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Advances in RAMS Engineering

In Honor of Professor Ajit Kumar Verma on His 60th Birthday

Springer

Springer Series in Reliability Engineering

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Hoang Pham, Department of Industrial and Systems Engineering,
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Dedication

To

Professor Ajit Kumar Verma, our dear teacher, a philosopher, friend, and guide to his students on the occasion of his sixtieth birthday the 10th December, 2019.

Brief Profile

He was educated at IIT Kharagpur and he taught at IIT Bombay as a Professor in Reliability Engineering/Electrical Engineering for around 15 years and is now with the Western Norway University of Applied Sciences as Professor (Technical Safety) for almost 8 years. He has co-supervised/supervised 39 Ph.D. students and around 100 Master's students. He has been the founding EIC of International Journal of System Assurance Engineering and Management, the EIC of Life Cycle Reliability and Safety Engineering, and has been in editorial capacity with several journals including being the EIC of Opsearch several years back, all published by Springer, besides being the Series Editor of three-book series published by Springer and associated with numerous books either as an author or an editor. His senior collaborators include Prof. Lotfi Zadeh, Prof. Roy Billinton, Prof. Osaki, Prof. Uday Kumar, and Prof. P. K. Kapur among others. He learnt Yoga in his early student days from the Bihar School of Yoga and taught Yoga through various workshops in India and abroad. His interests were greatly influenced by his spiritual mentors Paramhamsa Swami Satyananda Saraswati, a legendary Yogi and Bhagwan Sri Sathya Sai Baba of Puttaparthi and felt his life to be spiritually connected and touched by them. A significant part of his spare time in his life at IIT Bombay was spent in learning along with his wife, Prof. A. Srividya, the esoteric practices of Srichakra upasana from his Guru, Sri Jairamanji who had dedicated his life in teaching and initiating these mystical traditions for its continuity. An avid trekker in the Himalayas, he has led and trekked at high altitudes during the past three decades in the Himalayas in India, Nepal, and Tibet and has lectured extensively on Indian mysticism and Kundalini Yoga. He had been closely associated and coordinated various Devi Padmavathy temple activities and was a coordinator of NSS activities for many years at IIT Bombay. His mother was fond of him but his parents are no more. His son Amardeep and his two brothers Ranjit and Pradeep work and live in India. His wife Srividya accompanies him in Norway.

Foreword

I am pleased to write the foreword for this well-edited book on Advances in Reliability, Availability, Maintainability, and Safety (RAMS) Engineering. Contributed chapters in the book cover latest trends as well as applications to various fields including nuclear engineering, software engineering, power systems engineering, and mechanical engineering. The chapters have succeeded in achieving a fine balance between the theory and practice.

I am indeed delighted to know that this book was brought on a special occasion of 60th birthday of my dear friend Prof. Ajit Kumar Verma, who has contributed immensely to the field of reliability and safety. He truly deserves this special honor and tribute by some of his former Ph.D. students and collaborators.

Advances in safety assessment of nuclear power plants, maintenance aspects of complex engineering systems, and reliability of power systems are some of the highlights of the book. I am sure that students, research scholars, scientists, engineers, and practitioners of safety and reliability engineering will greatly benefit from this book.

I strongly recommend this book for its comprehensive coverage on the advances of reliability and safety engineering and their practical applications.

Many best wishes to you, Prof. Ajit Kumar Verma, on your 60th birthday!

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Preface

Reliability, Availability, Maintainability, and Safety (RAMS) engineering is attracting ever-increased attention in the era of Industry 4.0, fuelled by digitalization, Internet of things, and artificial intelligence. RAMS tasks inevitably appear throughout life cycle of engineering systems, ranging from concept phase to decommissioning. Typical RAMS activities include apportionment of RAMS requirements, evaluation of design alternatives, hazard analysis, maintenance planning, operator support systems, RAM demonstration, safety assessment, etc. These activities significantly contribute to efficient and economical design and operation of systems as well as supports homologation and regulation.

Ever-increasing complexity of today's engineering systems requires multidisciplinary expertise. This book presents advances in RAMS analysis for several engineering disciplines including software engineering, electrical and electronics engineering, civil and mechanical engineering, chemical engineering, and nuclear engineering. This book presents practical applications from the various industries including software, electrical and electronic, nuclear power plants, process and chemical plants, railways, etc. The book is organized as follows:

Chapters "DC and AC Contingency Solvers in Composite Power System Adequacy Assessment" to "Reliability Considerations in Analysis of Tunnels in Squeezing Rock" cover advances in reliability and availability of engineering systems; chapters "Integrated RAMS, LCC and Risk Assessment for Maintenance Planning for Railways" to "Fuzzy Logic Based Analysis of Dissolved Decay Contents in Transformer Oil" focus on maintainability; and chapters "Probabilistic Safety Assessment in Nuclear and Non-nuclear Facilities: In a Glimpse" to "Integrated Deterministic and Probabilistic Safety Assessment" are on safety engineering. Power systems and electrical/electronic systems reliability are addressed in chapters "DC and AC Contingency Solvers in Composite Power System Adequacy Assessment" to "Fatigue Life Model for PLCC Solder Joints Under Thermal Cycling Stress". Chapters "An Integrated Approach of BOCR Modeling Framework for Decision Tool Evaluation" to "The Unpopularity of the Software Tester Role Among Software Practitioners: A Case Study" emphasize software reliability, followed by focus on mechanical and civil engineering in chapters “A Study on Reliability of Rotors Using XLrotor” to “Reliability Considerations in Analysis of Tunnels in Squeezing Rock”. An overview of these chapters is presented below.

Reliability and Availability

Application of probabilistic methods in power system reliability studies—both at the generation level and at the composite (generation plus transmission) level—is a highly developed field with plenty of available literature. Adequacy assessment studies deal with the evaluation of whether the generation capacity of a system is sufficient to supply the load requirement of the system. Chapter “DC and AC Contingency Solvers in Composite Power System Adequacy Assessment” elaborates on both DC and AC contingency solvers used in composite power system adequacy studies.

Reliability analysis is crucial for the design and maintenance of a microgrid system. In chapter “Reliability Analysis of Microgrid Systems Using Hybrid Approaches”, few hybrid techniques are proposed to assess failure probability and reliability of microgrid system. Hybrid approaches are presented using both fault tree analysis (FTA) and binary decision diagram (BDD) to evaluate performance of a microgrid system.

Chapter “Reliability Prediction of Instrumentation and Control Cables for NPP Applications” deals with the methods and models developed toward determination of the reliability of instrumentation and control (I&C) cables used in nuclear power plants (NPPs). Several reliability prediction methodologies based on performance indicators were developed from analytical and experimental approaches. Chapter “Reliability Prediction of Instrumentation and Control Cables for NPP Applications” demonstrates these methodologies with the accelerated life testing data obtained under thermal and radiation aging, and also from the data from literature.

Solder joints are inevitable part of assembly of an electronic system. Life cycle stresses affect the integrity of these contacts and lead to jeopardizing of its functions and in turn to failure of system. Life estimation of solder joints is important to predict the time to failure and take countermeasures. Chapter “Fatigue Life Model for PLCC Solder Joints Under Thermal Cycling Stress” addresses this issue by specializing an established empirical model for fatigue failure, Coffin-Manson, for a PLCC solder joint using experimental data.

Chapter “An Integrated Approach of BOCR Modeling Framework for Decision Tool Evaluation” illustrates an analytical methodology representing benefits & opportunities (BO), and latter costs & risks (CR) BOCR models. The modeling has been carried out in the combination of appropriate analytical models and suitable data aggregation techniques. The proposed framework is illustrated by two case studies. The first case study illustrates a holistic model in the context of prototype dependability assessment of software at the prototype level. The second case study demonstrates a model validation quantitatively for quality of services (QoS) for real-world SOA-based applications.

IT is backbone of modern business in the digital world, which is increasingly becoming complex, due to disruptive technologies and co-existing with legacy applications. Chapter “DevOps for IT Service Reliability and Availability” discusses DevOps framework, practices across the software development life cycle. The impact of DevOps practices to improve software reliability and availability will be discussed with metrics that are available. The chapter will provide practices for reliability and availability improvement.

Software testing is one of the crucial supporting processes in software development. Unfortunately, the role is stigmatized partly due to misperception and partly due to the treatment of the role in the industry. Chapter “The Unpopularity of the Software Tester Role Among Software Practitioners: A Case Study” aims to analyze the situation exploring what limits an individual from taking up a testing career, in a way that exposes actual reactions to this role in the software industry.

Chapter “A Study on Reliability of Rotors Using XLrotor” is focused on computation of rotating machines in XLrotor in order to predict the failure due to disk offset and to check reliability. Reliability of rotary machines is not only dependent on static design stress but also dynamic forces generated during operating speeds. To check reliability of rotating machines, the XLrotor computational tool is considered optimum in incorporating the effect of mass, stiffness, inertia & imbalance effectively. The simulation-based methodology is used for modeling and analysis for the simple & complex rotors. The vibration results determine the impact of disk offset on rotor model and its performance.

Most of the advanced nuclear reactors implement passive systems for better safety and availability in order to reduce human error and active component malfunctions. Reliability of the passive systems degrades with time due to aging, random/stochastic loading or strength degradation. Hence, it is very important to evaluate the passive system reliability by considering both static and time variant analysis. Chapter “Time Variant Reliability Analysis of Passive Systems” deals with these aspects.

Underground openings and excavations are increasingly being used for civilian and strategic purposes all over the world. Evaluation of safety of a tunnel, especially a non-conforming one, in soft ground or poor rock mass needs an interactive analysis. Interaction is an issue of great relevance in the case of tunnels in lower Himalayas. Chapter “Reliability Considerations in Analysis of Tunnels in Squeezing Rock” evaluates tunnel safety and stability through reliability analysis under squeezing conditions.

Maintainability

Chapters “Integrated RAMS, LCC and Risk Assessment for Maintenance Planning for Railways” to “Fuzzy Logic Based Analysis of Dissolved Decay Contents in Transformer Oil” cover advances in maintainability engineering.

As of today, about 70% of the transportation infrastructure has already been built for the needs of customers, business, and society, where Railways is the major infrastructure. Due to the hierarchical nature of Railways, it is necessary for railway infrastructure managers to design a generic framework for the decision-making process when planning maintenance and interventions, which is an important functional block of asset management in railway infrastructures. Chapter "Integrated RAMS, LCC and Risk Assessment for Maintenance Planning for Railways" proposes an integrated methodology to perform maintenance decision-making using definitive "building blocks", namely, Reliability, Availability, Maintainability, and Safety (RAMS), Life Cycle Costing (LCC), and risk assessment.

Rapid developments in technologies such as robotics, digital automation, Internet of things, and AI have heralded the Fourth Industrial Revolution, commonly referred to as Industry 4.0 (i4.0). Industrial operations and products have since become more competitive and hence more demanding. Chapter "Implementation of Predictive Maintenance Systems in Remotely Located Process Plants under Industry 4.0 Scenario" highlights the need for identifying the needs of condition monitoring preparedness of process plants located in remote places, especially in a logistic sense. Issues related to assessment of the need for the new paradigm in condition monitoring, challenges faced by such plants in the transition from legacy systems to a new system, and customization and optimization of predictive maintenance under Industry 4.0 (PdM 4.0) have been discussed.

Unexpected failure of any component of the system may increase the maintenance and downtime cost due to unavailability of the system. A methodology using mathematical modeling facility of fuzzy set theory is presented in chapter "Application of Fuzzy Sets in Reliability and in Optimal Condition Monitoring Technique Selection in Equipment Maintenance", which is effective in situations wherein the data available is mostly subjective and it is difficult to get precise quantitative data. Multi-attribute decision-making methods with application to ranking and optimal condition monitoring technique selection from maintenance engineering domain is highlighted.

Chapter "Fuzzy Logic Based Analysis of Dissolved Decay Contents in Transformer Oil" presents a fuzzy logic methodology based on statistical techniques to monitor, diagnose, and predict the health index of electric transformer using furanic contents. This is to address transformer condition monitoring, ensuring good health, safety of operation, and maintenance.

Safety

Chapters "Probabilistic Safety Assessment in Nuclear and Non-nuclear Facilities: In a Glimpse" to "Integrated Deterministic and Probabilistic Safety Assessment" address advances and applications in safety engineering.

Chapter "Probabilistic Safety Assessment in Nuclear and Non-nuclear Facilities: In a Glimpse" presents a glimpse of probabilistic safety assessment (PSA) of nuclear and chemical facilities. An overview of PSA methodology in nuclear industry is given, followed by several applications in safety informed decision-making. PSA process steps in chemical industry are explained as well as its application in risk-based inspection of a chemical plant is demonstrated.

Chapter "Passive System Reliability Assessment and Its Integration into PSA" describes most widely used methods for Passive system reliability analysis and present an approach for its integration into PSA by modeling one of the operational transients, normally expected to occur in a typical nuclear power plant.

Chapter "Project Stage Considerations for an Inherently Safe and Reliable Chemical Plant" examines the factors that influence eventual safety-operability-reliability of a chemical manufacturing unit, right at the inception and execution stage. The relevant tools and practices used in the chapter are Engineering Project Process, Process Risk Assessment and management methods like Hazard and Operability (HAZOP) methodology, Layers of Protection Analysis (LOPA), Safety Integrity Level (SIL), and management of change.

Chapter "Integrated Deterministic and Probabilistic Safety Assessment" introduces the concept of integrated deterministic and probabilistic safety assessment (IDPSA), highlights benefits as well as its limitations. Challenges to these approaches include modeling of dynamic interactions among physical process, safety systems, and operator actions as well as propagation of these model uncertainties. Case study on a medium loss of coolant accident in a nuclear power plant is presented, which focuses on a comparison between IDPSA and traditional PSA considering impact of accident dynamics.

This book is useful for advanced undergraduate and postgraduate engineering students of electrical, electronic, information technology, mechanical, nuclear, and chemical disciplines. It will provide a good reference for research scholars of reliability and safety engineering, industrial engineering, and system engineering. Practicing engineers and safety managers will get an overview of latest trends in RAMS engineering.

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Mumbai, India Gopika Vinod
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October 2019

Durga Rao Karanki
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Contents

Reliability and Availability Engineering

Maintainability Engineering

Safety Engineering

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Reliability and Availability Engineering

DC and AC Contingency Solvers in Composite Power System Adequacy Assessment

Øystein Stake Laengen and Vijay Venu Vadlamudi

Application of probabilistic methods in Power System Reliability (PSR) studies—both at the generation level (also known as Hierarchical Level (HL) I) and at the composite (generation plus transmission) level (also known as HL II)—is a highly developed field with plenty of available literature. Such application has widespread applications in the planning, operation and management of power systems. Adequacy assessment studies, a subset of PSR studies dealing exclusively with static conditions of a power system, in their simplest form, deal with the evaluation of whether the generation capacity of a system is sufficient to supply the load requirement of the system. Other considerations can also be included in the assessment, such as whether the transmission and distribution facilities of the system can provide sufficient energy transportation from the generating facilities to the end consumers. Methodologies—both analytical and simulation-based—for the quantification of power system adequacy through indices such as Loss of Load Expectation (LOLE) and Expected Energy Not Served (EENS), are well established. However, there is a much felt need for more transparency and pedagogical clarity in the exposition of methodologies for assessing power system adequacy at the composite level. More importantly, details surrounding the contingency solvers for composite system state evaluation need elaboration so that it is easier to replicate the results of research works related to the assessment of power system reliability. This chapter elaborates on both DC and AC contingency solvers used in composite power system adequacy studies.

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1 Composite System Adequacy

In the adequacy assessment studies at the composite level of a power system, simply termed as composite power system adequacy assessment [1–7], there is a need for a model representing the network topology in addition to the load and generation models. The evaluation at HLI is limited to a comparison of the generation capacity against the load requirement, while the composite system assessment depends on a load flow based analysis. Therefore, a choice should be made regarding the desired accuracy of the load flow analysis. A simplified approach is to use a DC-based load flow analysis, but if more accurate results are desired, a full AC-based load flow analysis should be used. Whichever the analysis of choice, additional network data[1] must be supplied as input. More specific generation and load data are also needed where allocation of generation capacity and load requirement among the buses is specified.

Both analytical methods and Monte Carlo Simulation (MCS) methods include the step of the evaluation of system states; the selection of system states is done by some suitable contingency selection criterion [1–4] in the analytical methods, whereas in the case of MCS methods, a suitable sampling method is used. If considering the MCS, the two popularly used methods are state sampling method and state transition sampling method.

The system states are evaluated by the use of two different contingency solvers, one based on DC-load flow analysis and another based on AC-load flow analysis (Note that these are all easily implementable in MATLAB). The proposed methodology of constructing the solvers is presented in the following sections, with a section describing the general parts that are similar for both the DC and AC solvers. Thereafter, both contingency solvers are presented in detail. The explanation for solvers is given with the consideration of the selection of system states using MCS sampling methods. For fundamental details of the two popular sampling methods, the reader is referred to [3, 7].

1.1 General Elements

There are some general elements common for the two contingency solver approaches, AC and DC, proposed in this chapter. Both methods depend on input data in a specific format. For example, through MCS sampling the system state of a given time increment is obtained and handed over to the contingency solver for further evaluation. Thus, a specific format of input data to solver, e.g., the system state is needed.

---

[1] Network topology, impedances and current limits of the lines.

1.1.1 Input Data

A representation of the network data format used by the MCS state sampling method for full AC analysis is shown in Table 1. Per unit (p.u.) system of units is used for line parameters and line limits. If the load flow analysis is based on DC, the columns of the resistances and shunt susceptances are left out. The MCS state transition method uses a similar format except that the Forced Outage Rate (FOR) column is replaced by two columns, one for the failure rates and one for the repair rates.

For the AC based analysis to be conducted, reactive power capabilities of the generators must be added to the generator input data. Thus, the specified format used by the MCS state sampling method is presented in Table 2, where the minimum and maximum values of the reactive power capability of each generator are specified. If the MCS state transition method is used, the FOR column is replaced by two transition rate columns. The DC based analysis uses similar input, without the columns of reactive power capabilities.

An additional table specifying the specific bus data of the system is also included as input. Both the AC and the DC solvers need one column specifying the allocation of loads in the system and one column where the cost of load curtailments at each bus are specified. For the AC- analysis, the minimum and maximum voltage limits of the buses are included as well. The format used by the AC solver is presented in Table 3.

1.1.2 System State

A system state of a time increment is sampled through MCS sampling, giving the states of the generators and lines as two vectors. Each component state is given by a

Table 1 Line input data, state sampling AC-solver

Line	From Bus	To Bus	FOR	Resistance [p.u.]	Reactance [p.u.]	Half of shunt susceptance [p.u.]	Current limit [p.u.]
1	1	2	FOR_1	R_{12}	X_{12}	y_{10}	$Ilim_1$
2	2	3	FOR_2	R_{23}	X_{23}	y_{20}	$Ilim_2$
n	5	6	FOR_n	R_{56}	X_{56}	y_{50}	$Ilim_n$

Table 2 Generator input data, state sampling AC-solver

Generator	Capacity [MW]	Bus #	Min reactive [MVAr]	Max reactive [MVAr]	FOR
1	$P_{cap,1}$	N_1	$Qmin_1$	$Qmax_1$	FOR_1
2	$P_{cap,2}$	N_2	$Qmin_2$	$Qmax_2$	FOR_2
n	$P_{cap,n}$	N_n	$Qmin_n$	$Qmax_n$	FOR_n

Table 3 Bus specification, AC-solver

Bus	Share of load	Vmin [pu]	Vmax [pu]	Interruption cost [$/kWh]
1	Load_1	Vmin_1	Vmax_1	Cost_1
2	Load_2	Vmin_2	Vmax_2	Cost_2
n	Load_n	Vmin_n	Vmax_n	Cost_n

binary value [0, 1], termed X_i, where a value of zero denotes an available component and a value of one denotes that the component is unavailable. Thus, the vectors giving the states of the n generators and the m lines are of formats presented in the following.

$$P_g = [X_1 \quad X_2 \quad \ldots \quad X_n]^T \tag{1}$$

$$L = [X_1 \quad X_2 \quad \ldots \quad X_m]^T \tag{2}$$

Due to the allocation of generators at different buses of the system, the generator capacities at each of the k buses can be combined, according to their state given from (1) and their rated capacity, to give the bus generation capacities. Thus, the system's generation capacity can be represented by a generation capacity vector with k elements for the DC approach.

$$P_{g,\mathrm{lim}} = [P_{cap,1} \quad P_{cap,2} \quad \ldots \quad P_{cap,k}]^T \tag{3}$$

For the AC approach, the generation capacity vector is extended to a matrix with three columns, which give the respective active power, minimum reactive power and maximum reactive power capabilities of the buses.

$$G_{\mathrm{lim}} = \begin{bmatrix} P_{cap,1} & Q_{min,1} & Q_{max,1} \\ P_{cap,2} & Q_{min,2} & Q_{max,2} \\ \vdots & \vdots & \vdots \\ P_{cap,k} & Q_{min,k} & Q_{max,k} \end{bmatrix} \tag{4}$$

In addition, the load requirement allocation among the k buses of a system is needed. Hence, the active power load requirement is represented by a load vector of k elements for the DC approach.

$$P_{load} = [P_{load,1} \quad P_{load,2} \quad \ldots \quad P_{load,k}]^T \tag{5}$$

For the AC approach, the load requirement vector is extended with an additional column giving the reactive power requirement of the loads at the buses.

$$P_{load} = \begin{bmatrix} P_{load,1} & P_{load,2} & \cdots & P_{load,k} \\ Q_{load,1} & Q_{load,2} & \cdots & Q_{load,k} \end{bmatrix}^T \quad (6)$$

1.1.3 Isolated Buses

A possible situation that might arise during the selection of system states is the occurrence of multiple lines on outage at the same time. This might lead to isolation of one or more buses or parts of the system being islanded, depending on the number of outages and where they occur. If the developed load flow analysis tools lack a part that detects and handles the isolation of buses properly, the load flow problem becomes infeasible, due to the inclusion of isolated buses in the matrix representing the system, i.e., bus admittance matrix, Ybus. Among the problems encountered can be the nonexistence of an inverse admittance matrix. A point worth noting regarding the development of a suitable algorithm, is that a system of small size does not necessarily reveal the limitations of a proposed algorithm, which might become evident only when the approach is applied to a test system of larger size. The decision strategy on how to handle possible isolation of buses used by the *contingency solvers* presented is presented in the following:

Step 1: When the state of a line is sampled as a failure, i.e., outage, the admittance of the line is set to zero.

Step 2: When an isolated bus is identified, the elements corresponding to that bus are removed from the matrices and vectors representing the system. This step ensures that the optimal power flow (OPF) problem remains solvable.

Step 3: After the identification of isolated buses and the subsequent matrix modifications, the load curtailments due to the isolation of buses are given according to the following criteria:

(a) The slack bus of the system, i.e. bus 1[2] is the only bus able to operate in islanded mode.

  (i) If the slack bus is isolated from the rest of the system, all loads are shed in the system except from the loads at the slack bus.
  (ii) The generators at an isolated bus are not able to provide the load requirement at the bus.

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[2] The slack bus of the system must always be bus number 1 for the approach to be valid. If the slack bus of the system has a different original number, the buses of the system must be given new numbers.

Table 4 The susceptance matrix of the RBTS

11	0	−11	0	0	0
0	3	0	−3	0	0
−11	0	19	0	−8	0
0	−3	0	3	0	0
0	0	−8	0	17	−8
0	0	0	0	−8	8

1.1.4 Identification of Isolated Buses

The Roy Billinton Test System (RBTS) [8], is used as a simple example to show how isolated buses and possible islands can be identified through inspection of either the conductance or susceptance matrix. A case of islanding, i.e., isolation of bus 2 and bus 4 from the rest of the system, occurs if lines L3, L4 and L8 of the RBTS are on outage. The isolation can be identified by looking at the system's susceptance matrix presented in Table 4.

When investigating row two of the susceptance matrix, it can be identified that bus 2 has no connection to bus 1, but only a connection to bus 4. Further investigation of row 4 in the matrix reveals that bus 4 has a connection to bus 2 only. The other four buses of the system are interconnected. Based on the above observation, a simple approach is presented:

Step 1: Check for left-connectivity, i.e., examine whether the bus under consideration is connected to a bus with a lower number.

(a) Iterate from bus number 2 to the last bus [2, k].

  (i) For each bus under consideration, examine whether it is connected to a bus with a lower number.

  - If no, flag the bus under consideration as 'isolated'.
  - If yes, also check if the bus to which the bus under consideration is connected has already been marked as 'isolated'.
    - If yes, flag the bus under consideration as 'isolated'.

Step 2: Check the right-connectivity, i.e., examine whether the bus under consideration is connected to a bus with a higher number.

(a) Iterate from the last bus to bus number 2 [k, 2].

  (i) For each bus under consideration flagged as isolated from Step 1, examine whether it is connected to a bus with a higher number that is not flagged as isolated. If yes, the 'isolated' flag is removed for the bus under consideration. If no, the 'isolated' flag is retained.

However, the approach is found to be insufficient for more complicated system configurations, thus representing a possible pitfall. Even for the RBTS system, a

Fig. 1 The RBTS special case with outages

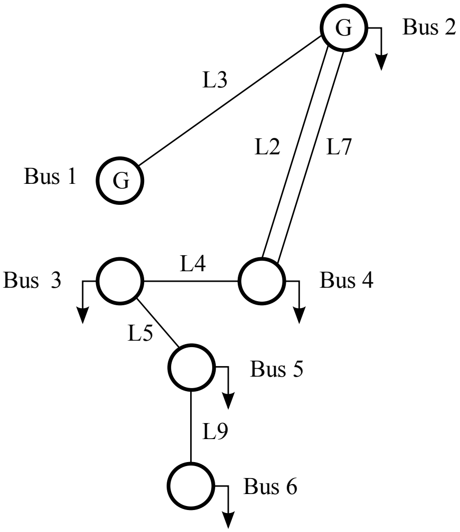


Table 5 Intermediate flags, RBTS case

Bus	Flag after step 1	Flag after step 2	Result
1	0	0	Not isolated
2	0	0	Not isolated
3	1	0	Not isolated
4	0	0	Not isolated
5	1	1	Isolated
6	1	1	Isolated

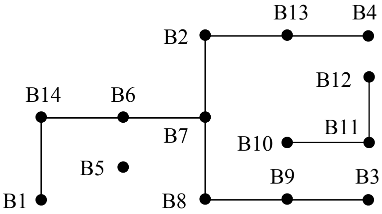
system of relatively small size, an error occurs if the approach is applied to the system configuration of Fig. 1 where lines L1, L6 and L8 are on outage.

If a thorough inspection of the algorithm's steps applied to the case of Fig. 1 is performed, it becomes clear that the algorithm marks buses 5 and 6 incorrectly as isolated. The intermediate results obtained by applying the algorithm step by step are presented in Table 5, where a one denotes an isolation flag.

When lines L1, L6 and L8 are on outage, a visual inspection of Fig. 1 shows that none of the buses is isolated. However, the algorithm has resulted in the incorrect isolation of buses 5 and 6. Thus, a limitation of the above presented bus isolation algorithm is revealed. Such a limitation is encountered when the outages of lines lead to the creation of new radials containing buses numbered in no particular sequence. An illustration of such a configuration where the bus isolation algorithm might encounter difficulties, is presented in Fig. 2, which is a sample illustration of a 14 bus system with buses (indicated as dots) numbered as B1, B2, B3,…… B14.

Based on the special configuration of the RBTS and the radial example of Fig. 2, a new more detailed algorithmic approach is proposed, with basis in the first suggested algorithm:

Fig. 2 Radial example



Step 1: Check the left-connectivity, i.e., examine whether the bus under consideration is connected to a bus with a lower number.

(a) Iterate from bus number 2 to the last bus [2, k].

  (i) For each bus under consideration, examine whether it is connected to a bus with a lower number.

   - If no, flag the bus under consideration as 'isolated'.
   - If yes, also check if the bus to which the bus under consideration is connected has already been marked as 'isolated'.
     - If yes, flag the bus under consideration as 'isolated'.
     - If no, check whether the bus under consideration is directly connected to any of the other buses with lower numbers that have already been flagged as isolated.

       If yes, clear the flags of all the buses that are directly connected to the bus under consideration.

Step 2: Examine whether the bus under consideration is connected to any other another bus. To ensure that none of the buses are incorrectly marked as isolated after finalization of step 2, the step is started over again if a special combination occurs; the bus is cleared from its isolation flag and leads to the clearing of additional buses' flags.

(a) Iterate from the last bus to bus number 2 [k, 2], iterator m.

  (i) For each bus under consideration flagged as isolated, examine whether it is connected to another bus.
  (ii) If a connection is found, clear the flag of bus m.

    (1) Iterate from bus number 2 to bus k [2, k], iterator n.

      - If bus n is flagged as isolated and a connection to bus m exists, clear the flag of bus n.

    (2) If one or more flags are cleared during the loop by iterator n, Step 2 is restarted from the beginning with iterator m starting from the last bus.

The importance of including a restarting of the algorithm's Step 2 becomes clear by applying the new suggested algorithm step by step on the radial example of

Table 6 Radial example for identification of isolated buses

Bus	Step 1	Step 2 # stage 1	Step 2 # stage 2	Step 2 # stage 3	Step 2 # stage 4
1	0				0
2	1	(0)			0
3	1			(0)	0
4	1		(0)		0
5	1				1
6	1 (0)				0
7	1	0			0
8	1	1 (0)			0
9	1	1		0	0
10	1	1		1	1
11	1	1		1	1
12	1	1		1	1
13	1	1	0	0	0
14	0	0	0	0	0

Fig. 2. In Table 6, the obtained intermediate results are presented. The parentheses surrounding some of the numbers indicate a clearing of a flag in the inner loop of the algorithm, i.e., point a.(ii).(1) in Step 2 described above. Under the column ‘Step 1’ in Table 6, if an entry is ‘1’, it denotes an isolation flag; if one starts with an entry 1 for a bus, and ends with entry ‘0’ in the last stage (i.e., stage 4) of Step 2 due to the application of the algorithm above, it means that the bus that was flagged as isolated in Step 1 is deemed as ‘not isolated’ by the time Step 2 is finished.

1.2 DC—Contingency Solver

The considerations of the DC contingency solver are presented in this section. First, an introduction to the approximations and equations used to represent the system is made, before the OPF problem is formulated. The solver is then tested on a selection of system states, before a final example illustrating the details is given.

1.2.1 Network Model

In the DC based approach, the network is represented by the DC power flow formulations and approximations found in most available power system analysis text books, for example [9]. By using the assumptions of DC-power flow, it is possible to formulate the power flows through the lines as linear functions of the net power injections at the buses. The assumptions of the DC-power flow formulations are listed in the following:

(i) The resistance of a line is much smaller than its reactance ($r_{ij} << x_{ij}$).
(ii) The difference in voltage phasor angle between two interconnected buses is small. Thus, two reasonable approximations are to set the *sin* of the difference in phasor angle equal to the difference and the *cos* of the same difference equal to one[3] ($\sin \delta_{ij} = \delta_{ij}$ and $\cos \delta_{ij} = 1$).
(iii) The lines' susceptances to earth are neglected ($b_{i0} = 0$ and $b_{j0} = 0$).
(iv) The voltages are fixed at a magnitude of one p.u., ($V_i = 1$).

By using the stated assumptions, the power flow equations are simplified to expressions in terms of the lines' susceptances and the differences in voltage phasor angles between the buses.

$$P_i = \sum_{j=1}^{k} B_{ij}\delta_{ij} \text{ where } \delta_{ij} = \delta_i - \delta_j \tag{7}$$

where the susceptance elements, B_{ij} and $B_{ii,}$ are defined according to.

$$B_{ij} = b_{ij} = -\frac{1}{X_{ij}} \text{ and } B_{ii} = -\sum_{j=1, j\neq i}^{k} b_{ij} \tag{8}$$

The formulation of (7) is rewritten to matrix notation in (9), where the net power injection vector is expressed in terms of the susceptance matrix and the column vector of voltage phasor angles δ.

$$[P] = [B] \cdot [\delta] \tag{9}$$

A general view of the elements in the susceptance matric, B, is given in (10).

$$B = \begin{bmatrix} B_{11} & B_{12} & \cdot & B_{1k} \\ B_{21} & B_{22} & \cdot & B_{2k} \\ \cdot & \cdot & \cdot & \cdot \\ B_{k1} & B_{k2} & \cdot & B_{kk} \end{bmatrix} \tag{10}$$

The set of linear equations is singular, since one of the rows could be expressed as the linear combination of the other rows. To overcome the problem, the concept of a slack bus is introduced. The implication is that the row and vector elements corresponding to the slack bus, are removed from the susceptance matrix, giving a sub matrix **B′**. If the first bus is chosen as the slack bus, the corresponding sub matrix is defined by (11).

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[3] The angles must be expressed in radians.