# A STRATEGY FOR CRITICAL ELECTRICAL SERVICE RESTORATION IN UNDERGROUND MINES USING GRAPH THEORY

W.H. Sterrenberg[1*], B. Pascoe[2], J.F. Van Rensburg[3] and J.H. Van Laar[4*]
[1,2,3,4]Center for Sustainable Mining
North-West University, South Africa
[1]lsterrenberg@rems2.com, [2]bpascoe@rems2.com, [3]jvanrensburg@rems2.com, [4]jvanlaar@rems2.com

## ABSTRACT

Underground mine blackouts can cripple safety, productivity, and equipment assets. Despite redundant design of the power distribution systems, inefficient switching procedures during outages lead to excessive downtime and loss of production. The number of switching operations must be reduced. This paper implements a LIP onto a graph to deliver a switching strategy, to restore critical electrical services faster than the current procedures allow.

By employing distributed generators, the proposed method aims to minimise electrical blackout impact through efficient load reconfiguration. Application on a case study mine in South Africa demonstrated a 58% reduction in switching events (from 117 to 54) compared to the mine's current approach, achieving 77% faster critical service restoration time. This method enhanced safety and efficiency, and reduced equipment damage during mine blackouts and should be considered for application across the entire Southern African mining industry.

Keywords: Mining, Electrical reticulation, Electrical distribution, Service restoration, Blackout, Critical load

---

* Corresponding Author

## 1 INTRODUCTION

Mining is a global industry that plays a crucial role in providing raw materials essential for modern society. By optimising the extraction process, mining companies can enhance their profitability and contribute to the long-term viability of the industry [1-3].

The application of electricity on the mining sector represents a distinctive domain, which is distinguished by its challenging operational environment, dynamic power loads, cyclic and mobile operations, and strict adherence to safety standards. To optimise safety, efficiency, and productivity, it becomes imperative to address the specific challenges posed by this sector [4].

The hazardous underground environments are often dusty, humid and contain toxic gases. These harsh environmental factors can lead to accelerated equipment degradation, corrosion, and potential short-circuits or electrical failures [4].

There is limited space for installing electrical distribution equipment in underground mines. This constraint can make maintenance, repair, and expansion of the electrical system more challenging. Many mines are in remote areas, making it difficult to access them for maintenance and repair. This can lead to longer downtime in case of equipment failure [6].

The risks of extended power outages are numerous and based on the specific equipment underground. The main risks in underground mining are [5-14]:

- Flooding due to pumps not running
- Loss of life due to insufficient ventilation
- Loss of production and injury due to insufficient lighting
- Failure to transport personnel leading to exhaustion or death
- Loss of production due to material transportation
- Loss of production due to lack of compressed air supply

All the risks listed above either lead to injury, death, or production losses which are critical drivers to mitigate in mining. Underground mining relies on real world underground electrical distribution systems to power equipment to effectively and safely mine. However, power outages occur and range in severity.

Service restoration planning is an important tool for improving modern distribution network resilience stated by Shen, et al. [15]. Improper handling of partial failures can lead to chain reactions that cause large scale damage to electrical distribution systems, budgets and human resources [16].

Service restoration plans are implemented to mitigate the risk of inefficiency and loss of life involved with extended power outages. Service restoration efforts in underground mines however face many challenges that lead to ineffective distributed generation utilisation and prolonged implementation periods.

This study aims to deliver a feasible service restoration plan for critical electrical services in underground mines' real-world distribution systems that employ distributed generation. Furthermore, it will attempt to shed light on service restoration plan efficiency through switching optimisation.

## 2 LITERATURE ON SERVICE RESTORATION SOLUTIONS

### 2.1 Network reconfiguration objectives and constraints

For this study, 37 papers were evaluated and categorised according to the objectives denoted by the studies. These studies were categorised further to determine the distribution network state (normal operations, abnormal operation and network design phase) that the network reconfiguration techniques were applied to. The outcome is shown in Figure 1.

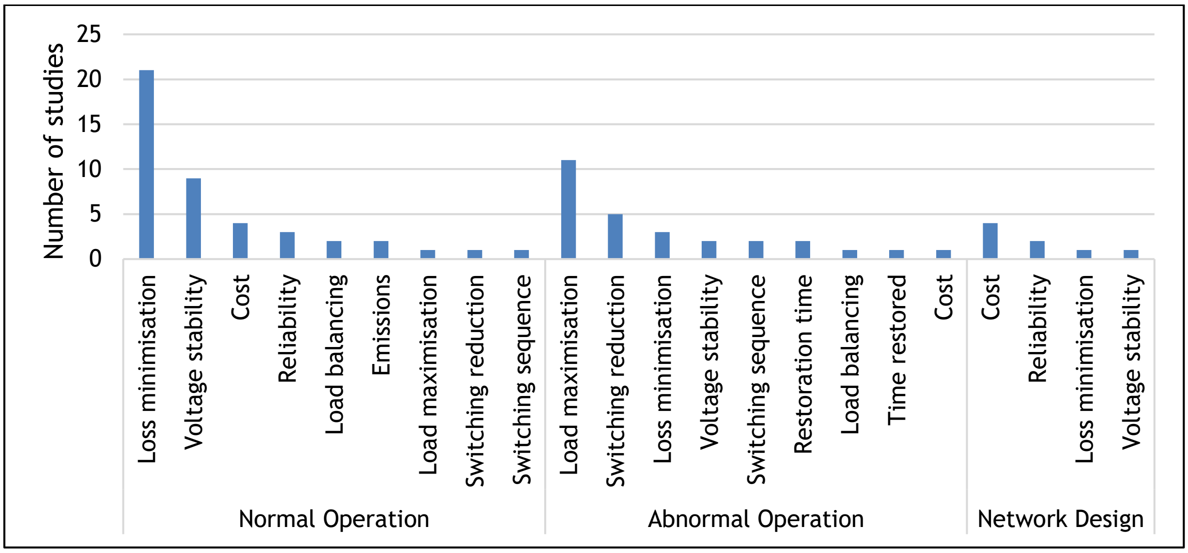


**Figure 1: Studies within the network reconfiguration field categorised according to objective**

Many studies in the network reconfiguration space denote objectives as multi-objective problems and are formulated as such. These are also included in Figure 1. Objective investigations are done using the objectives attempted in the most network configuration studies, as listed below:

- Loss minimisation [17-39]
- Voltage stability [17, 30-35, 37-41]
- Load maximisation [17, 36, 38-44]
- Cost minimisation [21, 43, 45-51]
- Switching minimisation [38, 41, 52-54]

From the most popular objectives load maximisation and cost minimisation are specifically used during abnormal operation of distribution systems.

Next, when solving service restoration problems, the solution is required to adhere to a set of constraints. The specific constraints can vary depending on the type of network and the optimisation goals, some common constraints are often encountered in network reconfiguration problems [37]:

- Radiality
- Bus voltage limits
- Loading limits of feeders/transformers
- Sequence of switching operations
- Number of switching operations

These constraints play a crucial role in defining the feasibility of service restoration solutions and ensuring that the resulting configurations are safe, reliable, and compliant with various operational and regulatory standards.

## 2.2 Graph Theory

A problem space is required for modelling the optimisation of objectives and constraints above. Graphs are mathematical structures used to model relations between objects. An undirected simple graph is an ordered pair shown in Equation ***(1)***.

$$G = (V, E) \qquad \textbf{\textit{(1)}}$$

Where ***G*** is the graph, ***V*** is a set of vertices/nodes, and ***E*** is a set of edges. Edges are defined in Equation ***(2)***.

$$E \subseteq \{\{x, y\} | x, y \in V \; and \; x \neq y\} \qquad \textbf{\textit{(2)}}$$

Here, edges $E$ is a set of unordered pairs of vertices with endpoints $\{x, y\}$; $x$ and $y$ is joined with an incident on $x$ and on $y$.

Graphs is used to model a wide range of real-world phenomena, including social networks, transportation networks, computer networks, biological networks, and logistics problems.

## 2.3 Network Reconfiguration Techniques

A literature review was conducted to establish what techniques are used to solve different service restoration problems. Categorisation was performed by multiple studies [19, 55-57] based on the type of solution models used. Two of the studies Mahdavi, et al. [19] and Mishra, et al. [55] specifically focussed on producing a comprehensive review that would categorise the state of the art by the following three solution model types:

- Mathematical Optimisation Methods
- Heuristic Methods
- Metaheuristic Methods

When considering the categories of solution models [55, 56, 58, 59] the following was noted:

- Network reconfiguration through **mathematical optimisation** can be slow due to complex search spaces and integer variables.
- **Heuristic methods** offer faster solutions to network reconfiguration problems by using simpler searches but may not find the absolute best answer.
- **Metaheuristics** are higher-level procedures that guide the search for solutions in optimisation problems with large solution spaces, aiming to find good solutions more efficiently than traditional methods.

## 2.4 Testing Methods

Network reconfiguration studies implement solution methods on test systems such as the IEEE bus systems, while service restoration studies focussed on scenario-based testing within the same test systems. The scenarios include faults on various equipment types, extending to multiple fault scenarios.

Figure 2 shows the standard test systems used in the studies considered in this literature review, split between service restoration studies and network optimisation studies.

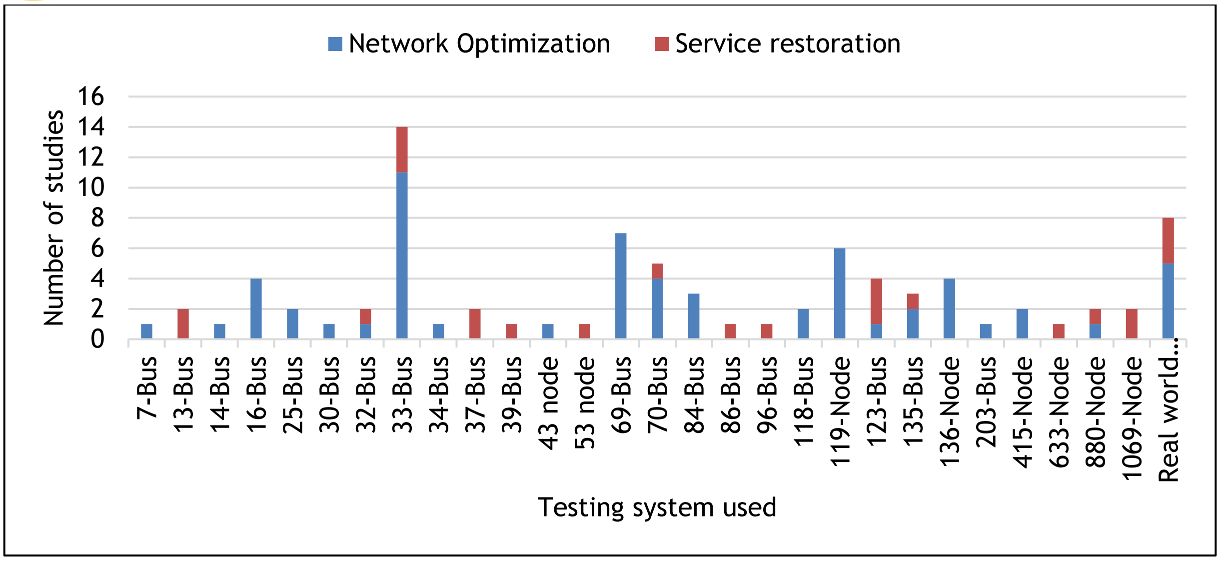


**Figure 2: Testing considered in literature review [17-54]**

For service restoration problems there are fewer specific systems that are used for testing. This may be due to the different scenarios that can be tested on one test system. Faults can be induced in multiple ways on a single test system, which is less work than characterising multiple test systems to form separate problem spaces.

### 2.5 Need for the study, and its objective

The previous sections showed that the shortcomings in this research field still require further illumination. Two of the shortcomings observed is optimising switching events and uncertainty as to how a LIP solution compares with a benchmark solution on a real-world electrical distribution system.

This study aims to apply a LIP solution method to deliver a feasible service restoration plan for critical electrical services in underground mines' real-world distribution systems that employ distributed generation. Furthermore, it will attempt to shed light on service restoration plan efficiency through switching optimisation.

## 3 A NEW METHOD FOR SERVICE RESTORATION IN UNDERGROUND MINING

### 3.1 Step 1: Gather data

A strategy of data gathering is used as described by Pascoe [5]. Identifying data sources, acquiring data and validating data.

The sensor data generated by the system must be stored to facilitate subsequent analysis and modelling. Data validation is an essential process that safeguards the integrity and accuracy of collected data. It encompasses a series of crucial steps to maintain the veracity of data within data collection systems [60].

Once data has been validated, it can be used to create a verified graph.

### 3.2 Step 2: Characterise problem space

The data gathered is used to populate a graph model based on the technique used by Ibrahim, et al. [38] and Zhang, et al. [61].

The purpose of a graph model is to emulate an electrical reticulation system. The graph model is required to model load, bus, source and line components as nodes and edges to emulate a distribution system. Combining these components, models an electrical distribution network as a graph. The IEEE 13 feeder test system [62] is shown in Figure 3.

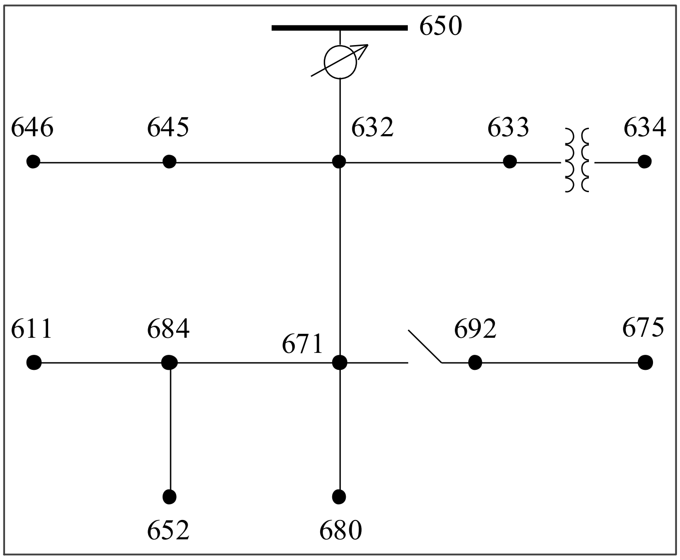


**Figure 3: IEEE 13-node test feeder [63]**

This small circuit model, operating at 4.16 kV, serves as a benchmark for evaluating common features of distribution analysis software. Its distinguishing characteristics include a short length, a relatively high load, a single voltage regulator at the substation, a combination of overhead and underground lines, shunt capacitors, an in-line transformer, and unbalanced loading.

The system is now converted to a simplified graph model shown in Figure 4.

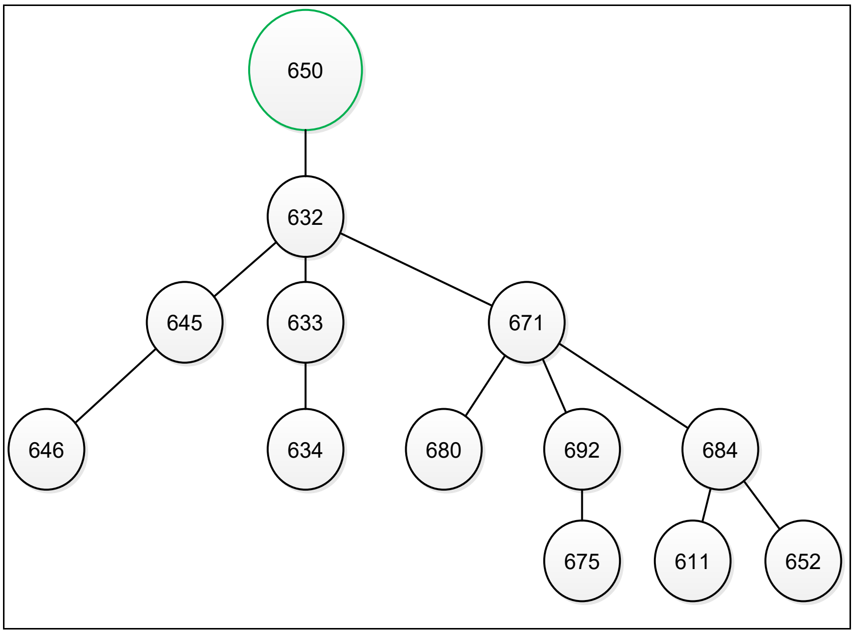


**Figure 4: Graph model of 13-node test feeder**

As seen in Figure 4, the graph model is developed based on the buses and edges of the system. As shown in this system, one of the constraints of this study is that the solution must remain radial for any source and bus combination. Next, the need to traverse the system using a graph optimisation algorithm is needed.

## 3.3 Step 3.1: Construct restoration trees

To construct restoration trees, the distribution system was modelled as an undirected graph. Nodes representing critical loads are termed critical load nodes. The restoration path between a given "source-critical load" pair is defined as any path with the minimum weight among all paths connecting them. Dijkstra's algorithm is employed to determine restoration paths from a given source to all critical loads. These paths are validated through power flow analysis, and unfeasible ones are removed, resulting in a feasible restoration tree.

To minimise the number of power flow calculations and dynamic simulations, the programme initially checks if the total load on the restoration path exceeds the maximum power that the corresponding source can provide. If it does, the restoration path is deemed infeasible without a power flow calculation. Conversely, a power flow calculation is performed if the load does not exceed the source's capacity. If any operational constraint is violated during the calculation, the restoration path is considered infeasible.

## 3.4 Step 3.2: Form load groups

Next, load groups are formed by exploring all possible combinations of critical loads on the restoration tree for a given source. Each combination forms a load group, consisting of loads on the restoration path spanning from the source to each critical load in the combination. Load groups containing two or more critical load zones undergo feasibility evaluation through power flow calculations. Infeasible load groups are removed from the set, leaving only feasible ones.

## 3.5 Step 3.3: Analyse constraints

The constraints noted in literature have been considered and in accordance with most of the reviewed work, the following operational constraints have been identified that will be considered when determining the feasibility of a solution.

| | |
|---|---|
| **Power flow:** | Balanced power flow equations must be satisfied. |
| **Bus voltage:** | Steady state bus voltages should be maintained within acceptable operating limits. |
| **Line Current:** | Steady state line currents should not exceed their limits. |
| **Power balance:** | Each microgrid's steady state output power should not exceed the maximum amount of power that it is able to provide. |
| **Radiality:** | Adhering to a radial network structure is crucial, meaning that each critical load should be supplied by a single microgrid through a unique path. |

## 3.6 Step 3.4: Solve restoration problem

The optimisation problem is formulated based on these load groups. Suppose load group $j$ corresponds to source $k$ and covers critical load zones $i_1, i_2, \dots, i_p$ $(p \geq 1)$. This implies that zones $i_1, i_2, \dots, i_p$ can be restored by source $k$ without violating any constraints along their respective restoration paths. The goal is to select a set of disjoint load groups where any two distinct load groups in the set correspond to different sources. Therefore, the critical load restoration problem is framed as an optimisation problem that aims to maximise the total number of critical loads and reduce the number of non-critical loads as follows:

*Objective:*

$$max \sum_{j:g_j \in G_{uni}} y_j c_{sum,j} \quad \textbf{(3)}$$

for each load group $j$ in universal set of load groups $G_{uni}$. Where $y_j$, is the control variable, and the status of load group $j$: If load group $j$ is selected $y_j = 1$; otherwise $y_j = 0$. $c_{sum,j}$ is the total weighting factor of load zones in load group $j$ and are the state variables.

No more than one load group associated with the same microgrid is selected, i.e.

$$\sum_{j:g_j \in G_k} y_j \leq 1, k \in \boldsymbol{M} \tag{4}$$

Here $G_k$ is a set of load groups corresponding to microgrid $k$ and $\boldsymbol{M}$ is the set of available microgrids. Lastly no more than one load group including the same load zone is selected, i.e.

$$\sum_{j:i \in g_j} y_j \leq 1, k \in \boldsymbol{Z}_{uni} \tag{5}$$

where $\boldsymbol{Z}_{uni}$ is a universal set of load zones.

The optimisation problem can be formulated as a Linear Integer Program (LIP). Numerous tools are available for solving LIPs such as python libraries and MATLAB.

### 3.7 Determine restoration actions

To ensure that the constraints outlined are upheld, careful consideration is given to the feeders and incomers from each substation within the load group combination. The sequence of actions involves initially opening the main above ground substation feeders and then executing switching events to apply the load groups effectively. Lastly, actions to disconnect all busses that are not included in the load groups are removed, thus ensuring the restoration process is carried out in compliance with the defined constraints.

## 4 RESULTS AND FINDINGS

### 4.1 Case study overview

An underground platinum mine situated in South Africa was selected as a case study. The mine has an underground electrical distribution system that reticulates energy up to 1.3 km deep underground.

The mine employs standard scenario-based restoration procedures developed by system experts in the case of full power loss from power providers. This procedure is implemented as a measure to protect personnel and mining assets using distributed generation and reducing the energy demand of the network to essential equipment only.

The electrical distribution system operates at 6.6 kV and has a maximum supply capacity of 67.6 MVA. The layout of the underground mining operation is shown in Figure 5.

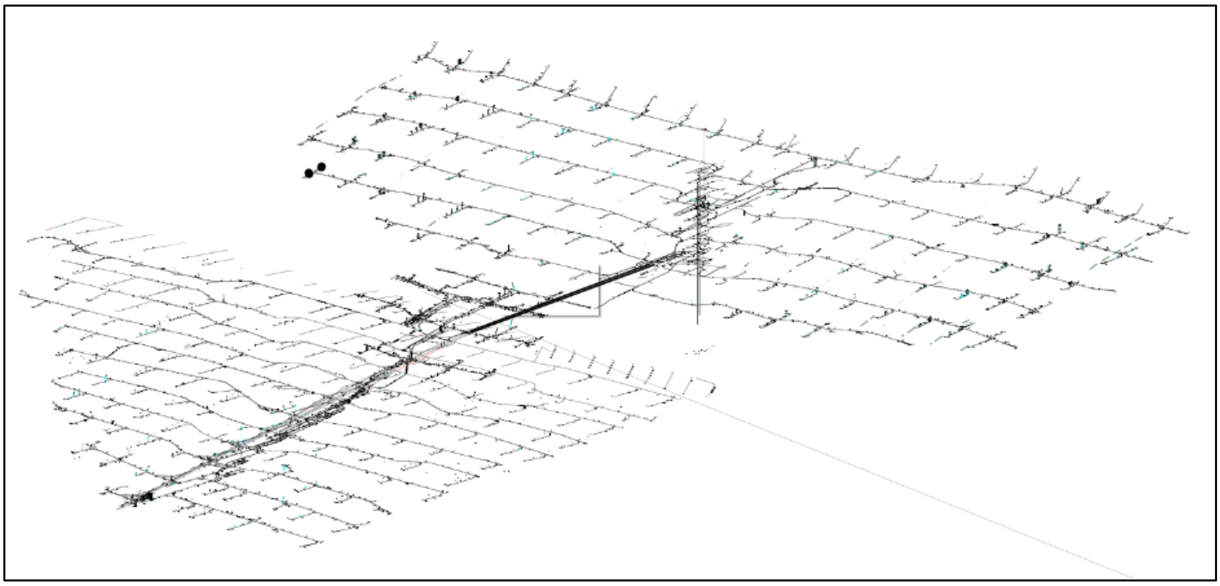

**Figure 5: Case study underground mining operation**

In the case of a full blackout scenario, the total system supply capacity reduces to 9.7 MVA. The system in Figure 5 has five usable supply points (three PP incomers and two distributed generators). There are 88 loads and 49 buses.

The distribution system has seven critical loads as shown in Table 1, which are defined by a restoration procedure document. Active mining areas are on Level 10 to Level 28; where all personnel will be located.

All switches are manual. The travel time to substations is linear and for safety purposes a maximum of two switching teams are dispatched when a service restoration procedure is implemented. The first team operates the main consumer substation and the second operates the underground substations.

### 4.2 Step1: Data gathering

Data spanning an entire month, collected at half hour intervals, was acquired from the existing Electrical Monitoring System for each feeder. To ensure the accuracy of this data and its alignment with the system's characteristics, the validation processes was rigorously applied. Table 1 indicates the critical loads.

**Table 1: Critical loads identified in the case study**

| Name | Level | Load (kW) | Comment |
|---|---|---|---|
| Man Winder | Surface | 214 | Main transportation from level 15 and above to surface for personnel |
| Service Winder | Surface | 28 | Secondary transportation from level 15 and above to surface for personnel |
| CL 15L-23L | Level 15 | 36 | Chairlift that extends from level 23 to 15 |
| CL 23L-28L | Level 23 | 57 | Chairlift that extends from level 28 to 23 |
| 15L Pump No. 1 | Level 15 | 140 | Main shaft dewatering pump for pumping water to surface reservoirs from level 15 |
| 22L Clear water pumps | Level 22 | 36 | Intermediate pumpstation to pump water to Level 15 reservoir |

| Name | Level | Load (kW) | Comment |
|---|---|---|---|
| 28L Pump No. 1 | Level 28 | 139 | Shaft bottom pump to pump water to level 22 reservoirs |

The location of critical loads was identified through inspection of the single line drawing and the emergency response procedure document. These critical loads are required to protect personnel and mining assets in the event of power loss.

The system's generation capabilities were also identified by inspection of the energy system while the size was confirmed by the data management system. Table 2 shows the supply equipment in the distribution system.

**Table 2: System generation**

| Name | Location | Maximum Capacity | Level |
|---|---|---|---|
| Diesel Generator | Surface | 3.6 MVA | Surface |
| Diesel Generator | Surface | 3.6 MVA | Surface |
| Turbine Generator | Surface | 2.5 MVA | Surface |
| Eskom Incomer 1 | Surface | 20 MVA | Surface |
| Eskom Incomer 2 | Surface | 20 MVA | Surface |
| Eskom Incomer 3 | Surface | 20 MVA | Surface |

During a blackout scenario the Eskom incomers shown in Table 2 are unavailable as a supply to the distribution system as they will be out of commission. The mine must then rely on the 9.7 MVA generators to provide power to the network and the critical loads.

Switching procedures for the response to a black start scenario was provided by the electrical engineering team on site and is used as a baseline. The full switching procedure aligns with the goal of switching on all necessary equipment to sustain life and protect assets.

### 4.3 Step 2: Characterise problem space results

From the data gathered the distribution system has 50 loads of which 7 loads are considered critical during the blackout scenario. Table 1 shows the characteristics of the 7 critical loads.

The priorities of these loads are based on their switching priority and the usefulness of each piece of equipment to either evacuate staff from the underground area, sustain life or protect mining assets.

Non-critical loads' have a lower priority compared to their critical load counterparts. This is done to ensure speed of service restoration. It is evident that the expected sum of critical load on the system is 6.8 MW. The following graph in Figure 6 was developed using the components described above.

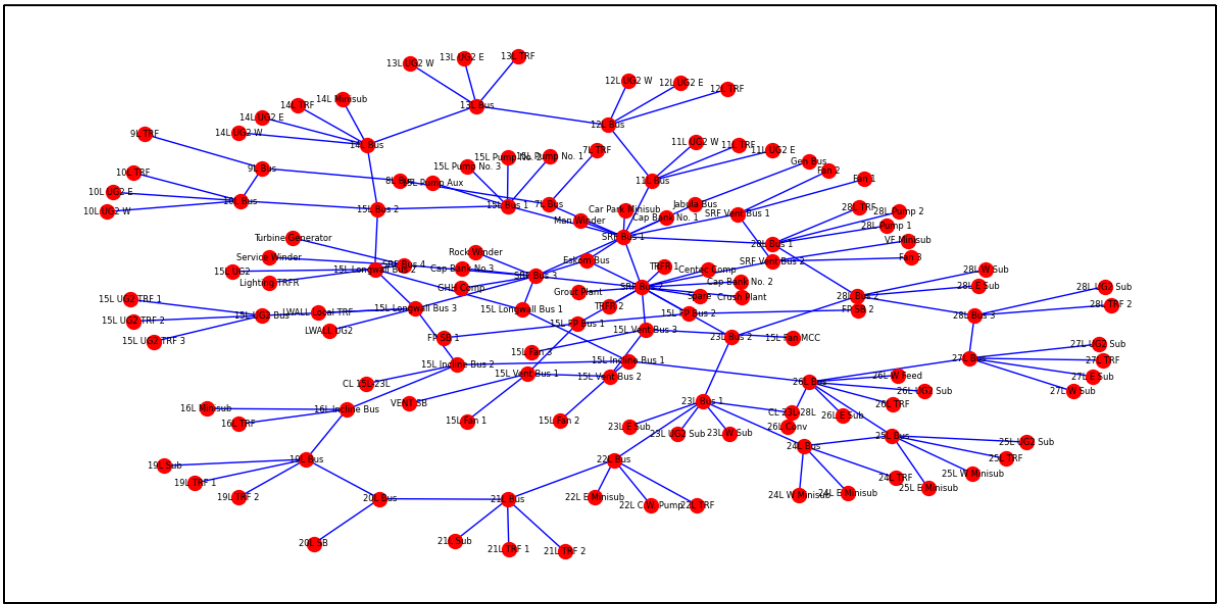

**Figure 6: Graph model developed of case system**

Figure 6 is developed with the components discussed above to form a complete unidirectional graph that represents the electrical distribution system. The edges are all available for transition as all switches are considered accessible to the solution model. All switches are weighted equally for the purpose of this study focusing on reducing switching events and restoring the most critical load.

### 4.4 Step 3.1: Construct restoration trees results

Restoration trees are constructed for the graph model to route from each feasible source to critical load node. Seven restoration paths are produced for diesel generators and seven more restoration paths for the turbine generator. The restoration paths are tested for feasibility through load flow analysis, which lead to zero exclusions as each generator can supply each restoration path with sufficient power.

It is assumed that the restoration paths are isolated from bus nodes around them whilst determining feasibility. Therefore, all loads connected to intermediate bus nodes will remain connected, however bus-bus edges are removed to reduce the cold load pick-up and maximum load required by each restoration path.

Critical loads have different path lengths based on the source of the restoration path. This is due to the topological location of the sources in the graph. It is noted that the main difference between the length of restoration trees seem to occur on the surface nodes, i.e. how the surface bus is configured to energise the bus that leads to an underground area. The underground switching is similar for each bus.

This is found to be positive as employing similar tactics when switching allows for less confusion and therefore improved execution performance from switching teams [24, 64]. That in turn, should lead to more reliable switching times. To find efficient solutions within the given constraints, load groups need to be formed to ensure the best combination of critical load to source connections are formed.

### 4.5 Step 3.2: Form load groups results

Load groups are formed using the restoration trees constructed in the previous section. From the combinations 256 load groups are formed which are available for inspection and testing.

Initial feasibility testing led to 50 load groups being eliminated due to the critical load nodes' load being larger than the power that the specific sources could supply. All the eliminated load groups were from the turbine generator load groups as it has a lower capacity than the total load required to supply all consumers.

Weighting factors $C_{sum,j}$ and load capacity are calculated for each load group. These are not just totalled, as the routes for certain restoration paths are superimposed on each other as can be seen for critical loads CL 23L-28L and 22L Clear water Pumps. Therefore, efficient bus navigation will be achieved by implementing each load group.

As discussed earlier, power flow analysis is required to test the feasibility of load groups.

## 4.6 Step 3.3: Analyse constraints results

The constraint results are analysed using basic load calculations to verify that none of the generated load groups are unfeasible and will overload the sources or lines. The solutions that will overload are disregarded from the pool considered.

## 4.7 Step 3.4: Solve the critical load restoration problem results

After all feasible load groups were verified using power flow analysis developed in the previous section, the optimisation problem was solved to deliver the best combination of load groups. The results of the optimisation algorithm formation are shown in Table 3.

**Table 3: Solutions found through solving optimisation problem**

| Sources | Critical Loads | $C_{sum,j}$ | Load (kW) |
|---|---|---|---|
| Diesel Generators | Man Winder, Chairlift 23L-28L, 15L Pumps, 22L Pump, 28L Pumps | 4.8 | 4200 |
| Turbine generators | Service Winder, Chairlift 15L-23L | 1.8 | 700 |

The load groups selected are a subset of the full set of loads groups. The turbine generators function far below their power capacity indicating the diesel generator is better centralised to deliver power to the critical loads. A visualisation of the graph model is shown in Figure 7.

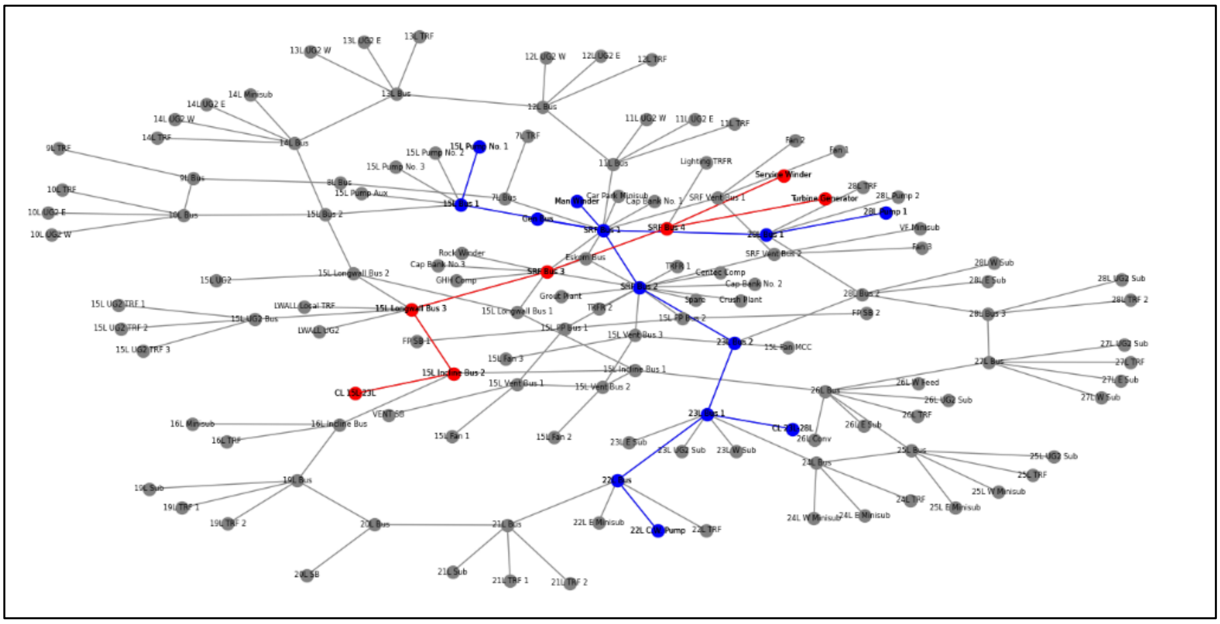

**Figure 7: Service restoration graph developed from solution model**

The system shows two separate trees that are radial in nature which indicates a successful application of the solution model to restore load to the graph model. The physical constraints of the network are described by the equipment rating in the distribution system. None of the constraints are exceeded by this solution.

Next, the focus will be on the last problem to solve, which is the application of the solution to the electrical network. The objective function was solved and visualised using python and with the networkx library used to generate the graph

### 4.8 Step 3.5: Determine Restorative Actions

The solution for the graph model was converted into a switching procedure that can be applied to the necessary electrical grid as described in the previous section. If the power balance between the generation capacity and the load cannot be maintained. This leads to an overload due to non-critical load connections on the network.

Firstly, the system does not maintain radial structures within the graph space leading to loops. A radial structure is one of the main constraints to the service restoration problem. Secondly, when tested for feasibility the load exceeds the capacity of the generator. This led to the implementation of the last step of the solution method which involves opening all switches that lead out of the substations that are being traversed that do not specifically lead to the solution.

The interim steps are numbered in such a way that they define the sub actions that need to be completed before the main action is executed. This leads to a combinatorial action switching procedure shown in Table 4.

**Table 4: Combinatorial restorative action table**

| Critical load | Step | Substation | Panel | Action | Effect |
|---|---|---|---|---|---|
| Initial | 0A | Main consumer sub | All | Open | Disconnect all loads |
| Man winder | 1 | Gen Bus | 3 | Close | Gen Bus - SRF Bus 1 |
| | 2 | Main consumer sub | 2 | Close | Gen Bus - SRF Bus 1 |
| | 3 | Main consumer sub | 3 | Close | SRF Bus 1 - Man Winder |
| Service Winder | 4 | Main consumer sub | 30 | Close | Link Turbine Gen - SRF Bus 4 |
| | 5 | Main Consumer sub | 31 | Close | SRF Bus 4 - Service Winder |
| 28L Pumps | 6 | Main Consumer sub | 1A | Close | SRF Bus 1 - 28L Bus 1 |
| 15L Pumps | 7 | Main Consumer sub | 4 | Close | SRF Bus 1 - 15L Bus 1 |
| CL 15L-23L | 8A | 15 Level Incline Shaft sub | Open | 6 | Disconnect entire 16L Bus to 23L Bus |
| | 8 | Main Consumer sub | 29 | Close | SRF Bus 4 - SRF Bus 3 |
| | 9 | Main Consumer sub | 25 | Close | SRF Bus 3 - 15L Longwall Bus 3 |
| CL 23L-28L & 22L C.W. | 10A | 23L Cluster sub | 12 | Open | Disconnect 28L Bus 3 Feeder |
| | 10B | 22L sub | 5 | Open | Disconnect 21L Bus |
| | 10 | Main Consumer sub | 10 | Close | SRF Bus 1 - SRF Bus 2 |

| Critical load | Step | Substation | Panel | Action | Effect |
|---|---|---|---|---|---|
| | 11 | Main Consumer sub | 20A | Close | SRF Bus 1 – 23L Bus 2 |
| | 12 | 23L Cluster sub | 10 | Close | 23L Bus 2 - 23L Bus 1 |

When the service restoration procedure is applied, the restoration trees will be implemented effectively as shown in Figure 7. At this point all the steps in the solution procedure are complete.

### 4.9 Evaluation of results

Power flow analysis is used to test feasibility in the previous sections and evaluation of solution found. A MATLAB simulation package, Simscape, was used as a tool to conduct the power flow analysis.

This network had power meters on the main consumer substation only. This led to the need to approximate each individual load by averaging the power across all loads per feeder power meter.

#### *4.9.1 Restored Load*

Similar load restoration results were achieved in the baseline switching procedure that was developed by system experts using practical experience. However, the experts only leveraged one of the distributed generators as a source of power. Figure 8 shows the comparison of load restored in the case study.

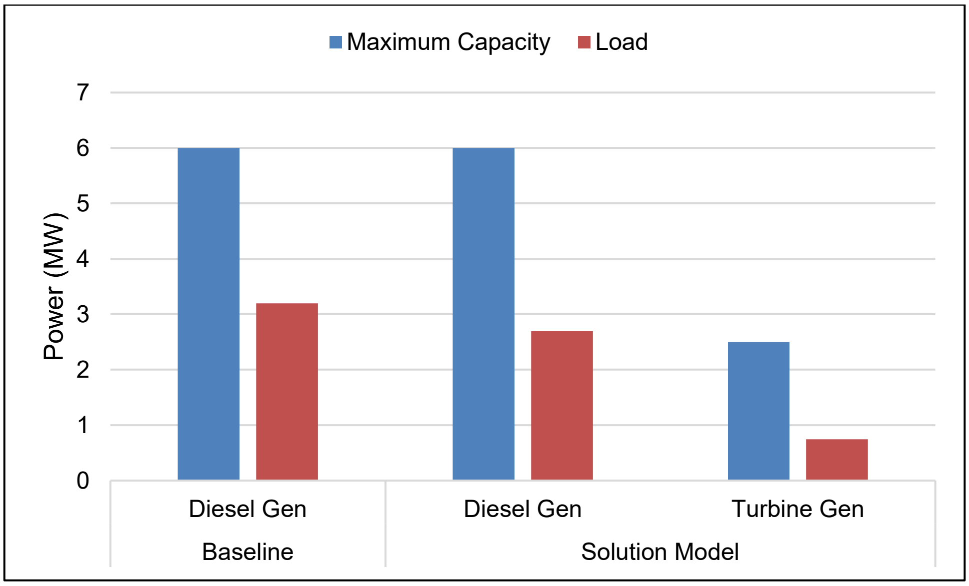


**Figure 8: Load restored comparison in case study**

Figure 8 shows that both switching procedures restore service to each critical load in the distribution network. The solution model result has a slightly higher load of 246 kW. To save time, loads on restoration path buses are not removed.

The instructions on the baseline service restoration plan indicated that the man winder should run at half speed due to limited capacity of the system. With the inclusion of the turbine generator, the man winder can run at full speed as shown by the loads.

### *4.9.2 Switching event evaluation*

The generated switching procedure shows the solution method for a full blackout scenario. The goal is to deliver electrical energy from the diesel generators to the critical loads in the electrical network. Table 5 evaluates the number of switching events of the baseline and solution method.

**Table 5: Evaluation of switching events between baseline and solution**

| Index | Critical Load | Baseline Switching events | Solution model Switching events |
|---|---|---|---|
| 0 | Pre-emptive isolation | 40 | 39 |
| 1 | Man Winder | 3 | 3 |
| 2 | Chairlift 15L-23L | 23 | 3 |
| 3 | Service Winder | 5 | 2 |
| 4 | Chairlift 23L-28L | 22 | 5 |
| 5 | 15L Pumps | 13 | 1 |
| 6 | 22L Pumps | 1 | 0 |
| 7 | 28L Pumps | 13 | 1 |
| Total | | 117 | 54 |

For the specific scenario where switches are placed as described by the switching events required in the baseline, switching events are more than double that of the solution model as shown in Table 5. When comparing the worst-case scenario for each case, the number of switching procedures required with the restoration paths, was 117 switching events and the solution presented reduced switching events to 54. In this case study the 22L Bus and 23L Bus are joined. Therefore, Chairlift 23L-28L and 22L Pumps are connected without any switching.

One of the key areas where the baseline switching procedure is outperformed by the solution model, is when load is disconnected from the planned path. Instead of routing underground restoration paths through 23L, the experts used a similar path to normal operations reticulating from level to level instead of using feeders that travel directly from surface to buses near the critical loads. This in turn, requires de-loading each bus in the network by opening load switches at each underground substation. This then prevents overloading due to unnecessary load that is connected during normal operation and isolating the restoration path.

The switching procedure for activating Chairlift 15L-23L is reduced by 20 events and Chairlift 23L-28L switching events are reduced by from 22 to 5 events. Lastly, all pump switching has been reduced to 2 switching events.

In terms of switching event reduction, the solution model switching procedure is an improvement on the baseline switching procedure.

### *4.9.3 Restoration time comparison*

As stated earlier the implementation of the solution switching procedure was not cleared by the on-site personnel that preferred to rely on the baseline switching plan. An electrical blackout test is performed on the real-world equipment. The total time of the test lasted 1 hour 43 minutes from initial power loss to power restoration on for all critical loads.

The switching performance of underground teams is of interests as this is where the most impact will be made on the number of switches required. Table 6 shows the time to restoration for each of the critical loads underground.

**Table 6: Time estimation of underground switching reduction**

| Index | Critical Load | Baseline Switching events | Baseline restoration time (minutes) | Solution model Switching events | Estimated restoration time (minutes) |
|---|---|---|---|---|---|
| 2 | Chairlift 15L-23L | 23 | 92 | 3 | 12 |
| 4 | Chairlift 23L-28L | 22 | 103 | 5 | 23 |
| 5 | 15L Pumps | 13 | 59 | 1 | 4.5 |
| 6 | 22L Pumps | 1 | 100 | 0 | 12 |
| 7 | 28L Pumps | 13 | 101 | 1 | 7.7 |

It is seen that there is a long initial switching time before services are restored to the first critical load. The teams implement the switching plan of restoration of the first critical load. This is due to most of the switching being done before re-energising each area. As there where an upper shaft team responsible for critical loads two and four the switching of this team was completed simultaneously with critical load four, six and seven. This is why there is a small amount time between switching load two and four in the baseline case.

Estimated restoration times are based on an average switching rate for each critical load. The teams are also allocated to the same areas during implementation. The switching times are seen to be greatly reduced.

The 22L Pumps service restoration is performed during the switching of critical load two. This further reduces the switching time required from underground switching teams. However, the estimated restoration time will be the same as critical load two.

Through the efficiencies generated by the solution model switching procedure a total time of implementation is reduced from 103 minutes to 23 minutes. The 77.6% estimated improvement in implementation of the baseline service restoration plan is achieved.

The method is feasible for application of the solution method to deliver an adequate switching plan to improve critical electrical service restoration efficiency. This reduces the risk involved with power outages in underground mines through improved planning and reduced implementation time.

Risk reduction of power outages in underground mines are one of the factors that will allow for a bright future in the mining industry that can achieve zero-harm.

## 5 CONCLUSION

This study illuminates the critical challenge of minimising downtime caused by electrical outages in underground mines. Inefficient utilisation of redundancy within the electrical distribution networks can lead to extended downtime during maintenance, faults, or blackouts. This research investigated optimisation techniques for network reconfiguration to improve service restoration during blackouts.

The proposed solution leverages graph theory and optimisation methods to develop a switching procedure that restores power to critical loads using distributed generation. A case study from a South African platinum mine demonstrated the effectiveness of the approach. Compared to the mine's current procedure, the proposed method achieved service restoration with significantly fewer switching events (54 vs. 117) and ensured full restoration of critical loads.

These findings highlight the potential of the proposed solution method to enhance service restoration plans in underground mines. By reducing the number of switching events and guaranteeing complete critical load restoration during blackouts, this approach can significantly enlighten overall mining reliability, safety, and efficiency.

This is a step towards a bright zero harm future in mining.

## 6 REFERENCES


[1] K. Behrang, A.-N. Hooman, and D. Clayton, "A linear programming model for long-term mine planning in the presence of grade uncertainty and a stockpile," International Journal of Mining Science and Technology, vol. 24, no. 4, pp. 451-459, 2014/7// 2014, doi: 10.1016/J.IJMST.2014.05.006.

[2] E. Ben-Awuah, O. Richter, T. Elkington, and Y. Pourrahimian, "Strategic mining options optimization: Open pit mining, underground mining or both," International Journal of Mining Science and Technology, vol. 26, no. 6, pp. 1065-1071, 2016/11// 2016, doi: 10.1016/J.IJMST.2016.09.015.

[3] B. King, M. Goycoolea, and A. Newman, "Optimizing the open pit-to-underground mining transition," European Journal of Operational Research, vol. 257, no. 1, pp. 297-309, 2017/2// 2017, doi: 10.1016/j.ejor.2016.07.021.

[4] L. A. Morley, Mine Power Systems. Washington, D.C: U.S. Dept. of the Interior, Bureau of Mines, 1990.

[5] B. Pascoe, "Improved control processes to sustain electricity cost savings on a mine water reticulation system," in North West University, ed. Potchefstroom, 2019.

[6] P. J. Oberholzer, "Best practices for automation and control of mine dewatering systems," ed. Potchefstroom, 2015.

[7] D. P. Mishra, D. C. Panigrahi, and P. Kumar, "Computational investigation on effects of geo-mining parameters on layering and dispersion of methane in underground coal mines- A case study of Moonidih Colliery," Journal of Natural Gas Science and Engineering, vol. 53, no. March, pp. 110-124, 2018, doi: 10.1016/j.jngse.2018.02.030.

[8] M. Zhong, W. Xing, F. Weicheng, L. Peide, and C. Baozhi, "Airflow optimizing control research based on genetic algorithm during mine fire period," Journal of Fire Sciences, vol. 21, no. 2, pp. 131-153, 2003, doi: 10.1177/0734904103021002003.

[9] S. Azam and D. P. Mishra, "Effects of particle size, dust concentration and dust-dispersion-air pressure on rock dust inertant requirement for coal dust explosion suppression in underground coal mines," Process Safety and Environmental Protection, vol. 126, pp. 35-43, 2019, doi: 10.1016/j.psep.2019.03.030.

[10] E. Preis, W. Leuschner, J. Jacobs, and R. Agency, "Proposed Illumination Guidelines for Equipment Operating in the South African Mining Industry (SAMI)," 2019/4// 2019.

[11] J. C. Vosloo, "Control of and underground rock winder system to reduce electricity costs on RSA gold mines," ed, 2006, pp. i-100.

[12] R. C. W. Webber-Youngman and G. M. J. Van Heerden, "Engineering principles for the design of a personnel transportation system," Journal of the Southern African Institute of Mining and Metallurgy, vol. 116, no. 5, pp. 441-454, 2016, doi: 10.17159/2411-9717/2016/v116n5a10.

[13] R. Zimroz, M. Hardygóra, and R. Blazej, "Maintenance of Belt Conveyor Systems in Poland – An Overview," pp. 21-30, 2015, doi: 10.1007/978-3-319-12301-1_3.

[14] D. Nell, "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure," ed. Potchefstroom, 2017, pp. 162-162.

[15] F. Shen, Q. Wu, S. Huang, J. C. Lopez, C. Li, and B. Zhou, "Review of Service Restoration Methods in Distribution Networks," in Proceedings - 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT-Europe 2018, 2018/12// 2018: Institute of Electrical and Electronics Engineers Inc., doi: 10.1109/ISGTEurope.2018.8571821.

[16] Y. Liu, R. Fan, and V. Terzija, "Power system restoration: a literature review from 2006 to 2016," Journal of Modern Power Systems and Clean Energy, vol. 4, no. 3, pp. 332-341, 2016/7// 2016, doi: 10.1007/s40565-016-0219-2.

[17] H. Hong, Z. Hu, R. Guo, J. Ma, and J. Tian, "Directed graph-based distribution network reconfiguration for operation mode adjustment and service restoration considering distributed generation," Journal of Modern Power Systems and Clean Energy, vol. 5, no. 1, pp. 142-149, 2017, doi: 10.1007/s40565-016-0198-3.

[18] K. Song, J. Wang, J. Liu, Q. Zhou, C. Wang, and Y. Xie, "An intelligent optimization method of power system restoration path based on orthogonal genetic algorithm," in Chinese Control Conference, CCC, 2016/8// 2016, vol. 2016-Augus: IEEE Computer Society, pp. 2751-2755, doi: 10.1109/ChiCC.2016.7553780.

[19] M. Mahdavi, H. H. Alhelou, N. D. Hatziargyriou, and A. Al-Hinai, "An Efficient Mathematical Model for Distribution System Reconfiguration Using AMPL," IEEE Access, vol. 9, pp. 79961-79993, 2021, doi: 10.1109/ACCESS.2021.3083688.

[20] A. E. B. Abu-Elanien, M. M. A. Salama, and K. B. Shaban, "Modern network reconfiguration techniques for service restoration in distribution systems: A step to a smarter grid," Alexandria Engineering Journal, vol. 57, no. 4, pp. 3959-3967, 2018, doi: 10.1016/j.aej.2018.03.011.

[21] C. Wang, S. Lei, P. Ju, C. Chen, C. Peng, and Y. Hou, "MDP-Based Distribution Network Reconfiguration with Renewable Distributed Generation: Approximate Dynamic Programming Approach," IEEE Transactions on Smart Grid, vol. 11, no. 4, pp. 3620-3631, 2020/7// 2020, doi: 10.1109/TSG.2019.2963696.

[22] H. Haghighat and B. Zeng, "Distribution System Reconfiguration under Uncertain Load and Renewable Generation," IEEE Transactions on Power Systems, vol. 31, no. 4, pp. 2666-2675, 2016/7// 2016, doi: 10.1109/TPWRS.2015.2481508.

[23] A. M. Tahboub, V. R. Pandi, and H. H. Zeineldin, "Distribution System Reconfiguration for Annual Energy Loss Reduction Considering Variable Distributed Generation Profiles," IEEE Transactions on Power Delivery, vol. 30, no. 4, pp. 1677-1685, 2015/8// 2015, doi: 10.1109/TPWRD.2015.2424916.

[24] J. Zhan, W. Liu, C. Y. Chung, and J. Yang, "Switch Opening and Exchange Method for Stochastic Distribution Network Reconfiguration," IEEE Transactions on Smart Grid, vol. 11, no. 4, pp. 2995-3007, 2020/7// 2020, doi: 10.1109/TSG.2020.2974922.

[25] M. A. Tavakoli Ghazi Jahani, P. Nazarian, A. Safari, and M. R. Haghifam, "Multi-objective optimization model for optimal reconfiguration of distribution networks with demand response services," Sustainable Cities and Society, vol. 47, 2019/5// 2019, doi: 10.1016/j.scs.2019.101514.

[26] N. V. Kovački, P. M. Vidović, and A. T. Sarić, "Scalable algorithm for the dynamic reconfiguration of the distribution network using the Lagrange relaxation approach," International Journal of Electrical Power and Energy Systems, vol. 94, pp. 188-202, 2018/1// 2018, doi: 10.1016/j.ijepes.2017.07.005.

[27] H. Ahmadi and J. R. Martí, "Mathematical representation of radiality constraint in distribution system reconfiguration problem," International Journal of Electrical Power and Energy Systems, vol. 64, pp. 293-299, 2015, doi: 10.1016/j.ijepes.2014.06.076.

[28] F. R. Alonso, D. Q. Oliveira, and A. C. Zambroni De Souza, "Artificial immune systems optimization approach for multiobjective distribution system reconfiguration," IEEE Transactions on Power Systems, vol. 30, no. 2, pp. 840-847, 2015/3// 2015, doi: 10.1109/TPWRS.2014.2330628.

[29] J. C. López, M. Lavorato, and M. J. Rider, "Optimal reconfiguration of electrical distribution systems considering reliability indices improvement," International Journal of Electrical Power and Energy Systems, vol. 78, pp. 837-845, 2016/6// 2016, doi: 10.1016/j.ijepes.2015.12.023.

[30] Y. Song, Y. Zheng, T. Liu, S. Lei, and D. J. Hill, "A New Formulation of Distribution Network Reconfiguration for Reducing the Voltage Volatility Induced by Distributed Generation," IEEE Transactions on Power Systems, vol. 35, no. 1, pp. 496-507, 2020/1// 2020, doi: 10.1109/TPWRS.2019.2926317.

[31] J. Wang, W. Wang, Z. Yuan, H. Wang, and J. Wu, "A chaos disturbed beetle antennae search algorithm for a multiobjective distribution network reconfiguration considering the variation of load and dg," IEEE Access, vol. 8, pp. 97392-97407, 2020, doi: 10.1109/ACCESS.2020.2997378.

[32] N. C. Koutsoukis, D. O. Siagkas, P. S. Georgilakis, and N. D. Hatziargyriou, "Online Reconfiguration of Active Distribution Networks for Maximum Integration of Distributed Generation," IEEE Transactions on Automation Science and Engineering, vol. 14, no. 2, pp. 437-448, 2017/4// 2017, doi: 10.1109/TASE.2016.2628091.

[33] A. Lotfipour and H. Afrakhte, "A discrete Teaching-Learning-Based Optimization algorithm to solve distribution system reconfiguration in presence of distributed generation," International Journal of Electrical Power and Energy Systems, vol. 82, pp. 264-273, 2016/11// 2016, doi: 10.1016/j.ijepes.2016.03.009.

[34] H. Wu, P. Dong, and M. Liu, "Distribution Network Reconfiguration for Loss Reduction and Voltage Stability with Random Fuzzy Uncertainties of Renewable Energy Generation and Load," IEEE Transactions on Industrial Informatics, vol. 16, no. 9, pp. 5655-5666, 2020/9// 2020, doi: 10.1109/TII.2018.2871551.

[35] A. Asrari, S. Lotfifard, and M. Ansari, "Reconfiguration of Smart Distribution Systems with Time Varying Loads Using Parallel Computing," IEEE Transactions on Smart Grid, vol. 7, no. 6, pp. 2713-2723, 2016/11// 2016, doi: 10.1109/TSG.2016.2530713.

[36] S. Naveen, K. Sathish Kumar, and K. Rajalakshmi, "Distribution system reconfiguration for loss minimization using modified bacterial foraging optimization algorithm," International Journal of Electrical Power and Energy Systems, vol. 69, pp. 90-97, 2015, doi: 10.1016/j.ijepes.2014.12.090.

[37] A. M. Eldurssi and R. M. O'Connell, "A fast nondominated sorting guided genetic algorithm for multi-objective power distribution system reconfiguration problem," IEEE Transactions on Power Systems, vol. 30, no. 2, pp. 593-601, 2015/3// 2015, doi: 10.1109/TPWRS.2014.2332953.

[38] M. M. R. Ibrahim, H. A. Mostafa, M. M. A. Salama, R. El-Shatshat, and K. B. Shaban, "A graph-theoretic service restoration algorithm for power distribution systems," Proceedings of 2018 International Conference on Innovative Trends in Computer Engineering, ITCE 2018, vol. 2018-March, pp. 338-343, 2018, doi: 10.1109/ITCE.2018.8316647.

[39] H. Hijazi and S. Thiébaux, "Optimal distribution systems reconfiguration for radial and meshed grids," International Journal of Electrical Power and Energy Systems, vol. 72, pp. 136-143, 2015/3// 2015, doi: 10.1016/j.ijepes.2015.02.026.

[40] H. Gao, Y. Chen, Y. Xu, and C. C. Liu, "Resilience-Oriented Critical Load Restoration Using Microgrids in Distribution Systems," IEEE Transactions on Smart Grid, vol. 7, no. 6, pp. 2837-2848, 2016/11// 2016, doi: 10.1109/TSG.2016.2550625.

[41] M. Gholami, J. Moshtagh, and L. Rashidi, "Service restoration for unbalanced distribution networks using a combination two heuristic methods," International

Journal of Electrical Power and Energy Systems, vol. 67, pp. 222-229, 2015/5// 2015, doi: 10.1016/j.ijepes.2014.11.024.

[42] P. Prabawa and D. H. Choi, "Multi-Agent Framework for Service Restoration in Distribution Systems with Distributed Generators and Static/Mobile Energy Storage Systems," IEEE Access, vol. 8, pp. 51736-51752, 2020, doi: 10.1109/ACCESS.2020.2980544.

[43] G. Huang, J. Wang, C. Chen, J. Qi, and C. Guo, "Integration of Preventive and Emergency Responses for Power Grid Resilience Enhancement," IEEE Transactions on Power Systems, vol. 32, no. 6, pp. 4451-4463, 2017/11// 2017, doi: 10.1109/TPWRS.2017.2685640.

[44] Y. Wang et al., "Coordinating Multiple Sources for Service Restoration to Enhance Resilience of Distribution Systems," IEEE Transactions on Smart Grid, vol. 10, no. 5, pp. 5781-5793, 2019/1// 2019, doi: 10.1109/tsg.2019.2891515.

[45] M. Sedighizadeh, M. Esmaili, and M. Esmaeili, "Application of the hybrid Big Bang-Big Crunch algorithm to optimal reconfiguration and distributed generation power allocation in distribution systems," Energy, vol. 76, pp. 920-930, 2014/11// 2014, doi: 10.1016/j.energy.2014.09.004.

[46] A. R. Malekpour, T. Niknam, A. Pahwa, and A. K. Fard, "Multi-objective stochastic distribution feeder reconfiguration in systems with wind power generators and fuel cells using the point estimate method," IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 1483-1492, 2013, doi: 10.1109/TPWRS.2012.2218261.

[47] E. kianmehr, S. Nikkhah, and A. Rabiee, "Multi-objective stochastic model for joint optimal allocation of DG units and network reconfiguration from DG owner's and DisCo's perspectives," Renewable Energy, vol. 132, pp. 471-485, 2019/3// 2019, doi: 10.1016/j.renene.2018.08.032.

[48] H. Xing and X. Sun, "Distributed generation locating and sizing in active distribution network considering network reconfiguration," IEEE Access, vol. 5, pp. 14768-14774, 2017/7// 2017, doi: 10.1109/ACCESS.2017.2732353.

[49] A. Ameli, A. Ahmadifar, M. H. Shariatkhah, M. Vakilian, and M. R. Haghifam, "A dynamic method for feeder reconfiguration and capacitor switching in smart distribution systems," International Journal of Electrical Power and Energy Systems, vol. 85, pp. 200-211, 2017/2// 2017, doi: 10.1016/j.ijepes.2016.09.008.

[50] Y. Takenobu, N. Yasuda, S. Kawano, S. I. Minato, and Y. Hayashi, "Evaluation of Annual Energy Loss Reduction Based on Reconfiguration Scheduling," IEEE Transactions on Smart Grid, vol. 9, no. 3, pp. 1-11, 2018/5// 2018, doi: 10.1109/TSG.2016.2604922.

[51] S. Ray, S. Bhattacharjee, and A. Bhattacharya, "Optimal allocation of remote control switches in radial distribution network for reliability improvement," Ain Shams Engineering Journal, vol. 9, no. 3, pp. 403-414, 2018, doi: 10.1016/j.asej.2016.01.001.

[52] D. S. Sanches, J. B. A. London Junior, and A. C. B. Delbem, "Multi-Objective Evolutionary Algorithm for single and multiple fault service restoration in large-scale distribution systems," Electric Power Systems Research, vol. 110, pp. 144-153, 2014, doi: 10.1016/j.epsr.2014.01.017.

[53] J. Li, X. Y. Ma, C. C. Liu, and K. P. Schneider, "Distribution system restoration with microgrids using spanning tree search," IEEE Transactions on Power Systems, vol. 29, no. 6, pp. 3021-3029, 2014/11// 2014, doi: 10.1109/TPWRS.2014.2312424.

[54] Y. Y. Fu and H. D. Chiang, "Toward optimal multiperiod network reconfiguration for increasing the hosting capacity of distribution networks," IEEE Transactions on Power

Delivery, vol. 33, no. 5, pp. 2294-2304, 2018/10// 2018, doi: 10.1109/TPWRD.2018.2801332.

[55] S. Mishra, D. Das, and S. Paul, "A comprehensive review on power distribution network reconfiguration," Energy Systems, vol. 8, no. 2, pp. 227-284, 2017/5// 2017, doi: 10.1007/s12667-016-0195-7.

[56] P. Konwar and D. Sarkar, "Strategy for the Identification of Optimal Network Distribution Through Network Reconfiguration Using Graph Theory Techniques – Status and Technology Review," Journal of Electrical Engineering and Technology, vol. 17, no. 6, pp. 3263-3274, 2022/11// 2022, doi: 10.1007/s42835-022-01139-7.

[57] H. F. Habib and O. Mohammed, "Decentralized Multi-Agent System for Protection and the Power Restoration Process in Microgrids," IEEE Green Technologies Conference, pp. 358-364, 2017, doi: 10.1109/GreenTech.2017.58.

[58] M. Mahdavi, H. H. Alhelou, N. D. Hatziargyriou, and F. Jurado, "Reconfiguration of Electric Power Distribution Systems: Comprehensive Review and Classification," IEEE Access, vol. 9, pp. 118502-118527, 2021, doi: 10.1109/ACCESS.2021.3107475.

[59] O. Badran, S. Mekhilef, H. Mokhlis, and W. Dahalan, "Optimal reconfiguration of distribution system connected with distributed generations: A review of different methodologies," in Renewable and Sustainable Energy Reviews vol. 73, ed: Elsevier Ltd, 2017, pp. 854-867.

[60] N. Branisavljević, Z. Kapelan, and D. Prodanović, "Improved real-time data anomaly detection using context classification," Journal of Hydroinformatics, vol. 13, no. 3, pp. 307-323, 2011, doi: 10.2166/hydro.2011.042.

[61] B. Zhang et al., "A Distribution System State Estimation Analysis Considering the Dynamic Load Effect," IEEE Region 10 Annual International Conference, Proceedings/TENCON, vol. 2018-Octob, no. October, pp. 2485-2489, 2019, doi: 10.1109/TENCON.2018.8650087.

[62] K. P. Schneider et al., "Analytic Considerations and Design Basis for the IEEE Distribution Test Feeders," IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 3181-3188, 2018, doi: 10.1109/TPWRS.2017.2760011.

[63] W. H. Kersting, "Radial distribution test feeders," in 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194), 28 Jan.-1 Feb. 2001 2001, vol. 2, pp. 908-912 vol.2, doi: 10.1109/PESW.2001.916993.

[64] L. T. Marques, A. C. B. Delbem, and J. B. A. London, "Service Restoration With Prioritization of Customers and Switches and Determination of Switching Sequence," IEEE Transactions on Smart Grid, vol. 9, no. 3, pp. 2359-2370, 2018, doi: 10.1109/TSG.2017.2675344.