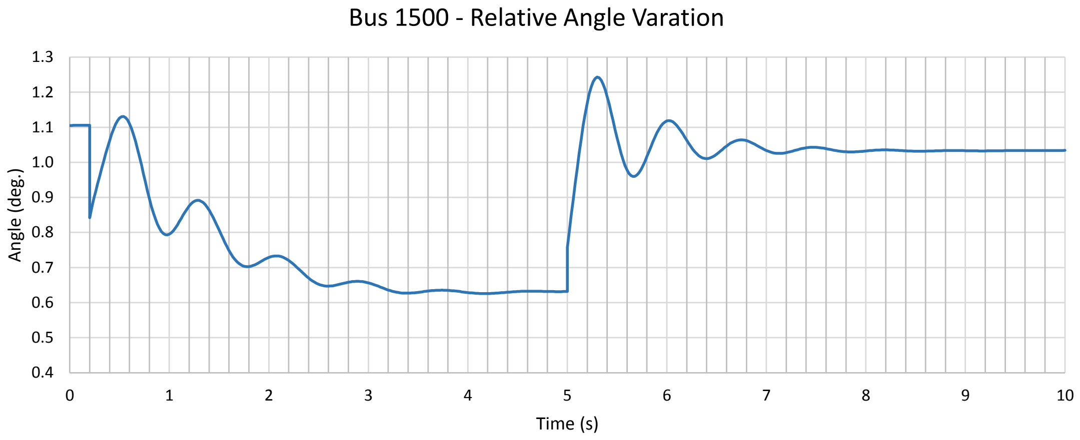

Figure 17 – Load Angle variation of Bus 1500 [Kosgama 132 kV]

The voltage angle of the bus 1500 shifts from approx. 1.1^{o} to 0.625 ^{o} after switching ON the first line. Thereafter, it rose to 1.045^{o} and stabilized at 1.45^{o}.

Bus frequencies have been found converging after the switching operations as shown in **Figure 18**.

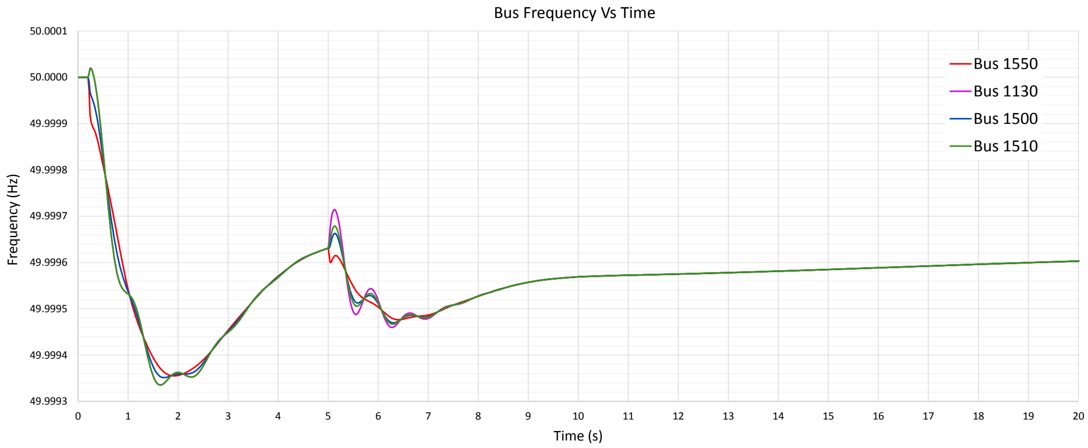

Figure 18 - Frequency variation of synchronizing buses

On the other hand, Rate of Change of Frequency (RoCoF) was also observed to avoid tripping by exceeding df/dt less than -0.85 (**Figure *19***). The estimated maximum $|df/dt|$ of 0.00230 Hz/s had occurred at first switching operation (t=0.2s).

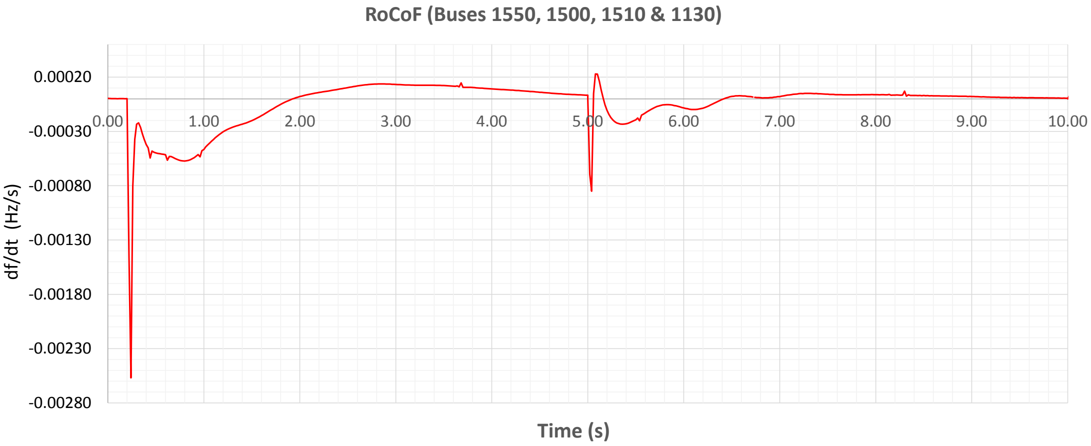

Figure 19 - Rate of Change of Frequency variation during Attempt 4

The predicted behaviour is informative for taking further decisions for adjusting the RoCoF setting or attempting an alternative path in the event of real blackout restoration process.

This chapter presented the system performances during each attempt with and without the aid of proposed decision support tool. The importance of individual element of the tool was brought to focus by considering sets of system controller decisions. Next chapter will highlight the conclusion of the research study.

Chapter Summary

This chapter carried out a detailed analysis on the results obtained from the case study. It highlighted the drawbacks of trial-and-error approach while marking the importance of each step in the proposed analytical approach. Next chapter will bring out the conclusions and future direction of the thesis study.

6 CONCLUSIONS AND FUTURE DIRECTIONS

6.1 Conclusions

In the event of blackouts, the SCC operators have a grave responsibility of restoring the PS within least possible time. Restoration plans become advantageous to lay guidelines to solve the complex problem. However, as each blackout have their unique identities, the operators are not convinced to follow them technically. This thesis presented analysis showing the effectiveness in following a decision support methodology when restoring the Sri Lankan power system after a blackout.

This study demonstrated that a detailed investigation of the steady state and dynamic securities of the next state is required before adding subsequent loads and generators into the system. It was shown that some trial decisions can lead the next state of the power system to an insecure steady state. In that regard, it is important to perform load flow analysis and observe the line voltages, line loadings, frequency and also the generator capability. Further, transient stability studies are also playing an equally major role before executing the restoration decision.

The case study showed that although a part of the Colombo loads could be restored, the frequency controlling BS generator was found susceptible to trip by exceeding stator current limits. It was proven that the commonly practiced trial and error approach has a likelihood of cascaded failing during restoration.

All the aspects of proposed methodology is vital to avoid unexpected tripping. The importance of observing the transmission line load percentages were proven when a 132 kV line was estimated to overload by controller decision.

With the complete proposed decision support methodology, it was demonstrated that the Colombo-Kelanitissa system could be restored safely and could be synchronized with the simultaneously restored Laxapana subsystem.

With evolving computer and networking technologies, load prediction studies and more accurate PS parameters, restoration decision support programs run in parallel could efficiently assists the operators to forecast the next system state. Computer languages (like Python) could be used to retrieve data from PS simulation software while SCADA systems could update system parameters and component availability information.

6.2 Future Directions

6.2.1 Blackout Restoration in Sri Lanka

With the evolution of SL power system, more complex restoration problems are prone to take place. While the generation planning teams are preparing for increase of maximum demand with load forecasts, transmission system improvement projects are ensuring PS security. In the meantime, blackout restoration plans are being modified in order to face imminent blackouts. Yet, the post-outage system status becomes unique each time and system status during restoration becomes vaguer.

But with advancements of SCADA capabilities in 2018, SCC could resolve blackouts more efficiently if fast and secure restoration decisions are clearly identified. The proposed methodology could be implemented as a platform where concurrent computer programs running in parallel with power system simulators. To enhance more realistic outputs, following inputs shall be fetched more accurately.

- Post-outage system configuration
- Post-outage equipment availability (including operability of healthy equip.)
- Intelligent load forecasts
- Revised dynamic parameters of machines
- Transmission line parameters
- Revised Generator Reactive Capability curves
- Protection settings of all units

Due to lack of maintenance or inherent failures after long inactive periods of station equipment (battery bank, control switchgear, etc.), they become unresponsive during the attempts of system restoration. Therefore, modification of maintenance plans to prepare all system equipment to contribute a restoration will be significant.

With the collaboration of engineering expertise, revised system data, modern flexible software platforms, effective algorithms, SCADA system integrated with decision support methodology, restoration after blackouts could be shifted to the next level.

6.2.2 Impact of future Renewable Energy penetration on restoration

The complexity of power system has been changing over the past decade with the introduction of renewable energy (RE) sources market such as Wind and Solar to the electricity market. Solar energy integration is implemented as utility-scale solar and rooftop solar photovoltaic (PV) installations. The uncertainty and variability characteristics of connected RE sources are transforming the restoration problem more challenging. Some key challenges are:

- Variable output from RE units contribute to fluctuating generation-load imbalances and hence frequency variations
- Acquiring knowledge on regulations (voltage, frequency protection settings) of individual RE installation and disparities among each installation over the time
- When RE operate under same regulation, frequency deviations trigger them to connect or disconnect during restoration period
- Absence of remote controlling for embedded generations (EG). They operate autonomy while the only available control is disconnection of feeder

The advancements of technology and research could address these challenges in a newer direction. Approaches for restoration has become more widening with the algorithmic optimizations in microgrids and distributed generation comprising RE. [25][26][27]

Therefore, requirement of customized and modified decision support tools will be mandatory in solving future restoration problems while maintaining system stability. The proposed generalized methodology can be adopted to assist the system operators even during such complex blackout restoration processes.

Publications

L. Sirisena, D. Prasad and R. Fernando, "Development of Generalized Methodology for Blackout Restoration: A Case Study of Sri Lankan Power System", 112th Annual Sessions IESL, 2018. (Under Review)

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