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Chapter 4

Model Development for Analysis of Steam Power Plant Reliability

Bernard Tonderayi Mangara

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Abstract

The graph theoretical analysis and a graph's characteristic polynomial are deployed as the basis for a system approach employed to develop a model for estimating the reliability index and evaluating the availability index for a coal-fired generating power station. In this research, the coal-fired generating station system is divided into six sub-systems. Elementary to evaluating the reliability (estimate) of the said system is the consideration of all the sub-systems and their interrelations. Approximate reliability attributes of the graph are used to model the approximate reliability of the coal-fired generating station. Sub-system reliability is represented by the nodes in the graph, and the links represent the reliability of interrelations of these sub-systems. Computing a graph's characteristic polynomial using three different methods, namely, the linearly independent cycles, the figure equation and the adjacent matrix, the approximate reliability of the system is determined. Three methods are used, for comparison purposes, as estimating reliability is always an imperfect endeavour. The methodology proposed in this study is illustrated step-by-step with the help of examples.

Keywords: Reliability, coal-fired, steam, method, components

1. Introduction

Figure 1 shows the schematic diagram of a coal-fired generating station [1–3]. The energy conversion in a coal-fired generating station is as follows [1–3]. Coal is conveyed to a mill and the mill crushes the coal into fine powder, which is pulverized. Thereafter, the pulverized fuel is blown into the boiler where it mixes with a supply of pre-heated air for combustion. The said combustion of a mixture of pulverized fuel and pre-heated air in the boiler produces steam, at high temperatures and pressures, which is passed through the steam turbine. The boiler drives the steam turbine, which is coupled to the electricity generator. The generator then supplies the national electrical load. In spite of the advances in the design and materials in the last few

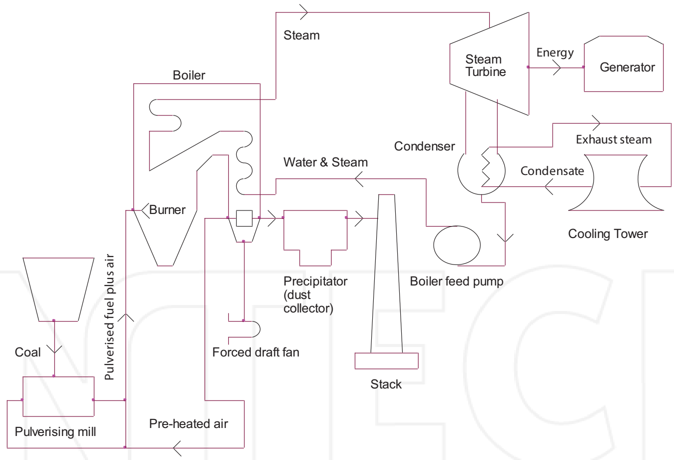

Figure 1. Schematic view of a coal-fired generating station.

years, the efficiency of the most modern coal stations is in the region of 40%. Therefore, the 60% of energy rejected as heat forms the exhaust steam from the low pressure turbine, which is cooled to form condensate by the passage through the condenser of large quantities of sea- or river-water. If the station is located inland or if there is concern over the environmental effects of raising the temperature of the sea- or river-water, cooling towers are then used.

Steam power-stations operate on the Rankine cycle [1]. The Rankine cycle, in a steam power-station, is modified to include super-heating, feed-water heating, and steam re-heating. To achieve high efficiency, the steam has to be used at maximum possible pressures and temperatures. Furthermore, for economic construction of turbines, the larger the size, the less the capital cost per unit of power output. Consequently, turbo-generator sets of 500 MW and more have been used. For steam turbines 100 MW and above, efficiency is increased by using an external heater to re-heat the steam, after it has been partially expanded. In addition, the re-heated steam is then returned to the turbine where it is expanded through the final stages of blading.

The study of reliability of complex systems such as steam power plants is of interest for power utility companies. This is so because the power utilities have to minimize operation and maintenance expenses while ensuring the reliability, safety, and security of supply to their national electrical load in order to remain competitive in the global market. In this study, complex systems are defined as large collections of interconnected components whose interactions lead to macroscopic behaviours [2, 3]. For complex systems, it is required to translate system reliability requirements into detailed specifications for all components that constitute the system. This process is often referred to as the reliability apportionment. During reliability apportionment, the reliability analyst has to perceive and develop the relationships between component, sub-system, and system reliabilities. The decisive role in this process is in understanding and quantifying the reliability importance of different parts of the equipment.

Steam power plant reliability encompasses a range of issues related to the design and analysis of these power plant generating networks. Furthermore, the said coal-fired thermal power plant components are prone to random failures. Generally, network models are comparatively simple, and yet quite generic. Varied applied problems of steam power plant environments can be modelled with networks [2, 3]. In the field of steam power plant reliability, the final goal of research is to provide design engineers with procedures to further improve the quality of designs whereupon reliability is a significant factor to take into account.

In this study, a system is defined as a bounded physical entity that achieves in its domain a defined objective through interaction of its components ([4], pp. 604). It follows from this definition of system that the following notation is going to be used for system reliability ([4], pp. 148):

Since the state variables $X_i(t)$ for $i = 1,\ 2,\ \ldots,\ n$ are binary, then

$$E[X_i(t)] = 0 \cdot \Pr(X_i(t) = 0) + 1 \cdot \Pr(X_i(t) = 1) = p_i(t), \quad \text{for } i = 1, 2, \ldots, n \tag{1}$$

Similarly the system reliability (at time t) is

$$p_s(t) = E\Big(\varnothing\Big(X(t)\Big)\Big) \tag{2}$$

It can be shown that when the components are independent, the system reliability, $p_s(t)$, will be a function of the $p_i(t)'s$ only. Hence, $p_s(t)$ may be written as follows

$$p_s(t) = h\Big(p_1(t), p_2(t), \ldots, p_n(t)\Big) = h\Big(p(t)\Big) \tag{3}$$

Unless stated otherwise, the letter h will be used to express system reliability in situations *where the components are independent*.

The size of the state space is one of the major impediments in steam power plant system reliability analysis. For a complex and large-scale power plant system, the number of system states is enormous. It can be noted that a system consisting of n components and each component with binary states (working or failed) has a total of 2^n states. For example, if one considers a case when n is 300, the number of states is 2.04×10^{90}. For the preceding example, if one would analyse all the possible states individually in order to identify the contingencies that help to bring about the system unreliability, this would require much computational effort. Furthermore, it would be impractical for typical steam power plants. Therefore, there is need to choose a methodology which reduces the state space, and a subsequent selection and evaluation of contingencies. The graph theoretical analysis (GTA) method [5, 6] is chosen for this study.

Graph theory is a branch of mathematics which has existed for many years not only as an area of mathematical study but also as a tool for intuition and illustration [7]. Graphs can be used in wiring diagrams to represent the physical elements of an electrical circuit; a street map is also a graph with the streets as links (edges), intersections of streets as nodes (vertices), and street names as labels of the links (edges). In the above-mentioned cases, the graphs resemble the physical objects that they represent. Thus, the application (and sometimes the genesis) of the graph-theoretic ideas is immediate. Computer program flow diagrams and road maps with one way streets are examples of graphs that contain the *concept of direction or flow to the links (edges)*; and these are called *directed graphs*. The applications of graphs and directed graphs in almost all areas of the physical sciences and mathematics have been known for half a century or more years [7]. In this study, graph-theoretic ideas are applied to some of the fundamental topics in power plant engineering. While there are many such applications, we shall focus on only using graph-theoretic ideas for estimating the reliability index and evaluating the availability index for a coal-fired generating power station.

Graph theory has been successfully used to model many different types of systems, inclusive of coal-based steam power plants [2, 3, 5, 6]. The GTA modelling requires the large and complex systems, such as the steam power plant network, to be reduced and divided into sub-systems for convenience of the analysis procedure. The GTA model simulates the inheritances and interdependencies of the sub-systems of the coal-fired generating station in addition to giving a quantitative measure of the system reliability. The GTA procedure is composed of three steps namely: (1) digraph representation; (2) matrix representation; and (3) development of a permanent structure function. The quantitative measure of the steam power plant system reliability enables the design engineer to determine the similarity or dissimilarity between the present reliability and the design value.

The GTA procedure is used here to model the entire system of a coal-fired generating station, as shown in **Figure 1**. The system is divided into six sub-systems $(N_i : i = 1,\ 2,\ \ldots.6)$ which are given below [2, 3]:

N1: The coal system;

N2: The boiler system;

N3: The steam turbine;

N4: The boiler feed pump;

N5: The cooling system; and

N6: The generator.

The identified and above-mentioned sub-systems for the steam power plant of **Figure 1** are displayed in **Figure 2** [2, 3]. The discourse on the said six sub-systems follows in Section2.

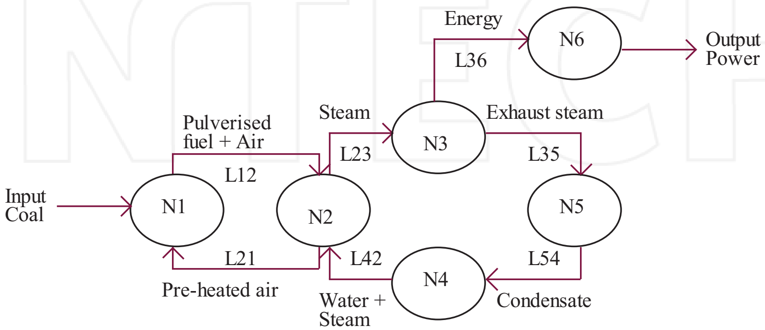

Figure 2. System structure digraph for a coal-fired generation station.

2. System structure function for the coal-fired generating station

In this research, consideration is made of systems of components that satisfy the following hypothesis ([2, 3], [4], pp. 123):

Systems that are composed of n components are denoted as systems of order n. The constituent components are assumed to be numbered consecutively from 1 to n. The study is confined to situations where it suffices to distinguish between only two states, a functioning state and a failed state. The preceding study limitation applies to each component as well as to the system itself. The state of component i, $i = 1, 2, \ldots n$ can then be described by a binary[1] variable (function) x_i, where:

$$x_i = \begin{cases} 1, & \textit{if component } i \textit{ is functioning} \\ 0, & \textit{if component } i \textit{ is in a failed state} \end{cases} \tag{4}$$

Then, vector $X = (x_1, x_2, \ldots, x_n)$ denotes the states of all components. Vector $X = (x_1, x_2, \ldots, x_n)$ is known as the component *state vector*. In addition, the assumption is that if one knows all of the n components' states, then it follows that they also know the state of the system, that is whether it is functioning or failed. The system state is determined completely by and is an inevitable consequence of the states of the components that constitute the system.

In a similar way, the system state can then be delineated using a binary function: $\varnothing(X) = \varnothing(x_1, x_2, \ldots, x_n)$, where:

$$\varnothing(X) = \begin{cases} 1, & \textit{if the system is functioning} \\ 0, & \textit{if the system is in a failed state} \end{cases} \tag{5}$$

and where $\varnothing(X)$ is called the *structure function* of the system or just the *structure* (e.g., the system structure digraph for a coal-fired generation station as shown in **Figure 2**). Each unique system corresponds to a unique structure function $\varnothing(X)$. Thus, one also talks about *structures* instead of *systems*.

The performance of a coal-fired generating power station is a function of its basic *structure* (i.e., the layout and design), availability, safety and security, dependability, and other regulatory aspects. Availability here is defined as the ability of an item (under combined aspects of its reliability, maintainability, and maintenance support) to perform its required function at a stated instant of time or over a stated period of time (BS 4778) ([4], pp. 599). Understanding of its *structure function* will help in the improvement in performance, design, and maintenance planning. A mathematical model using the graph theory and matrix method is developed to evaluate the performance of a coal-based steam power plant in the subsequent sections.

[1]In this context a binary variable (function) is a variable (function) that can take only the two values, 0 or 1.

3. Graphical representation of the coal-fired generating station

In general, networks are any systems which admit abstract mathematical representations as graphs. The nodes (vertices) of these networks indicate these systems' components [2, 3]. The occurrence of a relation or intercommunication in the midst of the components in these networks is represented by the set of connecting links (edges). It can be noted that the preceding high level of abstraction can, in general, be applied to wide-ranging systems. Consequently, within that sense, a theoretical framework is provided by networks. This theoretical framework enables convenience of conceptual representation of system relations in which characterization at system level provides for component interactions mapping.

The thermal power plant system as shown in **Figure 1** is represented in the form of a graph $G = (N,\ L)$ of **Figure 2**, where N is the set of nodes (or vertices) and L the set of links (or edges) [2, 3]. Let each of the six sub-systems of the generating station be denoted by nodes $N_i's(i = 1,\ 2,\ \ldots.\ 6)$, and the interconnection between the systems (N_i, N_j) is represented by links $L_{ij}'s\ (i, j = 1,\ 2,\ \ldots.\ 6\ and\ i \neq j)$ joining nodes N_i and N_j. The flow of heat and energy, steam, water, pulverized fuel, and pre-heated air connects all the six sub-systems. Nodes and links aid in illustrating this flow in **Figure 2**. When the thermal power plant is graphically represented, this then is termed as the system *structure* function (i.e., as discussed in Section2) [2–4].

When the links (arcs/edges) can be traversed in both directions, the graph is undirected. On the other hand, the graph is directed if the links (arcs/edges) can be traversed only in one direction indicated by an arrow. If an undirected graph has no self-loops the presence of at least one link per node guarantees that all the nodes are connected [2, 3]. Practical structures are in general substantially more connected as compared to this minimal threshold. Consequently, there exist numerous paths between any node pair. For directed graphs, the connectivity property is unwieldy because the nodes can relate to any of the following three of categories: (1) the nodes that are strongly connected (i.e., for this subset the nodes can be arrived at from any other node that is a member of the subset. The access is through following the direction of the links); (2) the transient nodes that only have outgoing links. Therefore, transient nodes cannot be accessed from any other node; and (3) the absorbing nodes that only have ingoing links. Thus, once reached, the absorbing nodes cannot be left [2, 3].

The main intuitive and illustrative tool to be used, for the coal-fired generating station system structure function, is the directed graph [2, 3]. Intuitively the directed graph can be considered as a set of points (or vertices/nodes) with arrows (or arcs/links/edges) joining some of the points [7]. An arc may be labelled. Conventionally, a digraph consists of a set of vertices (nodes/points), V(N) and a subset of ordered pairs of arrows called the arcs (links). The labelling of the digraph is a function from the arcs (links) to the real numbers. One can visualize a labelled digraph by considering the vertices (nodes) as points with arcs (links) as arrows going from vertex (node) i to vertex (node) j whenever (i, j) belongs to the sets of arcs (links). The ith vertex (node) of the arc (link) (i, j) is called its initial vertex (node), while the jth vertex (node) is called its terminal vertex (node). The arc (link) is then given a label which is the representation of that arc (link) under the labelling function. When the initial and terminal vertices (nodes) are identical, the arc (link) is called a loop. It can be noted that sometimes an arc (link) originates from its initial vertex (node) and that it terminates into its terminal vertex (node). The number of arcs (links) that originate from a vertex (node) is called its out degree, and the number of arcs (links) that terminates into that vertex is called its in degree.

4. Reliability assessment of the coal-fired generating station

According to Ref. [8] as cited in ([4], pp. 5): "When the words are used sloppily, concepts become fuzzy, thinking is muddled, communication is ambiguous, and decisions and actions are suboptimal, to say the least." Therefore, it follows from this saying that a precise definition of reliability and some associated concepts is needed. There are several definitions of what reliability is. In this study reliability is defined as the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time (ISO 8402) ([4], pp. 5). The terms in this definition are explained as follows [4]:

- The word "item" within the context of this research stands for any component, sub-system, or system which can be envisaged as an entity;
- A requisite utility could be a single utility or a combination of utilities which are needed to carry out a service;
- Components, sub-systems, and systems are herein referred to as technical items. These items have been designed so as to carry out one or more (needed) functions. Furthermore, some of these functions are active, whereas others are passive. An example of a passive function is containment of fluid in a pipeline. Involved and intricate systems (e.g., a steam power plant) usually have a wide range of required functions. To assess the reliability (e.g., of a steam power plant), one needs to state all the function(s) required for consideration; and
- A hardware item has to be reliable. This reliability level is satisfied when the item in question performs above the initial factory specification. Furthermore, it is imperative that the hardware item operates satisfactorily in the actual environment for which it is designed, for a specified period of time.

Reliability has two abstract meanings; probabilistic and deterministic. The probabilistic approach is based upon statistical failure modelling, without researching and itemizing causes of failure. On the other hand, the deterministic approach focuses on understanding how and why a component or system has failed, and how it can be designed, repaired and tested to prevent such failure from occurrence or recurrence. In the present analysis, the probabilistic approach in conjunction with the graph theory is applied for the steam power plant.

Let $R_i(i = 1,\ 2,\ \ldots.\ 6)$ denotes the reliability of node N_i and $r_{ij}(i, j = 1,\ 2,\ \ldots.\ 6\ and\ i \neq j)$, the reliability of the link (or interconnection) between the nodes, N_i and N_j [2, 3]. Consequently, associating reliability to the system structure of **Figure 2** results in the system reliability graph modelling. The system reliability graph for the coal-fired generating station corresponding to its abridged system structure graph is obtained by associating R_i with N_i and r_{ij} with $L_{ij,}$ and this is shown in **Figure 3** [2, 3].

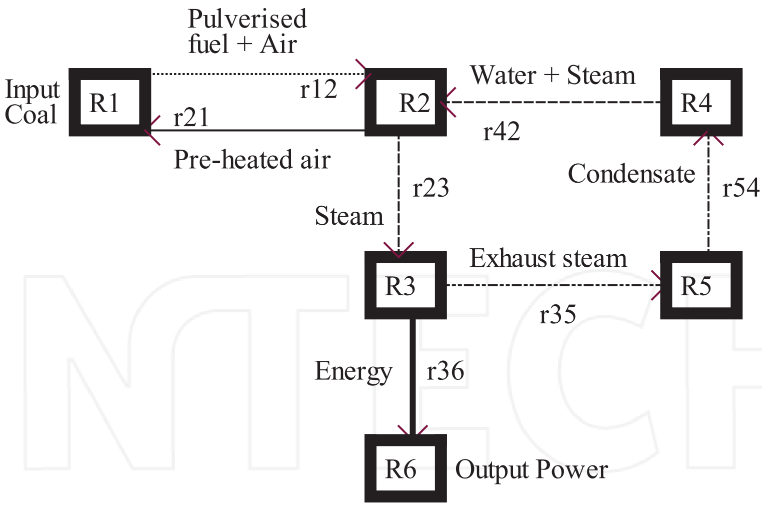

Figure 3. System reliability digraph for a coal-fired generating station.

The reliability structure function of the system of **Figure 3** is estimated by computing the graph's characteristic polynomial [2, 3]. Each and every finite directed graph has a characteristic polynomial [9]. In the beginning, the characteristic polynomial was believed to be a complete invariant, or unique to a graph and all its isomorphism. Later, it was discovered that there are cases where structurally different graphs share the same characteristic polynomial [9]. Although there are cases where structurally different graphs share the same characteristic polynomial, characteristic polynomials are highly studied because they provide much information about a graph in concise format. Characteristic polynomials are useful in steam power plants, mathematics, chemistry, economics, and physics, among others. For example, a graph's spectrum (i.e., the roots of its characteristic polynomial) has significance in the atomic structure.

There exist several ways of determining the characteristic polynomial of a graph with n vertices. In this research, we utilize three methods, namely: (1) the linearly independent cycles; (2) the formula called the figure equation; and (3) the adjacent matrix method. These three methods are in turn employed to estimate the system reliability structure function. Estimating reliability is always an imperfect endeavour (i.e., the reliability (estimate) ranges from the lower bound to the upper bound) and hence the use of these three methods for comparison purposes [2, 3]. The three methods are discussed in the subsequent sections.

4.1. The linearly independent cycles method

In the linearly independent cycles procedure, the structure function is characterized by the presence of a sufficient number of certain cycles which have the property that they are linearly independent [2, 3, 10]. These cycles are denoted in a matrix form (i.e., the cycles are denoted by the links (edges/arcs) present in them). Let $A = (a_{ij})$ of dimension $L \times L$, where L denotes the

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number of links and an element a_{ij} denotes whether link j is present in cycle i or not. When the cycle accumulates the link metrics on its path, then the value observed at m is the sum of the link metrics. Furthermore, the assumption here is that the monitor node is responsible for starting and terminating probes. In the preceding case, m is the monitor node.

One assigns B to denote $(L \times 1)$ a column matrix which contains the accumulated metrics that correspond to the linearly independent cycles. Furthermore, one assigns x to denote $(L \times 1)$ a column matrix that contains the link variables which one has to identify. One's ultimate goal is to solve $Ax = B$ which represents a system of linear equations. For one to be able to uniquely determine x, A has to be invertible. A is also referred to as identifiable, because it has full rank. Cycles that make up such a matrix (i.e., matrix A) are referred to as linearly independent cycles. All link metrics can be uniquely identified by solving Eq. (6) [2, 3, 10]:

$$x = A^{-1}B \tag{6}$$

4.2. The figure equation method

The figure equation procedure provides a direct link between a graph's structure function and the coefficients of its characteristic polynomial. Unlike the linearly independent cycles and the adjacent matrix methodologies, the figure equation method does not use determinants but calculates the characteristic polynomial of any graph by counting the cycles in the graph [2, 3, 9]. In this procedure, coefficients of the graphs' characteristic polynomials are calculated. The calculations are done when one considers the set of linearly-directed sub-graphs of a corresponding length. i nodes and i links constitute a linearly-directed sub-graph of length i in such a way that each node bears in degree and out degree of one (1).

The figure equation states that for any graph $G = (N, L)$ with n vertices, the characteristic polynomial is [2, 3, 9] as follows:

$$X(G) = x^n + c_1x^{n-1} + \ldots + c_{n-1}x + c_n \tag{7}$$

such that for $1 \le i \le n$, the coefficient is as follows:

$$c_i = \sum_{L \in L_i} (-1)^{P(L)} \tag{8}$$

where L_i is the set of all linearly directed subgraphs of G and $P(L)$ is the number of *linearly directed cycles*, or the number of pieces in L.

4.3. The adjacent matrix method

An adjacency matrix tells which vertex (node) in the graph is connected to which. The adjacency matrix of the system reliability digraph for a coal-fired generating station is defined to represent the steam power plant. The adjacent matrix should be defined such that it incorporates the structural information of the components and sub-systems (i.e., of the steam power plant) and interconnections between them [2–4].

The system structure matrix of the steam power plant is defined as follows [2, 3]. Here, a general case of a macro level coal-fired generating station with N sub-systems is considered. Thus, leading to a symmetric adjacency, matrix $\{0, 1\}$ of order $N \times N$. $c_{ij}(i, j = 1,\ 2,\ \ldots 6\ and\ i \neq j)$ represents the connectivity between node (vertex) i and j such that $c_{ij} = 1$ if node (vertex) i is connected to node (vertex) j. In the system reliability digraph of **Figure 3**, this is represented by the link (edge) reliability r_{ij} between nodes i and j. c_{ij} is equal to zero otherwise. Thus, $c_{ij} = 0$ for all i, as a node (vertex) cannot be connected to itself. In the case, where the node (vertex) is connected to itself, $c_{ij} = 1$. This implies a self-loop at node (vertex) i in the graph.

Each row or column of the system structure matrix corresponds to a node (vertex). The six sub-systems of the system reliability digraph of **Figure 3** correspond to the six columns or rows of this matrix [2, 3]. The off-diagonal matrix elements, c_{ij}, represent a connection between nodes (vertices) i and j. In the adjacent matrix $c_{ij} \neq c_{ji}$, as only directional connections between nodes (vertices) are considered. The characteristic polynomial of the graph is the characteristic polynomial of its adjacency matrix. The determinant of the characteristic system reliability matrix is called the characteristic system reliability polynomial.

The reliability of the system is estimated by obtaining the determinant of the characteristic system reliability matrix as follows [2–6]:

$$R_{system} = det\{RI - A_{adjacent}\} \tag{9}$$

where R represents the reliability of the nodes constituting the system; I is the node identity matrix; and $A_{adjacent}$ is the system structure adjacency matrix.

5. Illustration of the system reliability methodology assessment

5.1. Illustration of the linearly independent cycles procedure

The linearly independent cycles (LIC) method computes the list of cycles (top) and the corresponding cycle-link matrix (bottom) as shown in **Figure 4**. The two (2) cycles computed in **Figure 4** are linearly independent. Thus, all link metrics may be identified. We use node R_1 (see **Figure 3**) as the monitor that can start and terminate probes. The reliability of the structure of **Figure 3** is determined using Eq. (6) as [2–6]:

$$R_{system} = \det\{(R \times eye(7)) - A_{LIC}\} = R^7 - 2R^6 \tag{10}$$

For constant unit failure rate, substituting $R(t) = e^{-\lambda t}$ into Eq. (10) yields:

$$R_{system}(t) = e^{-7\lambda t} - 2e^{-6\lambda t} \tag{11}$$

where $R_{system}(t)$ is the coal-fired generating station reliability at time t and λ is the unit constant failure rate.

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$$r_{12} \to r_{21}$$

$$r_{12} \to r_{23} \to r_{35} \to r_{54} \to r_{42} \to r_{21}$$

$$A_{LIC} = \begin{pmatrix} r_{12} r_{21} r_{23} r_{35} r_{36} r_{42} r_{54} \\ 1\ 1\ 0\ 0\ 0\ 0\ 0 \\ 1\ 1\ 1\ 1\ 0\ 1\ 1 \\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \end{pmatrix}$$

Figure 4. List of linearly independent cycles (top) and the corresponding cycle-link matrix (bottom).

5.2. Illustration of the figure equation procedure

The calculation of characteristic polynomials using the figure procedure is relatively unfamiliar [9]. In the figure equation procedure, coefficients of the graphs' characteristic polynomials are calculated. The calculations are done when one considers the set of linearly-directed sub-graphs of a corresponding length. i nodes and i links constitute a linearly-directed sub-graph of length i in such a way that each node bears in degree and out degree of one (1) [9].

From Section4.2, we recall that a factor F of a digraph H is a subgraph containing all the vertices of H in which each vertex (node) has both in degree and out degree equal to one. In other words, it consists of a collection of disjoint cycles that go through each vertex (node) of H. The number of cycles in the factor F is denoted $n(F)$. If the digraph H is labelled, then $W(F)$ denotes the weight of the factor [7]. Given the digraph H of order n; F its factor; F its set of all linearly directed subgraphs; $n(F)$ the number of cycles in the factor F; $W(F)$ the weight of the factor F, then the coefficients, c_i of H are determined as follows:

$$c_i = \sum_{F \in F} (-1)^{n(F)} W(F) \tag{12}$$

where $1 \le i \le n$ and in this study we assume $W(F) = 1$.

Using the figure equation formulae (Eqs. (7), (8), and (12)), we get the list of sub-graphs (left) and the corresponding coefficients (right) as shown in **Table 1**. From the information as shown in **Table 1**, the characteristic polynomial of the structure in **Figure 3** is as follows:

Cycles in the sub-graph	Coefficients
$r_{12} \to r_{21}$	2 *pieces*, $c_1 = (-1)^2 = 1$
$r_{12} \to r_{23} \to r_{35} \to r_{54} \to r_{42} \to r_{21}$	6 *pieces*, $c_2 = (-1)^6 = 1$
$r_{23} \to r_{35} \to r_{54} \to r_{42}$	4 *pieces*, $c_3 = (-1)^4 = 1$

Table 1. Linearly directed cycles and their coefficients.

$$R(G) = x^6 + x^5 + x^4 + x^3 \tag{13}$$

For constant unit failure rate, substituting $R(t) = e^{-\lambda t}$ into Eq. (13) yields:

$$R_{system}(t) = e^{-6\lambda t} + e^{-5\lambda t} + e^{-4\lambda t} + e^{-3\lambda t} \tag{14}$$

where $R_{system}(t)$ is the coal-fired generating station reliability at time t and λ is the unit constant failure rate.

5.3. Illustration of the adjacent matrix procedure

The digraph for the coal-fired generating station of **Figure 3** characterizes the visual representation of the system and its interdependence [2, 3]. The adjacent matrix procedure converts the digraph into a mathematical form, and the structure function is a mathematical model that helps to determine the reliability index [2, 3]. It may be noted here that the development of a structure function is not merely the determinant of the matrix. The structure function is developed in such a manner that no information regarding the system reliability is lost [2, 3]. For this purpose, a step-by-step procedure is proposed in Section 4.3.

Using the adjacent matrix method, the reliability of the structure of **Figure 3** is determined using Eq. (9) as [2–6]:

$$R_{system} = \det\left\{\left(\begin{bmatrix} R_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_6 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}\right) - \left(\begin{bmatrix} 0 & r_{12} & 0 & 0 & 0 & 0 \\ r_{21} & 0 & r_{23} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_{35} & r_{36} \\ 0 & r_{42} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & r_{54} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}\right)\right\} \tag{15}$$

$$= R_6\,(R_3\, R_4\, R_5\, r_{12}\, r_{21} + R_1\, r_{23}\, r_{35}\, r_{42}\, r_{54} - R_1\, R_2\, R_3\, R_4\, R_5)$$

For identical units (i.e., for illustration purposes only) (i.e., $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = R$) with the link reliability assumed to be unity (i.e., $r_{ij} = 1$), Eq. (15) simplifies to:

$$R_{system} = \left|\left(R \times (-R^5 + R^3 + R)\right)\right| \tag{16}$$

where $|\bullet|$ denotes the absolute value and det is the matrix determinant.

For constant unit failure rate, substituting $R(t) = e^{-\lambda t}$ into Eq. (16) yields:

$$R_{system}(t) = |e^{-\lambda t}(e^{-\lambda t} + e^{-3\lambda t} - e^{-5\lambda t})| \tag{17}$$

where $R_{system}(t)$ is the coal-fired generating station reliability at time t and λ is the unit constant failure rate.

6. Results

6.1. The approximate system reliability

The system reliability value of the coal-fired generating station of **Figure 1** as illustrated by Eqs. (11), (14), and (17), respectively, is plotted as shown in **Figure 5**. It should be noted that the results in **Figure 5** have been obtained assuming that the components are identical and assuming constant unit failure rate. This is only for the example to illustrate the methods. In practice, components are not identical, and different failure rates could be used for each component, which is the real-life scenario. The results of the approximation of the system reliability for the three methods which are shown in **Figure 5** have three bounds: (1) the lower; (2) the in-between; (3) and the upper. The lower bound is given by the linearly independent cycles method; the in-between bound by the adjacent matrix method and then the upper bound by the figure equation method. **Figure 5** reveals that the approximate system reliability value starts to decrease gradually with time as is expected. There are various reasons for this

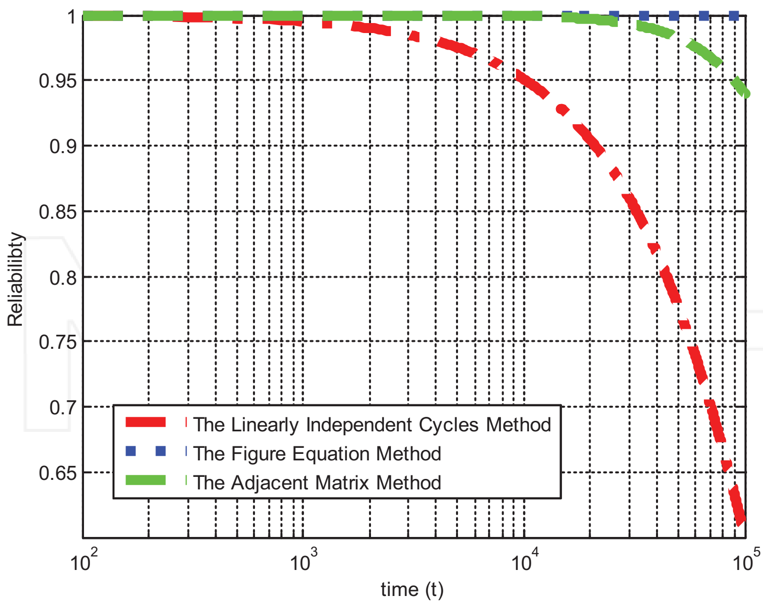

Figure 5. Coal-fired generating station system reliability.

phenomenon. Some of the possible causes are: (1) the ageing effects of the system; and (2) the unavailability of some of the components that constitute the sub-systems of the thermal power plant. The thermal power plant actual or real-time performance system reliability, when available, is compared with the design system reliability (approximate/estimate) by way of the graph-theoretical analysis. The main objective of this comparison is to optimize the design system reliability (estimate).

6.2. The Birnbaum's measure of structural importance

In 1969, Birnbaum advocated the measure for the structural importance of component i as follows [3, 4]:

$$B_{\varnothing}(i) = \frac{\eta_{\varnothing}(i)}{2^{n-1}} \tag{18}$$

The measure of structural importance, $B_{\varnothing}(i)$, proposed by Birnbaum and illustrated in Eq. (18), shows the comparative portion of the 2^{n-1} possible state vectors, that is, $(\cdot_i, x)$.These possible sate vectors form critical path vectors for component i. Birnbaum's measure of structural importance, as expressed in Eq. (18), can be used to partially rank components constituting a system in accordance with the size of $B_{\varnothing}(i)$.

Figure 6 shows the results for Birnbaum's structural importance for the components in the coal-fired generating station of **Figure 1**. **Figure 6** illustrates how much worse the coal-fired generating station system reliability would be if component i would fail. **Figure 6** shows that eight components (N_2, N_6, L_{12}, L_{21}, L_{23}, L_{35}, L_{42}, and L_{54}) have the same Birnbaum structural importance (i.e., 3.12%) with four components (N_1, N_3, N_4, and N_5) having a negligibly small Birnbaum structural importance (i.e., 0%). Birnbaum's measure of structural importance only takes into account the system structure function and not the lifetime distributions of the components. Therefore, it is relatively easy to calculate and is in general used in the design

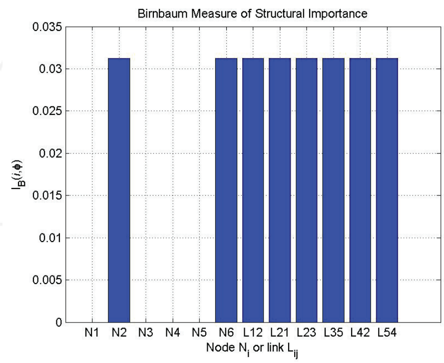

Figure 6. Birnbaum's measure of structural importance for components in the thermal power plant.

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phase or when the lifetime distributions of components are not known. Birnbaum's measure of structural importance is also an alternative when the more advanced measures would be too time-consuming to compute or difficult to use.

6.3. The Birnbaum's measure of reliability importance

In 1969, Birnbaum proposed the measure of the reliability importance of component i at time t as follows [3, 4]:

$$I^B(i|t) = \frac{\partial h\big(p(t)\big)}{\partial p_i(t)} \; for\; i = 1,\; 2,\; \ldots, n \tag{19}$$

In order to obtain Birnbaum's measure of the reliability importance of component i at time t. A partial derivative of the system reliability with respect to $p_i(t)$ is taken. Birnbaum's measure of the reliability importance is a specific case of sensitivity analysis that was used in various engineering applications for ages [4]. A large $I^B(i|t)$ results in a comparatively large change in the system reliability at time t, for a small change in the reliability of component i. Birnbaum's measure of the reliability importance depends on the component reliabilities at various points in time. Therefore, it gives perhaps a more global view of component importance.

Figures 7 and **8** show that all components except (N_1, N_3, N_4, and N_5) have the same Birnbaum's measure of the reliability importance. We deduce how the components behave with respect to time in **Figures 7** and **8**.

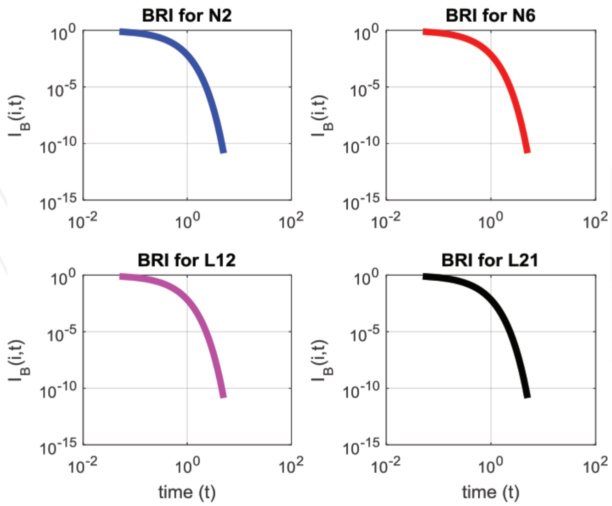

Figure 7. Birnbaum's measure of reliability importance for components: N_2, N_6, L_{12}, and L_{21}.

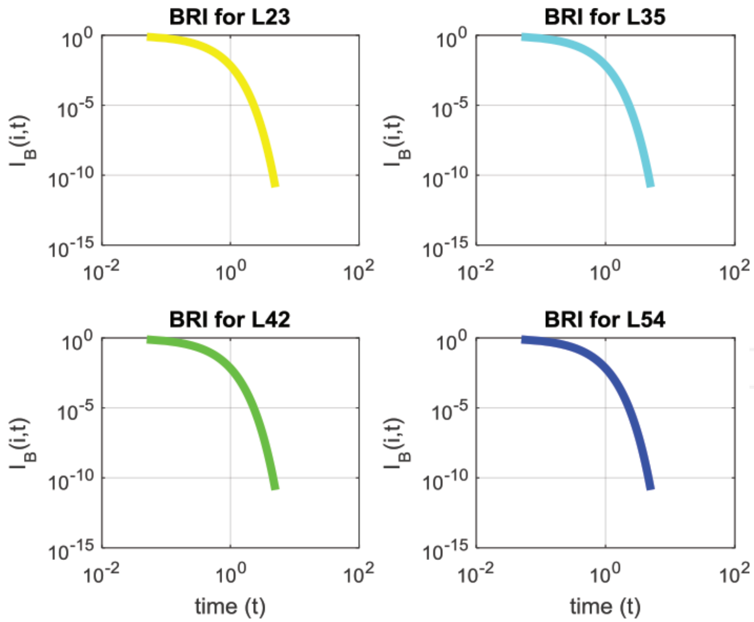

Figure 8. Birnbaum's measure of reliability importance for components: L_{23}, L_{35}, L_{42}, and L_{54}.

7. Conclusion

The graph-theoretical analysis procedure was used for the analysis of several reliability parameters of a steam power plant, in this chapter. **Figure 5** illustrates the system reliability as a function of time with failure rates assumed to follow exponential time distributions. It is worth noting that the results of **Figure 5** have been attained assuming identical components and constant unit failure rates. This is only for the example to illustrate the methods. In practice, components are not identical and different failure rates could be used for each component, which is the real-life scenario.

The structure function model for the steam power plant developed in this chapter represents its structural information, including its systems, their sub-systems, their components and their interconnections. The procedure transforms a real-life steam power plant into the following representations: its block (see **Figure 1**); its system structure digraph (see **Figure 2**); and then finally its system reliability digraph (see **Figure 3**). The structure function of the coal-fired generating station embodies all probable composites of its components and sub-systems at a specific state of hierarchy. These composites and interactions create a method which can be used to analyse the structure and the function of the parameters that are dependent on the structure. The said methodology allows for either a top-down or bottom-up analysis and design of various systems, sub-systems, and their interconnections. The model enables one to determine optimal maintenance strategies that will ascertain upper bound reliability of the thermal power station. Power plant managers can benefit from use of the model for the analysis of the reliability of the thermal power plants. The procedure permits changes in the model to make it plant-specific as well as design-specific.

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In general, a collection of components performing a specific task or function is referred to as a system. It goes without saying that in a system, some components are more important for the system reliability than others. For example, in a system, if a component is in series with the rest of the components, it is a cut set of order one (1). A component which is a cut set of order one (1) is in general more important than a component that is a member of a cut set of higher order ([4]: pp. 149–150). In Section 6, Birnbaum's measure of structural importance and Birnbaum's measure of the reliability importance have been defined and discussed. Component importance measures may be used to rank the components, that is, to arrange the components in ascending or descending order of importance. Component importance measures may also be used for classification of importance, that is, to allocate the components into two or more groups, according to some pre-set criteria.

Systems usually consist of multiple components. The components constituting a system are not necessarily equally important for the performance (reliability, availability, risk, and throughput) of the constituent system. Ordinarily limited resources are available to design, enhance and/or maintain such a system efficiently. Nevertheless, for complex and large systems, it may be too tedious, or not even possible, to develop a formal optimal strategy. In analogous situations, it is advantageous for one to allocate resources in accordance of how important the components are to the system. Furthermore, it is desirable to concentrate the resources on the subset of components that are most important to the system ([11]: pp. 49–53). Therefore, the notion of component importance measures (also called sensitivity).

A basic problem that faces the reliability engineer in attempting to achieve maximum reliability for a large and complex system is that of evaluating the relative importance of the various components constituting the system. Thus, in reliability, a component importance measure evaluates the relative importance of individual components or group of components in that system. This relative importance can be determined based on the system structure, component reliability and/or component lifetime distributions. Measuring the relative importance of components may allow the engineer to: (1) determine which of these components deserve additional research and warrant development in order to improve the overall system reliability under cost (and/or effort) constraints; and (2) find the component that caused the failure of a system. By using importance measures, it is possible to draw conclusions about which components are the most important to improve in order to achieve better reliability of the whole system. In Sections 6.2 and 6.3, we have provided Birnbaum's measure of structural importance and Birnbaum's measure of the reliability importance for that specific purpose and given the results thereof.

Author details

Bernard Tonderayi Mangara

Address all correspondence to: aragnam@gmail.com

Central University of Technology, Free State (CUT), Bloemfontein, South Africa

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