EXECUTIVE SUMMARY OF THE THESIS

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

TESI MAGISTRALE IN ELECTRICA ENGINEERING – INGEGNERIA ELLETRICA

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1. Introduction

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. This thesis focuses on the best circuit breakers (CBs) scheme operation to isolate the fault concerning the achievement of the minimum load shedding (LS). Therefore, this investigation creates a novel approach to reach this objective to maintain the reliability and stability of the network in supplying electrical power. For the selection the optimal CBs scheme operation, three different criteria of optimality are defined: (1) the minimum LS, (2) the minimum distance of CBs to the fault location, and (3) the minimum number of CBs to be operate to clear the fault. A single algorithm was implemented in the MATLAB® environment to find the optimal operation scheme of CBs. 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 regarding 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 the created approach is applied to the power system under analysis, all possible solutions are found to isolate the fault concerning the CBs operation to achieve the minimum LS. This is possible by the four methods formulated to find possible solutions to isolate the fault and by applying the defined conditions of optimality. Finally, this results in the selection of the optimal option among the solutions.

1.1. Theory background

Graph theory is one of the main tools used for the network analysis in this thesis, where it is defined a graph G = (V,E), which consists of a set of V (vertices) and E (edges) [1]. For this work, the vertices are considered as the elements of the network (generators, TLs/CBs, and loads) and the active power that flows through the TLs are the edges. An example is shown in Figure 1.

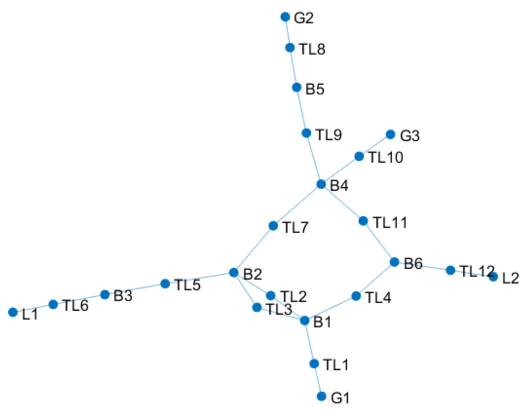

Figure 1 - Graph representation of meshed network presented in Figure 14

Also, for the network investigation, one possible solution to isolate the fault is to analyze the admittance matrix for a fault in the bus. This matrix contains the information about the direction of the power flow in the bus concerning the TL, i.e., in case of a fault in B_x, it is possible to know in which line the power is flowing and its direction (going into the bus or going out from it).

Having the tool to analyze the power system, it is important to define how to investigate the fault isolation. For this case, there are studies that evaluate the best approach to clear the fault based on achieving the minimum LS, which means to have a minimum power loss. Laghari et al. mention three ways to make this analysis [2]:

- Conventional LS: Under frequency load shedding techniques and Under voltage load shedding techniques.
- Adaptive load shedding techniques.
- Computational intelligent load shedding techniques: Artificial Neural Network, Fuzzy logic control, Adaptive Neuro Fuzzy Interference System, GA and Particle Swarm Optimization.

There are also other studies that use algorithms that find the paths between the fault location and the electrical components of the grid, such as Floyd-Warshall [3][4], Dijkstra algorithm [4][5], Bellman Ford algorithm [6]. However, these works do not focus on the minimum LS, but on finding the shortest path between the fault and the electrical components of the grid.

Laghari et al. mention studies of fault isolation to obtain the minimum LS by using different techniques, such as the computational ones aforementioned [2]. Zhang et al. and Arya et al, differently, use an approach to find the shortest path to provide one CBs scheme operation to clear the fault.

1.2. Research regarding fault isolation

Past works focused on the analysis of fault isolation using computational techniques such as Fuzzy logic [2][7] and Genetic Algorithm [8]. With the same purpose, other algorithms, such as Floy-Warshall [2] or Dijkstra [7], find the CBs path to trip which connect the protected electrical component by finding the shortest path between the fault location and these components. Zhang et al. showed in their paper a novel scheme for fault isolation by using the Floyd-Warshall algorithm [3]. However, this last work does not make further analysis to select an optimal CBs scheme to reach the minimum LS.

The present thesis proposes a new algorithm, where all paths between the fault location and the sources of the power system are found, and then the optimal CBs scheme to isolate the fault is selected, ultimately achieving the minimum LS.

Finally, a benchmark is made as a comparison between the outcome of the created algorithm of this thesis and Zhang et al. results in whose study aimed to minimize the area of fault isolation and to obtain a quick trip of CBs under the changes in the network topology [3].

1.3. Purpose, problem statement, and objective

To create a new method to provide a more reliable and secure network and according to the previous points concerning the fault isolation based on the criteria of optimality defined, 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 criteria?
- Question 3: how effective is to trip the CBs closer to the fault location regarding the other defined condition of optimality?
- Question 4: how efficacious is to trip the minimum amount of CBs to isolate the fault concerning the previous two criteria?

The present thesis aims to create a novel method for the optimal scheme of CBs to isolate the fault achieving the minimum LS.

2. Methodology

2.1. Network

A total of four power systems were analyzed: one radial, and three meshed. For explanations purpose, a simple meshed network is used, which is shown in Figure 2.

Once the fault location is known, the first step is to find all paths between the fault and the sources of the power system. Figure 2 presents an example of a path between the fault in B_5 and generator G_1 of the simple meshed network.

Note in Figure 2 that the paths are composed of the TLs. Therefore, in Figure 2, it is possible to see that Path #1 is $TL_1 \rightarrow TL_2 \rightarrow TL_3$. This is one possible path between the generator G_1 and the fault in B_5.

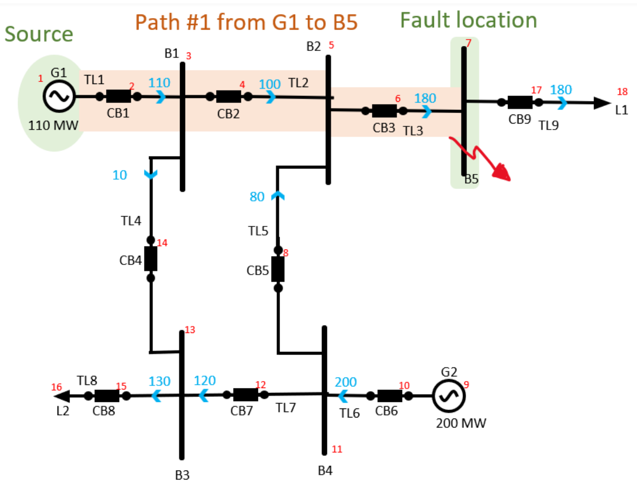

Figure 2 - Simple meshed network, highlighting a path between the fault in B_5 and generator G_1

2.2. Fault in the TL and in the load

The approach to clear the fault a TL and in a load is similar. For the first case, the best solution is to open the CB (CB_x) installed in the TL (TL_x) where the fault occurred because it provides the minimum LS. For the second case, the best approach is to trip the CB (CB_y) installed in the TL (TL_x) where it is connected to the faulted load (L_x). Figure 3 and Figure 4 show an example of a fault in the TL and a fault in the load, respectively, in the meshed network of Figure 14, which corroborates with the previous statement.

Note that, in Figure 4, the optimal solution is to open CB_{12} because it gives the minimum LS (Criterion 1), also this CB is closest to the fault location (Criterion 2), and only opening this CB is enough to isolate the fault (Criterion 3).

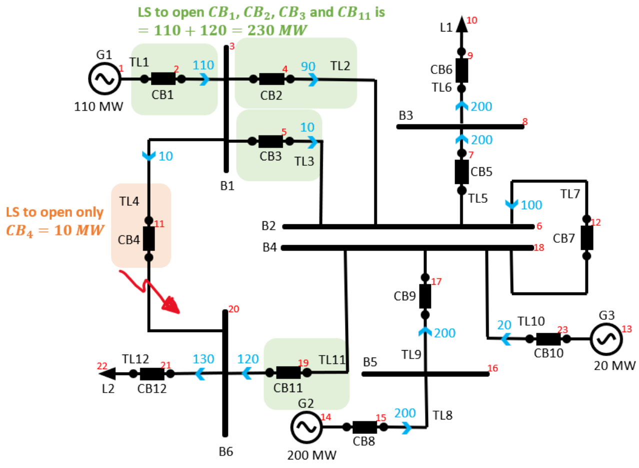

Figure 3 - Fault in TL_4 of the meshed network of Figure 14, and the different solutions to clear it

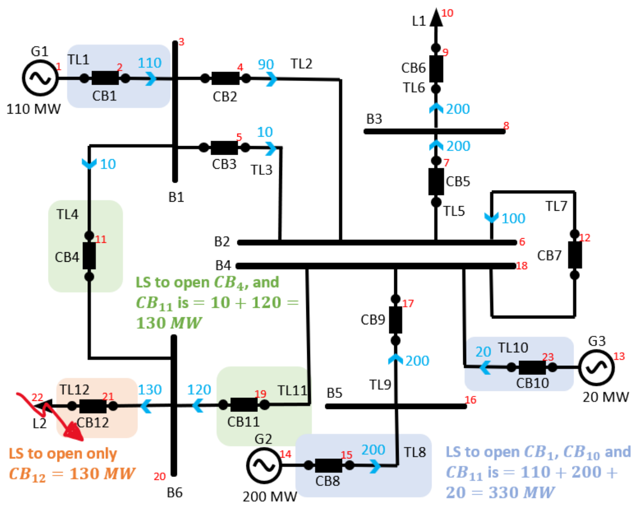

Figure 4 - Fault in L_2 of the meshed network of Figure 14, and the different solutions to clear it

2.3. Fault in the bus

The analysis of a fault in a bus is more complex than in a TL and a load. For this fault event, it is developed four methods (Solution Types) to find all possible ways to isolate the fault from all the sources of the grid, and then, it is selected the optimal solution among the ones found by applying the criteria of optimality.

2.3.1. Solution Type 1

As previously mentioned, after knowing the fault location, the first step is to find all paths between the fault location and the generators. Then, the logic of this method is to take the common TLs in all existing paths. Figure 6 shows this procedure and an example based on the simple meshed network of Figure 2. And Figure 5 shows the application of the solution given by Solution Type 1. Observe that, in Figure 5, the opening of CB_3 is an effective solution to isolate the fault in B_5 regarding the sources of the grid, which are G_1 and G_2.

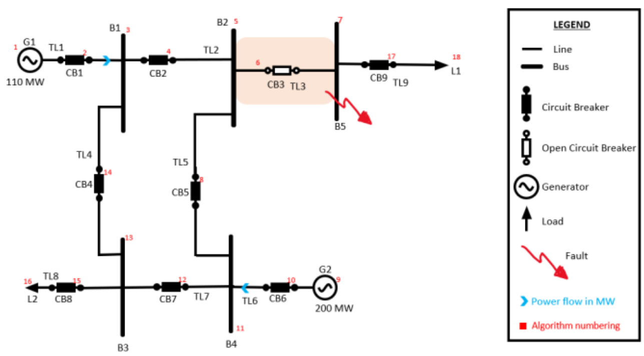

Figure 5 - Application of Solution Type 1 in the network of Figure 2

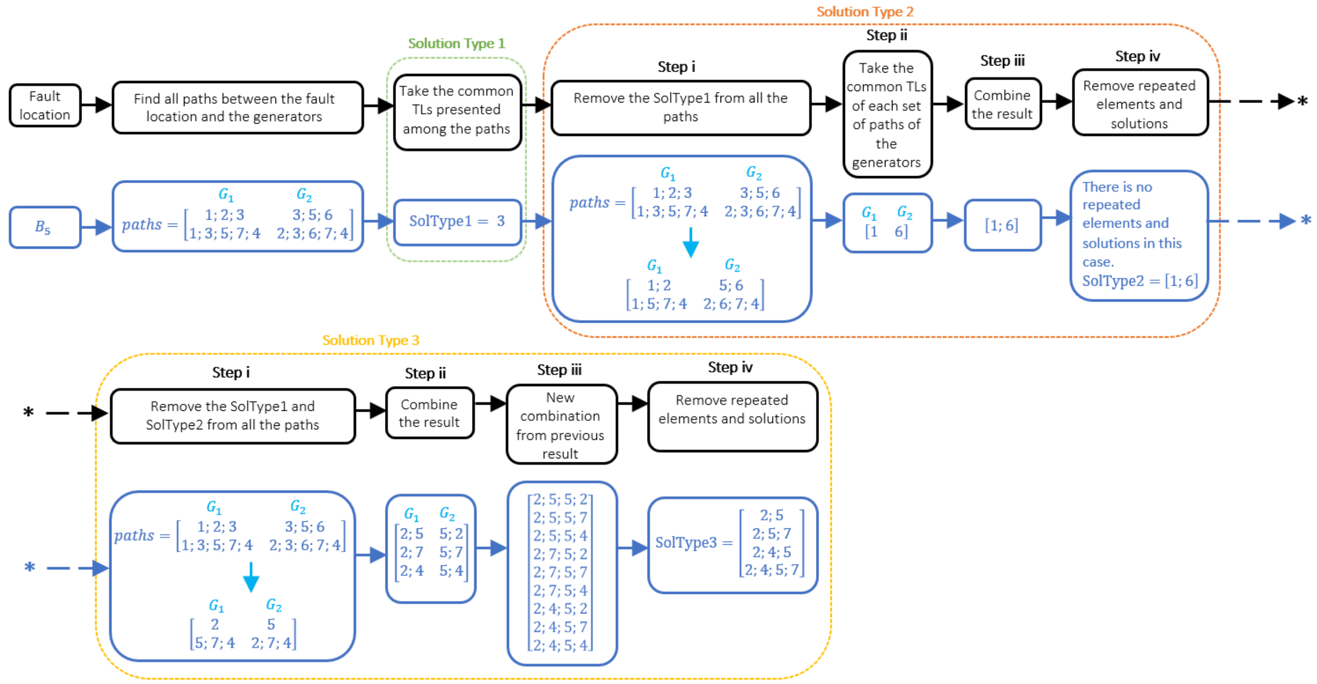

Figure 6 - Solution Types procedures

2.3.2. *Solution Type 2*

The logic of this method is to take the common TLs of each set of paths of each generator. Figure 6 presents this procedure showing the step by step of Solution Type 2.

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

$$c_{total} = m_1 \cdot m_2 \cdot \ldots \cdot m_n \quad (1)$$

Where:

- m_x is the number of TLs that are in common within the set of G_x. For example, regarding the example shown in Figure 6, $m_1 = 1$, because there is only one common TL within the set of G_1, which is 1 (TL_1). And for G_2, $m_2 = 1$, as the common TL is just 6 (TL_6).
- n: number of generators of the power system.

Taking the example shown in Figure 6, the total number of combinations is:

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

Which is one solution given by Solution Type 2: (1;6).

2.3.3. *Solution Type 3*

This method take the remaining TLs, i.e., exclude the TLs of the outcomes of Solution Types 1 and 2, then it is made two mathematical operations (combinations) to find possible solutions to isolate the fault. Figure 6 shows the procedure of this method and an example of a fault in the simple meshed network of Figure 2.

Concerning the "Step ii", the total number combination ($comb_{step\_ii}$) is:

$$comb_{step_{ii}\ for\ G_x} = NumElem_{array1} \cdot NumElem_{array2} \cdot \ldots \cdot NumElem_{array\_k} \quad (2)$$

Where:

- $NumElem_{array\_i}$ is the total number of TLs presented in the array i of generator G_x. Taking the example of Figure 6, assuming $i = 2$ and $x = 2$, then $array\_2\ (= array\_i)$ of generator $G_2\ (= G_x)$ is $(2;7;4)$, therefore, the total number of TLs of this array is equal to 3 (TL_2, TL_7 and TL_4).
- k is the total number of arrays of generator G_x.

Applying Equation (2) to the example shown in Figure 6:

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

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

Clarifying the calculation above, $NumElem_{array2}$ of G_1 is equal to 3, because the TLs are (5;7;4), as it can be seen in Figure 6.

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 ($comb_{total}$):

$$comb_{total} = comb_{step_{ii}\ for\ G_1} \cdot comb_{step_{ii}\ for\ G_2} \cdot \ldots \cdot comb_{step_{ii}\ for\ G_n} \quad (3)$$

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

Applying Equation (3) in the example given in Figure 6:

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

Observe that, in the example of Figure 6, "Step iii" provides nine solutions. However, the repeated ones are deleted in "Step iv". In the end, Solution Type 3 gives four different possible solutions to isolate the fault in B_5 of the network of Figure 2.

2.3.4. Solution Type 4

For all these three previous methods, the source of information is the paths between the fault location and the generators. For the fourth method, the source of information is distinct: the admittance matrix B whose columns correspond to the TLs and the rows refer to the bus of the grid. An example of this matrix is presented in Figure 7.

B =

	TL1	TL2	TL3	TL4	TL5	TL6	TL7	TL8	TL9
B1	1	−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	−1	0
B4	0	0	0	0	−1	1	−1	0	0
B5	0	0	1	0	0	0	0	0	−1

Figure 7 - Admittance matrix B of the simple meshed network of Figure 2

Where "1" means that the power is flowing into the bus, "-1" means that the power is flowing out from it, and "0" means that there is no power flow. For instance, $B_{4,5} = -1$, it is the element located in the fourth row and fifth column. This means that the power, which is flowing through TL_5, is flowing out from B_4.

Figure 7 shows matrix B, highlighting the logic applied in Solution Type 4, which is: assuming a fault in B_4, it is verified in the row 4 of matrix B in which columns there is "1" and "-1" (TL_5, TL_6 and TL_7). Therefore, the proposed solution given by this method is to open CB_5, CB_6 and CB_7.

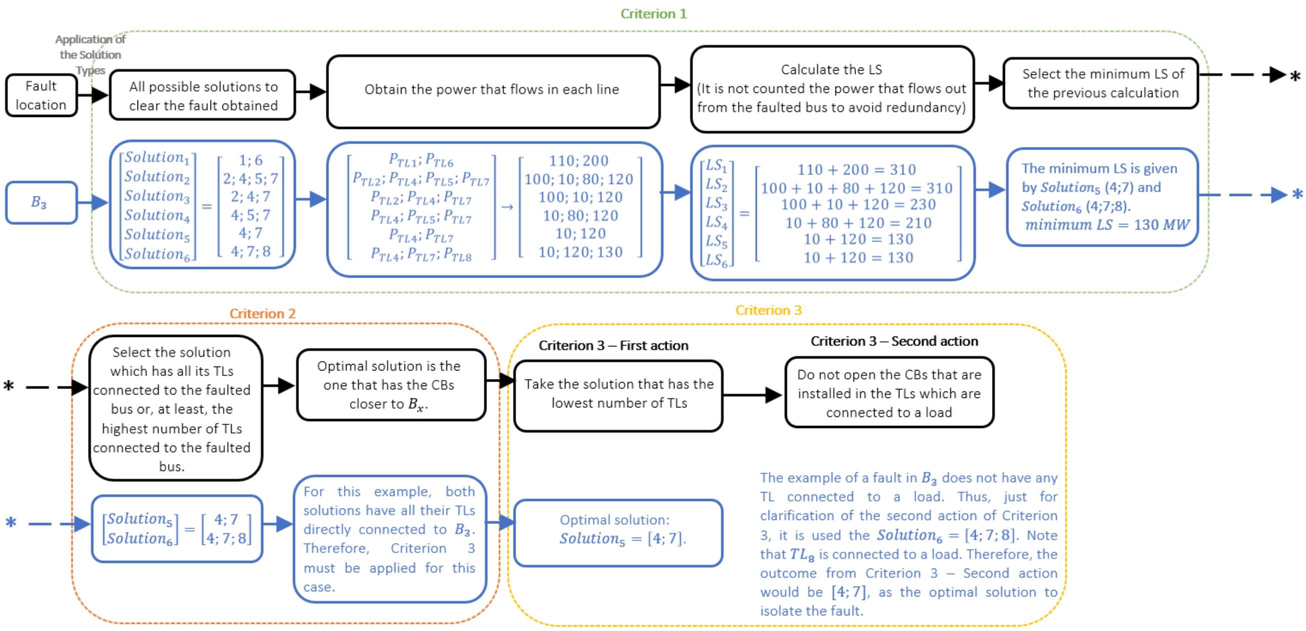

Figure 8 - Procedures of the criteria of optimality

2.3.5. Selection of the optimal CB scheme

All possible solutions to isolate the fault in the bus are found after the execution of the four methods aforementioned. Then, the next step is to select the best option among them based on the criteria of optimality: (1) minimum LS; (2) open the CBs closest to the fault location, which is considered the ones installed in the TLs that are connected to the faulted bus; and (3) trip the minimum number of CBs. Figure 8 shows the logic applied for the conditions of optimality, and an example based on the simple meshed network of Figure 2.

Criterion 2 is applied if the outcome of Criterion 1 is more than one, which means that there are more than one solution that result in the minimum LS. This second criterion uses also the admittance matrix to find the CBs that are installed to the TLs connected to the fault location. This is the reason why Solution Type 4 englobes this condition of optimality.

Finally, Criterion 3 focuses on tripping the minimum number of CBs. It is divided in two actions: (1) if Criterion 2 results in more than one solution, then it is selected the one which has the lower number of CBs; (2) if in the solution has any TL connected to a load, this CB will not be opened, as it is not necessary to trip it, because the fault will be isolated from the sources. For the second action, it is used a similar matrix concerning B, which is B_{mod}:

B_{mod} =	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

Figure 9 - Analysis of B_{mod} for the application of Criterion 3 - Second action

The second part of Criterion 3 realizes the verification if there is any TL connected to a load which corresponds to "−2" in the matrix B_{mod}, while "2" means the connection of the TL to a generator, and the other elements meanings are the same as of matrix B. Therefore, based on Figure 9, assuming a fault in B_3 of the simple meshed network of Figure 2, it is possible to verify that TL_8 is connected to a load, and this can be checked observing also Figure 2, where TL_8 is connected to the load L_2. Thus, it is not necessary to open CB_8.

Finally, after the application of the conditions of optimality, it is selected the optimal solution. Figure 10 shows the application of the best CBs scheme chosen after the execution of the algorithm for a fault in B_3 of the simple meshed network of Figure 2.

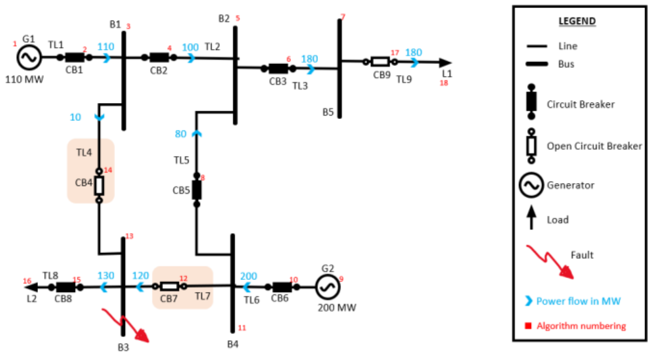

Figure 10 - Application of the optimal solution after the execution of the algorithm for a fault in B_3

Note that, the optimal solution selected is CB_4 and CB_7, which are the CBs closest to the fault location (Criterion 2). The opening of these CBs provides the minimum LS, which is 130 MW (Criterion 1). In addition, observe that CB_8 is not tripped because it is installed in the TL where it is connected to a load (Criterion 3).

The following three flowcharts show the methodology of the created algorithm:

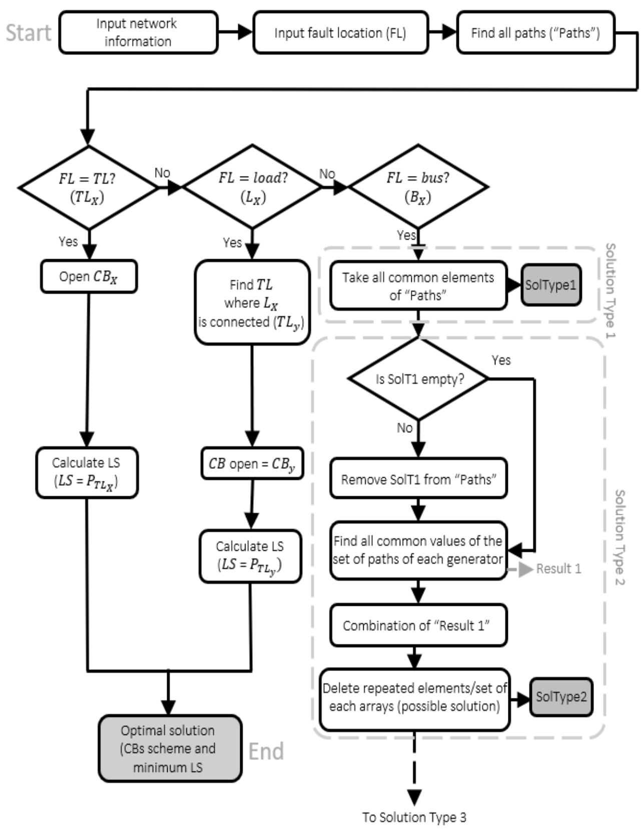

Figure 11 - Flowchart - Part 1

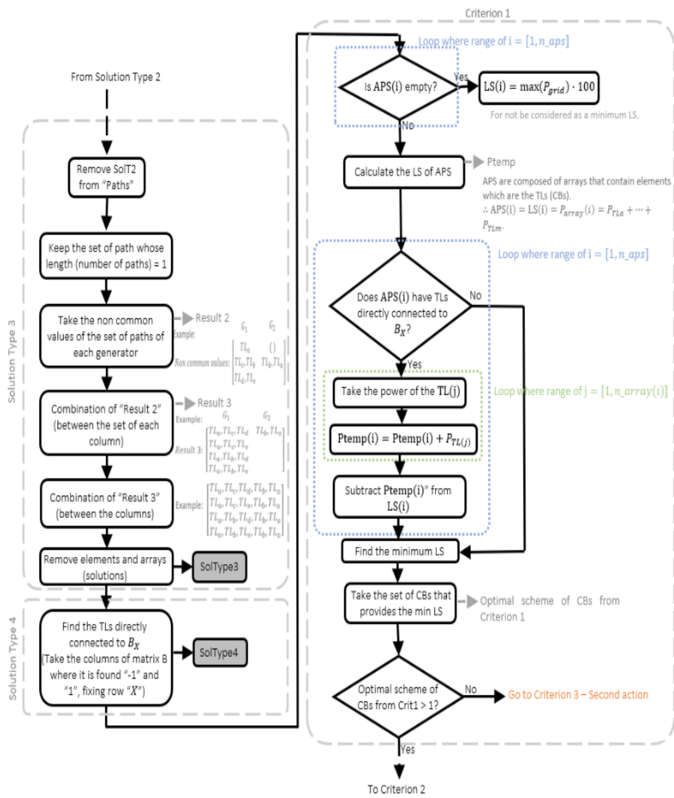

Figure 12 - Flowchart - Part 2

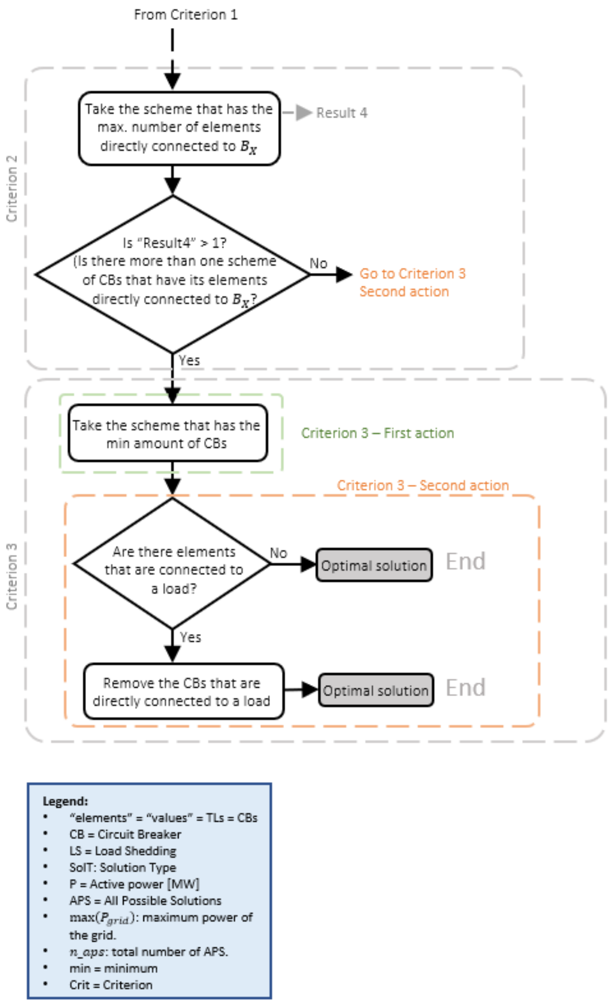

Figure 13 - Flowchart - Part 3

3. Results

In Section 2, it was shown the simple meshed network (Figure 2) that was used as an example for the explanation of the methodology. The next three power systems presented were studied, with the application of the built algorithm, analyzing the fault in each TLs, loads and busbars presented in these grids.

It is important to mention that, the step by step of the algorithm implementation is detailed only for the meshed network in subsection 3.1. For the other three grids, it is made brief comments because the approach is the same, except for the real network, where it was found an important detail that will be further explained.

3.1. Meshed network

Figure 14 shows the meshed network analyzed.

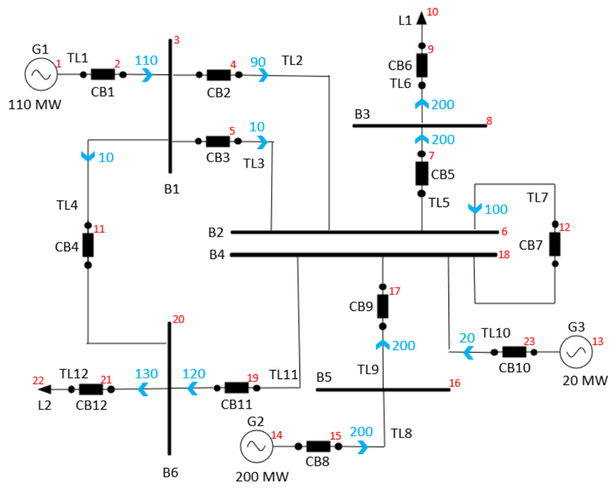

Figure 14 - Meshed network

First, it is necessary to insert the fault location. Then it is found all paths between the generators and the fault location are found ("Paths").

3.1.1. Fault in the TL

According to the approach described in Section 2 of a fault in the TL, Table 1 presents the solution for the fault in each TL of the power system and the minimum LS achieved.

Table 1 - 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

3.1.2. Fault in the load

Similarly to a fault in the TL, the approach developed in Section 2 is applied for the fault in both loads of the power system and the result is shown in Table 2.

Table 2 - Optimal solution in case of a fault in the load

Fault location	TL connected to the load	Optimal CBs scheme	LS [MW]
$\boldsymbol{L_1}$	TL_6	CB_6	200
$\boldsymbol{L_2}$	TL_{12}	CB_{12}	130

3.1.3. *Fault in the bus*

As the fault in the bus is more complex, it is presented an example with details: assuming the fault in B_6, the paths between the fault location and the three sources of the grid are ("Paths"):

Table 3 - Paths between the fault at B_6 and the generators

#	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

Knowing the paths, it is possible to realize the Solution Types, because it is where the solutions are obtained regarding the three first methods:

- Solution Type 1: null, because there is no common TLs among all the paths, as it can be observed in Table 3.
- Solution Type 2: its outcome is composed by the combination of the common TLs of the set of paths of each generator.

$$\mathrm{SolType2} = \begin{bmatrix} 1;8;10 \\ 1;9;10 \end{bmatrix}$$

- Solution Type 3: its outcome is the result of the two steps of combinations of the remaining TLs after the execution of the first two methods.

$$\mathrm{SolType3} = \begin{bmatrix} 2;3;4;7;11 \\ 2;3;4;11 \\ 2;4;7;11 \\ 2;4;11 \\ 3;4;7;11 \\ 3;4;11 \\ 4;7;11 \\ 4;11 \end{bmatrix}$$

- Solution Type 4: this method analyzed the following matrix.

B =

	TL1	TL2	TL3	TL4	TL5	TL6	TL7	TL8	TL9	TL10	TL11	TL12
B1	1	−1	−1	−1	0	0	0	0	0	0	0	0
B2	0	1	1	0	−1	0	1	0	0	0	0	0
B3	0	0	0	0	1	−1	0	0	0	0	0	0
B4	0	0	0	0	0	0	−1	0	1	1	−1	0
B5	0	0	0	0	0	0	0	1	−1	0	0	0
B6	0	0	0	1	0	0	0	0	0	0	1	−1

Figure 15 - Matrix B of the meshed network, fault in B_6

The outcome is: $\mathrm{SolType4} = (4;11;12)$.

Therefore, all possible solutions are:

Table 4 - All possible solutions for a fault in B_6

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	
7		3;4;7;11	240	
8		3;4;11	140	
9		4;7;11	230	
10	■ ■ ■	4;11	130	
11	■ ■	[4;11;12]	310	4

Table 4 also highlights which solution fits each criterion of optimality. Thus, the selected solution is Solution #10 (4;11), trip CB_4 and CB_{11} as the optimal option. Table 5 shows all the optimal solutions for each fault in the bus:

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

Fault location	Optimal CBs scheme	Minimum LS [MW]
B_1	CB_1, CB_2, CB_3, CB_4	110
B_2	CB_2, CB_3, CB_7	200
B_3	CB_5	200
B_4	$CB_7, CB_9, CB_{10}, CB_{11}$	220
B_5	CB_8, CB_9	200
B_6	CB_4, CB_{11}	130

3.2. *Radial network*

The radial network analyzed is:

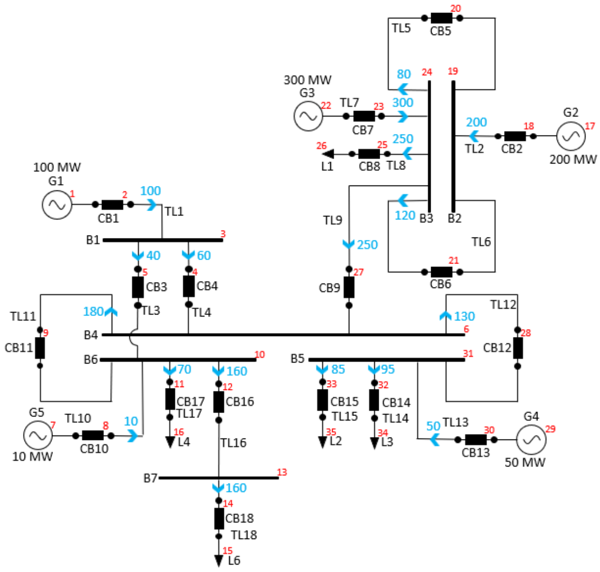

Figure 16 - Radial network

The application of the algorithm in the radial network is the same as it is in the meshed. The result for the fault in the TLs and in the loads is as expected and explained in Section 2. Therefore, for example, if the fault is in TL_{18}, CB_{18} is the one selected to trip and the LS is 160 MW. The same outcome happens for a load in L_6. Table 6 presents the optimal solution for the fault in each bus of this power system:

Table 6 - Optimal solution in case of a fault in the bus

Fault location	Optimal CBs scheme	Minimum LS [MW]
B_1	CB_1, CB_3, CB_4	100
B_2	CB_2, CB_5, CB_6	200
B_3	CB_5, CB_6, CB_7, CB_9	500
B_4	$CB_7, CB_9, CB_{10}, CB_{11}$	310
B_5	CB_{12}, CB_{13}	180
B_6	CB_3, CB_{10}, CB_{11}	230
B_7	CB_{16}	160

3.3. Comparison with Zhang et al. example

The network presented by Zhang et al is:

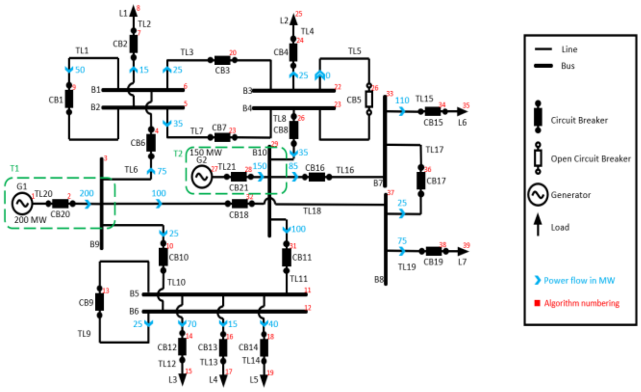

Figure 17 - Zhang et al network adapted

The transformers T_1 and T_2 of Zhang et al. example were replaced by the set of generators, CBs, TLs and busbars highlighted by the green dashed line in Figure 17.

Zhang et al. analyze two fault locations: (1) in the bus B_2, and (2) in the transformer T_2, for this case, it is considered the fault in B_{10}.

- Case 1: fault in B_2

The solution proposed by Zhang et al. using the Floyd-Warshall algorithm is to open CB_1, CB_2 and CB_7 [3]. The created algorithm for this thesis gives 48 possible solutions to clear this fault. The optimal one selected based on the conditions of optimality is to trip CB_1 and CB_7. The solution (1;2;7) is also included in the 48 solutions given by the algorithm, however, due the criteria of optimality, the best one is (1;7), because CB_2 is installed in the TL where it is connected to a load, as it can be seen in Figure 17. The minimum LS achieved is 50 MW.

- Case 2: fault in B_{10}

The optimal solution given by the created algorithm is to open CB_8, CB_{11}, CB_{16} and CB_{21}, which is the same proposed by Zhang et al. The minimum LS is 185 MW.

3.4. Real network analysis

Figure 18 shows a real network in a graph representation. By analyzing this network, it is verified that it is not possible to realize the Solution Type 3 in big power systems because of the number of mathematical operations. For instance, for a fault in $B_{slack345}$, the number of paths between the fault location and each generators is around 2035. The total number of combinations in "Step ii" in Solution Type 3 would be around 10^{2035}, just for one generator, note that, the grid has ten sources in total. Therefore, it is not feasible to realize this method.

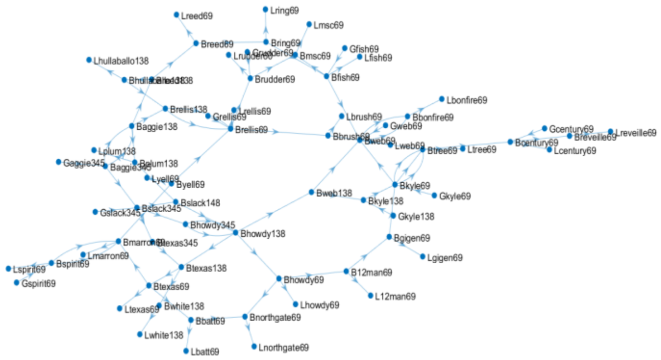

Figure 18 - PoliTSO Power and Light [9], from MATLAB®

Thus, it is proposed two actions to find the optimal solution: (1) implement only Solution Types 1, 2 and 4 to find the optimal CBs scheme among the ones obtained by these three methods; or (2) split the network into smaller ones to apply the four Solution Types, and finally find the optimal CBs scheme to isolate the fault.

Regarding the faults in the TLs and in the loads, the algorithm is well executed.

4. Conclusion

This thesis aims to contribute to the current discussions on new strategies for the operation of the CBs for fault isolation focusing on minimum load shedding. After the analysis of the presented networks, it is possible to remark on the following conclusions:

Criterion 1, minimum load shedding, is the basis condition of optimality defined in this work. It is noticed that in 100% of the fault events this criterion is met. And, by opening the CBs that are installed in the TLs connected to the fault location provides the minimum power loss, which fits the Criterion 2 as well. There are cases that is obtained more than one CHs scheme that gives the minimum LS, once they trip. The graph presented in Figure 19 presents an example about this argument.

It is possible to observe in this graph that, in all fault events, the optimal solutions always fit Criterion 1. Also for the second condition, therefore, there is at least one optimal solution in each case which fit Criterion 2 as well. However, not in all fault occurrences, the optimal solution fits the third condition of optimality, as it can be observed for faults in B_1 and B_4. This means that the optimal solution does not present the minimum number of CBs among the possible solutions obtained for these cases.

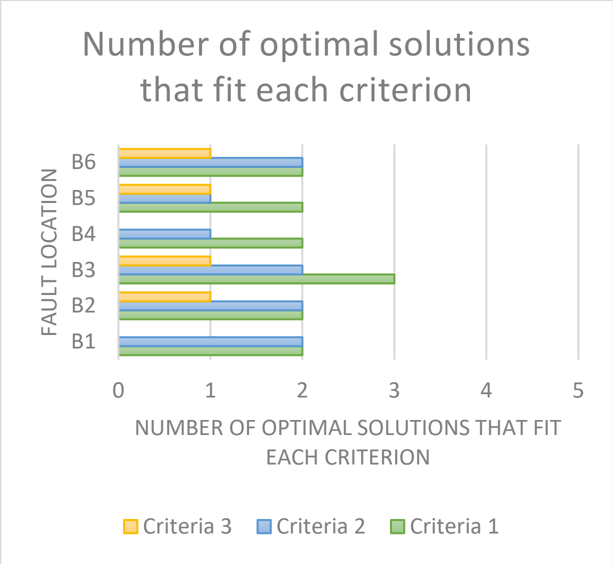

Figure 19 - Number of optimal solutions that fit each criterion for fault in the busbars of the meshed network of Figure 14

Regarding the benchmark with Zhang et al. example, interestingly, the Floyd-Warshall algorithm gives only one solution to clear the fault, which is the shortest path between the fault and the electrical components, while the proposed algorithm considers all the existing connections between the fault location and the sources to find all possible solutions to clear the fault. This results in a more robust approach since it considers all possible CBs schemes for fault isolation, and selects the optimal one based on the conditions of optimality defined.

Finally, it is not feasible to realize Solution Type 3 in power systems of big magnitude. Thus, it is proposed two ways to implement the created algorithm: (1) apply only Solution Types 1, 2 and 4 to obtain some solutions and apply the three criteria to select the best option among them; or (2) split the network into smaller ones in such a way that it makes possible to implement also Solution Type 3.

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