Optimal operation of circuit breakers in different types of networks for minimum load shedding

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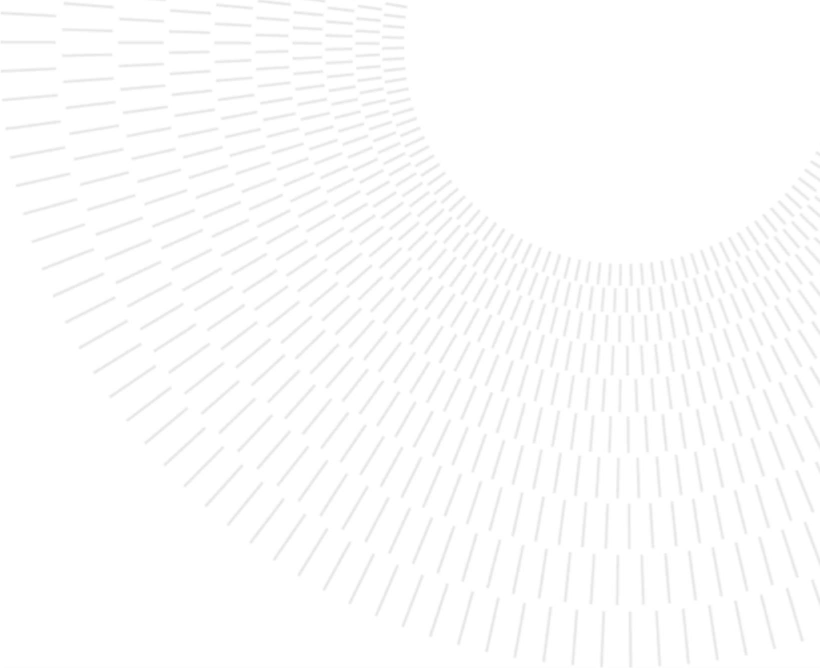

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To my family,
The ones who are physically distant by an entire ocean but always present in my heart, and to my beloved husband who always encourages me to overcome great challenges.

"Have I not commanded you? Be strong and courageous. Do not be afraid; do not be discouraged, for the Lord your God will be with you wherever you go."
Joshua 1:9

Abstract

Reliability in electric power systems is a vital characteristic, as the continuous supply of the required power in the network is the foundation of sustainable development in a world which grows in its electricity penetration and the onboarding of new green technologies. In the case of a fault, it is of paramount importance to apply a countermeasure to clear it. Hence, the importance to apply and develop faster and more efficient solutions to isolate the fault focusing on obtaining the minimum power loss, or the minimum amount of circuit breakers (CBs) to be tripped.

This investigation aims at finding a criterion for determining the best opening procedure for CBs in order to clear the fault. Three different criterion of optimality were defined: the minimum load shedding, the minimum distance of CBs to the fault location, and the minimum number of CBs to be operated to isolate the fault. A single algorithm was implemented in the MATLAB® environment to find the optimal operation scheme for circuit breakers to clear a fault based on these three criterion. The algorithm finds all possible paths (transmission lines/CBs) between the fault location and the sources, by using a combination technique to obtain all the possible ways to isolate the fault concerning the CBs operation. A total of four electrical grids, one radial, and three meshed, were studied considering three places for a generic fault location: transmission line (TL), load, and bus.

Once this approach is applied to the power system under analysis, all possible solutions to isolate the fault concerning the CBs operation are found. And it is obtained solutions that provide the minimum load shedding by applying the three defined conditions of optimality. In all the studied cases, the optimal scheme of CBs to clear the fault is composed mostly of CBs installed in the TLs which are connected to the bus where the fault happened. The second condition of optimality is always present in the set of solutions that gives the minimum load shedding. However, it is possible to obtain the optimal solution by applying the mathematical operation proposed in this thesis or by tripping the CBs linked to the fault location as well.

Keywords: fault location, fault isolation, optimal solution, circuit breaker scheme, minimum load shedding, closest circuit breakers, path.

Sommario

L'affidabilità dei sistemi di alimentazione elettrica è una caratteristica fondamentale, poiché la fornitura continua della potenza richiesta nella rete è alla base dello sviluppo sostenibile. In caso di guasto, è di fondamentale importanza applicare una contromisura per eliminarlo. Da qui l'importanza di applicare e sviluppare soluzioni più rapide ed efficienti per isolare il guasto concentrandosi sull'ottenimento della minima perdita di potenza o della quantità minima di interruttori da far scattare.

Questa indagine mira a trovare un criterio per determinare la migliore procedura di apertura degli interruttori al fine di eliminare il guasto. Sono stati definiti tre diversi criteri di ottimalità: il distacco minimo di carico, la distanza minima degli interruttori dalla posizione del guasto e il numero minimo di interruttori da azionare per isolare il guasto. È stato implementato un algoritmo per trovare lo schema di funzionamento ottimale per gli interruttori automatici per eliminare un guasto in base a questi tre criteri. L'algoritmo trova tutti i percorsi possibili tra il guasto e le sorgenti, utilizzando una tecnica combinatoria. Sono state studiate in totale quattro reti elettriche, una radiale e tre magliate, considerando tre punti per una posizione di guasto generico: linea di trasmissione (TL), carico e bus.

Una volta applicato l'approccio ideato al sistema elettrico in analisi, si trovano tutte le soluzioni possibili per isolare il guasto. Si ottengono soluzioni che prevedevano il soddisfacimento di uno dei tre criteri di ottimalità. In tutti i casi studiati, lo schema ottimale di interruttori per eliminare il guasto è composto principalmente da CB installati nei TL che sono direttamente collegati al bus dove si è verificato il guasto. La seconda condizione di ottimalità è sempre presente nell'insieme delle soluzioni che danno il minimo distacco del carico, tuttavia non è l'unica. Tuttavia, è possibile ottenere la soluzione ottimale applicando l'operazione matematica proposta in questa tesi o facendo scattare anche i CB collegati alla localizzazione del guasto. Pertanto, oltre a questo approccio, è anche possibile ottenere la migliore selezione di CB da viaggio utilizzando la metodologia matematica sviluppata in questa tesi.

Parole chiave: localizzazione del guasto, isolamento del guasto, soluzione ottimale, schema dell'interruttore, eliminazione del carico minimo, interruttori più vicini, percorso.

Acknowledgments

All glory, honor and praise I give to my God. Because of my Lord Jesus, I am here. Only because of Him, who trained my hands to win each battle (Psalm 18:34).

I had such an amazing supervisor. Professor Samuele Grillo helped me and guided me during this period of research and development of the thesis. Thank you for all the advice and availability. I must say that are some people who have a big talent to be a professor. For sure, you are one of them.

I thank my family, even though they are physically distant by an ocean, they always supported me in my studies. My mother and father always did it, even when I could not find a job in Brazil. They always invested in me. Thanks also to my little brother who is an amazing little brother. I thank all my family.

I thank also the brothers and sisters of the church for all your prayers.

Thank you to my friends, who always prayed for my life to achieve the victories that Lord already had prepared for us. I miss you very much! Surely, God gives friends to us who are also His friends.

Thanks to my friends here in Italy for all the help! I appreciate so much our friendship!

And finally, I am grateful to my husband, Hugo Pozo, my blessing. Always by my side, helping me, calming me down in the hardest moments, praying with me, giving me the leap of faith even though we saw the impossible, but we trusted in Jesus together. Our God never failed us and He never will. My dear husband, you are the greatest blessing that Lord gave to me, after the Salvation that we have in Jesus Christ. Thank you for your patience, your kindness, your care, and your love.

Contents

1

Introduction

1.1. MOTIVATION

Stability and reliability in a grid play a key role in the correct operation of the network. Maintaining the continuity of the appropriate functioning is extremely important for the power system electrical engineer. Faults in the network can lead to severe consequences such as loss of synchronism of the generators, power losses, blackouts, etc, if the fault is not clear on time and efficiently. A competent way for the fault isolation can be achieved by focusing on the minimum load shedding, selectivity of the fault isolation concerning the load priority to be disconnected from the grid, etc.

There is plenty of research concerning the minimum load shedding in an occurrence of a fault in a network. They englobe the application of computational intelligent load shedding techniques, such as Genetic Algorithm (GA) [1], Fuzzy Logic [2][3], or Artificial Neural Network (ANN) [4], to achieve the minimum power loss. On the other hand, some approaches do not use computational intelligence, they focus on the shortest path between the fault and the source to trip the CBs that belong to the obtained path. For this last method, the graph theory is used (for the power system), and the Floyd-Warshall algorithm, as well as the Dijkstra algorithm, to find the shortest path [5]. Hence, the minimum load shedding is found.

Unlike the previous studies whose objective is to obtain the minimum power loss when a fault happens to isolate it, the objective of this thesis is to find the optimal scheme of CBs to clear the fault having as criterion the minimum load shedding, the distance of the CBs to the fault location, and the number of the CBs to trip. There is scarce research regarding this method. Most of the papers found regarding this subject present methods to isolate the fault using computational techniques such as

Laghari et al. and Hsu et al. works [2][4]. The ones that do not use this approach, and focus on finding the shortest path between the source and fault to isolate it, uses mainly Dijkstra and Floyd-Warshall algorithms, like Arya et al. and Zhang et al. papers. This investigation proposes a novel approach by using an algorithm that was created to develop it. No supplementary algorithm, such as Floyd-Warshall or Dijkstra, was used because they only give the shortest path between the fault location and the generators. The propose of this thesis is to analyze not only an unique path or solution, but all ways to isolate the fault. The developed algorithm in this thesis implements all the proposed solutions to select the best scheme of CBs to open for clearing the fault regarding the defined optimality.

1.2. OBJECTIVES OF THE STUDY

The present thesis aims to contribute to a better strategy to obtain an optimal operation scheme for CBs to isolate the fault using the three conditions of optimality: minimum load shedding, the distance of the CBs concerning the fault location, and the minimum number of CBs that must trip when a fault occurs.

The objectives of the thesis were formulated as follows:

- Study to achieve the optimal operation of the CBs in case of a fault in two types of networks to achieve a minimum load shedding:
    i. Radial and
    ii. Meshed.
- To obtain the OPTIMAL CBs scheme to trip to clear the fault, it is important to define the optimality to be acquired, which are:
    i. **First criterion:** reach the minimum load shedding, which means the minimum active power that will be lost once the CBs open to clear the fault.
    ii. **Second criterion:** select the set of CBs that are closest to the fault, which are the ones that are directly connected to the bus where the fault occurred. This method is applied if there is more than one set of CBs that results in the minimum load shedding.
    iii. **Third criterion:** open the minimum amount of CB as possible to isolate the fault. This condition is subdivided is two investigations: (1) If there is more than one set of CBs whose elements are all directly connected to the bus where the fault happened; (2) It is verified if the solution contains TLs that are connected to a load, if it is true, the CB of this TL is not opened, because it is enough to isolate the fault from the generators, as no more power will be supplying the load that is connected to the fault.

These criteri are only used for a fault in the bus. In case of a fault in the transmission line (TL) or in the load, the approach is different. For the first one, it is tripped the CB that is directly connected to the TL where the fault happened. For the second one, the approach is to open the CB that is connected to the TL where the load is linked.

In summary, the focus is on the optimal selectivity of the CBs operation to isolate the fault from the generators of the power system. For that, three criterion of optimality are defined:

i. Minimum load shedding;
ii. Trip the CBs that are closest to the fault.
iii. Trip the minimum number of CBs.

1.3. THESIS OUTLINE

The thesis presents six chapter and one appendix. The content is as follows:

- Chapter 1 – Introduction: presentation of the thesis.
- Chapter 2 – Background: previous studies regarding the main subject of this work.
- Chapter 3 – Methodology: the analysis and solution developed to obtain the objective proposed.
- Chapter 4 – Results: application of the created solution in three different networks.
- Chapter 5 – Real network analysis: application of the built algorithm in a real power system.
- Chapter 6 – Concluding remarks: conclusion of the analysis and the results obtained.

2

Background

2.1. POWER SYSTEM

A power system (PS) has three main objectives: supply (by the generators), transmit (by the transmission lines), and consume electric power (by the loads). A network can have different types of configurations such as radial, ring, star, meshed, etc.

It is significant to have a secure power system to obtain a reliable grid for keeping provide the required power. Therefore, in case of a fault, it is imperative to apply countermeasures to clear the fault that can occur in the power system. If it is not cleared on time and efficiently, it can result in instability in the system.

Grainger and Stevenson state that the network can undergo disturbances when operating in a steady-state condition, for example, transmission system faults, sudden load changes, loss of generating units, etc. As consequence, the system can become unstable. Thus, once a fault happens and it is not cleared on time, it can result in a loss of synchronism of the generator, i.e., the generator will lose synchronism. Which results in instability of the PS [6]. Hence, it is essential to isolate the fault. One way to do so is the opening of the circuit breakers or switches to clear the fault. The main objective is the best approach to make this operation feasible, as it is necessary the fault isolation to prevent damage to the whole system and to avoid its instability. For this purpose, it is analyzed the minimum load shedding, i.e., the active power that will be lost once a fault happens, to make the best selection of CBs to trip.

2.2. GRAPH THEORY

A network can be represented using the graph theory. Accordingly to Gross and Yellen, "[…] *any mathematical object involving points and connections between them may be called a graph.". In* their book "Handbook of a graph theory", the definition is presented as: "*a graph G = (V,E) consists of two sets V and E*". Where the elements of *V* are called vertices or nodes; and the elements of *E* are called edges [7]. For example:

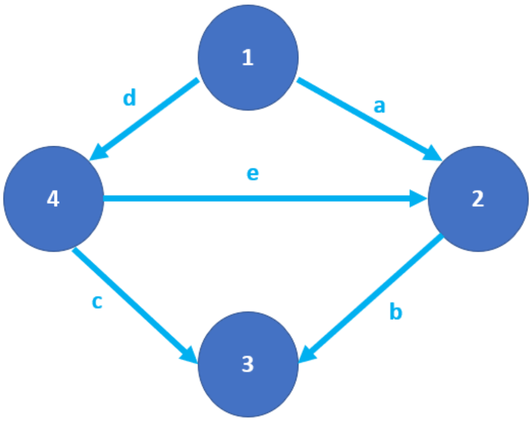


Figure 1 - Example of a graph

In Figure 1, the set *V* is {1,2,3,4} and the set *E* is {a,b,c,d,e}.

This theory can be used to represent the power system. For instance, the vertices can be generators, busbars, loads and the edges can be the active power that flows in the transmission line. In the Chapter 3, the application of this theory is described in the proposed study.

2.3. LOAD SHEDDING

When a fault occurs, load will be shed. Load shedding is the disconnection of a certain number of loads from the feeder [3]. The minimum load shedding is a strategy to achieve an optimal operation of CBs in the network in case of a fault. This means that if a fault happens in any component of the power system, this approach focuses on the minimum load that will be shed, i.e., the minimum active power that will be lost (power that will no longer be provided in the grid while the fault is not cleared).

There are several ways to achieve the minimum load shedding to have an optimal operation to isolate the fault. Laghari et al. mention three cases [2]:

i. Conventional load shedding
    a. Under frequency load shedding techniques and
    b. Under voltage load shedding techniques.

ii. Adaptive load shedding techniques
iii. Computational intelligent load shedding techniques
    a. Artificial Neural Network,
    b. Fuzzy logic control,
    c. Adaptive Neuro Fuzzy Interference System (ANFIS),
    d. Genetic Algorithm and
    e. Particle Swarm Optimization.

There is also a different method to achieve the minimum load shedding from the ones aforementioned: the optimal operation of the circuit breaker to isolate the fault focusing preferably on the minimum load shedding, which makes part of the proposal of this thesis. For this last proposal, the research regarding this subject is very scant.

2.4. FAULT ISOLATION

The objective of fault isolation is to set apart the fault from the sources. Therefore, it is important to know all the paths that interconnect the fault to the generators.

There are strategies for this purpose, such as the use of the algorithms that find the shortest path between the fault location and the generators, for instance: Floyd-Warshall [5][8], Dijkstra algorithm [8][9], Bellman Ford algorithm [10], etc.

There are scarce bibliographic references regarding the optimal operation of the CBs to obtain the minimum power loss in a fault occurrence. For the clear/isolation of a fault, CBs and switches are used to isolate it from the rest of the "healthy" system (the part where there is no fault). Therefore, this work proposes a novel approach to enhance the protection of the power systems in a fault event.

2.5. RESEARCH ABOUT THE FAULT ISOLATION

To reach the thesis objective, the graph representation is used, and an algorithm is built. Regarding this subject, there are types of research with similarities concerning this topic, but not exactly with the same proposal. For instance:

- Qin et al. present a paper use the graph theory to represent the power system. Their paper shows a new method to select the bus protection zones in microprocessor-based relays [11].
- Swathika and Hemamalini propose a method in the paper to find the shortest path to clear a fault in the power system. For this case, they used the Floyd-Warshall algorithm to achieve the proposed objective [12].
- Zhang et al. show in their paper a novel scheme for fault isolation by using the Floyd-Warshall algorithm. The objective of their studies is to minimize the

area of fault isolation and to obtain a quick trip of CBs under the changes in the network topology [5].

There is scant research regarding the proposed subject in this thesis. As the graph theory is used in Qin et al. paper, also in this study is applied. Because it is important the identification of the power flow in the busbars of the network and for the application of one of the proposed methods to accomplish the thesis goal. Furthermore, this subject is detailed and explained.

Unlike the Swathika and Hemamalini, and also Zhang et al. papers concerning the study to find the shortest path, this thesis focuses on finding all the paths that connect the fault to the sources of the grid. With the path data, it is possible to analyze all the possible solutions to isolate the fault from the generators and, consequently, to find all the load shedding for all these cases and obtain the minimum load shedding in these results. Swathika and Hemamalini use the Floyd-Warshall algorithm to find the shortest path. In the case of this thesis, it is built a new algorithm to find all the paths between the fault and the sources, and also to apply the three criterion of optimality for the operation scheme of the CBs.

2.6. SUMMARY AND PROBLEM STATEMENT

To propose a new method to provide a more reliable and secure network and according to the points highlighted in the literature review, the following questions are addressed through the thesis:

- Question 1: what is the optimal operation scheme for CBs to clear a fault?
- Question 2: how powerful is the minimum load shedding condition in a fault occurrence over the other two criterion?
- Question 3: how effective is to trip the CBs closer to the fault location regarding the other defined criterion?
- Question 4: how efficacious is to trip the minimum number of CBs to isolate the fault concerning the previous two criterion?

3

Methodology

This chapter presents step by step of the developed algorithm for the proposed problem.

3.1. INTRODUCTION

An algorithm was created as a novel solution for the proposed problem: *find the optimal operation scheme for circuit breakers to clear a fault applying three criterion of optimality:*

- *Criterion 1: Achieve the minimum load shedding.*
- *Criterion 2: Trip the CBs closer (directly connected) to the fault location.*
- *Criterion 3: Open the minimum number of CBs.*

Once the first criterion is met, if it results in more than one solution, the second criterion is applied, which searches for the solutions that have all elements directly connected to the bus where the fault occurred. The third condition of optimality is applied after Criterion 2 if the second condition also gives more than one solution. In this case, the set of CBs selected is the one that has the minimum number of CBs. In addition, in Criterion 3 it is also verified if the optimal solution has TL that is connected to the load, if there is, the CB connected to that line is not opened as it is not necessary to trip it, because the fault is isolated from the generators by the others CBs of this solution.

These criterion are applied for the fault in a bus. For the fault in the TL or in the load, a simpler solution is applied and it is described in the next subsections.

The methodology is built concerning two different types of networks: radial and meshed. The proposed solution (algorithm) is applied to both types.

It is considered that the fault can occur in the bus, in the transmission line (TL) or in the load. For each fault location, different approaches are followed, as previously mentioned.

It is assumed one CB installed in each TL. Although, usually there are two CBs installed in the line: one at the receiving end, and another one at the sending end. Therefore, CB_x is composed by CB_{x_re} and CB_{x_se}. Once CB_x must trip, it means that CB_{x_re} and CB_{x_se} will open to clear the fault. These nomenclature refers to:

- CB_{x_re} is the CB at the receiving end of the TL_x and
- CB_{x_se} is the CB at the sending end of the TL_x.

This terminology is used for the sake simplicity.

Finally, the given paths and solutions are composed by numbers that correspond to TLs, which also refer to CBs.

3.2. NETWORK INFORMATION

The networks used for the formulation of the algorithm are presented in the following figures:

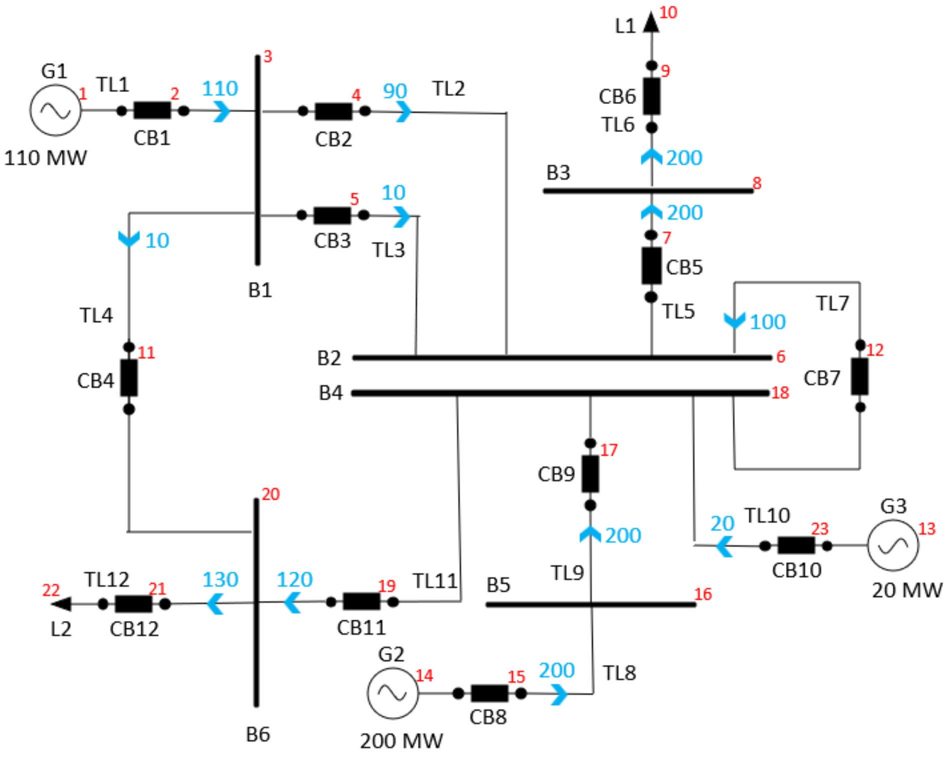


Figure 2 - Meshed network

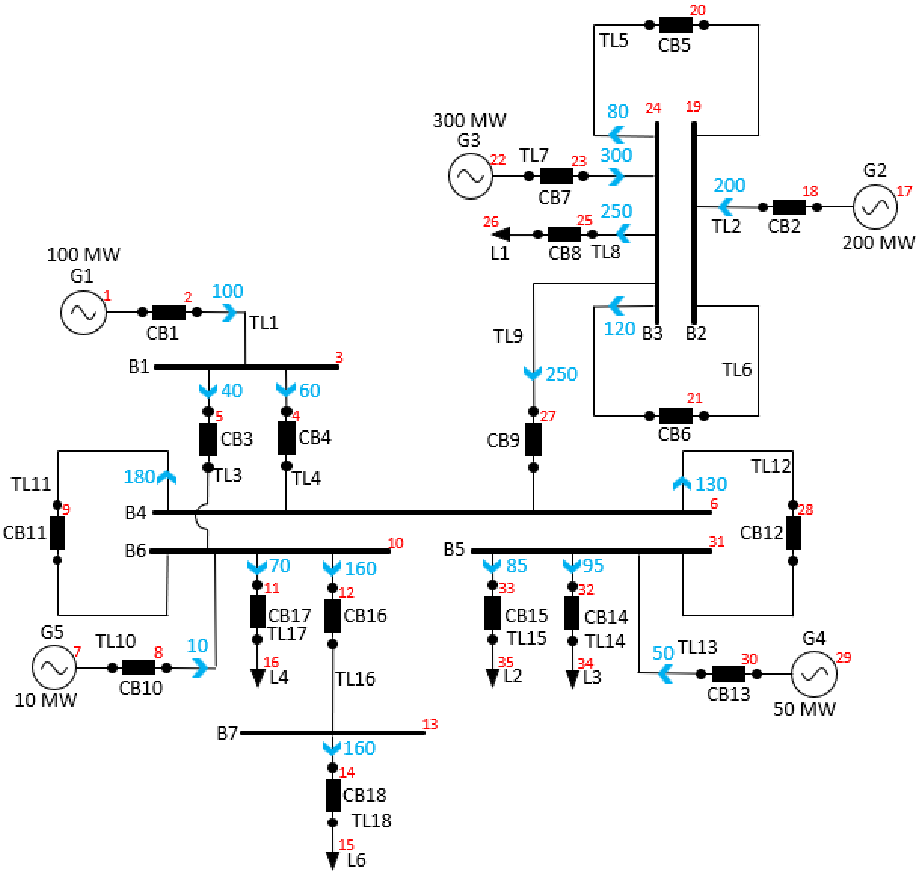


Figure 3 - Radial network

About Figure 2 and Figure 3, the active power and its direction is highlighted in blue. The numbers in red are for the identification of each component of the grid in the algorithm. Observe that CB and TL refers to the same number ($TL_x \leftrightarrow CB_x$).

The following network is used for explanation of the logic built in Methodology, while, the results of power systems of Figure 2 and Figure 3 are presented in Chapter 4.

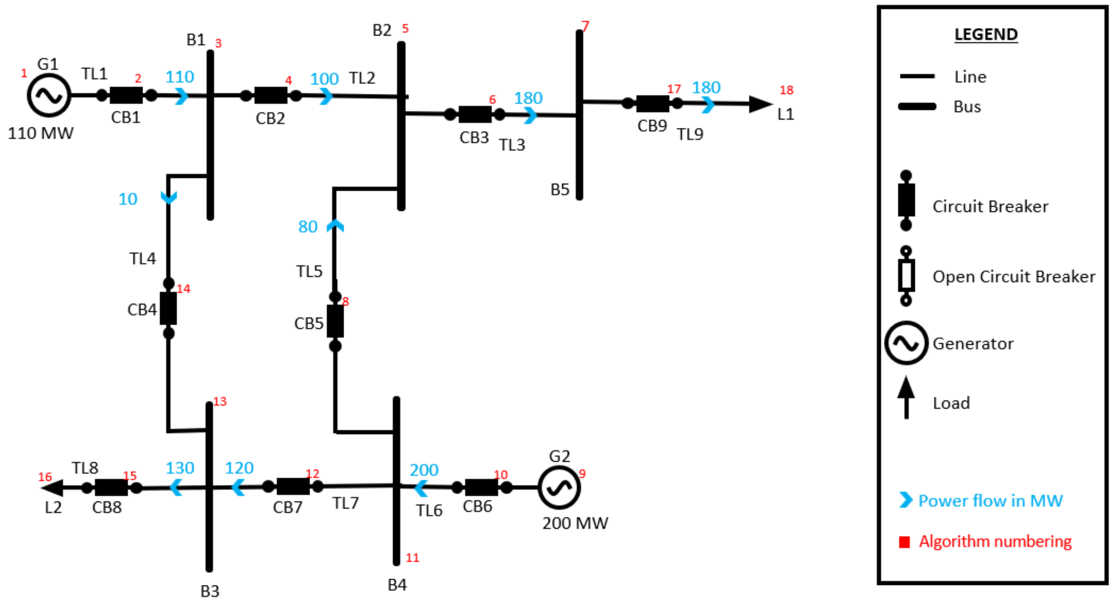


Figure 4 - Simple meshed network

3.3. GRAPH REPRESENTATION

The graph representation for the network of Figure 2 and Figure 3 are:

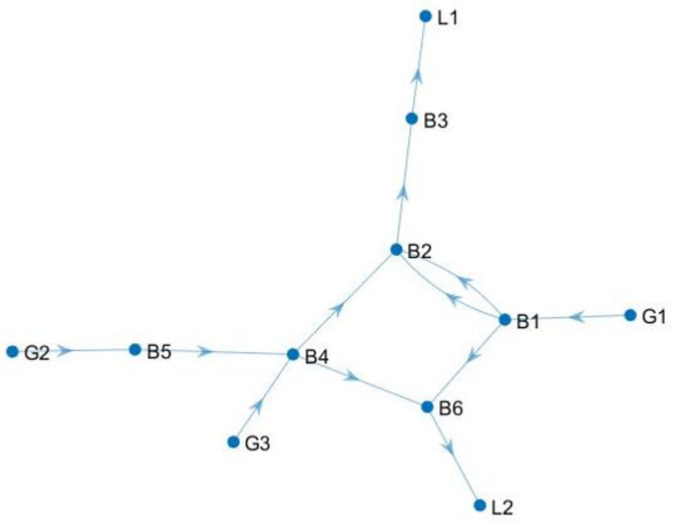


Figure 5 - Graph representation of the meshed network of Figure 2**Error! Reference source not found.**

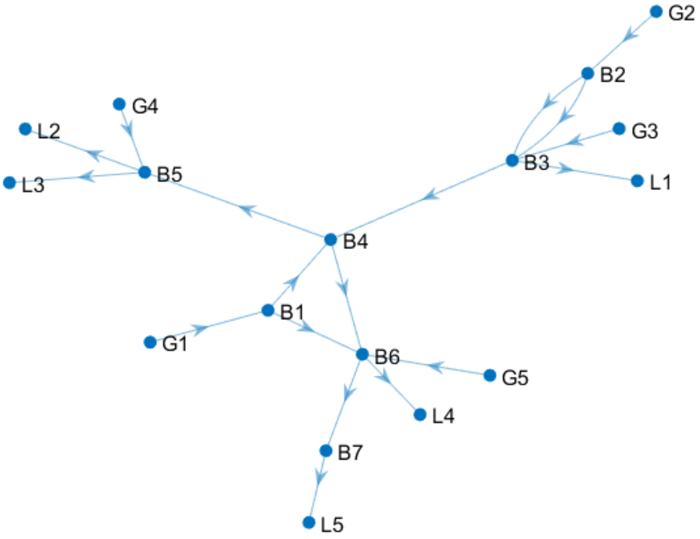


Figure 6 - Graph representation of the radial network of Figure 3

For the development of the solution for the proposed study, the graph representation is adapted to obtain the paths between the fault location and the generators. Note that, the difference between Figure 5 and Figure 7 is that the TLs are included in the last one. This is applied because it is necessary to track the TL of the grid in the code as the paths are composed by this variable. This is only for the use on the MATLAB® for the proposed analysis.

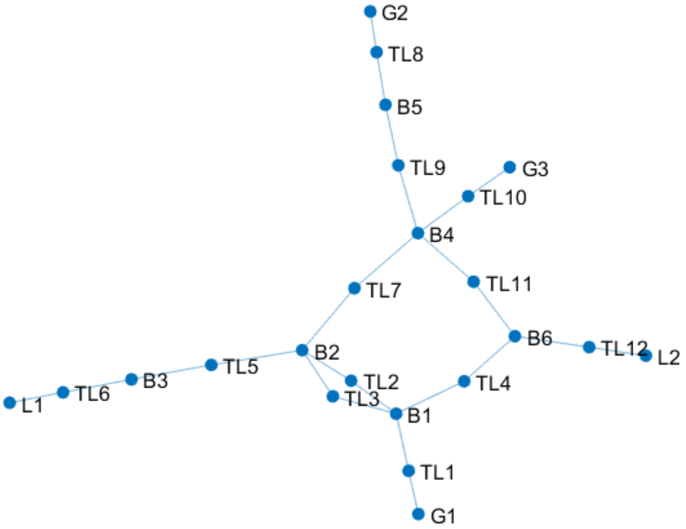


Figure 7 - Graph representation adapted for the algorithm - Meshed network

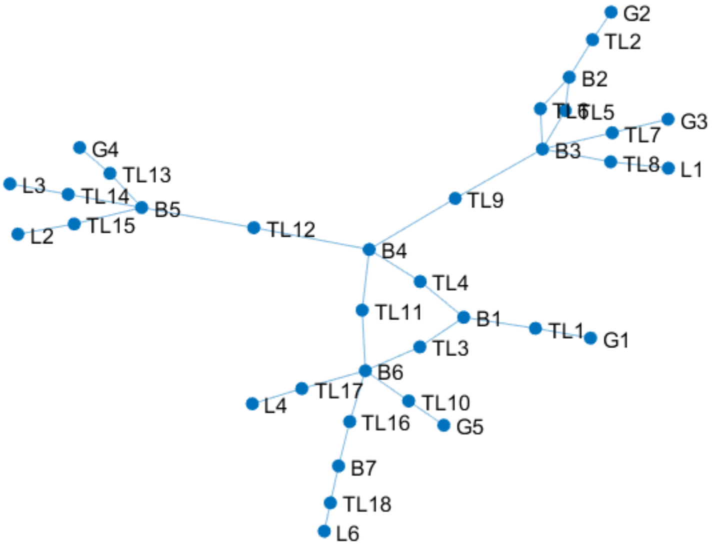


Figure 8 - Graph representation adapted for the algorithm - Radial network

3.4. FAULT IN THE TRANSMISSION LINE OR IN THE LOAD

In case of a fault in the TL or in the load, the approach is the same concerning achieving the optimal CB operation for the minimum load shedding: open the CB installed in the faulted TL or in the TL where the faulted load is connected to.

3.4.1. ANALYSIS OF THE FAULT IN THE TL

Considering the fault in TL_x, then the CB that must be tripped to isolate the fault is CB_x. The load shedding (LS) is the power that flows through this line, which will be $LS = P_x$. Figure 9 presents an example of a fault in the TL of the network of Figure 4 and the countermeasure to clear the fault:

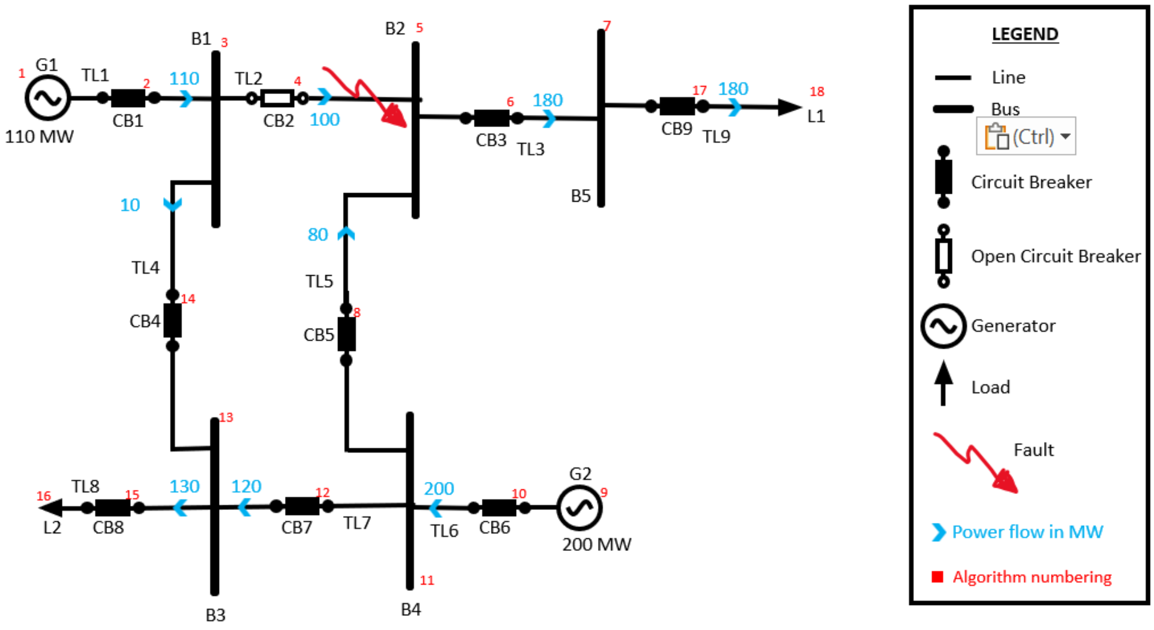


Figure 9 - Fault in TL_2 of the simple meshed network, and the trip of CB_2

As the line where the fault happened is TL_2, then the CB that must open is the one installed in it, which is CB_2.

The power loss in this case is calculated based on the power that flows in the TL where the fault occurred. For the case of Figure 9, the load shedding is: $LS = 100\ MW$. The diagram below shows the procedure applied to clear the fault and to achieve the minimum LS as well, in case of a fault in the TL:

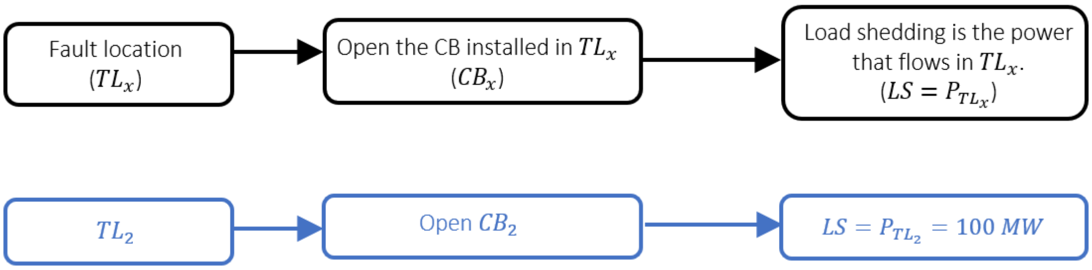


Figure 10 - Procedure to isolate a fault and to achieve the minimum load shedding in case of a fault in the TL

3.4.2. ANALYSIS OF THE FAULT IN THE LOAD

The same logic applied previously for the TL is also used for the fault in the load, with the exception that it is important to know which line the load is connected to. Thus, considering the fault in L_x, this load is connected to the transmission line TL_y. Then the load shedding is $LS = P_y$. Figure 11 highlights a fault in load L_1 of the network of Figure 4 and the countermeasure to clear it:

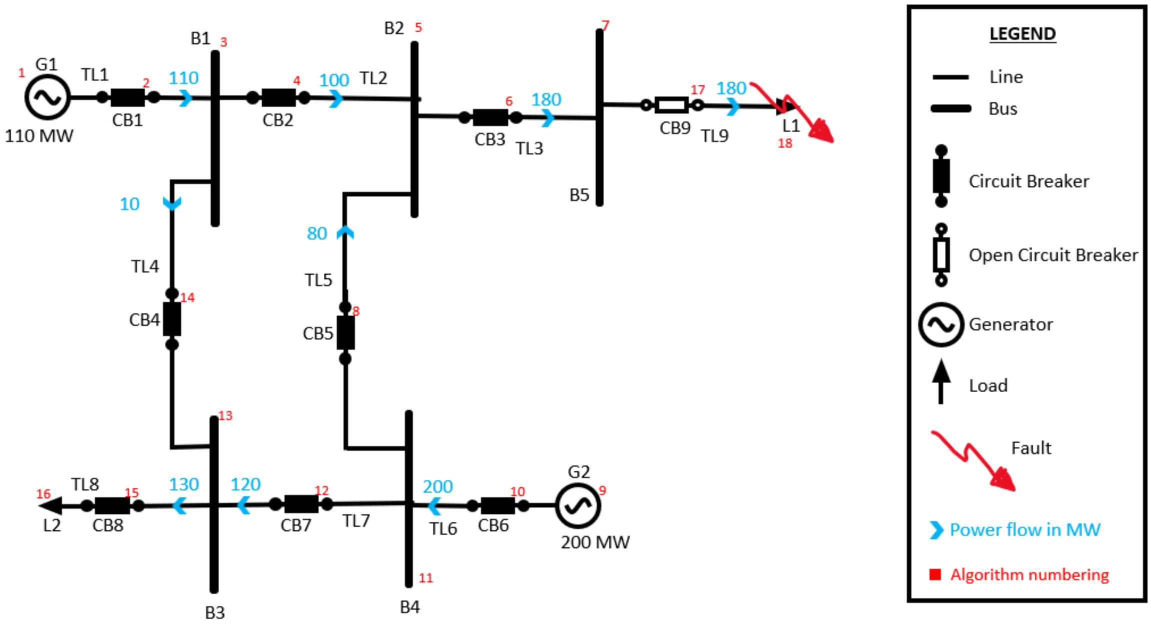


Figure 11 - Fault in L_1 of the simple meshed network, and the trip of CB_9

This if the fault location is at load L_1 of the network presented in Figure 4, the CB that must be opened is the one installed in the TL where this load is connected to, which is CB_9, as it is connected to TL_9. Therefore, the load to be shed is 180 MW. The diagram below shows the procedure applied to clear the fault in the load and to achieve the minimum LS:

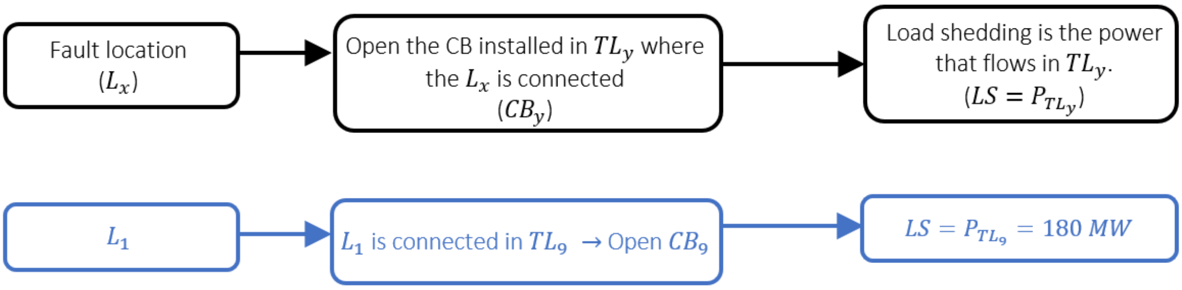


Figure 12 - Procedure to isolate a fault and to achieve the minimum load shedding in case of a fault in the load

3.5. FAULT IN THE BUS

The analysis of the fault in the bus is more complex because it is necessary to realize mathematical operations using the paths obtained between the fault location and the generators. Then four methods (Solution Types) are proposed and applied in the created algorithm. The path information is composed of the TLs/CBs. The paths give the information between the fault location and the generators presented in the grid. The diagram below shows the logic applied for a fault in the bus, using as an example the simple meshed network of Figure 4:

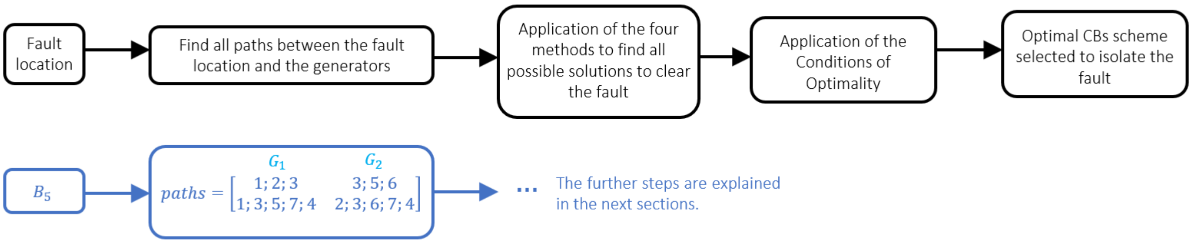


Figure 13 - Procedure of fault isolation in a bus

After the insert of the fault location and then obtaining the path information, it is possible to apply the four methods created for the proposed problem. And finally the application of the Criteria of Optimality to find the best solution among them.

The following sections present the logic applied for each method (Solution Type) and also for the Condition of Optimality, where it is found the optimal solution.

3.1.1. SOLUTION TYPE 1

Four methods were created to achieve the proposed objective of this thesis. They are identified as Solution Types. The network of Figure 4 is used for the explanation regarding the development of these methods.

Solution Type 1 takes all common values among all existing paths between the fault location and generators. Taking the same example presented in Figure 13, fault in B_5, all paths between the fault location and the two sources of the grid are:

Table 1 - Paths between the generators and the fault in B_5

#	**Paths from G_1 to the fault location**	**Paths from G_2 to the fault location**
1	1;2;3	3;5;6
2	1;3;5;7;4	2;3;6;7;4

Note that, the paths are composed by the TLs, or CBs. For example, path #1 from G_1 to B_5 is TL_1, TL_2 and TL_3. Figure 14 highlights this path:

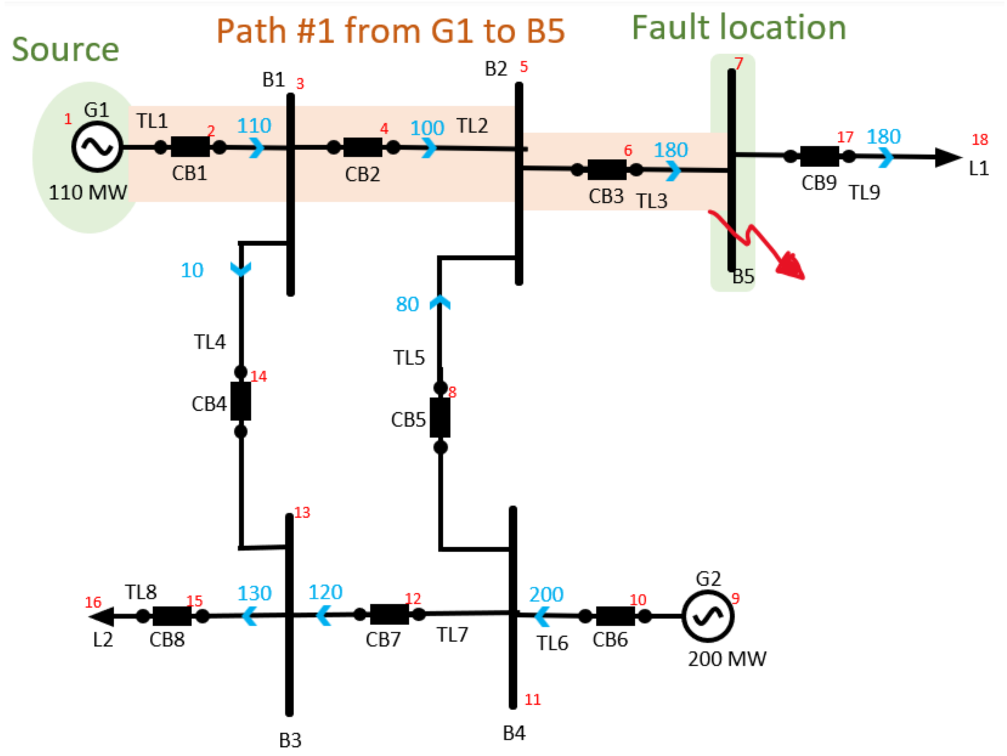


Figure 14 - Path #1 from G_1 to B_5

The total number of existing paths between the fault location to the generators is:

$$total\ number\ of\ paths = n_{G1} + n_{G2} + \cdots + n_{Gn} = n_{total}$$

Where n_{Gx} is the total number of paths between the fault location and generator G_x.

For the case of the power system of Figure 4, $n_{G1} = 2$ and $n_{G2} = 2$. Therefore, $n_{total} = n_{G1} + n_{G2} = 2 + 2 = 4$, as it can be verified in Table 1.

Following the Solution Type 1 proposal, the outcome of the example of Figure 4, using the information of Table 1, it is an array that contains all the elements (TLs/CBs) that are in common between all the paths. For the example of a fault in B_5, the outcome of this method is:

$$SolType1 = (3)$$

The diagram below shows the process executed in this method:

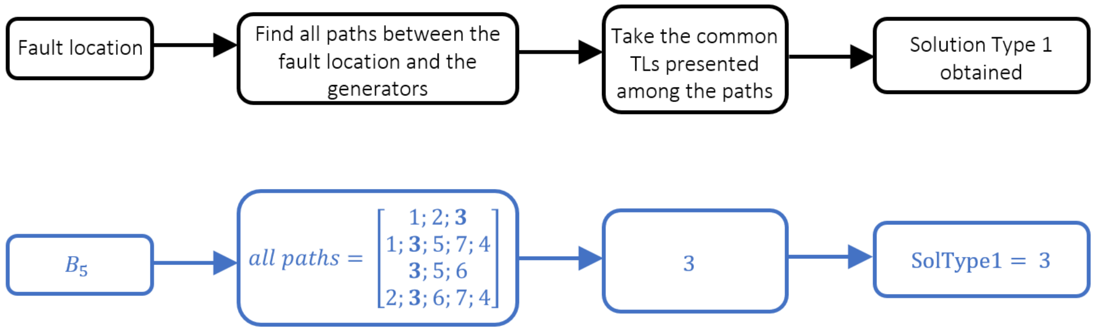


Figure 15 - Solution Type 1 procedure

Thus, opening CB_3 is a solution to clear the fault in B_5.

In general, if all the paths between the fault location and the sources contain x number of TLs that are in common between them. Then, there are x solutions to isolate the fault, opening one of the elements that belong to “SolType1”. The size of “SolType1” is x. For the previous example, $x = 1$, because there is only one element: “3”. Figure 16 presents the new configuration of the network with the trip of CB_3:

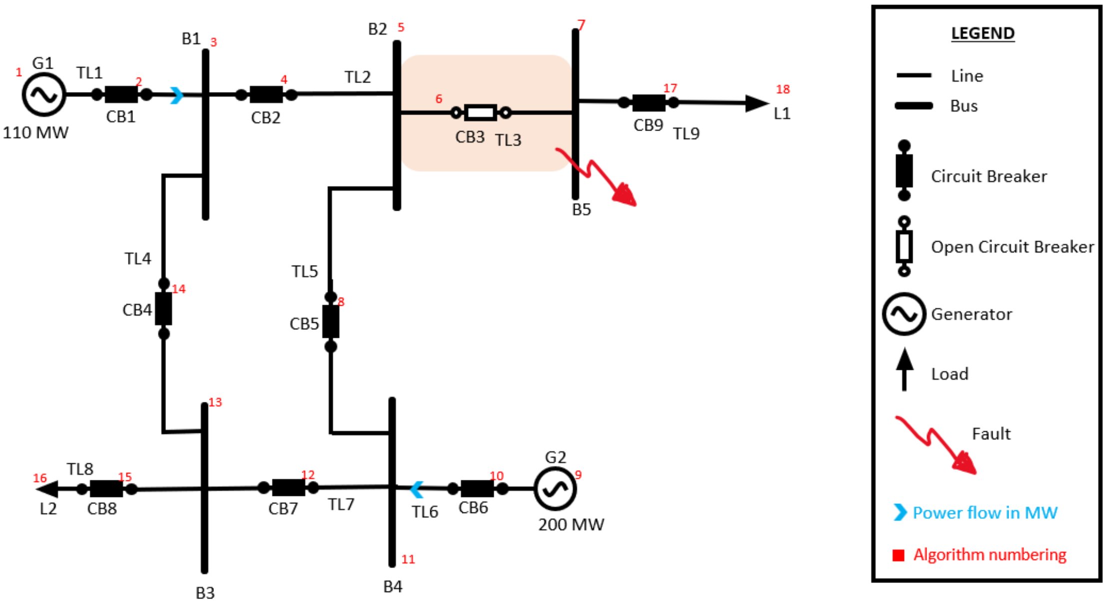


Figure 16 - Application of Solution Type 1 in the simple meshed network

Note that, opening CB_3, the fault is isolated from the two sources of this network (G_1 and G_2).

3.1.2. SOLUTION TYPE 2

The logic of Solution Type 2 is to find the common values present in each set of paths of each generator. The steps are:

i. First, the elements of “SolType1” are removed from all existing paths.

ii. Find all the common values in the set of paths of each generator.
iii. Realize a mathematical operation which is the combination of each solution of each column of generators.
iv. Remove repeated elements of the possible solutions and delete repeated solutions as well.

The diagram below presents the logic of the steps aforementioned, and a fault in a bus of the simple meshed network of Figure 4 as an example:

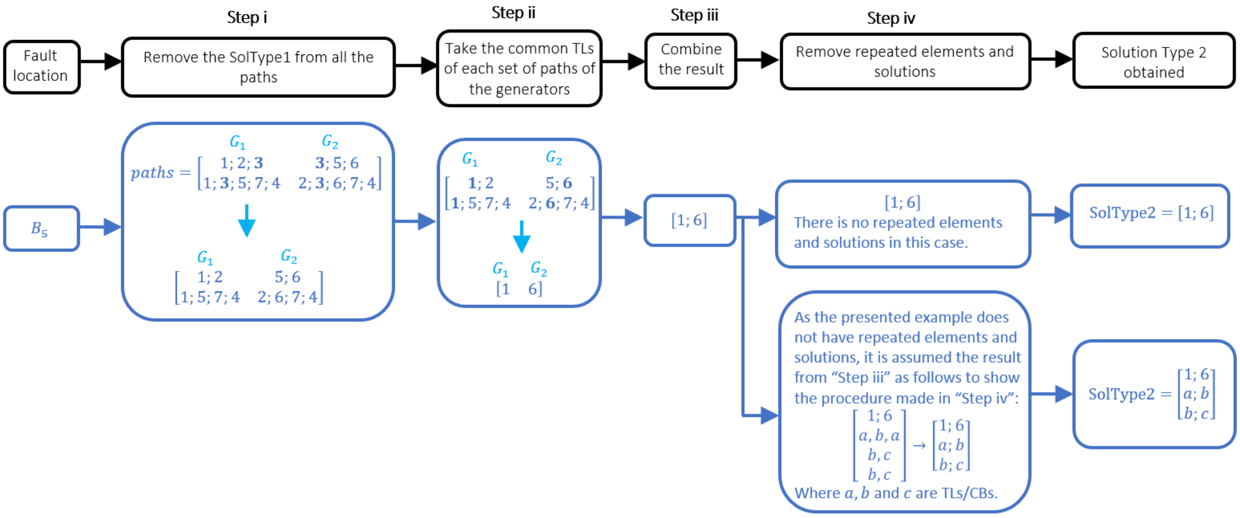


Figure 17 - Solution Type 2 procedure

The total number of possible solution of Solution Type 2 is the total number of combinations (c_{total}) can be obtained as follows:

$$c_{total} = m_1 \cdot m_2 \cdot \ldots \cdot m_n$$

Where:

- m_x is the number of elements that the array contains from the result of "Step ii".
- n: number of generators of the power system.

Taking the previous example shown in Figure 17, the total number of combinations is:

$$c_{total} = m_1 \cdot m_2 = 1 \cdot 1 = 1\ combination$$

As can be seen in the block of "Step ii" in Figure 17, $m_1 = m_2 = 1$ because there is only one element which is (1) and (6) respectively.

The example shown in Figure 17 provides one possible solution:

$$SolType2 = (1; 6)$$

Figure 18 shows the configuration of the network if it is applied the proposed solution of Solution Type 2, open CB_1 and CB_6, to clear the fault at B_5:

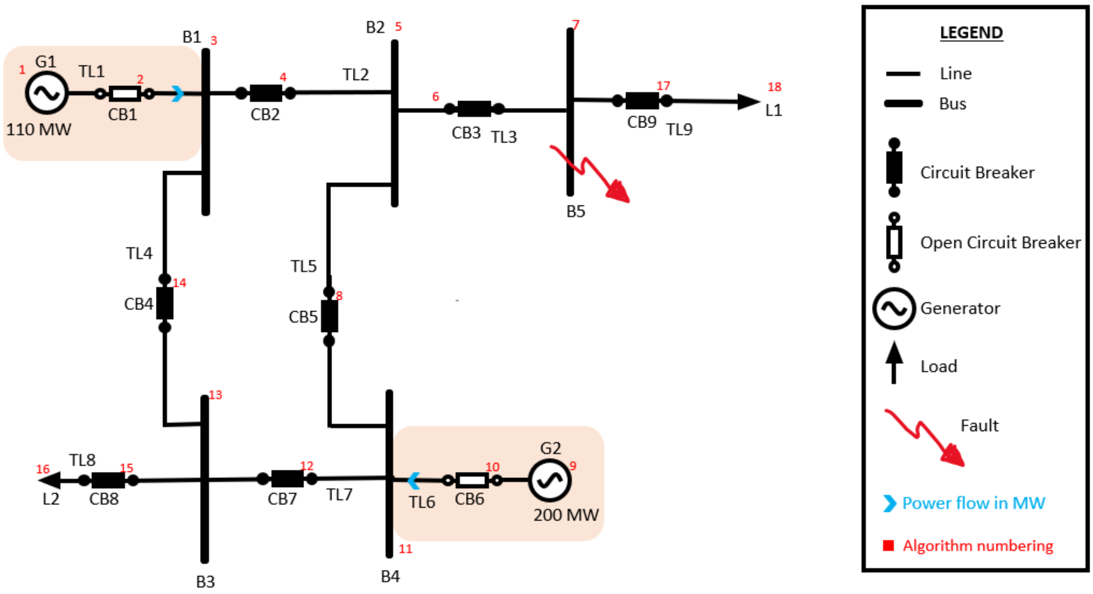


Figure 18 - Application of Solution Type 2 in the simple meshed network

Note that, the total number of possible solutions provided by this method can be less than c_{total} due the possibility of the existence of repeated solutions.

3.1.3. SOLUTION TYPE 3

The logic of Solution Type 3 is to do the combinations of all the remaining values that do not include the ones of Solution Type 1 and 2, except the set of paths that has only one path, which must be included in the logic of this method for the final result of Solution Type 3, to obtain all the possible solutions to isolate the fault location from the all the sources. The steps are:

i. First, the elements of “SolType1” and “SolType2” are removed from all existing paths, except the set of paths that has only one path.
ii. Realize a mathematical operation which is the combination of each solution regarding the set of paths of each generator from the previous step.
iii. A new mathematical operation is applied doing the combinations from the result of the previous step.
iv. Remove repeated elements present in the array and repeated solutions.

The diagram below presents the steps, and a fault in a bus of the simple meshed network of Figure 4 as an example:

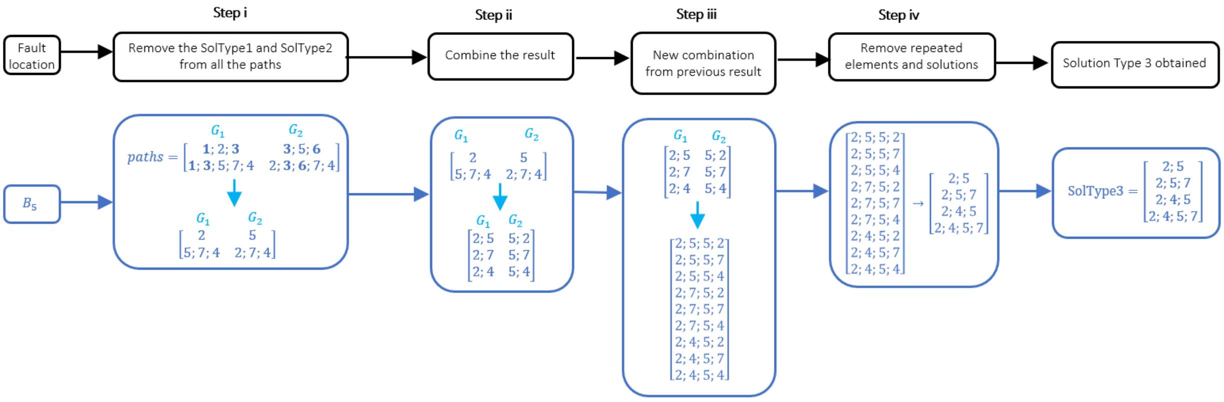


Figure 19 - Application of Solution Type 3 in the simple meshed network

As the presented example does not have a case of unique path, it is assumed a third generator connected to B_5. This is used only to show the procedure made in “Step i”:

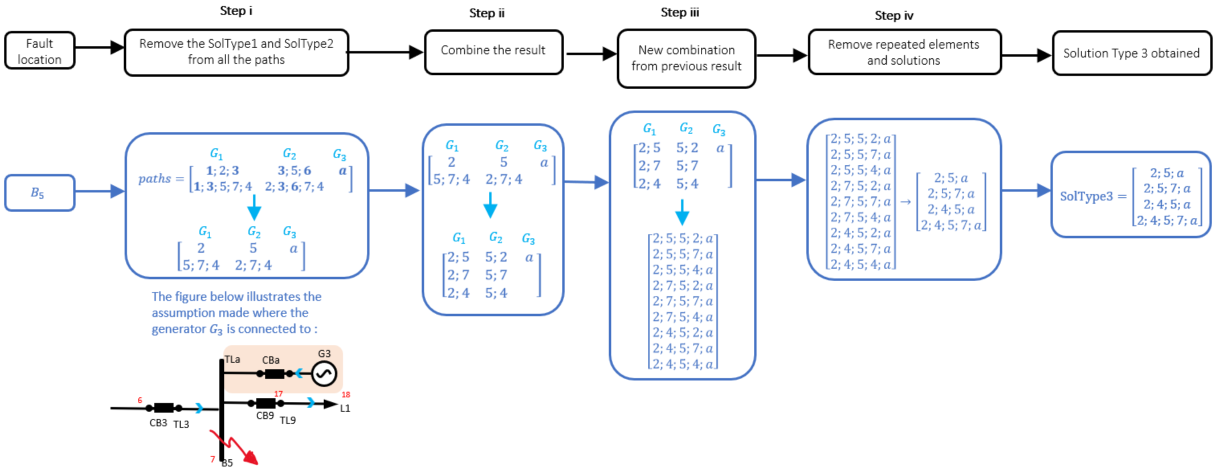


Figure 20 - Application of Solution Type 3 in the simple meshed network, considering the existence of one path

For the Solution Type 3, the total number combination in “Step ii” is ($comb_{step\_ii}$):

$$comb_{step_{ii}\ for\ G_x} = NumElem_{array1} \cdot NumElem_{array2} \cdot \ldots \cdot NumElem_{array\_k}$$

Where:

- $NumElem_{array\_i}$ is the total number of elements presented in the array i of generator G_x. Taking the example of Figure 19, $array2$ of generator G_2 is $(2; 7; 4)$, therefore, the total number of elements of this array is equal to 3.
- k is the total number of arrays of generator G_x.

Applying this equation to the example shown in Figure 19:

$$comb_{step_{ii}\ for\ G_1} = NumElem_{array1} \cdot NumElem_{array2} = 1 \cdot 3 = 3\ combinations$$

$$comb_{step_{ii}\ for\ G_2} = NumElem_{array1} \cdot NumElem_{array2} = 1 \cdot 3 = 3\ combinations$$

In “Step iii”, it is possible to obtain the total number of possible solutions of Solution Type 3, which is the total number of combinations of this step ($comb_{total}$):

$$comb_{total} = comb_{step_{ii}\,for\,G_1} \cdot comb_{step_{ii}\,for\,G_2} \cdot \ldots \cdot comb_{step_{ii}\,for\,G_n}$$

Where n is the number of generators of the power system.

Applying this equation in the example given in Figure 19:

$$comb_{total} = comb_{step_{ii}\,for\,G_1} \cdot comb_{step_{ii}\,for\,G_2} = 3 \cdot 3 = 9\ combinations$$

In Figure 19, it is possible to observe in “Step iii” that the total number of combinations are exactly nine. However, note that, the total number of possible solutions given by Solution Type 3 can be less than $comb_{total}$ if there is repeated solutions. In “Step iv” in this same figure, it can be seen that this statement is true.

Figure 21 shows the configuration of the network applying the third solution (2;4;5) given by SolType3 in the example of Figure 19 to clear the fault in B_5:

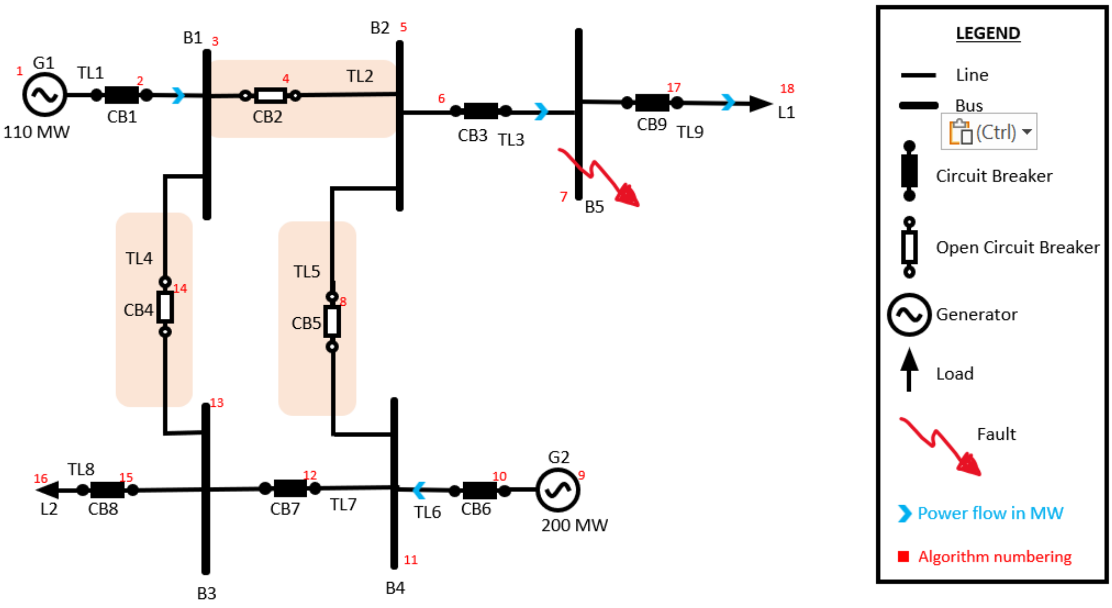


Figure 21 - Application of one of the possible solutions provided by Solution Type 3 in the simple meshed network

Note that, the application of Solution Types 1, 2 and 3 are methods that use mathematical operations for obtaining the possible solutions.

3.1.4. SOLUTION TYPE 4

The logic of this method is to take all the CBs that are installed in the TLs which are connected to the bus where the fault happened. For this purpose, the matrix B is used, which is an admittance matrix adapted for the power flowing into the bus and flowing out from it.

Therefore, once the fault happens in B_x, the solution obtained using this method is composed by the TLs connected directly to this bus, which can be identified by the columns where there are elements "-1" and "1" in the row x of matrix B. Taking the network of Figure 4, its matrix B is:

$$B = \begin{array}{c} \\ B1 \\ B2 \\ B3 \\ B4 \\ B5 \end{array} \begin{array}{c} \begin{array}{ccccccccc} TL1 & TL2 & TL3 & TL4 & TL5 & TL6 & TL7 & TL8 & TL9 \end{array} \\ \left[\begin{array}{ccccccccc} 1 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \end{array}\right] \end{array}$$

Figure 22 - Matrix B of Figure 4

Where:

- "-1" means that the power is flowing out from the bus.
- "1" means that the power is flowing into the bus.
- "0" no power flowing.

Considering a fault in B_4, and following the methodology proposed by Solution Type 4, it is search the columns in row 4 where the elements are "-1" and "1":

$$B = \begin{array}{c} \\ B1 \\ B2 \\ B3 \\ B4 \\ B5 \end{array} \begin{array}{c} \begin{array}{ccccccccc} TL1 & TL2 & TL3 & TL4 & \boxed{TL5} & \boxed{TL6} & \boxed{TL7} & TL8 & TL9 \end{array} \\ \left[\begin{array}{ccccccccc} 1 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & \boxed{-1} & \boxed{1} & \boxed{-1} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \end{array}\right] \end{array}$$

Figure 23 - Analysis of matrix B for a fault in B_4

Regarding Figure 23, the outcome is:

$$SolType4 = (5; 6; 7)$$

Figure 24 presents the configuration of the network when it is applied this solution in the grid of Figure 4:

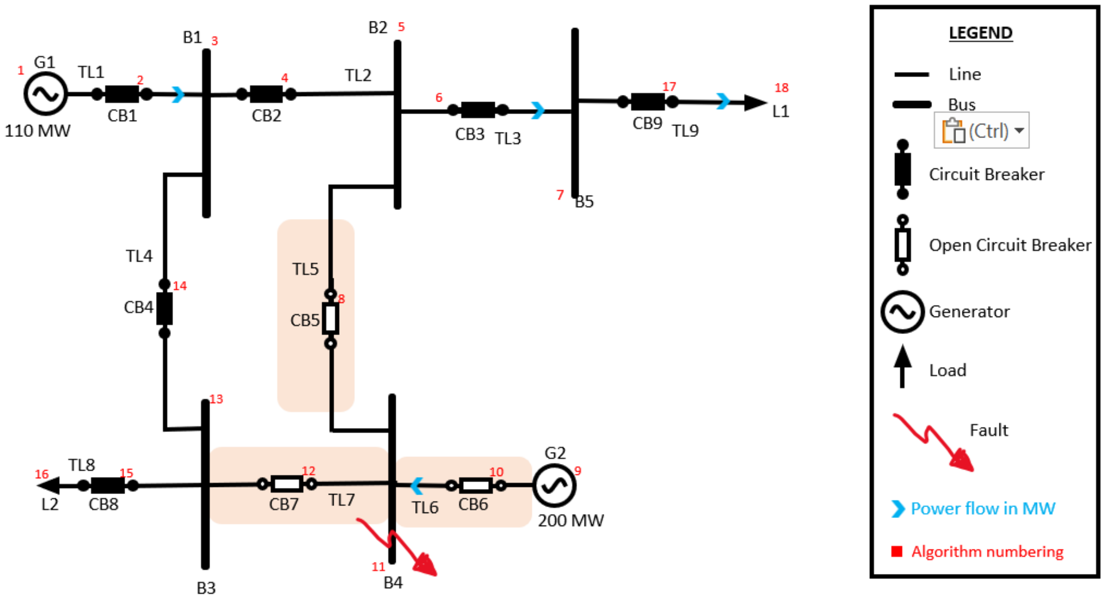


Figure 24 - Application of Solution Type 4 in the simple meshed network

3.6. SELECTION OF THE OPTIMAL CB SCHEME

All possible solutions are obtained by applying the previous four methods explained. The possible solutions are CBs schemes to clear a fault once it is known the fault location. Having these solutions, it is selected one of them as the optimal solution. To choose the best option it is made three classifications that are called as Criteria of Optimality (or Conditions of Optimality). For this work, it is determined three, which are:

i. Minimum load shedding,
ii. Trip the CBs that are closer (directly connected) to the fault location and
iii. Open the minimum number of CBs.

3.6.1. MINIMUM LOAD SHEDDING

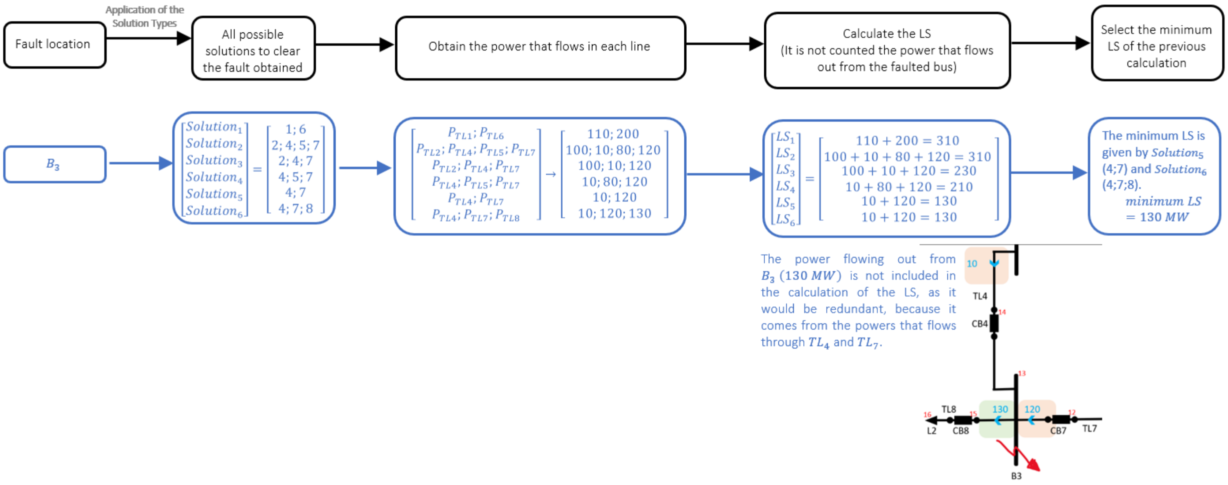
Criterion 1 is the prime condition of optimality. It is applied in two different ways because it depends of the origin of the fault: bus, TL or load.

In the Section 3.4, it is already presented the logic to achieve the minimum LS in case of a fault in the TL and in the load. However, the methodology applied in case of a fault in the bus is more complex and it is necessary a different approach, which is shown is this section.

In possession of the information regarding the fault location and then all possible solutions to clear the fault, it is calculated all the load to be shed of all these solutions obtained by applying the Solution Types. The load to be shed is the power loss, which corresponds to the power that flows in the lines whose CBs must open to clear the fault. Therefore, if there are k possible solutions to isolate the fault from all the sources of the grid, then there are k load shedding calculations. Thus the minimum LS is selected among them.

Note that, there is the possibility that more than one solution exists, which gives the same amount of the minimum load shedding obtained. For this case, the second criterion is applied.

Before entering the discussion of the second condition of optimality, it is important to clarify the calculation of the minimum load shedding. The diagram below presents the logic to obtain the minimum load shedding, also showing an example (in blue), considering the fault at B_3 of the network in Figure 4:



The power flowing out from B_3 $(130\ MW)$ is not included in the calculation of the LS, as it would be redundant, because it comes from the powers that flows through TL_4 and TL_7.

Figure 25 - Procedure of Criterion 1

Note that, Figure 25 presents in its example two possible solutions that provide the minimum LS. In this case, the second criterion should be applied for the selection of the optimal solution among them. Otherwise, if there is only one solution that gives the minimum LS, this one would be the final and optimal solution.

3.6.2. TRIP THE CIRCUIT BREAKERS THAT ARE CLOSER TO THE FAULT LOCATION

The second criterion is applied according to the following condition: if there is more than one solution which provides that same value of minimum load shedding. In this case, it is selected the solution which has all TLs connected to the faulted bus, or if this is not the case, at least the one that has the highest number of TLs connected to it. There is the possibility of the these solutions have all their TLs linked to the faulted bus, and if this is the occasion, the Criterion 3 is applied. The diagram below presents this logic and an example that clarifies this methodology:

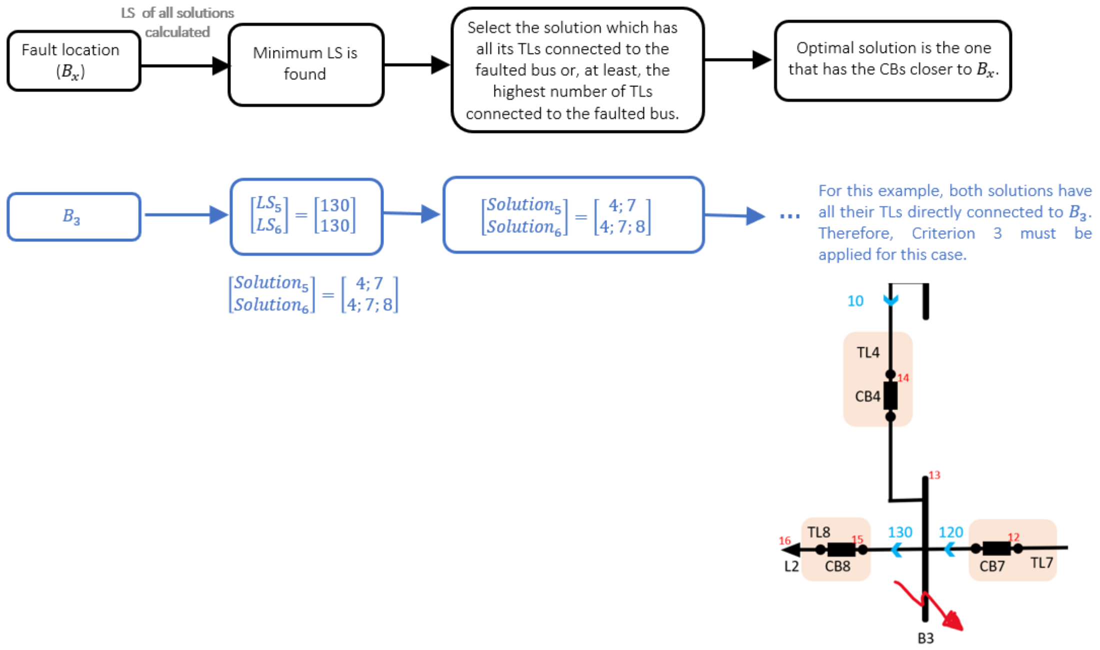


Figure 26 - Procedure of Criterion 2

Note that, the outcome from Solution Type 4 will always fit the second condition of optimality, because its solution provides the TLs that are directly connected to the fault where the fault happened. Observing the example of Figure 26, the $Solution_6 = (4;7;8)$ is the one provided by Solution Type 4.

3.6.3. TRIP THE MINIMUM NUMBER OF CIRCUIT BREAKERS

The third criterion englobes two actions: (1) It is applied if there is more than one solution from Criterion 2, then it is selected the option where there is the minimum number of TLs; (2) If there is any element (TL) connected to a load, this TL is not considered in the solution, which means that is not necessary to open the CB installed on this line. For this second action, it is used the following matrix (B_{mod}), which is the matrix B modified to highlighted where the generators and loads are located. For instance, taking the same matrix B of Figure 22, B_{mod} is:

$$B_{mod} = \begin{array}{c|ccccccccc|} & TL1 & TL2 & TL3 & TL4 & TL5 & TL6 & TL7 & TL8 & TL9 \\ B1 & 2 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ B2 & 0 & 1 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ B3 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & -2 & 0 \\ B4 & 0 & 0 & 0 & 0 & -1 & 2 & 0 & -1 & 0 \\ B5 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -2 \end{array}$$

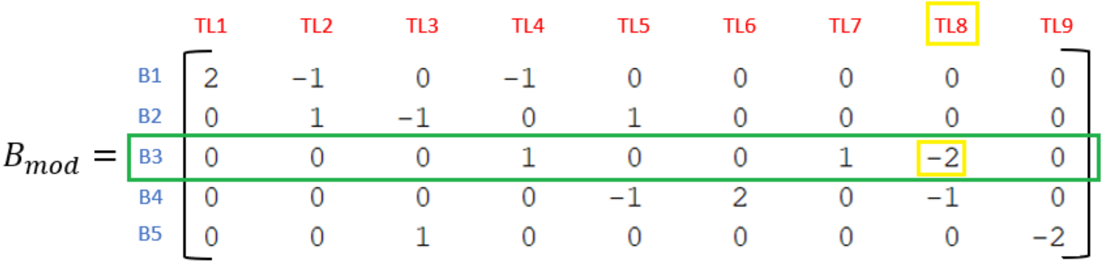
Figure 27 - Matrix B_{mod}

Where:

- “2”: means that the connection is to a generator.

- "-1": power flowing out from the bus.
- "1": power flowing into the bus.
- "-2": means that the connection is to a load.
- "0": no power flow.

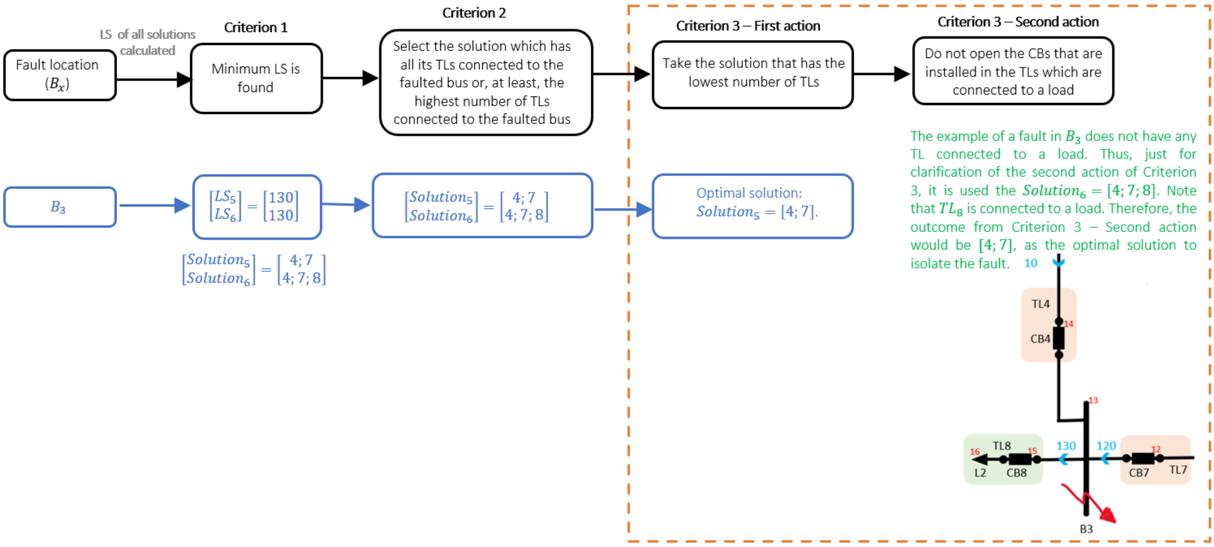
For example, considering a fault in B_3, observe that B_{mod} of Figure 27, TL_8 is connected to a load, therefore, CB_8 would not be opened. Figure 28 highlights this statement:



$$B_{mod} = \begin{array}{c|ccccccccc|} & TL1 & TL2 & TL3 & TL4 & TL5 & TL6 & TL7 & \boxed{TL8} & TL9 \\ \hline B1 & 2 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ B2 & 0 & 1 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ B3 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & \boxed{-2} & 0 \\ B4 & 0 & 0 & 0 & 0 & -1 & 2 & 0 & -1 & 0 \\ B5 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -2 \end{array}$$

Figure 28 - Analysis of B_{mod} for the application of Criterion 3 - Second action

The diagram below presents the logic regarding the Criterion 3 (first and second actions), with an example of a fault in B_3 of the simple meshed network of Figure 4:



The example of a fault in B_3 does not have any TL connected to a load. Thus, just for clarification of the second action of Criterion 3, it is used the $Solution_6 = [4;7;8]$. Note that TL_8 is connected to a load. Therefore, the outcome from Criterion 3 – Second action would be $[4;7]$, as the optimal solution to isolate the fault.

Figure 29 - Procedure of Criterion 3

In general, if there is n number of CBs in the optimal solution and m that are connected to a load, then the total number of CBs that must trip are $n - m$. For instance, taking the example presented in Figure 29 and $Solution_6 = [4;7;8]$. The number of CBs is $n = 3$. Knowing that the TL_8 is connected to a load, then $m = 1$. Therefore the total number of CBs that must open is $n - m = 3 - 1 = 2$, which are CB_4 and CB_7. Figure 30 shows the application in opening these CBs to isolate the fault in B_3:

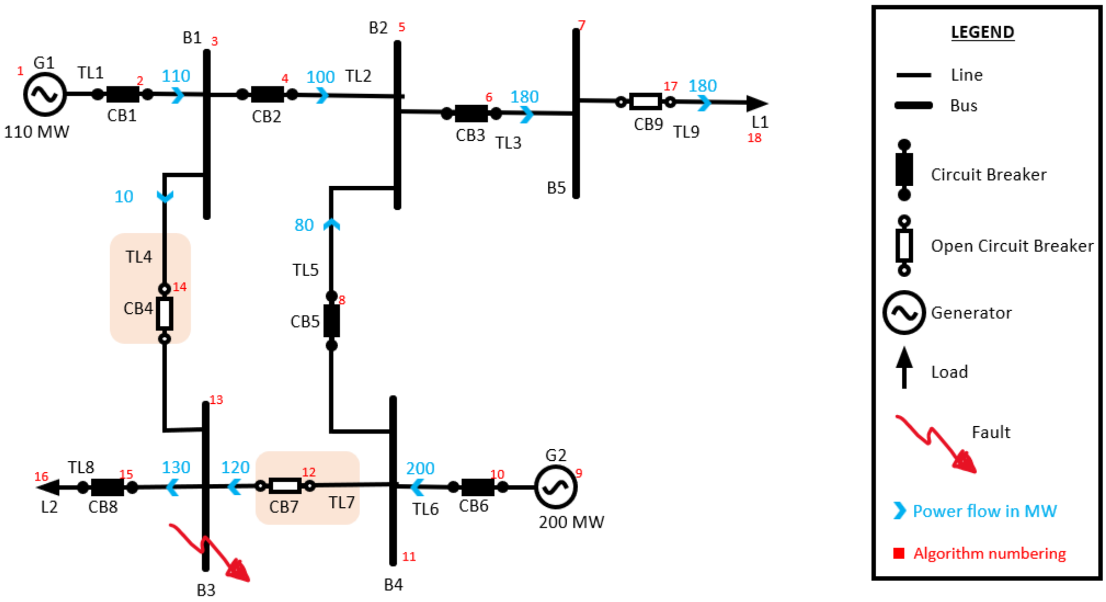


Figure 30 - Application of the solution after the execution of Criterion 3 in case of a fault in B_3

3.7. FLOWCHART

The following figures present the logic of the algorithm, represented by flowcharts:

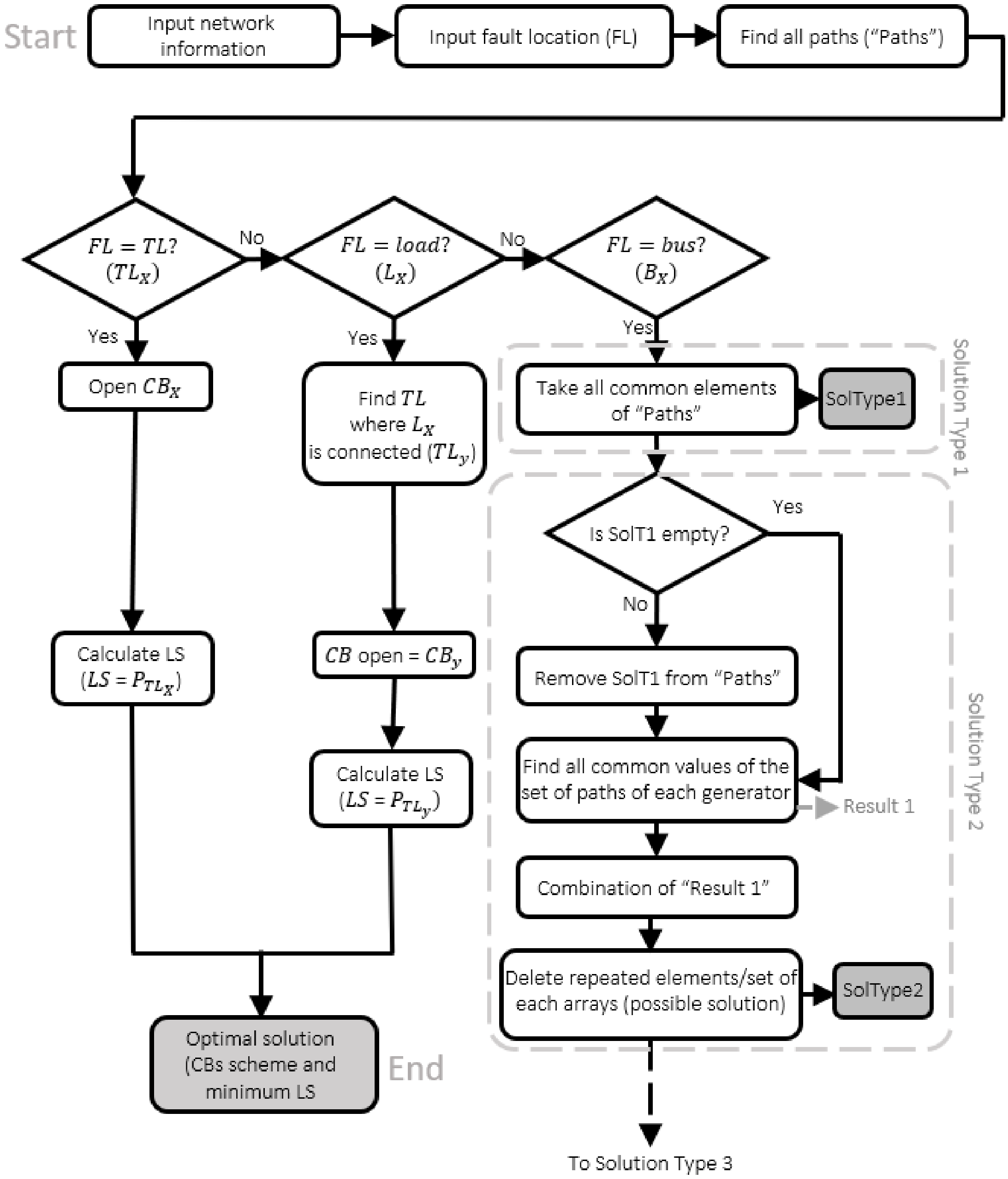


Figure 31 - Flowchart - Part 1

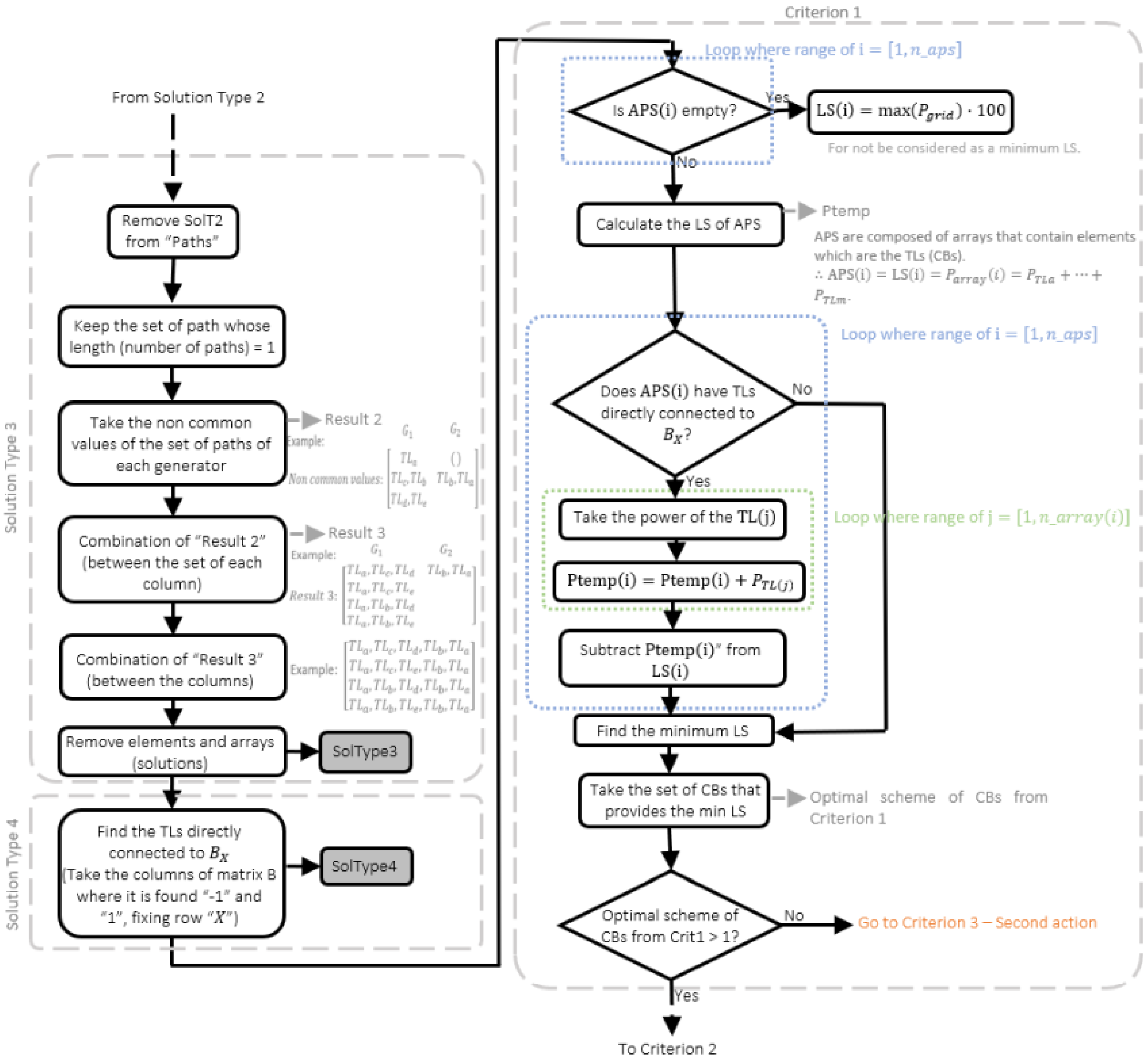
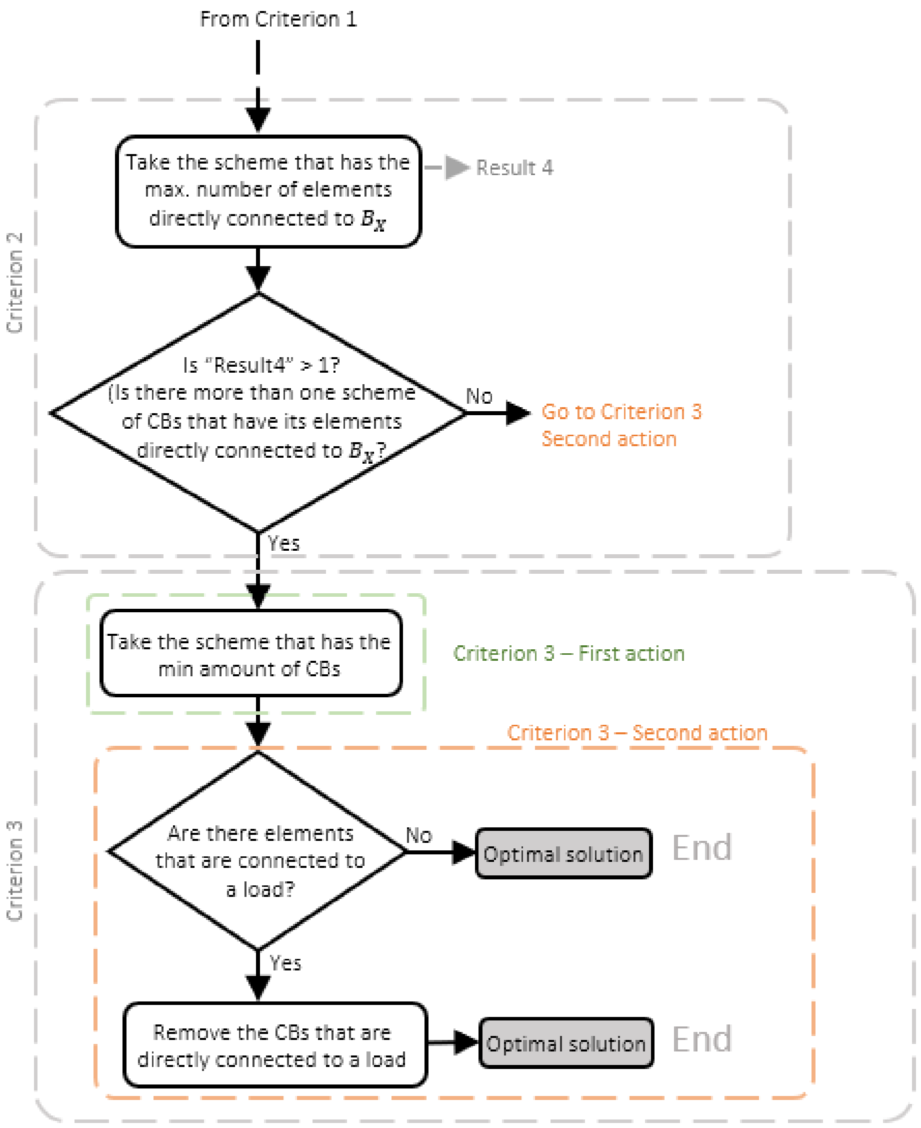


Figure 32 - Flowchart - Part 2



Legend:

- "elements" = "values" = TLs = CBs
- CB = Circuit Breaker
- LS = Load Shedding
- SolT: Solution Type
- P = Active power [MW]
- APS = All Possible Solutions
- max(P_{grid}): maximum power of the grid.
- n_aps: total number of APS.
- min = minimum
- Crit = Criterion

Figure 33 - Flowchart - Part 3

4

Results

4.1. INTRODUCTION

This chapter contains the results of the application of the methodology built and applied in the created algorithm implemented in MATLAB® for the purpose of this thesis. The investigation englobes the two networks presented in the previous chapter.

It is important to mention that when referred to optimal solution the basis is the minimum load shedding achieved.

4.2. MESHED NETWORK

The meshed network under analysis is the one presented in Figure 2, and its graph representation in Figure 5**Error! Reference source not found.**. Both of them are once m ore presented in the figures below:

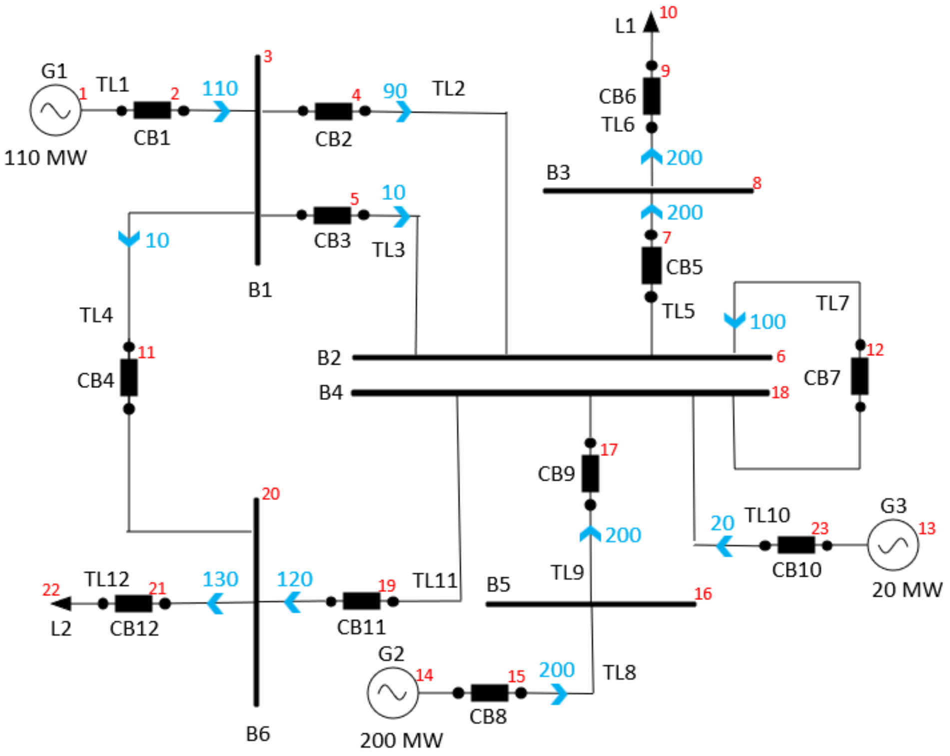


Figure 34 - Meshed network

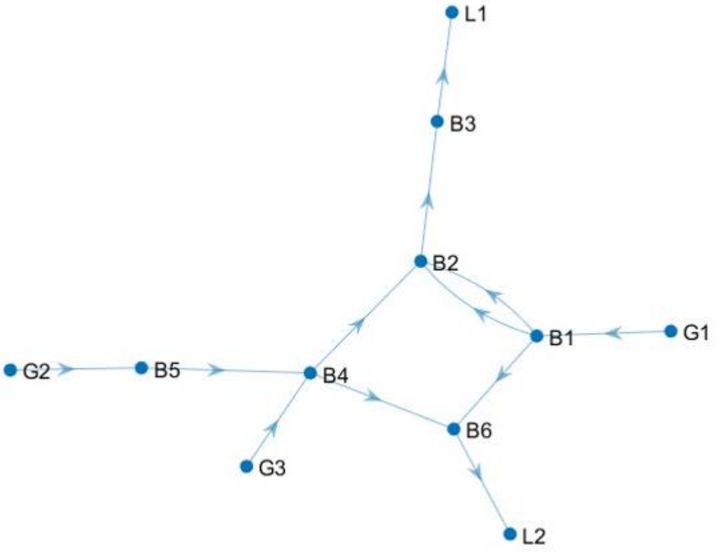


Figure 35 - Graph representation of the meshed network of Figure 34

4.2.1. FAULT IN THE TL

Once the fault location is determined, it is obtained all the paths between the fault location and the generators of the network, called “Paths”.

As previously explained in Chapter 3, the approaches for analysis in case of a fault in the TL and in a load are similar.

Example 1: fault in TL_4. Then "Paths" is:

Table 2 - Paths between the fault at TL_4 and the sources

#	G_1	G_2	G_3
1	1;2;4;7;11	2;4;7;8;9	2;4;7;10
2	1;3;4;7;11	3;4;7;8;9	3;4;7;10
3	1;4	4;8;9;11	4;11;10

Regarding this table, it is possible to see that there are three paths between the fault location and each generator. The columns correspond to the paths that belong to the possible paths between the fault in TL_4 to generator G_i, where the range of i is between 1 and 3. Therefore in the column of generator G_1, for example, it is possible to see all the paths between the fault location to it.

The minimum load shedding is 10 MW, as it is opened CB_4, where the active power, that is flowing in the TL_4, is 10 MW.

Example 2: fault in TL_{11}. Then "Paths" is:

Table 3 - Paths between the fault at TL_{11} and the sources

#	G_1	G_2	G_3
1	1;2;7;11	2;4;7;8;9;11	2;4;7;11;10
2	1;3;7;11	3;4;7;8;9;11	3;4;7;11;10
3	1;4;11	8;9;11	11;10

The elements of paths are the TLs, but they also can be seen as the CBs, because it is assumed that each line has one CB, therefore, for example, the third path between the fault location to the generator G_3 is (11,10). So the path is $TL_{11} \rightarrow TL_{10}$, which means CB_{11} and CB_{10}, respectively.

The minimum load shedding is 120 MW, as it is opened CB_{11}, where the power that flows in the TL_{11}, is 120 MW.

Example 3: fault in TL_6. Then the "Paths" is:

Table 4 - Paths between the fault at TL_6 and the sources

#	G_1	G_2	G_3
1	1;2;5;6	5;6;7;8;9	5;6;7;10
2	1;3;5;6	2;5;6;4;8;9;11	2;5;6;4;11;10
3	1;5;6;4;7;11	3;5;6;4;8;9;11	3;5;6;4;11;10

Following the logic explained in the subsection 3.4, the outcome is the same as when a fault happens in the load L_1. The load shedding is 200 MW and the CB that must be opened is the one that is installed in this line: CB_6.

Note that, instead of opening the CB that is installed in TL where the fault occurred, but the ones that can isolate the fault from the generators by using the information of "Paths", the power loss will increase, which diverges the main objective of reaching the minimum load shedding. This also applies for the fault in the load.

Table 5 summarizes the optimal solution for the fault in the TL:

Table 5 - Optimal solution in case of a fault in the TL

Fault location	CB that must trip	Load shedding [MW]
$\boldsymbol{TL_1}$	CB_1	110
$\boldsymbol{TL_2}$	CB_2	90
$\boldsymbol{TL_3}$	CB_3	10
$\boldsymbol{TL_4}$	CB_4	10
$\boldsymbol{TL_5}$	CB_5	200
$\boldsymbol{TL_6}$	CB_6	200
$\boldsymbol{TL_7}$	CB_7	100
$\boldsymbol{TL_8}$	CB_8	200
$\boldsymbol{TL_9}$	CB_9	200
$\boldsymbol{TL_{10}}$	CB_{10}	20
$\boldsymbol{TL_{11}}$	CB_{11}	120
$\boldsymbol{TL_{12}}$	CB_{12}	130

It is very important to notice that, the best solution is opening the CB connected to the faulted TL as the objective is to obtain the minimum load shedding. If the methodology for a fault in the bus is also applied to a fault in the TL or even to the load, the optimal solution remains the first one proposed, as opening the CBs installed in others TLs closer to the fault location, will result in a higher load shedding. Figure 36 exemplifies this statement taking as an example the fault in TL_4:

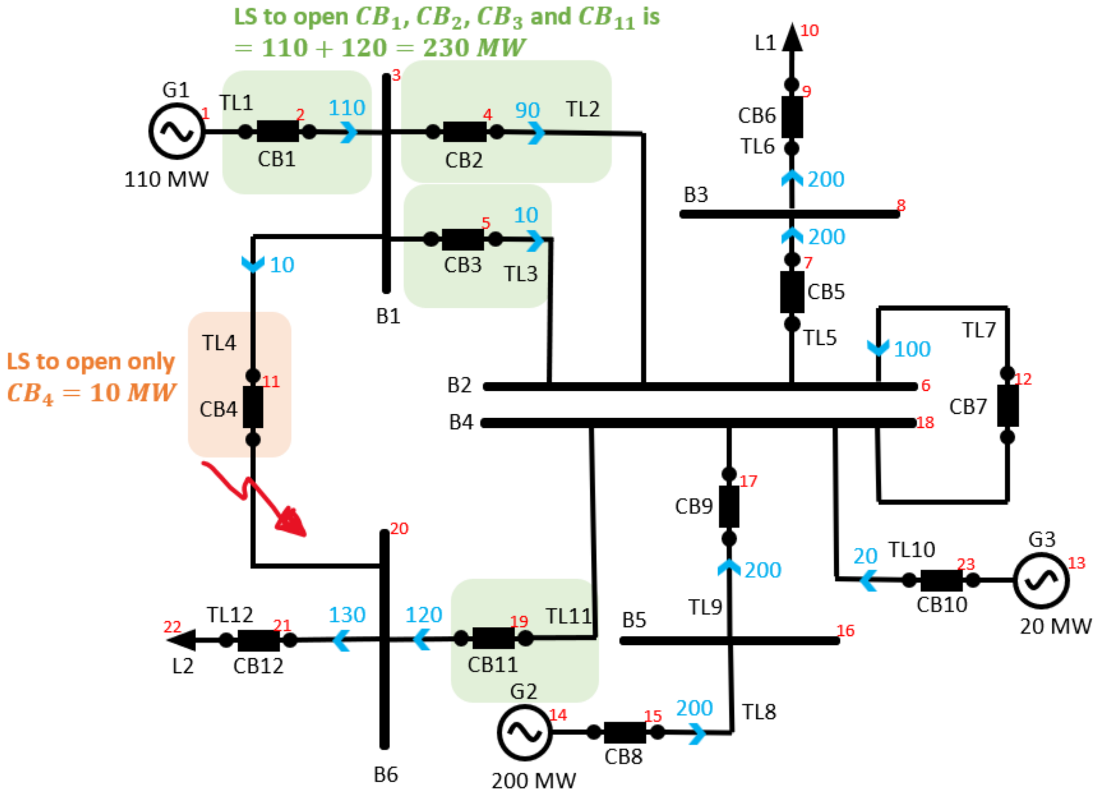


Figure 36 - Example for the fault in TL_4 of the simple meshed network

Note that, in Figure 36, opening only CB_4 is enough to clear the fault in TL_4, and it results in a power loss of 10 MW. Another way to isolate the fault in this line is to trip CB_1, CB_2, CB_3 and CB_{11}, however, the load shedding is higher (230 MW).

4.2.2. FAULT IN THE LOAD

The meshed network under analysis has two loads, thus assuming the fault in L_1, the "Paths" is very similar as presented in Table 3, except for the inclusion of TL_{12} to reach L_1**Error! Reference source not found.**. This confirms that the logic described in t he previous chapter works. Therefore, the outcome is also the same: $LS = 200\ MW$, and CB that must trip is CB_6.

For the fault in the load L_2, "Paths" is:

Table 6 - Paths between the fault at L_2 and the sources

#	G_1	G_2	G_3
1	1;2;7;11;12	2;4;7;8;9;12	2;4;7;12;10
2	1;3;7;11;12	3;4;7;8;9;12	3;4;7;12;10
3	1;4;12	8;9;11;12	11;12;10

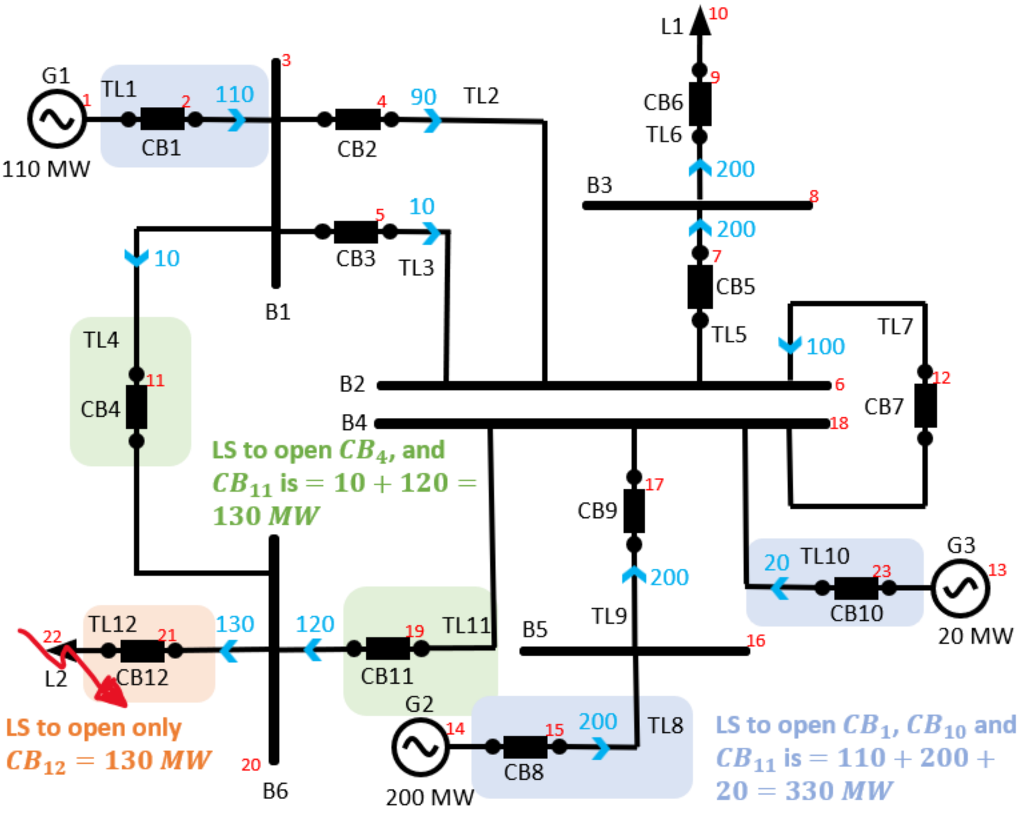
The load shedding is the power that flows in the transmission line where L_2 is connected, which is TL_{12}. So $LS = 130\ MW$ and CB that must trip is CB_{12}. Note that, for a fault in TL_{12}, the result is equivalent.

Table 7 summarizes the optimal solution for the fault in the loads:

Table 7 - Optimal solution in case of a fault in the load

Fault location	TL where the load is connected	Optimal scheme of CBs to clear the fault	Load shedding [MW]
$\boldsymbol{L_1}$	TL_6	CB_6	200
$\boldsymbol{L_2}$	TL_{12}	CB_{12}	130

As mentioned for a fault in the TL, **it is very important to observe that,** the best solution is opening the CB connected to the TL linked to the faulted load as the objective is to obtain the minimum load shedding. If the methodology for a fault in the bus is also applied to a fault in the load or even to the TL, the optimal solution remains the first one proposed, as opening the CBs installed in others TLs that is not the one linked to the load, will result in a higher load shedding. Figure 37 exemplifies this statement taking as an example the fault in L_2:



LS to open CB_4, and CB_{11} is $= 10 + 120 = 130\ MW$

LS to open only $CB_{12} = 130\ MW$

LS to open CB_1, CB_{10} and CB_{11} is $= 110 + 200 + 20 = 330\ MW$

Figure 37 - Example for the fault in L_2 of the simple meshed network

Observe in Figure 37 that opening only CB_{12} the load shedding is 130 MW, and the same LS is obtained by tripping CB_4 and CB_{11}, however, the optimal solution remains the first one because only one CB is tripped. Another way to isolate the fault is to open CB_1, CB_8 and CB_{10}, where result a higher LS (330 MW).

4.2.3. FAULT IN THE BUS

The analysis of the fault in a bus is made with more complex steps to correctly achieve the minimum load shedding. As mentioned in Chapter 3, four methods (Solution Types) were built. The application of the Solution Types results in all possible ways to isolate the fault in the bus where the fault happened. The next step is to select the optimal solution among them, which is chosen based on the condition of optimality described in Section 3.6. The logic explained in Chapter 3 for the fault in a bus is applied in some examples, shown as follows:

Example 1: fault in B_2. "Paths" is:

Table 8 - Paths between the fault at B_2 and the sources

#	G_1	G_2	G_3
1	1;2	7;8;9	7;10
2	1;3	2;4;8;9;11	2;4;11;10
3	1;4;7;11	3;4;8;9;11	3;4;11;10

After obtaining the paths between the fault location and the generators, the four Solution Types are applied. The outcome is:

- Solution Type 1: null. As can be observed in Table 8, there is no common TL in all the paths.
- Solution Type 2: it finds the common value of each set of arrays of each generator, and does the mathematical operation as described in Chapter 3.

Table 9 - All possible solutions using Solution Type 2 for a fault in B_2, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	1;8;10	330
2	1;9;10	330

Table 9 shows that by applying Solution Type 2, there are only two possible solutions to isolate the fault from the sources. For both solutions, the load shedding has the same value: 330 MW.

- Solution Type 3: take the remaining elements not used in Solution Type 1 and 2, they are elements that are not in common between all the paths and between each set of each generator and does the mathematical operation described in Chapter 3.

Table 10 - All possible solutions using Solution Type 3 for a fault in B_2, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	2;3;4;7	210
2	2;3;4;7;11	330
3	2;3;7	200
4	2;3;7;11	320

- Solution Type 4: open the CBs that are directly connected to the bus where the fault occurred. Therefore, the CBs are: $[CB_2, CB_3, CB_5, CB_7]$. And the load shedding is: $LS = 200\ MW$.

Observe that, CB_5 is not present in Solution Types 1, 2 and 3, because the results from these methods are based on "Paths", which does not contain CB_5, because TL_5 does not lead to any generator of this grid; on the contrary, TL_5 leads to a load. While the logic of Solution Type 4 is based in another variable which is the admittance matrix B, where it is taken the TLs that are connected to the faulted bus. Figure 38 highlights the TLs connected to B_2, where the fault happened:

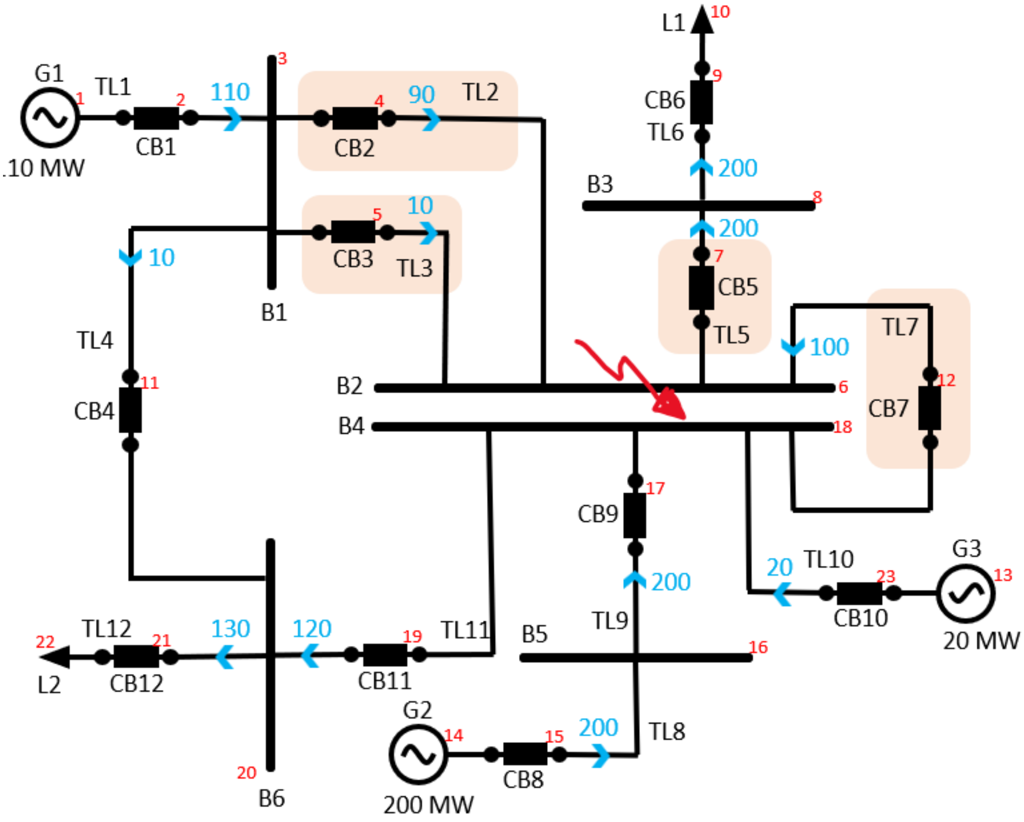


Figure 38 - Fault in B_2, highlight the solution given by Solution Type 4

Also, note that, there are two solutions where the minimum load shedding is 200 MW: (2,3,7) (in Solution Type 3), and (2,3,5,7) (in Solution Type 4). This case fits the application of Criterion 2 (select the solution which has the most elements (TLs) that are connected to the faulted bus). For this case, both solutions have all elements connected to the bus where the fault happened, therefore, Criterion 3 is applied. Then the optimal solution is (2,3,7). So the CBs that must open are CB_2, CB_3 and CB_7.

Regarding the discussion in Section 3.5.2, note that the total number of combinations (possible solutions given by Solution Type 2) for this case is:

$$c_{total} = m_1 \cdot m_2 \cdot m_3 = 1 \cdot 2 \cdot 1 = 2\ combinations$$

For the Solution Type 3, the total number combination in "Step ii" is ($comb_{step\_ii}$):

$$comb_{step_{ii}\ for\ G_x} = NumElem_{array1} \cdot NumElem_{array2} \cdot \ldots \cdot NumElem_{array\_k}$$

Then for the three generators:

$$comb_{step_{ii}\ for\ G_1} = NumElem_{array1} \cdot NumElem_{array2} \cdot NumElem_{array3} = 1 \cdot 1 \cdot 3 = 3\ combinnations$$

$$comb_{step_{ii}\ for\ G_2} = NumElem_{array1} \cdot NumElem_{array2} \cdot NumElem_{array3} = 1 \cdot 3 \cdot 3 = 9\ combinnations$$

$$comb_{step_{ii}\ for\ G_3} = NumElem_{array1} \cdot NumElem_{array2} \cdot NumElem_{array3} = 1 \cdot 3 \cdot 3 = 9\ combinnations$$

Where $NumElem_{array}$, that corresponds of each generator, can be seen in Table 11:

Table 11 - $NumElem_{array}$ which corresponds of each generator

G_1	G_2	G_3
2	7	7
3	2;4;11	2;4;11
4;7;11	3;4;11	3;4;11

In "Step iii" of Section 3.5.3, it is possible to obtain the total number of possible solutions of Solution Type 3, then for this example the total number of combinations ($comb_{total}$) is:

$$comb_{total} = comb_{step_{ii}\ for\ G_1} \cdot comb_{step_{ii}\ for\ G_2} \cdot comb_{step_{ii}\ for\ G_3} = 3 \cdot 9 \cdot 9 = 243\ combinations$$

It can be observed in Table 10, that Solution Type 3 gives in total four solutions, not 243. This is because 239 solutions are repeated from the last combination. Note that columns related to G_2 and G_3 of Table 11 are equal, this results in having repeated results in the mathematical operations when the combination is made.

Table 12 presents all possible solutions to clear the fault in B_2, where it is highlighted the solutions that each condition of optimality fits:

Table 12 - All possible solutions to clear the fault in B_2, highlighting the solutions that each criterion fits

Legend:

- 🟩 **Criterion 1** (Minimum LS)
- 🟦 **Criterion 2** (CBs closest to the fault location)
- 🟨 **Criterion 3** (Trip the minimum number of CBs)

#	Possible solutions to isolate the fault in B_2	$LS\ [MW]$	Solution Type
0	-	-	1
1	🟨 1;8;10	330	2
2	🟨 1;9;10	330	
3	2;3;4;7	210	3
4	2;3;4;7;11	330	
5	🟩 🟦 🟨 2;3;7	200	
6	2;3;7;11	320	
7	🟩 🟦 2;3;5;7	200	4

The main criterion of optimality is the minimum load shedding, therefore, there are two options that gives the minimum power loss of 200 MW, there are (2;3;7) and (2;3;5;7). In Table 12, it can be observed there is only one solution that fits the three criteria: (2;3;7). Therefore, this is the optimal CBs scheme to clear the fault in B_2.

<u>Example 2</u>**:** fault in the bus B_6. Then "Paths" is:

Table 13 - Paths between the fault at B_6 and the sources

#	G_1	G_2	G_3
1	1;2;7;11	2;4;7;8;9	2;4;7;10
2	1;3;7;11	3;4;7;8;9	3;4;7;10
3	1;4	8;9;11	11;10

Once it is known all the paths between the fault location and the sources of the grid, it is possible to apply the Solution Types to obtain the possible solutions to clear the fault in B_6:

- Solution Type 1: null. As can be observed in Table 13, there is no common TL in all the paths.
- Solution Type 2:

Table 14 - All possible solutions using Solution Type 2 for a fault in B_6, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	1;8;10	330
2	1;9;10	330

Table 14 shows that, by applying Solution Type 2, there are only two possible solutions to isolate the fault from the sources. For both solutions, the load shedding has the same value: 330 MW.

- Solution Type 3:

Table 15 - All possible solutions using Solution Type 3 for a fault in B_6, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	2;3;4;7;11	330
2	2;3;4;11	230
3	2;4;7;11	320
4	2;4;11	220
5	3;4;7;11	240
6	3;4;11	140
7	4;7;11	230
8	4;11	130

- Solution Type 4: open the CBs that are directly connected to the bus where the fault happened. Therefore, the CBs are: (CB_4, CB_{11}, CB_{12}). And the load shedding is: $LS = 130\ MW$.

As there is more than one solution that has the same value of the minimum power loss (130 MW): (4,11) and (4,11,12), Criterion 2 is applied. Criterion 3 is also processed as all the elements of each solution are connected to the bus where the fault occurred. Therefore, the optimal solution is to open CB_4 and CB_{11}.

Table 16 gathers all the possible solutions in case of a fault in the bus B_6, where it is highlighted the solutions that each condition of optimality fits:

Table 16 - All the possible solutions in case of a fault in the bus B_6, highlighting the solutions that each criterion fits

Legend:

🟩 **Criterion 1** (Minimum LS)

🟦 **Criterion 2** (CBs closest to the fault location)

🟨 **Criterion 3** (Trip the minimum number of CBs)

#	Possible solutions	Load shedding [MW]	Solution Type
0	-	-	1
1	1;8;10	330	2
2	1;9;10	330	
3	2;3;4;7;11	330	3
4	2;3;4;11	230	
5	2;4;7;11	320	
6	2;4;11	220	
5	3;4;7;11	240	
7	3;4;11	140	
8	4;7;11	230	
9	🟩 🟦 🟨 4;11	130	
7	🟩 🟦 4;11;12	130	4

Observe in Table 16 that the solution from Criterion 3 fits both Criterion 1 and 2 as well, which gives the minimum load shedding and all elements are directly connected to the faulted bus. This scheme of CBs "CB_4, CB_{11}" is the optimal solution to isolate the fault.

<u>Example 3</u>**:** fault in the bus B_3. "Paths" is:

Table 17 - Paths between the fault at B_3 and the sources

#	G_1	G_2	G_3
1	1;2;5	5;7;8;9	5;7;10
2	1;3;5	2;5;4;8;9;11	2;5;4;11;10
3	1;5;4;7;11	3;5;4;8;9;11	3;5;4;11;10

Table 18 gathers all the possible solutions in case of a fault in the bus B_3, where it is highlighted the solutions that each condition of optimality fits:

Table 18 - All possible solution in case of a fault in the bus B_3, , highlighting the solutions that each criterion fits

<u>Legend:</u>

🟩 **Criterion 1** (Minimum LS)

🟦 **Criterion 2** (CBs closest to the fault location)

🟨 **Criterion 3** (Trip the minimum number of CBs)

#	Possible solutions	Load shedding [MW]	Solution Type
1	🟩🟦🟨 5	200	1
2	1;8;10	330	2
3	1;9;10	330	
4	2;3;4;7	210	3
5	2;3;4;7;11	330	
6	🟩 2;3;7	200	
7	2;3;7;11	320	
8	🟩🟦 5;6	200	4

Observe that, Solution Type 1 gives one result: CB_5. Note that, there are nine paths in total between the fault location and the sources. Therefore, as seen in Chapter 3 about the approach of the Solution Type 1, this element is presented in all these paths.

Then the optimal scheme of CBs to isolate the fault in B_3 from all the generators concerning the three conditions of optimality is to trip CB_5, because this scheme results in minimum power loss (Criterion 1), this CB is installed in the line where it is connected to the fault location (Criterion 2), and it is the minimum number of CB to open (Criterion 3).

Table 19 shows all the optimal solutions for the fault in each bus of the power system:

Table 19 - Optimal solution in case of the fault in the bus

Fault location	Optimal scheme of CBs to clear the fault	Minimum load shedding [MW]
$\boldsymbol{B_1}$	CB_1, CB_2, CB_3, CB_4	110
$\boldsymbol{B_2}$	CB_2, CB_3, CB_7	200
$\boldsymbol{B_3}$	CB_5	200
$\boldsymbol{B_4}$	$CB_7, CB_9, CB_{10}, CB_{11}$	220
$\boldsymbol{B_5}$	CB_8, CB_9	200
$\boldsymbol{B_6}$	CB_4, CB_{11}	130

The graph below shows the number of the optimal solutions that fit each condition of optimality:

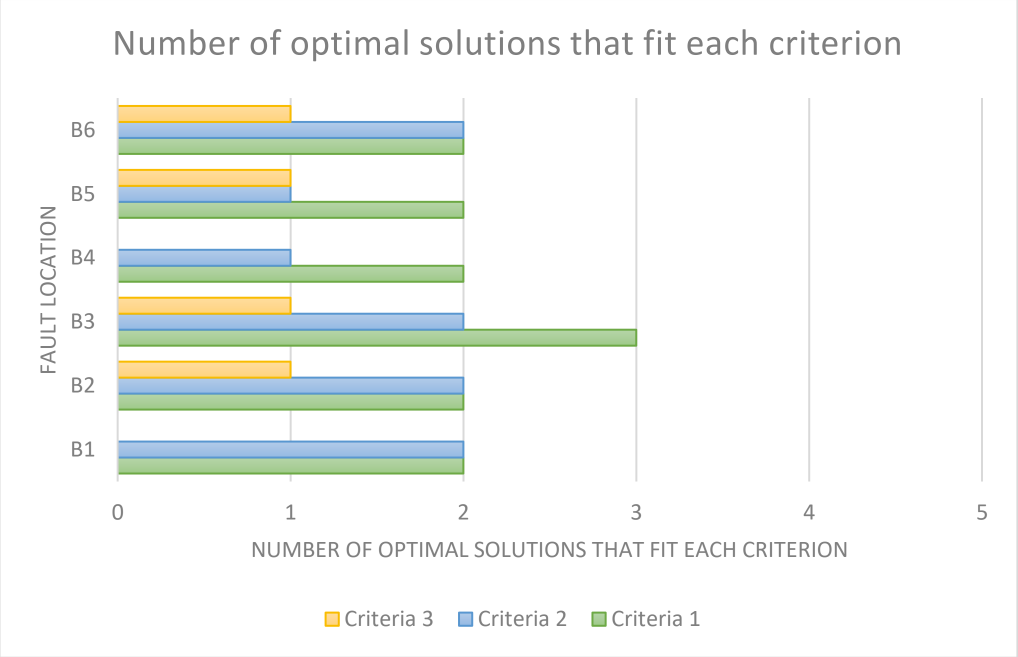


Figure 39 - Number of optimal solutions that fit each criterion

Note that, Criterion 1 will always provide at least one solution because it is the prime condition of optimality. <u>Optimal solution</u> means the scheme of CBs to open that provides the minimum load shedding once a fault occurs.

It can be observed in Figure 39 that in the fault occurrence in any bus of the network, there are at least two solutions that that fit the first criterion. In the case of Criterion 2, there are at least one optimal solution for the fault events in Figure 39 that fit this condition. Finally, it is possible to observe that the optimal solutions for a fault in B_1 and B_4 do not fir the third condition of optimality. For instance, when a fault happens in B_1, there are four possible solutions that fit Criterion 3: (1;8;10), (1;9;10), (1;4;7) and (1;7,11), they gives the following load shedding 330, 330, 210, 330 MW, respectively. Observe that none of these options provide the minimum power loss, therefore, in this case, the optimal solution (1;2;3;4) fits only Criterion 1 and 2.

The following graph shows the information the frequency in which the optimal solution fit each criterion:

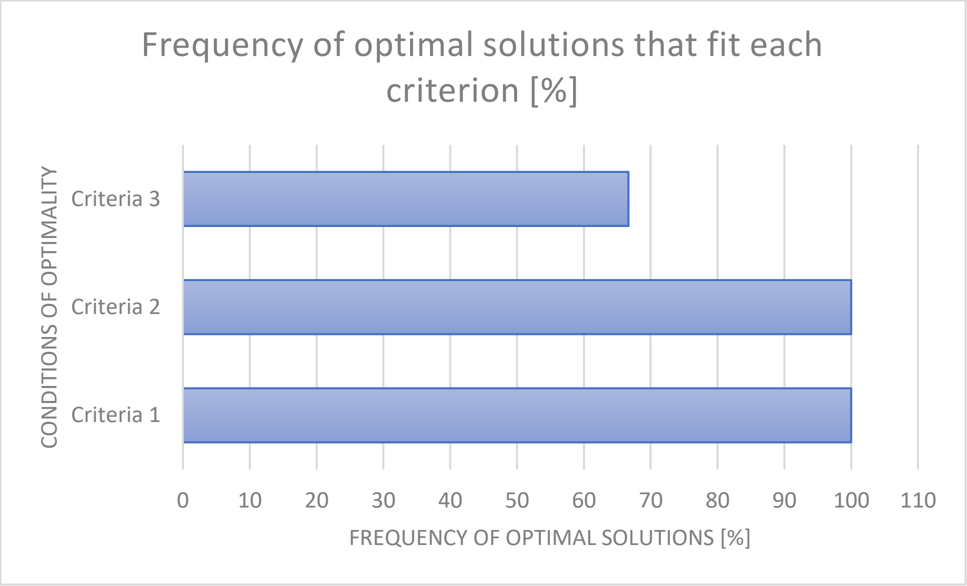


Figure 40 - Frequency of optimal solutions that fit each criterion [%]

Regarding Figure 40, in all the fault events in the busbars, all optimal solutions fit Criterion 1 and 2. This means that opening the CBs installed in the TLs that are connected to fault location provides the optimal choice for the minimum power loss.

Also, it is possible to observe that only in 67% of the fault events, the optimal solutions obtained fit Criterion 3.

It is important to mention that, there are optimal solutions that only fit Criterion 1, which means that opening the CBs installed in the TLs that are connected to the fault location (Solution Type 4) is not only the optimal solution obtained to clear the fault in the bus. For example, observing Figure 39, for a fault in B_3, it is verified that one solution fit only Criterion 1, the others two fit also Criterion 2.

4.3. RADIAL NETWORK

There is no distinction between the methodology applied in the meshed and the radial networks. The radial network under analysis is once more presented in the figures below:

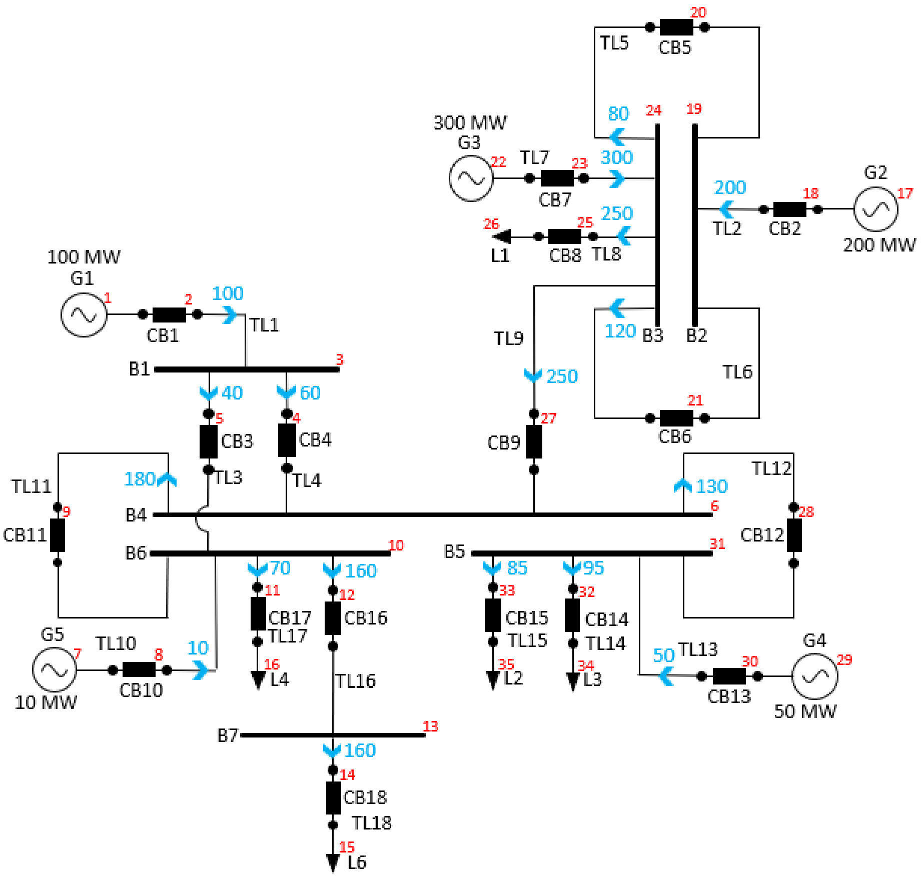


Figure 41 - Radial network

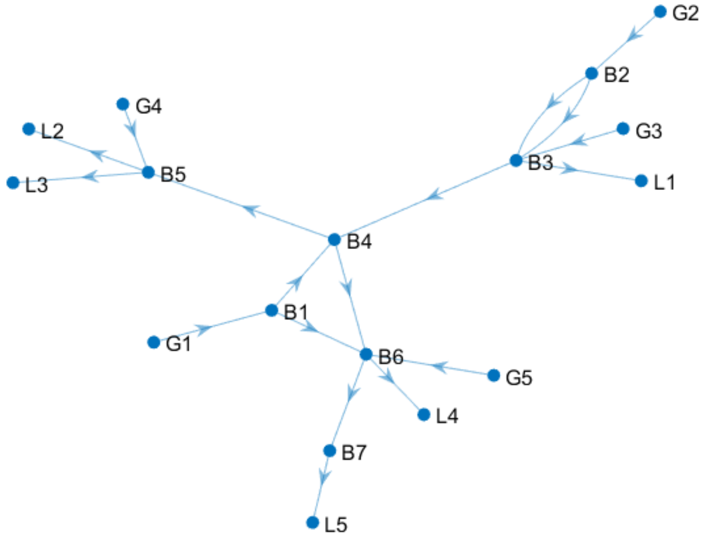


Figure 42 - Graph representation of the radial network of Figure 42

4.3.1. FAULT IN THE TL

Example: fault in TL_9. Then “Paths” is:

Table 20 - Paths between the fault at TL_9 and the sources

#	G_1	G_2	G_3	G_4	G_5
1	1;4;9	2;5;9	7;9	9;12;13	4;3;10;9
2	1;3;11;9	2;6;9			10;11;9

It is possible to see in Table 20 that there are different number of paths between the fault location and each generator. For instance, for generator G_1, there are 2 paths; but for generator G_3, there is only one. The columns correspond to the paths that belong to the possible paths between fault in TL_9 to each source.

The optimal solution is to open the CB connected to faulted TL, which is CB_9. Therefore, the minimum load shedding is 250 MW.

For this power system, Table 21 summarizes the optimal solution for the fault in the TL:

Table 21 - Optimal solution in case of a fault in the TL

Fault location	CB that must trip	Load shedding [MW]
TL_1	CB_1	100
TL_2	CB_2	200
TL_3	CB_3	40
TL_4	CB_4	60
TL_5	CB_5	80
TL_6	CB_6	120
TL_7	CB_7	300
TL_8	CB_8	250
TL_9	CB_9	250
TL_{10}	CB_{10}	10
TL_{11}	CB_{11}	180
TL_{12}	CB_{12}	130
TL_{13}	CB_{13}	50
TL_{14}	CB_{14}	95
TL_{15}	CB_{15}	85
TL_{16}	CB_{16}	160
TL_{17}	CB_{17}	70
TL_{18}	CB_{18}	160

4.3.2. FAULT IN THE LOAD

The radial network under analysis has five loads. Using one of them as an example of fault location: L_5. Then the paths between the fault location to the generators are ("Paths"):

Table 22 - Paths between the fault at L_5 and the sources

#	G_1	G_2	G_3	G_4	G_5
1	1;4;11;16;18	4;3;16;18;2;5;9	4;3;16;18;7;9	4;3;16;18;12;13	10;16;18
2	1;3;16;18	11;16;18;2;5;9	11;16;18;7;9	11;16;18;12;13	
3		4;3;16;18;2;6;9			
4		11;16;18;2;6;9			

The load shedding is the power that flows in the transmission line where L_5 is connected, which is TL_{18}. So $LS = 160\ MW$ and CB that must trip is CB_{18}. Note that, for a fault in TL_{18}, the result is equivalent.

Table 23 summarizes the optimal solution for the fault in the loads:

Table 23 - Optimal solution in case of a fault in the load

Fault location	TL where the load is connected	Optimal scheme of CBs to clear the fault	Load shedding [MW]
L_1	TL_8	CB_8	250
L_2	TL_{15}	CB_{15}	85
L_3	TL_{14}	CB_{14}	95
L_4	TL_{17}	CB_{17}	70
L_5	TL_{18}	CB_{18}	160

4.3.3. FAULT IN THE BUS

As the method for this fault event is already explained in subsection 3.5 and extended in 4.3.3, in this section, it is given objectively some examples:

Example 1: fault in bus B_3. So “Paths” is:

Table 24 - Paths between the fault at B_3 and the sources

#	G_1	G_2	G_3	G_4	G_5
1	1;4;11;16;18	4;3;16;18;2;5;9	4;3;16;18;7;9	4;3;16;18;12;13	10;16;18
2	1;3;16;18	11;16;18;2;5;9	11;16;18;7;9	11;16;18;12;13	
3		4;3;16;18;2;6;9			
4		11;16;18;2;6;9			

With the “Paths”, it is possible to obtain the possible solutions:

- Solution Type 1: null. As can be observed in Table 24, there is no common TL in all the paths.
- Solution Type 2: it finds the common value of each set of arrays of each generator, and does the mathematical operations described in Chapter 3.

Table 25 - All possible solutions using Solution Type 2 for a fault in B_3, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	1;2;7;9	600
2	2;7;9	500
3	1;2;7;9;12	730
4	2;7;9:12	630
5	1;2;7;9;13	650
6	2;7;9;13	550
7	1;2;7;9;10	610
8	2;7;9;10	510
9	1;2;7;10;12	740
10	2;7;9;10;12	640
11	1:2;7;10;13	660
12	2;7;9;10;13	560

- Solution Type 3: take the remaining elements not used in Solution Type 1 and 2, the ones that are not in common between all the paths and between each set of each generator and does the mathematical operations described in Chapter 3.

Table 26 - All possible solutions using Solution Type 3 for a fault in B_3, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	3;4;5;6;7;9;11	780
2	3;4;5;6;7;11;12	910
3	3;4;5;6;7;11;13	830
4	4;5;6;7;9;11	740
5	4;5;6;7;11;12	870
6	4;5;6;7;11;13	790

- Solution Type 4: open the CBs that are directly connected to the bus where the fault happened. Therefore, the CBs are: $(CB_5, CB_6, CB_7, CB_8, CB_9)$. And the load shedding is: $LS = 500\ MW$.

It is important to notice that: there are two solutions where the minimum load shedding is 500 MW: (2;7;9) (in Solution Type 2), and (5;6;7;8;9) (in Solution Type 4). This case fits the application of Criterion 2 (select the solution that has its elements connected to the faulted bus), then the result is $(CB_5, CB_6, CB_7, CB_8, CB_9)$. But the Criterion 3 is applied, where CB_8 is installed on TL_8 that is linked to the load L_1. So the final optimal scheme is to trip these CBs: (CB_5, CB_6, CB_7, CB_9).

Table 27 gathers all the possible solutions in case of a fault in the bus B_3:

Table 27 - All the possible solutions in case of a fault in the bus B_3, highlighting the solutions that each criterion fits

Legend:

- 🟩 Criterion 1 (Minimum LS)
- 🟦 Criterion 2 (CBs closest to the fault location)
- 🟨 Criterion 3 – First action (Trip the minimum number of CBs)
- 🟧 Criterion 3 – Second action (Trip the minimum number of CBs)

#	Possible solutions	Load shedding [MW]	Solution Type
0	-	-	1
1	1;2;7;9	600	2
2	🟩 🟨 2;7;9	500	
3	1;2;7;9;12	730	
4	2;7;9;12	630	
5	1;2;7;9;13	650	
6	2;7;9;13	550	
7	1;2;7;9;10	610	
8	2;7;9;10	510	
9	1;2;7;10;12	740	
10	2;7;9;10;12	640	
11	1;2;7;10;13	660	
12	2;7;9;10;13	560	
13	3;4;5;6;7;9;11	780	3
14	3;4;5;6;7;11;12	910	
15	3,4,5,6,7,11,13	830	
16	4;5;6;7;9;11	740	
17	4;5;6;7;11;12	870	
18	4;5;6;7;11;13	790	
19	🟩 🟦 🟧 5;6;7;8;9	500	4

An interesting case is shown in Table 27, where the Solution #19 fits the three criteria of optimality, but only the second action of Criterion 3, because TL_8 is a line connected to the load L_1. Therefore, the final and optimal solution is to open CB_5, CB_6, CB_7 and CB_9, because the second condition of optimality has higher priority than the third one. This is the reason the Solution #19 is selected instead of Solution #2.

Example 2**:** fault in the bus B_4. "Paths":

Table 28 - Paths between the fault at B_4 and the sources

#	G_1	G_2	G_3	G_4	G_5
1	1;4	2;5;9	7;9	12;13	4;3;10
2	1;3;11	2;6;9			10;11

With the "Paths", it is possible to obtain the possible solutions:

- Solution Type 1: null. As can be observed in Table 28, there is no common TL in all the paths.
- Solution Type 2:

Table 29 - All possible solutions using Solution Type 2 for a fault in B_4, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	1,2,7,10,12	610
2	1,7,9,10,12	660
3	1,2,9,10,12	560
4	1,9,10,12	360
5	1,2,7,10,13	660
6	1,7,9,10,13	710
7	1,2,9,10,13	610
8	1,9,10,13	410

- Solution Type 3:

Table 30 - All possible solutions using Solution Type 3 for a fault in B_4, and the LS of each solution

#	Possible solutions	Load shedding [MW]
1	3,4,5,6,7,11,12	600
2	3,4,5,6,7,11,13	650
3	3,4,5,6,9,11,12	550
4	3,4,5,6,9,11,13	600
5	4,5,6,7,11,12	560
6	4,5,6,7,11,13	610
7	4,5,6,9,11,12	510
8	4,5,6,9,11,13	560

- Solution Type 4: open the CBs that are directly connected to the bus where the fault occurred. Therefore, the CBs are: $(CB_4, CB_9, CB_{11}, CB_{12})$. And the load shedding is: $LS = 310\ MW$.

Observing the possible solution obtained from the Solution Types, the optimal solution, where it is achieved the minimum load shedding (310 MW), is to open the CBs: CB_4, CB_9, CB_{11} and CB_{12}.

Table 31 gathers all the possible solutions in case of a fault in the bus B_4:

Table 31 - All the possible solutions in case of a fault in the bus B_4

Legend:

🟩 Criterion 1 (Minimum LS)

🟦 Criterion 2 (CBs closest to the fault location)

🟨 Criterion 3 (Trip the minimum number of CBs)

#	**Possible solutions**	**Load shedding [MW]**	**Solution Type**
0	-	-	1
1	1,2,7,10,12	610	2
2	1,7,9,10,12	660	
3	1,2,9,10,12	560	
4	🟨 1,9,10,12	360	
5	1,2,7,10,13	660	
6	1,7,9,10,13	710	
7	1,2,9,10,13	610	
8	🟨 1,9,10,13	410	
9	3,4,5,6,7,11,12	600	3
10	3,4,5,6,7,11,13	650	
11	3,4,5,6,9,11,12	550	
12	3,4,5,6,9,11,13	600	
13	4,5,6,7,11,12	560	
14	4,5,6,7,11,13	610	
15	4,5,6,9,11,12	510	
16	4,5,6,9,11,13	560	
17	🟩 🟦 🟨 4;9;11;12	310	4

Note that, there are three solutions that fit Criterion 3. But only one of them (4;9;11;12) provides the minimum power loss (310 MW). Another point to highlight for this table is that the only solution that provides the minimum power loss is obtained by using Solution Type 4 in this case, that is to open all the CBs that are installed in the TLs that are connected to the faulted bus.

Finally, the following table presents the optimal solution for the minimum load shedding for a fault in each bus:

Table 32 - Optimal solution in case of a fault in the bus

Fault location	**Optimal scheme of CBs to clear the fault**	**Minimum load shedding [MW]**
$\boldsymbol{B_1}$	CB_1, CB_3, CB_4	100
$\boldsymbol{B_2}$	CB_2, CB_5, CB_6	200
$\boldsymbol{B_3}$	CB_5, CB_6, CB_7, CB_9	500
$\boldsymbol{B_4}$	$CB_7, CB_9, CB_{10}, CB_{11}$	310
$\boldsymbol{B_5}$	CB_{12}, CB_{13}	180
$\boldsymbol{B_6}$	CB_3, CB_{10}, CB_{11}	230
$\boldsymbol{B_7}$	CB_{16}	160

The graph below shows the number of the optimal solutions that fit each criterion of optimality:

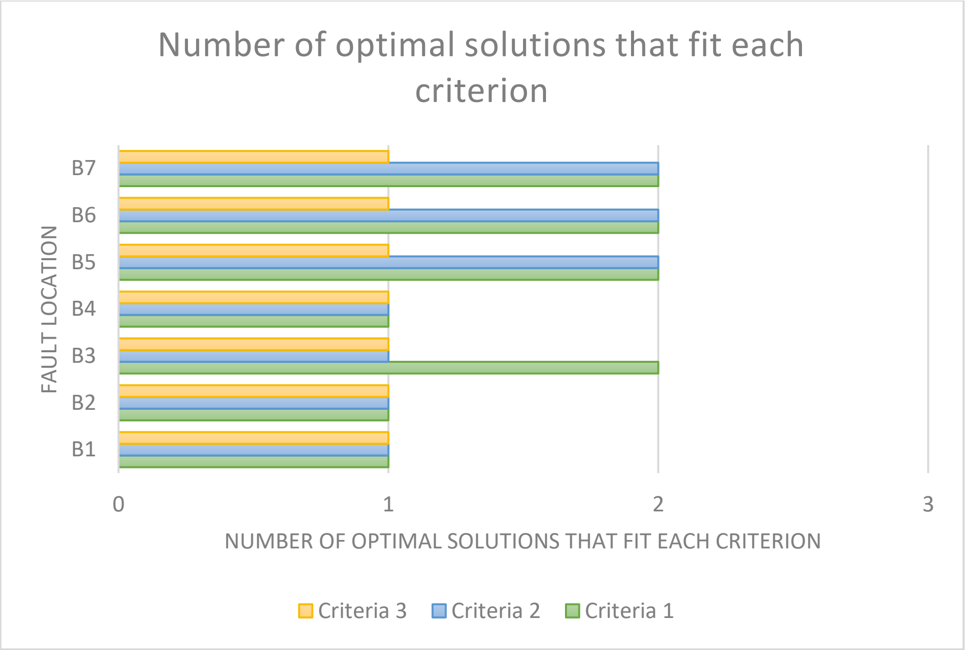


Figure 43 - Number of given optimal solutions that fit each criterion

It can be observed in Figure 43 that in all fault events the three conditions of optimality are presented and it is highlighted in the graph below:

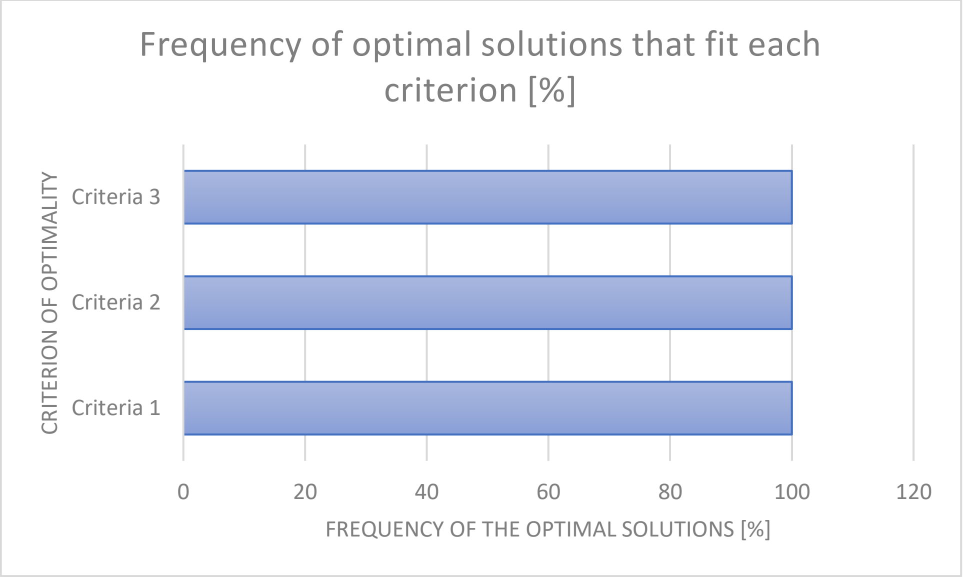


Figure 44 - Frequency of optimal solutions that fit each criterion [%]

Concerning Figure 44, it can be observed that the optimal solutions fit the three conditions for all the fault events in the busbar.

Observe that, the optimal solution is obtained by the application of the conditions of optimality. The basic criterion is the minimum load shedding. The other two can be compared as filters to refine the selection of the optimal scheme of CBs.

4.4. COMPARISON WITH ZHANG ET AL. EXAMPLE

Zhang et al. present a novel approach for fault isolation using the Floyd-Warshall [5]. In one proposed example, it is found the shortest paths from the fault isolation to all the CBs of the given grid. This means that it is acquired the possible solutions to isolate the fault. The mentioned power system is:

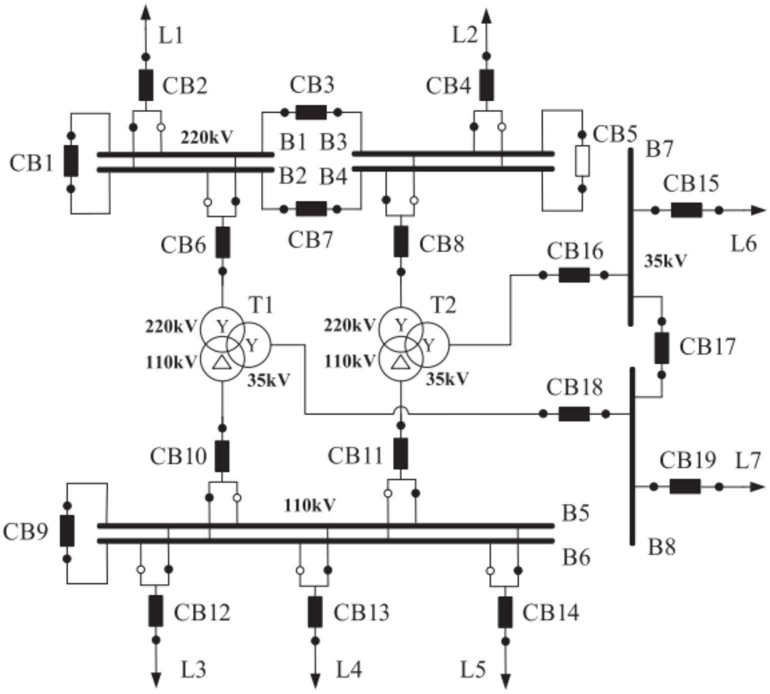


Figure 45 - Network from Zhang et al.

The Figure 45 is a single-line diagram of a 220 kV substation layout [5].

The work of Zhang et al. focuses on the fault isolation regarding the paths found between the fault location and the CBs, then it gives the shortest paths, i.e., the shortest set of CBs to isolate the fault. As for this thesis, the paths are also obtained, including the shortest one that is within “Paths”. Then it is possible to make a benchmark with their analysis. To do so, it is important to make some adaptations: transformers T_1 and T_2 are replaced by generators. The network adapted of the grid of Figure 45 is:

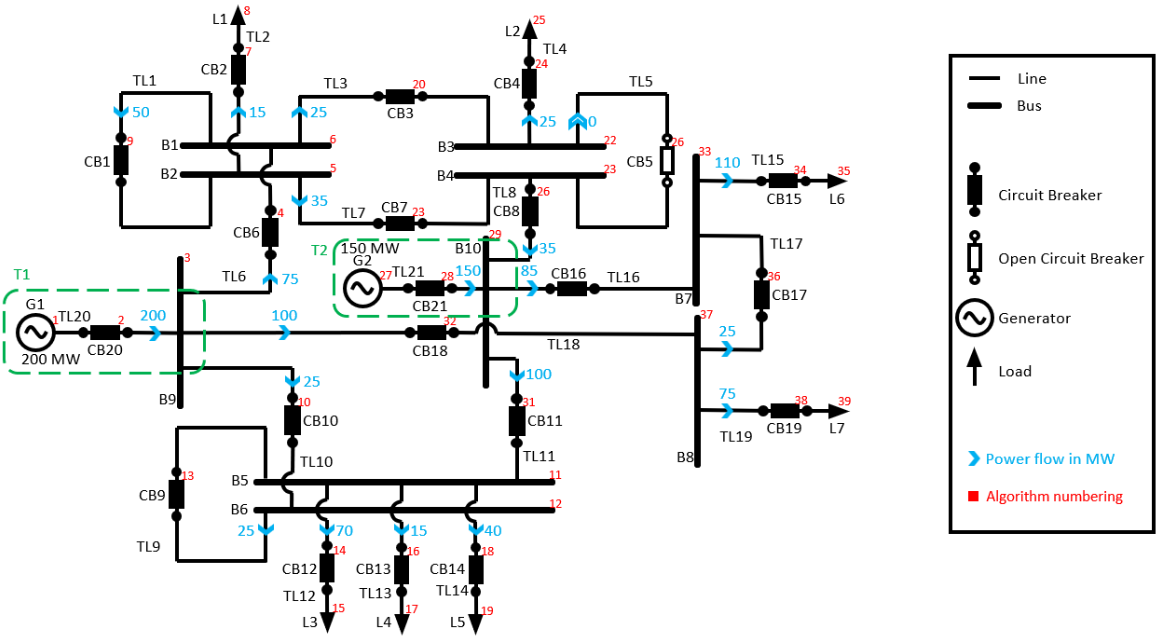


Figure 46 - Adapted network of Figure 45

The graph representation of this power system used in MATLAB® is:

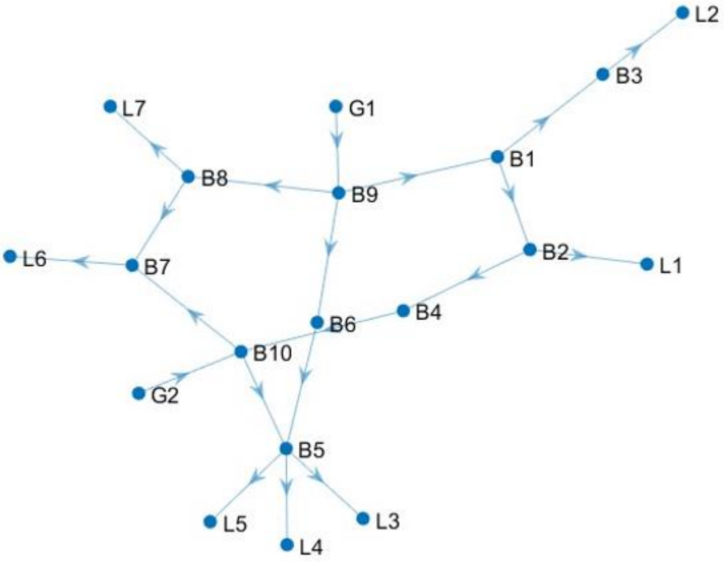


Figure 47 - Graph representation of the Zhang et al. example

Observe that, in Figure 46, the green dashed line is the adapted part from the Zhang et al. example. Also, it is assumed the active power that flows in the transmission lines and their directions. Note that, some connections were not considered, because they are opened.

Zhang et al. propose two fault events:

i. In the busbar B_2 and

ii. In the transformer T_2.

For the second case, it is assumed the fault in B_{10} in Figure 46.

Zhang et al. made the simultaneous faults for these two events. They considered the shortest path with a length equal to one, starting from the source vertex (which is the initial point, the reference). Compared with the case of this thesis, the vertex can be associated with the fault location. The length is measured by each electrical element found in the system. For example, the length of the path between T_1 and B_2 is equivalent to 4, because it counts just four elements from the T_1, which are: $T_1 \rightarrow CB_6 \rightarrow B_1 \rightarrow CB_1 \rightarrow B_2$ [5].

The proposed solution by Zhang et al. for each fault are:

i. Fault in B_2, the solution to isolate it is to open CB_1, CB_2 and CB_7.
ii. For T_2, trip CB_8, CB_{11} and CB_{16}.

The next sections shows the results and comparison with the outcomes provided by Zhang for the two fault events.

4.4.1. CASE 1: FAULT IN BUS 2

First, it is obtained the paths between the fault location and the sources:

Table 33 - Paths between the fault at B_2 and the sources

#	G_1	G_2
1	20;6;1	7;8;21
2	20;7;8;16;18;17	6;1;21;16;18;17

Table 34 presents the possible solutions for the fault in B_2:

Table 34 - All the possible solutions in case of a fault in the bus B_2

#	Possible solutions	Load shedding [MW]	Solution Type
0	-	-	1
1	20;21	350	2
2	1,6,7	125	3
3	1,6,7,8	160	
4	1,6,7,16	210	
5	1,6,7,17	150	
6	1,6,7,18	225	
7	1,6,8	160	
⋮	⋮	⋮	
12	1;7	50	
⋮	⋮	⋮	
46	6,8,17,18	235	
47	6;8;18	210	
48	1;2;7	50	4

Based on Table 34**Error! Reference source not found.Error! Reference source not found.**, the possible solutions that fit each criterion is highlighted in Table 35:

Table 35 - Optimal solutions that fit each criterion for a fault B_2

Criterion	Solution (set of CBs to trip)	Load Shedding [MW]
1	1;7	50
	1;2;7	50
2	1;7	50
	1;2;7	50
3	20;21	350
	1;7	50
	1;8	85
	6;7	75
	6;8	110

Regarding Table 35, the optimal solutions are highlighted in blue. The best option among them, based on the conditions of optimality, is to trip CB_1 and CB_7. Zhang et al. propose to open the CB_1, CB_2 and CB_7 [5]. Note that, (1;2;7) is also an optimal solution because it gives the minimum power loss. If the third criterion of optimality is not applied the final optimal solution proposed would be the same as Zhang et al.

4.4.2. CASE 2: FAULT IN BUS 10

Obtaining all the paths between the fault location and the generators:

Table 36 - Paths between the fault at B_{10} and the sources

#	G_1	G_2
1	20;6;1	7;8;21
2	20;7;8;16;18;17	6;1;21;16;18;17

Table 37 presents the possible solutions for the fault in B_{10}:

Table 37 - All the possible solutions in case of a fault in the bus B_{10}

#	Possible solutions	Load shedding [MW]	Solution Type
0	-	-	1
1	20;21	350	2
2	1,9,16,21	225	3
3	1,9,17,21	250	
⋮	⋮	⋮	
26	7,11,16,21	185	
⋮	⋮	⋮	
35	8,11,16,21	185	
36	8,11,17,21	210	
37	8,11,18,21	285	
38	8,11,16,21	185	4

Based on Table 37**Error! Reference source not found.Error! Reference source not found.**, the possible solutions that fit each criterion is highlighted in Table 38:

Table 38 - Optimal solutions that fit for each criterion for a fault B_{10}

Criterion	Solution (set of CBs to trip)	Load Shedding [MW]
1	7,11,16,21	185
	8,11,16,21	185
2	8,11,16,21	185
3	20;21	350

Regarding Table 38, the optimal solutions are highlighted in blue. The optimal CBs scheme of the created algorithm for the minimum load shedding is to open CB_8, CB_{11}, CB_{16} and CB_{21} because it fits the first and second conditions of optimality. This solution is equivalent to the one proposed by Zhang et al. because CB_{21} is one of the elements that refers to T_2 in the adaptive network of Figure 46**Error! Reference source not found.**.

4.4.3. COMMENTS ABOUT THE ANALYSIS

These two analyses made for the fault events show that opening the CBs closest to the fault location can provide the optimal solution to isolate a fault. The created algorithm gives the solution as the Floyd-Warshall does regarding the Zhang et al. application. However, the algorithm of this thesis provided a more refined selection of the CB scheme to clear the fault due the conditions of optimality.

The graph below shows the number of the optimal solutions obtained when applying each criterion alone:

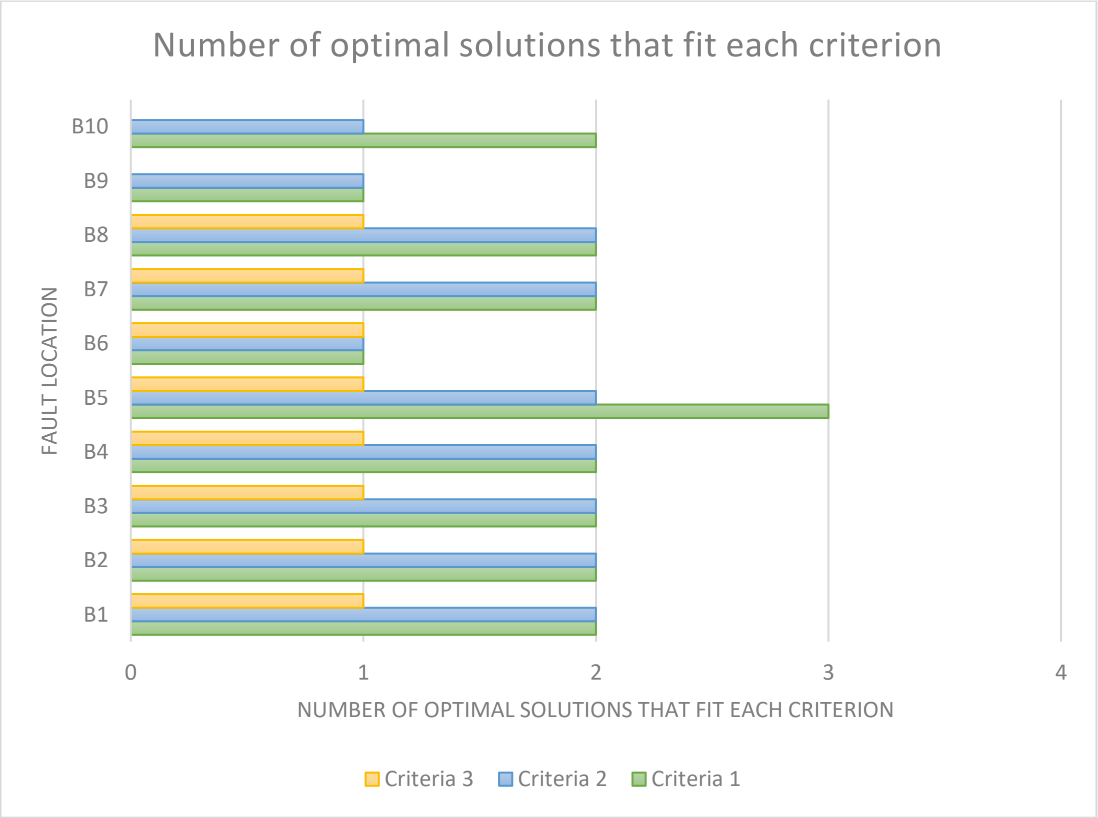


Figure 48 - Number of optimal solutions that fit each criterion

Figure 48 shows the number of optimal solutions that fit each criteria of optimality for the fault in the busbars. It is possible to observe that the optimal solutions fit the three criteria, except for faults in B_9 and B_{10}, where the optimal options do not fit Criterion 3. The graph below shows the frequency in which the optimal solutions fit each criterion for the fault event in the bus:

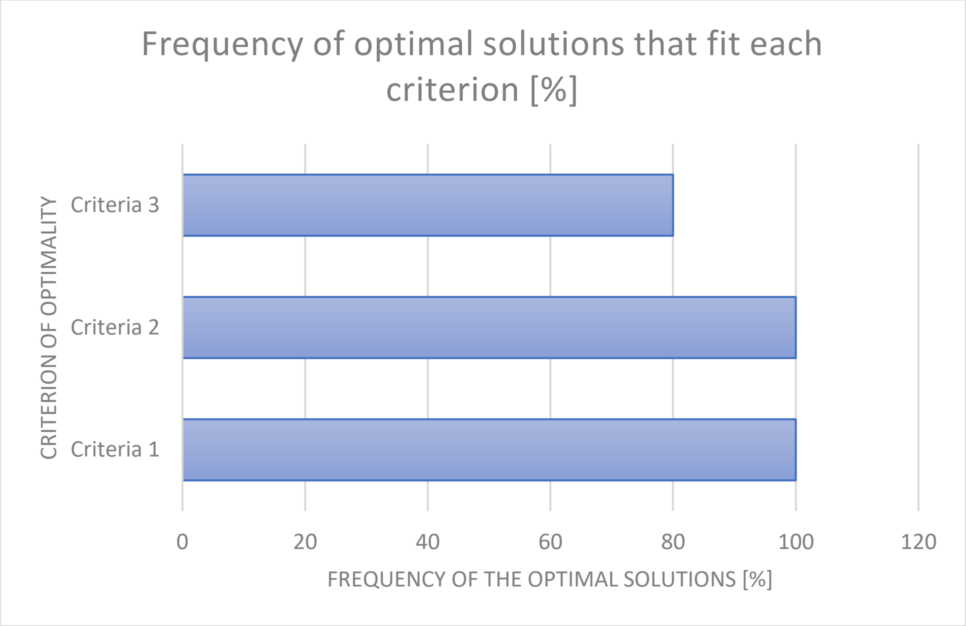


Figure 49 - Frequency of optimal solutions that fit each criterion [%]

Therefore, the optimal solutions fits in 100% of the cases Criterion 1 and 2, however, only in 80% regarding Criterion 3. This means that is not in all the fault events that the optimal CBs scheme obtained fit Criterion 3. This can be corroborate by observing Figure 49 (faults in B_9 and B_{10}).

5

Real network analysis

5.1. INTRODUCTION

In the chapters 3 and 4, it was presented two different networks: a meshed and a radial. These two power system were the basis of analysis for the built of the algorithm to find the optimal operation scheme of the CBs for the fault isolation. In this chapter, it is presented a new network: PoliTSO Power and Light (PPL). This power system has 37 busbars. It supplies Politecnico di Milano, and it is a 345/138/69 kV system [13]. The created algorithm is applied for the analysis of the fault isolation in certain busbars of this system.

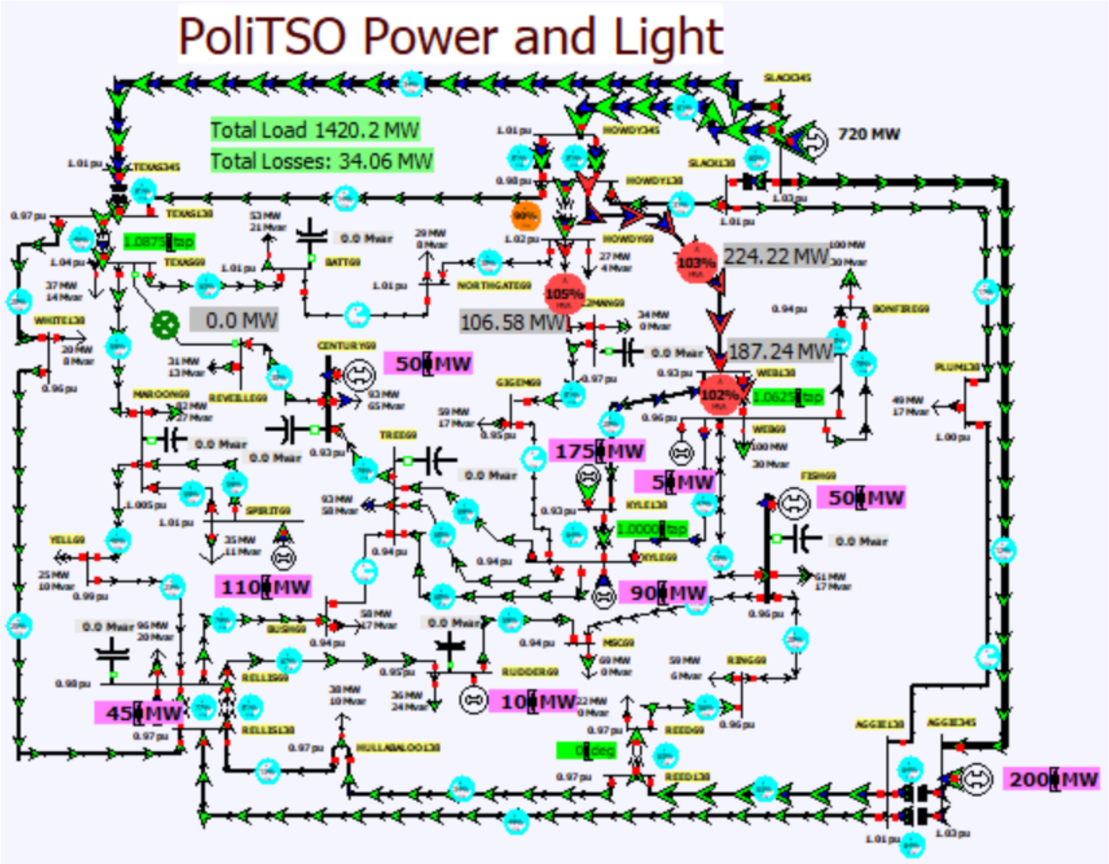


Figure 50 - PoliTSO Power and Light, from PowerWorld software

5.2. IMPLEMENTATION OF THE NETWORK IN THE ALGORITHM

The following network is PoliTSO Power and Light power system. Figure 51 shows with more details the grid information and also numbering used for the algorithm:

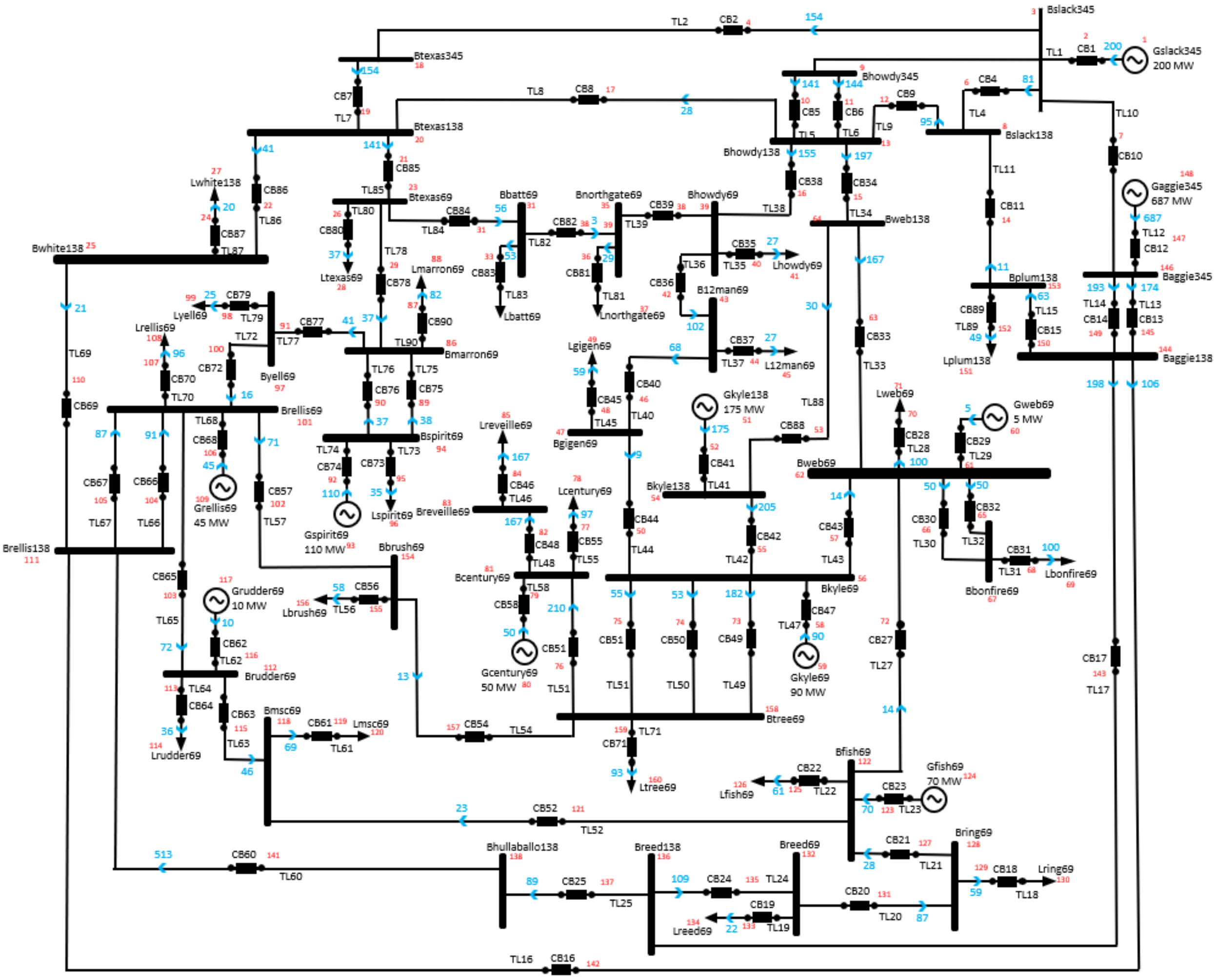


Figure 51 - PoliTSO Power and Light network

Figure 52 is a plot made in MATLAB® of the PoliTSO power system:

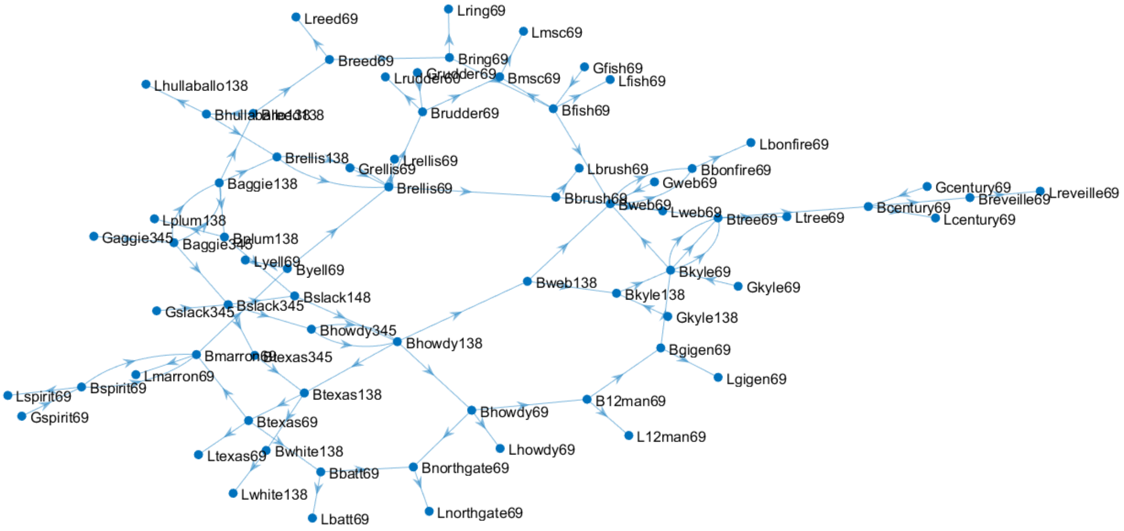


Figure 52 - Graph representation of PoliTSO Power and Light network

5.3. RESULTS OBTAINED

The Solution Types 1, 2 and 4 work for this network. However, it is not possible to implement the Solution Type 3 because the mathematical operation is burdensome in such way that it reaches a point that it is not possible to realize the combination. To corroborate with the previous statement, assuming the fault in the bus $B_{slack345}$, Table 39 presents the number of paths between the fault location and the generators:

Table 39 - Number of paths between the fault location and the sources

Generator	Number of paths
$\boldsymbol{G_{slack345}}$	1
$\boldsymbol{G_{aggie345}}$	2055
$\boldsymbol{G_{web69}}$	1884
$\boldsymbol{G_{kyle69}}$	1282
$\boldsymbol{G_{kyle138}}$	2308
$\boldsymbol{G_{spirit69}}$	4324
$\boldsymbol{G_{century69}}$	2717
$\boldsymbol{G_{rellis69}}$	1783
$\boldsymbol{G_{rudder69}}$	2277
$\boldsymbol{G_{fish69}}$	1719

The number of paths of each generator, except $G_{slack345}$, is enormous in such a way that it is not possible to perform this method. For instance, focusing only on $G_{aggie345}$, the number of arrays of non common TLs is 2055. Then the number of combinations for the $G_{aggie345}$ is:

$$\begin{aligned} comb_{step_{ii}\, for\, G_{aggie345}} \\ &= NumElem_{array1} \cdot NumElem_{array2} \cdot \ldots \cdot NumElem_{array_{2055}} \\ &= 1 \cdot 10 \cdot \ldots \cdot 7 \end{aligned}$$

Considering the average length of $NumElem_{array\_x}$ is 10, then the total number of combination $comb_{step_{ii}\, for\, G_{aggie345}}$ is around 10^{2054}, as just $NumElem_{array1}$ is equal to 1, and the rest is assumed to be 10. Note that, this is only for $G_{aggie345}$. This grid has ten sources in total. From Table 39, it is obtained the average of paths: 2035. So assuming that the average length of the arrays ($NumElem_{array}$) of each generator is also 10 (for instance, for $G_{aggie345}$ the fifth array is: $arr_{G_{aggie345}\,5} = 2; 7; 13; 16; 66; 72; 77; 78; 85$), then the number of combinations for each source is 10^{2035}. In addition, the total number of the final combination ($comb_{total}$) in “Step iii” will be:

$$comb_{total} = comb_{step_{ii}\, for\, G_{slack345}} \cdot comb_{step_{ii}\, for\, G_{aggie345}} \cdot \ldots \cdot comb_{step_{ii}\, for\, G_{fish69}} = 1 \cdot 10^{2035} \cdot \ldots 10^{2035} = (10^{2035})^{9}$$

Thus it is possible to observe that the Solution Type 3 is not feasible to realize. Therefore, one way to implement completely the algorithm with all four methods (Solution Types 1, 2, 3 and 4) is to split the grid in small networks.

Regarding the final result only applying the Solution Types 1, 2 and 4, the optimal solutions are:

- Fault in the TL

Table 40 summarizes the optimal solution for the fault in the TL:

Table 40 - Optimal solution in case of a fault in the TL

Fault location	CB that must trip	Load shedding [MW]	Fault location	CB that must trip	Load shedding [MW]
$\boldsymbol{TL_{1}}$	CB_{1}	200	$\boldsymbol{TL_{46}}$	CB_{46}	167
$\boldsymbol{TL_{2}}$	CB_{2}	154	$\boldsymbol{TL_{47}}$	CB_{47}	90
$\boldsymbol{TL_{3}}$	CB_{3}	285	$\boldsymbol{TL_{48}}$	CB_{48}	167
$\boldsymbol{TL_{4}}$	CB_{4}	81	$\boldsymbol{TL_{49}}$	CB_{49}	182
$\boldsymbol{TL_{5}}$	CB_{5}	141	$\boldsymbol{TL_{50}}$	CB_{50}	53
$\boldsymbol{TL_{6}}$	CB_{6}	145	$\boldsymbol{TL_{51}}$	CB_{51}	55
$\boldsymbol{TL_{7}}$	CB_{7}	154	$\boldsymbol{TL_{52}}$	CB_{52}	23
$\boldsymbol{TL_{8}}$	CB_{8}	28	$\boldsymbol{TL_{53}}$	CB_{53}	210
$\boldsymbol{TL_{9}}$	CB_{9}	95	$\boldsymbol{TL_{54}}$	CB_{54}	13
$\boldsymbol{TL_{10}}$	CB_{10}	320	$\boldsymbol{TL_{55}}$	CB_{55}	93
$\boldsymbol{TL_{11}}$	CB_{11}	14	$\boldsymbol{TL_{56}}$	CB_{56}	58
$\boldsymbol{TL_{12}}$	CB_{12}	687	$\boldsymbol{TL_{57}}$	CB_{57}	71
$\boldsymbol{TL_{13}}$	CB_{13}	174	$\boldsymbol{TL_{58}}$	CB_{58}	50
$\boldsymbol{TL_{14}}$	CB_{14}	193	$\boldsymbol{TL_{59}}$	CB_{59}	106
$\boldsymbol{TL_{15}}$	CB_{15}	63	$\boldsymbol{TL_{60}}$	CB_{60}	51
$\boldsymbol{TL_{16}}$	CB_{16}	106	$\boldsymbol{TL_{61}}$	CB_{61}	69
$\boldsymbol{TL_{17}}$	CB_{17}	198	$\boldsymbol{TL_{62}}$	CB_{62}	10
$\boldsymbol{TL_{18}}$	CB_{18}	59	$\boldsymbol{TL_{63}}$	CB_{63}	46
$\boldsymbol{TL_{19}}$	CB_{19}	22	$\boldsymbol{TL_{64}}$	CB_{64}	36
$\boldsymbol{TL_{20}}$	CB_{20}	87	$\boldsymbol{TL_{65}}$	CB_{65}	72
$\boldsymbol{TL_{21}}$	CB_{21}	28	$\boldsymbol{TL_{66}}$	CB_{66}	91
$\boldsymbol{TL_{22}}$	CB_{22}	61	$\boldsymbol{TL_{67}}$	CB_{67}	87
$\boldsymbol{TL_{23}}$	CB_{23}	70	$\boldsymbol{TL_{68}}$	CB_{68}	45
$\boldsymbol{TL_{24}}$	CB_{24}	109	$\boldsymbol{TL_{69}}$	CB_{69}	21
$\boldsymbol{TL_{25}}$	CB_{25}	89	$\boldsymbol{TL_{70}}$	CB_{70}	96
$\boldsymbol{TL_{26}}$	CB_{26}	38	$\boldsymbol{TL_{71}}$	CB_{71}	93
$\boldsymbol{TL_{27}}$	CB_{27}	14	$\boldsymbol{TL_{72}}$	CB_{72}	16

$\boldsymbol{TL_{28}}$	CB_{28}	100	$\boldsymbol{TL_{73}}$	CB_{73}	35
$\boldsymbol{TL_{29}}$	CB_{29}	5	$\boldsymbol{TL_{74}}$	CB_{74}	110
$\boldsymbol{TL_{30}}$	CB_{30}	50	$\boldsymbol{TL_{75}}$	CB_{75}	38
$\boldsymbol{TL_{31}}$	CB_{31}	100	$\boldsymbol{TL_{76}}$	CB_{76}	37
$\boldsymbol{TL_{32}}$	CB_{32}	50	$\boldsymbol{TL_{77}}$	CB_{77}	41
$\boldsymbol{TL_{33}}$	CB_{33}	167	$\boldsymbol{TL_{78}}$	CB_{78}	48
$\boldsymbol{TL_{34}}$	CB_{34}	197	$\boldsymbol{TL_{79}}$	CB_{79}	25
$\boldsymbol{TL_{35}}$	CB_{35}	27	$\boldsymbol{TL_{80}}$	CB_{80}	37
$\boldsymbol{TL_{36}}$	CB_{36}	102	$\boldsymbol{TL_{81}}$	CB_{81}	29
$\boldsymbol{TL_{37}}$	CB_{37}	34	$\boldsymbol{TL_{82}}$	CB_{82}	3
$\boldsymbol{TL_{38}}$	CB_{38}	155	$\boldsymbol{TL_{83}}$	CB_{83}	53
$\boldsymbol{TL_{39}}$	CB_{39}	26	$\boldsymbol{TL_{84}}$	CB_{84}	56
$\boldsymbol{TL_{40}}$	CB_{40}	68	$\boldsymbol{TL_{85}}$	CB_{85}	141
$\boldsymbol{TL_{41}}$	CB_{41}	175	$\boldsymbol{TL_{86}}$	CB_{86}	41
$\boldsymbol{TL_{42}}$	CB_{42}	205	$\boldsymbol{TL_{87}}$	CB_{87}	20
$\boldsymbol{TL_{43}}$	CB_{43}	14	$\boldsymbol{TL_{88}}$	CB_{88}	30
$\boldsymbol{TL_{44}}$	CB_{44}	9	$\boldsymbol{TL_{89}}$	CB_{89}	49
$\boldsymbol{TL_{45}}$	CB_{45}	59	$\boldsymbol{TL_{90}}$	CB_{90}	82

As it can be seen, the methodology applied for the fault in a TL is successfully executed for this power system.

- Fault in the load

Table 41 summarizes the optimal solution for the fault in the loads:

Table 41 - Optimal solution in case of a fault in the load

Fault location	**CB that must trip**	**Load shedding [MW]**	**Fault location**	**CB that must trip**	**Load shedding [MW]**
$\boldsymbol{L_{plum138}}$	CB_{89}	49	$\boldsymbol{L_{batt69}}$	CB_{83}	53
$\boldsymbol{L_{bonfire69}}$	CB_{31}	100	$\boldsymbol{L_{northgate69}}$	CB_{81}	29
$\boldsymbol{L_{howdy69}}$	CB_{35}	27	$\boldsymbol{L_{yell69}}$	CB_{79}	25
$\boldsymbol{L_{12man69}}$	CB_{37}	34	$\boldsymbol{L_{tree69}}$	CB_{71}	93
$\boldsymbol{L_{web69}}$	CB_{28}	100	$\boldsymbol{L_{fish69}}$	CB_{22}	61
$\boldsymbol{L_{reveille69}}$	CB_{46}	167	$\boldsymbol{L_{brush69}}$	CB_{56}	58
$\boldsymbol{L_{gigen69}}$	CB_{45}	59	$\boldsymbol{L_{ring69}}$	CB_{18}	59
$\boldsymbol{L_{marron69}}$	CB_{90}	82	$\boldsymbol{L_{rudder69}}$	CB_{64}	36
$\boldsymbol{L_{spirit69}}$	CB_{73}	35	$\boldsymbol{L_{msc69}}$	CB_{61}	69
$\boldsymbol{L_{rellis69}}$	CB_{70}	96	$\boldsymbol{L_{century69}}$	CB_{55}	93
$\boldsymbol{L_{texas69}}$	CB_{80}	37	$\boldsymbol{L_{hullaballo69}}$	CB_{26}	38
$\boldsymbol{L_{white138}}$	CB_{87}	20	$\boldsymbol{L_{reed69}}$	CB_{19}	22

Note that, the CBs selected to clear the fault are the ones installed in the TL where the faulted load is connected to.

- Fault in the bus

Table 42 presents the optimal solution for the minimum load shedding for a fault in each bus:

Table 42 - Optimal solution in case of a fault in the bus

#	Fault location	Optimal scheme of CBs to clear the fault	Minimum load shedding [MW]
1	$\boldsymbol{B_{slack345}}$	$CB_1, CB_2, CB_3, CB_4, CB_{10}$	520
2	$\boldsymbol{B_{slack138}}$	CB_4, CB_9, CB_{11}	95
3	$\boldsymbol{B_{howdy138}}$	$CB_5, CB_6, CB_8, CB_{34}, CB_{38}$	381
4	$\boldsymbol{B_{howdy345}}$	CB_3, CB_5, CB_6	285
5	$\boldsymbol{B_{howdy69}}$	$CB_{36}, CB_{38}, CB_{39}$	155
6	$\boldsymbol{B_{texas345}}$	CB_2, CB_7	154
7	$\boldsymbol{B_{texas138}}$	$CB_7, CB_8, CB_{85}, CB_{86}$	182
8	$\boldsymbol{B_{texas69}}$	$CB_{78}, CB_{84}, CB_{85}$	141
9	$\boldsymbol{B_{white138}}$	CB_{69}, CB_{86}	41
10	$\boldsymbol{B_{marron69}}$	$CB_{75}, CB_{76}, CB_{77}, CB_{78}$	123
11	$\boldsymbol{B_{batt69}}$	CB_{82}, CB_{84}	56
12	$\boldsymbol{B_{northgate69}}$	CB_{39}, CB_{82}	29
13	$\boldsymbol{B_{12man69}}$	CB_{36}, CB_{40}	102
14	$\boldsymbol{B_{web138}}$	$CB_{33}, CB_{34}, CB_{88}$	197
15	$\boldsymbol{B_{web69}}$	$CB_{27}, CB_{29}, CB_{30}, CB_{32}, CB_{33}, CB_{43}$	200
16	$\boldsymbol{B_{bonfire69}}$	CB_{30}, CB_{32}	100
17	$\boldsymbol{B_{plum138}}$	CB_{11}, CB_{15}	63
18	$\boldsymbol{B_{aggie345}}$	$CB_{10}, CB_{12}, CB_{13}, CB_{14}$	687
19	$\boldsymbol{B_{aggie138}}$	$CB_{13}, CB_{14}, CB_{15}, CB_{16}, CB_{17}$	367
20	$\boldsymbol{B_{kyle138}}$	$CB_{41}, CB_{42}, CB_{88}$	205
21	$\boldsymbol{B_{kyle69}}$	$CB_{42}, CB_{43}, CB_{44}, CB_{47}, CB_{49}, CB_{50}, CB_{51}$	304
22	$\boldsymbol{B_{gigen69}}$	CB_{40}, CB_{44}	68
23	$\boldsymbol{B_{reveille69}}$	CB_{48}	167
24	$\boldsymbol{B_{century69}}$	CB_{53}, CB_{58}	260
25	$\boldsymbol{B_{brush69}}$	CB_{54}, CB_{57}	71
26	$\boldsymbol{B_{tree69}}$	$CB_{49}, CB_{50}, CB_{51}, CB_{53}, CB_{54}$	303
27	$\boldsymbol{B_{yell69}}$	CB_{72}, CB_{77}	41
28	$\boldsymbol{B_{rellis69}}$	$CB_{57}, CB_{65}, CB_{66}, CB_{67}, CB_{68}, CB_{72}$	239
29	$\boldsymbol{B_{rellis138}}$	$CB_{59}, CB_{60}, CB_{66}, CB_{67}, CB_{69}$	178
30	$\boldsymbol{B_{spirit69}}$	$CB_{74}, CB_{75}, CB_{76}$	110
31	$\boldsymbol{B_{rudder69}}$	$CB_{62}, CB_{63}, CB_{65}$	82
32	$\boldsymbol{B_{msc69}}$	CB_{52}, CB_{63}	69
33	$\boldsymbol{B_{fish69}}$	$CB_{21}, CB_{23}, CB_{27}, CB_{52}$	98
34	$\boldsymbol{B_{ring69}}$	CB_{20}, CB_{21}	87

35	$\boldsymbol{B_{reed69}}$	CB_{20}, CB_{24}	109
36	$\boldsymbol{B_{reed138}}$	$CB_{17}, CB_{24}, CB_{25}$	198
37	$\boldsymbol{B_{hullaballo69}}$	CB_{25}, CB_{60}	89

Note that, the optimal solution for a fault in $B_{century69}$ is to open CB_{53} and CB_{58}. This last CB is obtained by Solution Type 2. There is another optimal solution for this case, which is to open all CBs directly connected to the faulted bus, which is to trip CB_{48}, CB_{53}, CB_{55} and CB_{58}. This solution is the outcome of Solution Type 4. Both solutions are optimal because they give the minimum load shedding (Criterion 1) and all of the CBs are directly connected to the faulted bus (Criterion 2). However, the first one was selected as the best option because it gives the minimum amount of CBs to trip (Criterion 3).

Taking one bus to highlight the possible solutions given by the Solution Types, then assuming fault in $B_{slack345}$:

Table 43 - All the possible solutions in case of a fault in the bus B_4

#	Possible solutions	Load shedding [MW]	Solution Type
0	-	-	1
1	1;12;23;29;41;47;53;62;68;74	1602	2
2	1;12;23;29;41;47;58;62;68;74	1442	
3	1;2;3;4;10	520	4

Observe in Table 43 that there is only one optimal solution, given by Solution Type 4, which is to open the CBs that are directly connected to the faulted bus.

A way to obtain all possible solutions by applying the four methods proposed in this thesis, is to split the grid into subsections. For instance, PoliTSO could be split in smaller networks such as:

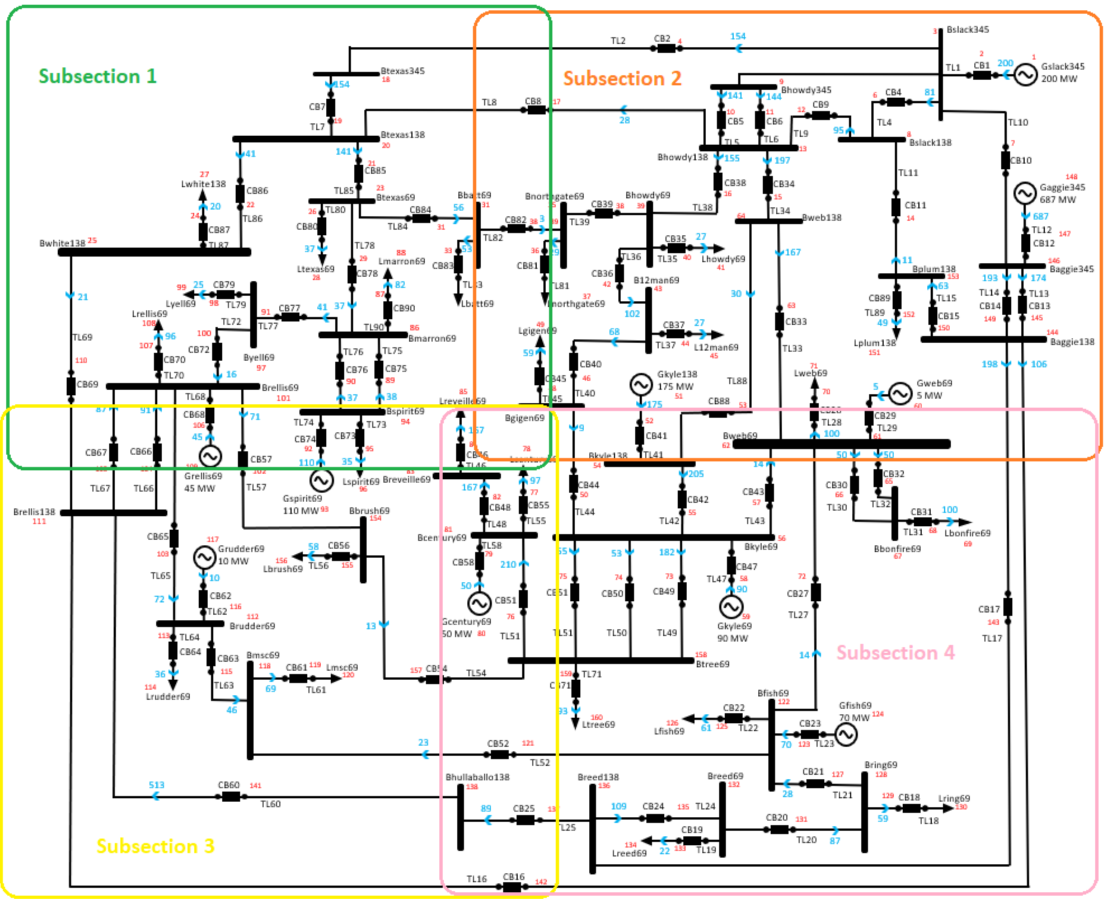


Figure 53 - PoliTSO network split in subsections

Figure 53 is an example of how the power system can be organized to implement it in the built algorithm to be able to apply the four methods proposed to find the optimal solution. Note that, it is important to split a big grid in such a way that the mathematical operation will be possible, as it was shown previously that, implement the code for this power system, it is necessary to realize around $(10^{2035})^9$ combinations.

6

Concluding remarks

The present thesis aimed to contribute to a better strategy for the operation of the CBs for fault isolation focusing on the minimum load shedding. The foundations of this work are based on the questions made in subsection 2.5. After the analysis presented in the previous chapters, it is possible to define the proper answers for them:

6.1. QUESTION 1

What is the optimal operation scheme for CBs to clear a fault?

The basis of the optimal operation proposed in this thesis is the minimum load shedding (Criterion 1), and then more two conditions of optimality were defined (Criterion 2 and 3).

For the faults in the TLs and in the loads, it can be seen that the best solution is opening the CB installed in the faulted TL; for the fault in the load, the answer is to trip the CB of the TL where the faulted load is linked.

It is possible to isolate the fault by also opening the others CBs that compose the paths between the fault location and the generators, however, once it is selected the CBs that are further from the fault location, the load shedding increases. This also applies to the fault in the bus.

For the case of a fault in the bus, the outcome, which fits Criterion 2, is present in all the optimal solutions (minimum load shedding), however, this does not mean that all optimal solutions fit the second condition of optimality. Criterion 1 prevails over Criterion 2, as it provides more optimal solutions (CBs schemes to trip) to clear the fault.

6.2. QUESTION 2

How powerful is the minimum load shedding condition in a fault occurrence over the other two criterion?

The minimum power loss criterion (Criterion 1) provides more number of possible solutions for fault isolation concerning Criterion 2, but not regarding Criterion 3. The difference in relation to the second condition of optimality is the number of optimal solutions. Concerning the third condition, the Criterion 1 is better, because it guarantees the minimum load shedding, which the Criterion 3 does not. This means that selecting the option, among the possible solutions, that has the minimum number of CBs does not guarantee the minimum load shedding.

In all the studied cases, Criterion 1 and 2 are 100 % effectively applied to select the best scheme of CBs to trip for clear the fault to achieve the minimum load shedding.

6.3. QUESTION 3

How effective is to trip the CBs closer to the fault location with respect to the other defined criterion?

This second criterion is 100% effective in obtaining the minimum load shedding. Therefore, it is always present among the optimal solutions obtained in the studies networks. However, the solution that fits Criterion 2 is not only the optimal solution, this means that there are optimal solutions that do not fit completely Criterion 2, but certainly Criterion 1. For instance, for the radial network presented in subsection 4.3, considering the fault in the bus B_3, all possible solutions are shown in Table 29 and the ones that fit each criteria. It can be seen two options for the minimum power loss, trip CBs (2;7;9) or (5;6;7;9). For the first case, CB_2 is installed in the TL that is not connected directly to the faulted bus. Therefore, depending on the definitions of the criterion of optimality, it is possible to select based, for example, on the minimum number of CBs, not considering if the elements are directly connected to the fault location, then the chosen solution is (2;7;9). Otherwise, if the priority is to select the scheme that has the greatest numbers of TLs directly connected to the fault location, then the second option is picked (5;6;7;9), because it has all of its TLs connected to the faulted bus, in comparison with the second solution that has two TLs directly connected to the fault location, which are TL_7 and TL_9.

6.4. QUESTION 4

How efficacious is to trip the minimum amount of CBs to isolate the fault in relation to the previous two criterion?

The third criterion proofs to be the least effective because, in certain cases, the optimal solutions do not fit this condition of optimality as it can be seen in Figure 39 and Figure 48, where it can be observed that the optimal solution for a fault in some busbars do not fit Criterion 3. For instance, in Figure 48, the optimal CBs scheme to clear the fault in B_9 only fits Criterion 1 and 2.

6.5. COMPARISON WITH ZHANG ET AL. EXAMPLE

This benchmark proved to be very productive, as it is possible to state that the closer the CBs selected to trip regarding the fault location, better is the outcome to achieve the minimum load shedding. The created algorithm englobes the function of the method applied by Zhang et al., but also it is more robust, because of the application of the three criterion of optimality, which gives more options for possible solutions to isolate the fault, and the optimal solutions as well. For the two examples analyzed, the algorithm of this thesis meets the solutions proposed by the authors and extends the possibility for more solutions to clear the faults. For instance, Zhang et al. provide one solution to isolate the fault in B_2 that is to trip CBs (1;2;7). The created algorithm provides 381 possible solutions to isolate the fault, where the Zhang et al. solution can also be found. In these 381 solutions is obtained two options for the optimal scheme of CBs to open to have the minimum load shedding, which are (1;7) and (1;2;7). Note that, one of them is the same proposed by Zhang et al. However, differently of their work, the built algorithm proposes the solution (1;7) due the defined criterion of optimality. In this case, especially regarding the third one.

6.6. REAL NETWORK ANALYSIS

As shown in Chapter 5, it is not possible to realize the mathematical operation (combination) of large grids comparing with the others three networks previously analyzed (meshed, radial and Zhang et al.). Therefore, it is proposed two ways to study this case: (1) split the grid in smaller ones and apply them in the algorithm; (2) do not realize the Solution Type 3 in the algorithm implementation. For this second case, the optimal solutions were obtained for the fault in the TLs, loads and busbars. For the fault location in the bus, the optimal solutions for each bus is to open the CBs that are installed in the TLs that are connected to the faulted bus.

6.7. FINAL COMMENTS

Criterion 1 is well applied to obtain the best selection of CBs to achieve the minimum load shedding. As it can be observed in the examples given in Chapter 4, the scheme of CBs to trip, that fit the Criterion 2, always results in minimum load shedding. Which possibilities to state for these three networks that: opening the CBs that are installed in the TLs which are connected to the bus, where the fault occurs, provides the minimum power loss. Regarding Criterion 3, it is not in all the cases that the optimal solutions fit this condition of optimality. Using only Criterion 1 and 2 makes it possible to reach the main objective which is to obtain the optimal scheme of CBs to clear the fault concerning the minimum load shedding. In summary, the optimal solution is always contained in the first condition, the second is within it and the third criterion does not give the optimal solution in all the fault events, as it is illustrated in Figure 54:

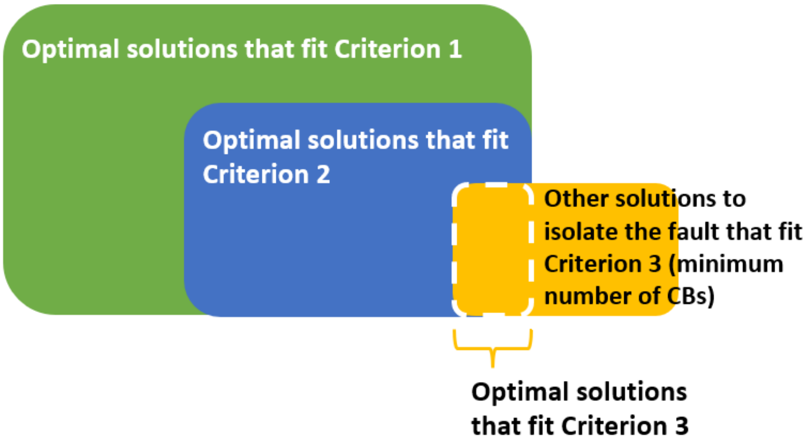


Figure 54 - Illustration regarding where the optimal solution can be found

Figure 54 illustrates where it is possible to find the optimal scheme of CBs to trip to clear the fault. Note that, the optimal solutions always fit Criterion 1 as its logic is to find the minimum load shedding, which is the basis of the optimality defined. Also for all fault events in the busbars, there is at least one of them that fits Criterion 2. Finally, just in some cases, the optimal solutions fit Criterion 3. Therefore, it can be stated that, regarding the networks analyzed, once a fault happens in a bus, tripping the CBs installed in the TLs which are connected to the faulted bus gives the minimum load shedding. However, it is important to highlight that doing this selection (by applying Solution Type 4) is not the only way to obtain the optimal solution as it can be seen in Chapter 4, as the optimal solution is also obtained using the mathematical operations described in the Solution Types 1, 2 and 3.

6.8. RECOMMENDATIONS FOR FURTHER WORK

The results of the investigation introduce features where it is possible to propose further work concerning the network analysis for fault isolation. More studies can be done regarding the conditions of optimality. For instance, instead of using the minimum load shedding, the first criterion can be the distance of the CBs in relation to the fault location.

Analysis regarding other types of power systems can also be made, for example, ring, star, hybrid networks.

Also it can be considered more characteristics of the power system, such as:

- The physical distance of the CBs. As in this work, it is considered only the CBs installed in the TLs that are connected to the fault location.
- Initial status of the CBs (opened/closed).
- Consider two CBs installed in the line and analyze which one should trip in case of a fault. For instance, if a fault happens in B_x, one of the solutions would be to open the CBs at the receiving end (CB_{x_re}) and sending end (CB_{x_se}) closer to the fault location. For example:

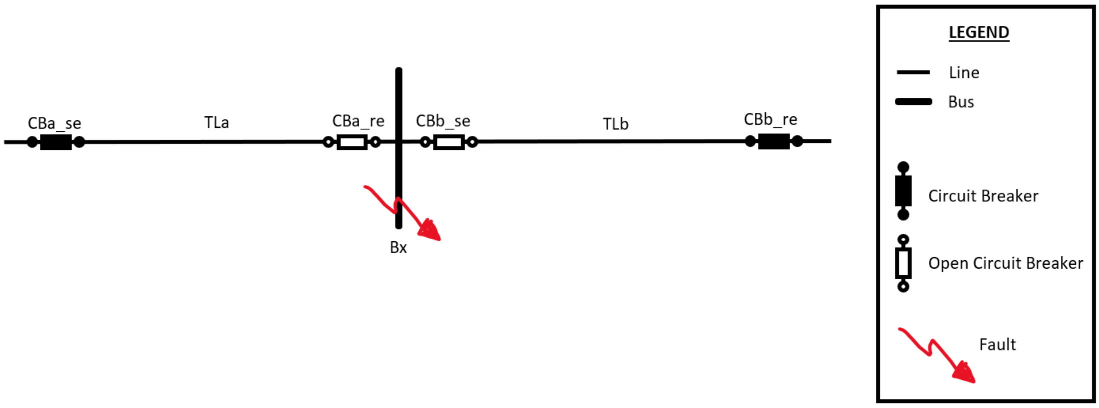


Figure 55 - Example for future analysis

Therefore, there are several approaches to effectively isolate the fault. Regarding this thesis, the focus is on the minimum load shedding as the prime condition of optimality to clear the fault, and then, applying the others two criterion.

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