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Research Article

A Contribution to the Conception of Madagascar's Interprovincial Network Topology Using Graph Theory and Power Flow

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Abstract

The purpose of this paper is to propose Madagascar Interprovincial Network using Graph Theory with Power Flow. This is accomplished by simulating the electrical network's topology using algorithms programmed with the Python language. The initial phase of the proposed algorithms consists in establishing connections between 17 source nodes and 94 load nodes, using the shortest path and maximizing the number of load nodes. The next phase consists in removing triangular links deemed superfluous. The third phase involves giving priority to load nodes located close to an electrical source node. The final phase involves removing any remaining superfluous links and applying the (n-k) rule. After the calculations, eight topologies of the Madagascar Interprovincial Network were established. Topology number 8 is the optimal one, comprising 126 links with optimal total distances of 7324 km. Based on this last topology, we carried out simulations of the transit and flow of energy in the static regime across the different busbars of the major mining projects and the different provinces of Madagascar by the PowerFactory software using the Newton-Raphson method. In the transmission line, we used the THTB 220 kV voltage. The simulation revealed, firstly, the location of reactive energy compensation devices, secondly, the removal and installation of new links, and thirdly, the placing on hold of 120 MW of electrical power out of the 300 MW of the slack bus Sahofika hydroelectric plant. For 2030 - 2040, with hydroelectric power plants generating a total of 1,454 MW and loads with a total capacity of 1,344.5 MW, the simulation results showed voltage drop levels with a ΔU value of ± 5% in all busbars and losses of 4.5% in relation to total production. In perspective, further studies in dynamic regime, interactions between emerging technologies and the power system across all voltage levels are to be carried out on the development of the Madagascar Interprovincial Network.

Keywords

Electrical Network Topology, Graph Theory, Power Flow, Voltage Drop, PowerFactory

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1. Introduction

In the fight against poverty, access to energy services is essential to improve the living conditions of the African population. According to Sustainable Development Goal 7 (SDG 7), by 2030, all people should have access to reliable, sustainable and modern energy services at an affordable cost [1, 2].

The energy situation in Madagascar is difficult. As for 2022, the rate of access to electricity was estimated at 36%, with 72% in urban areas and 11% in rural areas [3]. In 2019, per capita electricity consumption in Madagascar was 74.1 kWh, this is the lowest electricity consumption in the world [3]. The national electricity and water company of Madagascar JIRAMA (Jiro sy Rano Malagasy), responsible for the generation, transportation, and distribution of electricity. The company's energy portfolio is predominantly reliant on imported fossil fuels. In 2024, the total cross energy produced by JIRAMA's power plants was 1 984 011 MWh, with 45.80% of this energy attributed to thermal power plants, 47.90% to hydraulic power plants, 4% to solar power plants, and 2.30% to hybrid solar/Diesel power plants [4]. Madagascar has recently implemented a New Electricity Policy (NPE 2015-2030) with the objective of providing electricity to 70% of households and achieving an energy mix consisting of 80% renewable energies by the year 2030 [5]. We know that access to energy is the driving force behind economic and social development in many countries. According to V. I. Lenin, the Soviets created the foundations for a better world by electrifying all their country [6]. The island Madagascar has the third-largest technically feasible hydroelectric potential on the African continent, with an estimated output of energy 180,000 GWh. However, it is noteworthy that only 0.49% of this potential has been exploited [7], in addition to deposits of coal, bituminous sandstones, and heavy oil. Additionally, Madagascar boasts significant mineral wealth, with substantial deposits of nickel, cobalt, gold, titanium, iron, graphite and ilmenite, which are essential for the operation of electric vehicles and the reliable storage of renewable energy [8]. According to the United Nations (UN), the global demand for minerals necessary for the energy transition is expected to triple by the year 2030 [9]. In order to address the pervasive issue of poverty in Madagascar, it is imperative to leverage the country's abundant natural resources while concurrently enhancing the densification of interconnected and isolated electric power networks through the implementation of short extensions. Achieving universal access to electricity by 2030 will require 1.6 million densification connections [10]. This is the primary challenge confronting the development of Madagascar's Interprovincial Network (MIN), which necessitates an integrated and collaborative approach involving the Government, financial institutions, research centers, emerging technologies, private companies, and international organizations [11, 12]. The MIN has set forth the following objectives:

1) The supply of electricity from local resources to Madagascar's cities and major mining projects.
2) The reduction of the energy gap between Madagascar's six provinces.
3) The establishment of regional infrastructures for power generation, transmission, and distribution.
4) Finally, the promotion of Madagascar's green vision is imperative.

The objectives of this work of MIN topology are as follows:

1) design a topology for the MIN with shorter distances and a maximum number of connected cities, using the distance matrix of graph theory.
2) design algorithms to remove superfluous links and apply the (n-k) rule in this MIN's topology.
3) evaluate the transit capacity and power flow of this MIN's topology using Power Factory 15.1 software from JIRAMA.

2. Methodology for the Conception of MIN

2.1. State of the Art

The Madagascar Interprovincial Network MIN is simulated and analyzed according to two methods: Graph theory (GT) and Power Flow (PF). Murphy modeled electrical transmission and distribution networks as graphs, with nodes representing both energy sources and loads, and edges representing transmission lines. He developed the various methods of calculating the PF [13]. Bazohuo Xie and al. used basic concepts and basic theorems of graph theory in the analysis and design of electrical network [14]. Chaghi A developed the topology calculations of electrical energy distribution by Gt and PF [15]. The method of Gladkikh E involves the analysis of different networks sciences efficiency enhancement through structural modifications aimed at minimizing energy losses while maximizing reliability [16]. Bertrand J. worked on the application of GT to different electrical networks across all voltage levels [17]. Yassini and al. proposed the formulation of a maximal tree of graphs in order to optimize an objective function while respecting edge capacity constraints [18]. Xavier Giraud explained in his research where is proposed a new algorithm by combining depth-first search algorithm and Dijsktra algorithm [19]. Within the framework of MIN, OMAZAKI Group is one of technical and engineering design consultants, their competency and skills are in power system study and design [20].

In other scientific literature, Poirson, A. and Lehman, X. used the fractal method to characterize the topology, distance, density and dispersions in the area served by the electrical network, geospatial electrification [21, 22].

The problem of electrical power transport and distribution is approached under different formulations across all voltage levels. However, these formulations have been developed in the specific context of situations required by national and international electricity companies, whether for the planning or operation of their power grids.

2.2. Study Case

A graph G is defined as a pair (X,E) where X={x1, x2,..., xn } represents a finite non-empty set of elements called a Node or a Vertex of G and E={e1, e2,..., em} is a family of (unordered) pairs of elements of X, called Edges of G [13]. In modeling our power system, the standard approach is to consider source nodes s_i and load nodes c_j.

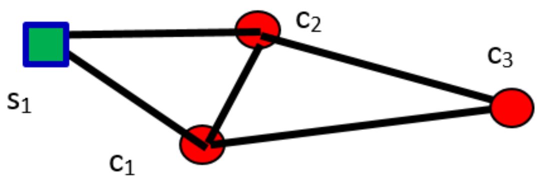


Figure 1. One source node and three load nodes.

In this figure 1, the graph is the set of nodes X = {s1, c1, c2, c3} and the set of edges E = {(s1, c1), (c1, c3), (s1, c2), (c2, c1), (c2, c3)}. The object of this study lies in the problem of long-term planning of MIN and more particularly in the search for a better topology taking into account he shortest links using the graph theory G = (X, E).

Figure 2. Green: source node s_i of hydroelectric power stations, Red: charge node c_i of cities or industries.

In the course of this work, an analysis was conducted of the characteristics of the transmission network. The analysis focused on large sources, including hydroelectric power stations, as well as cities and electrical loads (major mining projects). The analysis took into account the shortest lines.

Consider a planar graph G = (X,E) with the set of vertex (sources and loads) X = {Antananarivo, Ambatolampy, Antanifotsy, Sahofika, Mahanoro, Antsirabe, Betafo, Antetezambato, Ambositra, Ambohimahasoa, Ranomafana, Fianarantsoa } and the set of connecting edges, figure 2, E = {(Antananarivo, Ambatolampy), (Ambatolampy, Antanifotsy), (Antanifotsy, Antsirabe), (Sahofika, Antanifotsy), (Sahofika, Mahanoro), (Antsirabe, Betafo), (Betafo, Antetezambato), (Antetezambato, Ambositra), (Ambositra, Ambohimahasoa), (Ambohimahasoa, Ranomafana), (Ambohimahasoa, Fianarantsoa)}.

2.2.1. Data Presentation of Source and Load Nodes

For topology modeling, the source nodes if made by 17 hydroelectric power plants [5] presented in Table 1, and the load nodes are represented by cities with electrical power greater than or equal to 1 MW [4], and as well as the major mining projects listed in Table 2.

Table 1. Source nodes: 17 hydroelectric power stations.

Sources: s_i	Power: ps_i
Ampandriambazaha	90 MW
Mahavola	300 MW
Ambodiroka	42 MW
Antafofo	160 MW
Volobe 1	6 MW
Volobe 2	120 MW
Andekaleka	112 MW
Mandraka	24 MW
Antelomita	8 MW
Tsiazompaniry	5 MW
Mahitsy	20 MW
Maroantsetra Voloina	2, 5 MW
Sahofika	300MW
Antetezambato	120 MW
Sahanivotry	15 MW
Namorona	5 MW
Betoafo	300 MW

Table 2. *Electric power demand for some large mining projects [8, 23].*

Location	Minig project	Recoverable quantity	Power estimated
Bemolanga	Bituminous sandstone	3 000 000 000 T	100 MW
Tsimiroro	Heavy oil	538 000 000 T	80 MW
Sakoa	Coal	84 000 000 T	100 MW
Sakaraha	Natural gaz	20 000 000 000 m^3 per well	20 MW
Base Toliara	Ilmenite	800 000 T	20 MW
Ambatovy	Nickel Cobalt	125 000 000 T	30 MW
Manantenina	Bauxite	165 000 000 T	30 MW
Molo, Maniry	Graphite	17 000 T/an	50 MW
Soalala	Iron	800 000 000 T	20 MW

The electrical capacities of hydroelectric power stations are estimated under high scenarios [24]. While the capacities and energy required for mining are obtained from our estimation] [5, 10].

2.2.2. Conception of the Topology of the MIN

The objective of this work consists to design a topology for MIN, based on the charge and source nodes shown in figure 2. The first step in our algorithm is to minimize the total length of power lines connecting a electric charge node c_j to a power source node s_i, while traversing as many electric charge nodes as possible.

As part of article, we have studied various GT algorithms [19]. To model electrical distribution networks, we adopted the following method: let si and cj denote a source node and a charge node respectively. i = 0 to S-1 with S the total number of sources. j = 0 to C-1 with C the total number of charges. psi and pcj denote the power available at node si and the power demanded at node cj, respectively. Let's consider nk any node (regardless of whether it's source or charge) with k = 0 to (N-1) with N = S+C the total number of nodes in the network. The power at node nk is pnk. D is the distance matrix such that:

$$D = [D_{n_p,n_q}] \qquad (1)$$

with, $q = 0 \ldots (C-1)(N-S) \ldots \quad (N-1)$

D is a square matrix of order N and is symmetrical.

D_{n_p,n_q}: distance between nodes n_p and n_q

$$(D_{n_p,n_q} = D_{n_q,n_p}) \qquad (2)$$

n_p *et* n_q are charges nodes for p,q = 0...(C-1)

n_p *et* n_q are source nodes for p,q = (N-S)...(N-1)

L is the link matrix such that:

$$L = \left[L_{n_q,n_p}\right] \qquad (3)$$

avec, $q = 0 \ldots (C-1)(N-S) \ldots \quad (N-1)$,

L is square symmetrical of order N. $L_{n_p,n_q} = 0$ if no link exists between a node n_p and a node n_q

$$(L_{n_p,n_q} = L_{n_q,n_p})$$

$L_{n_p,n_q} = 1$ if a line connects nodes n_p and n_q.

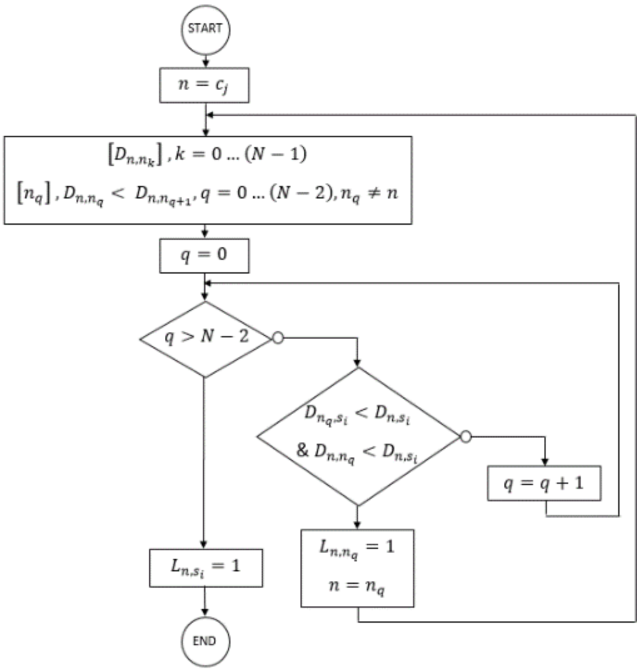


Figure 3. *Flowchart of maximum links between nodes by minimizing line lengths.*

The programming chosen to design the topologies is carried out using the Python language, which is simple, intuitive, powerful and open source.

2.3. Analysis of Power Flow of the MIN

2.3.1. Static Power Flow Modeling

Power system topology is a complex network, using mathematical methods to optimize and analyze energy distribution and transmission networks. The Power Flow (PF) is never stable, as loads are constantly changing. Only for 15 to 30 minutes is it possible to conceive of a static state, and loads can be considered constant [13].

The objective of the PF calculations is to determine the steady-state operating characteristics of the MIN for the charges and sources defined in tables 1, 2, 3, 4. Once we have this information, we can easily calculate real power flows in all branches, as well as voltage drop. In this work, busbars (nodes) are classified as follows [13, 15, 20]:

1) Load bus: P_i, Q_i.
2) Generator bus: P_i, V_i,
3) Slack bus.

A. Load bus i: P_i, Q_i

1) P_i and Q_i are known,
2) Generator power: $P_{ig} = 0$ and $Q_{ig} = 0$,
3) V_i and δ_i are unknown, to be determined,
4) Power output (scheduled): P_{id} and Q_{id} are known.

$$P_{ih} = P_{ig} - P_{id} = - P_{id} \tag{4}$$

$$Q_{ih} = Q_{ig} - Q_{id} = -Q_{id} \tag{5}$$

B. *Generator bus i*: P_i, V_i

1) P_i and V_i are known,
2) Q_i and δ_i are unknown, to be calculated

C. Slack bus i:

1) Vi and δi are known (as references),
2) Pi and Qi are unknown, to be calculated,
3) In general, the most important generator bus is selected as the slack bus and numbered bus 1.

Losses = Total generations - Total charges

$$P_L = \sum_{i=1}^{n} P_{gi} - \sum_{i=1}^{n} P_{di} = \sum_{i=1}^{n} P_i \tag{6}$$

2.3.2. Equation of Active and Reactive Power of Busbar *i*

To formulate the PF problem [13], we consider four variables at each busbar "i" of the power supply system. These variables are

1) Net active power injected: P_i
2) Net reactive power injected: Q_i
3) Voltage modulus: V_i
4) Voltage angle: δ_i.

The active and reactive powers injected are calculated as follows:

$$P_i = P_{ig} - P_{id} \tag{7}$$

$$Q_i = Q_{ig} - Q_{id} \tag{8}$$

In which P_{ig} and Q_{ig} are active and reactive powers generated on busbar i, while P_{id} and Q_{id} are active and reactive powers demanded on this busbar i.

According to Kirchhoff's laws at each set of bars:

$$I = YV \tag{9}$$

$$I_i = \frac{(P_i - jQ_i)}{|V_i|} e^{j\delta_i} \tag{10}$$

Where I_i Current injected on busbar i,

V: Bus voltage vector,

I: Vector of currents injected to buses,

Y: System admittance matrix,

I, V and Y are complex, $V_i = V_i e^{j\delta i}$ is the i^th^ element of the V vector.

The matrix Y is symmetrical. The diagonal element Y_{ij} (self-admittance of bus i) contains the sum of the admittances of all branches connected to bus i.

The off-diagonal element Y_{ij} (mutual admittance) is equal to the negative sum of admittances between buses i and j.

$Y_{ij} = |Y_{ij}| e^{j\gamma_{ij}} = G_{ij} + jB_{ij}$ is in the i^{th} row and j^{th} column of the Y matrix.

G and B are then called conductance and susceptance respectively.

Using (10) to replace I in (9) gives (11) and (12).

$$P_i = |V_i| \sum_{p=1}^{N} |Y_{ip}||V_p| \cos(\delta_i - \delta_p - \gamma_{ip}) \tag{11}$$

$$Q_i = |V_i| \sum_{p=1}^{N} |Y_{ip}||V_p| \sin(\delta_i - \delta_p - \gamma_{ip}) \tag{12}$$

Where N is the number of buses in the power system.

To solve the load flow equations, we need to know two of the four variables for each bus. The study of load flow is one of the most difficult tasks in the field of electrical systems. It is important to note that the power system is never in a steady state, as the charges are in a constant state of change. In this study, we hypothesize that the loads remain constant for a duration of 15 to 30 minutes. In such instances, the solution techniques employed involve numerical methods for solving the non-linear algebraic equations. The load flow equations are solved by numerical methods [13]:

1) Gauss-Seidel,
2) Newton-Raphson,
3) Decoupled-Rapid load flow,
4) Runge-Kutta,
5) Levenberg-Marquardt.

Each method has its advantages and disadvantages, and the choice depends on system size and accuracy requirements. Numerous software packages are available to help analyze PF, such as PowerFactory, ETAP, SKM, Easy-Power, PSS, Neplan. To analyze the PF in the optimal topology of the MIN, we will exploit the Newton-Raphson method with the PowerFactory 15.1 software provided by the Electricity Planning Department of JIRAMA.

Figure 4. Topology 1 of MIN.

3. Results and Discussions on the Design of MIN

3.1. Results and Discussions by GT

3.1.1. Result of Topology 1

After calculation according to the algorithm in Figure 3, we obtain the first topology 1 of the MIN as follows:

Topology 1 is obtained after minimizing the total length of the lines connecting charge nodes to a source node, while traversing as many charge nodes as possible. After the first simulation, we observe the formation of unnecessary triangular meshes in some places, as they will clog up the high-voltage transmission networks.

3.1.2. Result of Topology 2

To improve topology 1, in figure 4, we need to remove the triangular meshes. We keep the other links composed of more than three nodes to ensure the viability of the network even after a hypothetical hazard on the nominal situation leading to the loss of "k" structures (rule n-k).

Let x be a node such that;

$$\sum_{k=0}^{N-1} L_{x,n_k} \geq 3 \quad (13)$$

$[a_i]$ is a node matrix such that:

$$L_{x,a_i} = 1 \;\; with \;\; i = 0 \ldots \left(\sum_{k=0}^{N-1} L_{x,n_k} - 1\right)$$

A mesh forms a triangle if the summits are made up of n, a_i, a_j with

$L_{a_i,a_j} = 1 \;\; ou \;\; L_{a_j,a_i} = 1$. We calculate the following distances:

$$D_1 = D_{n,a_i} + D_{a_i,a_j} \quad (14)$$

$$D_2 = D_{n,a_j} + D_{a_j,a_i} \quad (15)$$

$$D_3 = D_{n,a_i} + D_{n,a_j} \quad (16)$$

If D_1 is the minimum distance, so $L_{n,a_j} = L_{a_j,n} = 0$.

If D_2 is the minimum distance, so $L_{n,a_i} = L_{a_i,n} = 0$.

If D_3 is the minimum distance, so $L_{a_i,a_j} = L_{a_j,a_i} = 0$.

After launching the simulation, we obtain topology 2.

To have an optimal configuration of the topology 2, it is necessary to exploit the available power of the power plant as much as possible. The power plant, is responsible for allocating electrical power to the charge nodes in close proximity. This process ensuring that the power supply is utilized in an efficient and balanced manner.

In this way we are going to develop another algorithm to configure directly the topology 3.

3.1.3. Result of Topology 3

A source node power plant must supply the load nodes closest to it. Going from the smallest source s_i to the largest, we determine the couples $SC = \{(s_i, c_j)\}$, the list of charge nodes to connect to the node source s_i.

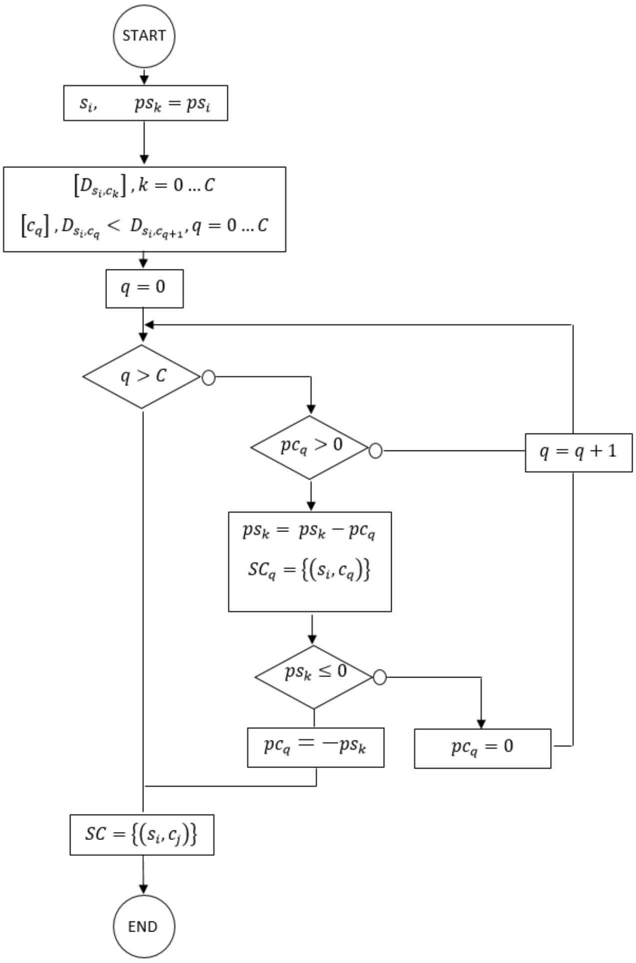


Figure 5. Flowchart of prioritization of charge nodes around of source node.

After the simulation, we have a following new topology 3.

Figure 6. Topology 3 of MIN.

Note that for source 3, hydroelectrical power plant Mahavola 300MW, there remains 37.5 MW undispatched, and that source 4 hydroelectrical power plant Betoafo 300MW has not been exploited, because after the calculations we obtained; $pc_q = 0 \ for \ all \ q = 0 \ to \ C$.

We remove the triangular meshes by applying the same principle of calculation of topology 2 to obtain the new topology 4.

3.1.4. Result of Topology 4

Figure 7. Topology 4 of MIN.

By tapping the remaining non-dispatched Betoafo 300 MW sources, i.e. in cases where p_{sk} remains unchanged from p_{si}. The method is identical to that for topology 3, but the node-charge powers p_{cq} are reset to the values initially given.

3.1.5. Result of Topology 5

Figure 8. *Topology 5 of MIN.*

With the Betoafo power station now in operation, new links are appearing, such as Amboasary-Tsiombe, Amboasary Beraketa and Midongy-Betroka. We also note the reappearance of 4 new superflous meshes which must be removed using the same calculation principle, giving us topology 6.

3.1.6. Result of Topology 6

Figure 9. Topology 6 of MIN.

Topology 6 of MIN is optimal in terms of number of links (120) and total length (6917 km). However, this topology does not provide sufficient redundancy for the provincial capital, Toliara, and other major loads with high peak power, to continue operating normally in the event of failure of upstream links.

For this reason, we initiated the following method: all major loads c_j including $pc_j \geq 20MW$ must be connected to at least two s_i et s_k nearest sources.

With $pc_j \leq ps_i$ and $pc_j \leq ps_k$.

Table 3. Power charge nodes greater than or equal to 20 MW [4, 5].

Location	Power
Antananarivo 1	140 MW
Antananarivo 2	128 MW
Antsirabe	26.8 MW
Moramanga	26.8 MW
Toamasina	67 MW
Antsiranana	40.20 MW
Mahajanga	29.48 MW
Morondava	26.8 MW
Fianarantsoa	40.2 MW
Manakara	20.10 MW
Toliara	26.8 MW
Project Ambatovy Tamatave	134 MW
Project QMM	60 MW
Project SakoaYOXFORD	50 MW
Project Tsimiroro Madagascar Oil	40 MW
Project Bemolanga	50 MW
Project Soalala	30 MW
Project Base Toliara	20 MW
Project Sakaraha	20 MW
Project Bauxite Manantenina	20 MW

Table 4. Hydroelectric source nodes of power greater than or equal to 20 MW [5].

Location	Power
Ampandriambazaha	90 MW
Ambodiroka	42 MW
Antafofo	160 MW
Mahavola	300 MW
Volobe 2	120 MW
Andekaleka	112 MW
Mandraka	24 MW
Mahitsy	20 MW
Antetezambato	120 MW
Sahofika	300 MW
Betoafo	300 MW

3.1.7. Result of Topology 7

Figure 10. Topology 7 of MIN.

After calculation, we obtain topology 7, according to which the provincial capital of Toliara and other nodes with loads above 20MW have reserve links. We note the reappearance of 5 superfluous meshes: mesh (Ranomafana-Ambohimahasoa-Ambositra), mesh (Sahanivotry-Antsirabe-Antanifotsy), mesh (Antanifotsy-Ambatolampy-Tsiazompaniry), mesh (Mananara Nord-Voloina-Mandritsara) and mesh (Ampandriambazaha-Ambilobe- Abanja). We use the same procedure to remove triangular meshes.

3.1.8. Result of Topology 8

Figure 11. Topology 8 of MIN.

After the various simulation steps, we obtain topology 8, figure 11. We note that the Bemolanga and Soalala projects do not have sufficient reserve links for their power supplies. Nevertheless, we can say that topology 8 represents the optimal topology of MIN. It comprises 126 links with a total length of 7324 km. The key results of our topology design study are presented in the following Table 5.

Table 5. *Summary of topologies of MIN.*

Central-number	Charge number	Methodology	Results		
			Link number	Total line length	Network
17	94	Conception of algorithm to create lines connecting load nodes to a source nodes, while crossing as many load nodes as possible with minimum length	173	11 161 km	Topology 1
17	94	Algorithm to remove triangular meshes	138	8 549 km	Topology 2
17	94	Algorithm to supply the load nodes closest to source node as a priority, taking into account the power available and demanded.	128	7 468 km	Topology 3
17	94	Algorithm to remove triangular meshes	120	6 855 km	Topology 4
17	94	Algorithm for exploiting remaining non-dispatched sources	128	7412 km	Topology 5
17	94	Algorithm to remove triangular meshes	120	6 917 km	Topology 6
17	94	Algorithm for application a rule (n-k)	134	7 806 km	Topology 7
17	94	Algorithm to remove superfluous meshes	126	7 324 km	Topology 8

According to the results of this work:

1) all 94 load nodes are supplied with electrical energy,
2) all 17 sources nodes deliver electrical energy,
3) load nodes with a power rating of 20 MW or more have at least two power supply links,
4) Topology 8 of the MIN is the optimal topology, taking into account all the constraints mentioned in the different topologies,
5) In this study, load nodes and source nodes are not prioritized,
6) HT transmission networks and MT distribution networks have not yet been distinguished.

Just like frequency, voltage is an essential parameter for power system operation. Voltage withstand is an essential component of power system reliability.

In the remainder of this work, we will study the transit and PF:

1) determining network voltages so as to achieve a balance between generators and loads,
2) locating overloaded elements of the Madagascar Interprovincial Network.

3.2. Results and Discussions on PF for Topology 8 of the MIN

Following our collaboration, the Electricity Planning Department of the JIRAMA [4], provided us with technical data and PowerFactory 15.1 software to study PF and possible improvements to the MIN 8 topology obtained using GT.

3.2.1. Realization of MIN by Topology 8 Under PowerFactory

The Electrical Transmission System (ETS) is a complex system that takes into account generation, transmission, distribution and consumption. The power the charges are in a constant state of change. In this study, we hypothesize that the loads remain constant for a duration of 15 to 30 minutes. We have modeled the High Voltage Transmission Network, taking into account the Least Cost Development Plan (PDMC) [24], data provided by the JIRAMA Electricity Planning Department [4] and the MIN under 8 topology obtained by GT.

Table 6. *Load states of power transformers in provincials capitals.*

Province	Power Transformer	Load charge
Antsiranana	TR63MVA	66%
Mahajanga	TR45MVA	67.3%

Province	Power Transformer	Load charge
Antananarivo	5 x TR90 MVA	59.2%
Fianarantsoa	TR63MVA	64.7%
Toamasina	2 x TR50MVA	68.8%
Toliara	TR50MVA	52.1%

We note that the provincial capitals have sufficient power until 2030-2040.

After the simulation under PowerFactory, to ensure the supply of electrical energy in all of Madagascar with voltage drops and energy losses within the norm [26], a few changes in topology 8 on figure 11 are necessary:

A. Change of some links in topology 8:

Subsequent to the PF study, a process of link removal and addition was initiated.

Table 7. *Change of links in topology 8.*

Additional links	Line distance	Removal links	Line distance
Antetezambato - Antsirabe	+50 km	Antetezambato - Betafo	-37.4 km
Sahofika - Antsirabe	+125 km	Sahanivotry - Antetezambato	-38.5 km
Betoafo - Fianarantsoa	+235 km	Ambalavao - Fianarantsoa	-45.1 km

The rearrangement of topology 8 of MIN was implemented and the total length becomes 7613 km.

B. Installation of reactive energy compensation devices.

Table 8. *Installation of compensators in MIN.*

Location busbar	Power of Compensators
Ambanja	10 MVAR
Ambatoboeny	30 MVAR
Antananarivo	90 MVAR
Mahabo	55 MVAR
Project Sakaraha	10 MVAR
Project Sakoa	30 MVAR
Toliara	45 MVAR

Reactive power compensation devices require well-defined locations and powers, depending on the PF in the electrical network [25]. The allocation and sizing of compensators in MIN are used to reduce system power loss and improve the voltage drops in the MIN.

A. Management of generator interlocking in the Slack bus 300 MW of Sahofika

Around Sahofika, the loads are insufficient. 120 MW, or two out of five had to be disconnected as they would create overloads on three other generators. Following the last PF simulation, according to figure 12, generators 4 and 5 are disconnected. They can be considered as reserve power, estimated at 120MW.

3.2.2. PF in the MIN Under Static Regime

We will carry out the simulation on PowerFactory according to the grid code, the long-term planning in force in Madagascar. We adopt the THTB voltage 220 kV with the authorized voltage drop $\Delta U = \pm 10\%$ [26].

The simulation results show us the voltage levels in all busbars of the MIN during operation. All voltage drops are within the norm, i.e. $\Delta U = \pm 10\%$. At 1454 MW, the total load is estimated at 1344.5 MW and the total losses are calculated at 66 MW or 4.5% compared to the total production. The result of the simulation of MIN of the big island Madagascar can be found in figure 14. The Newton-Raphson algorithm, in the PowerFactory software, converges in 6 iterations. The detailed of simulation by PowerFactory are shown in figure 15.

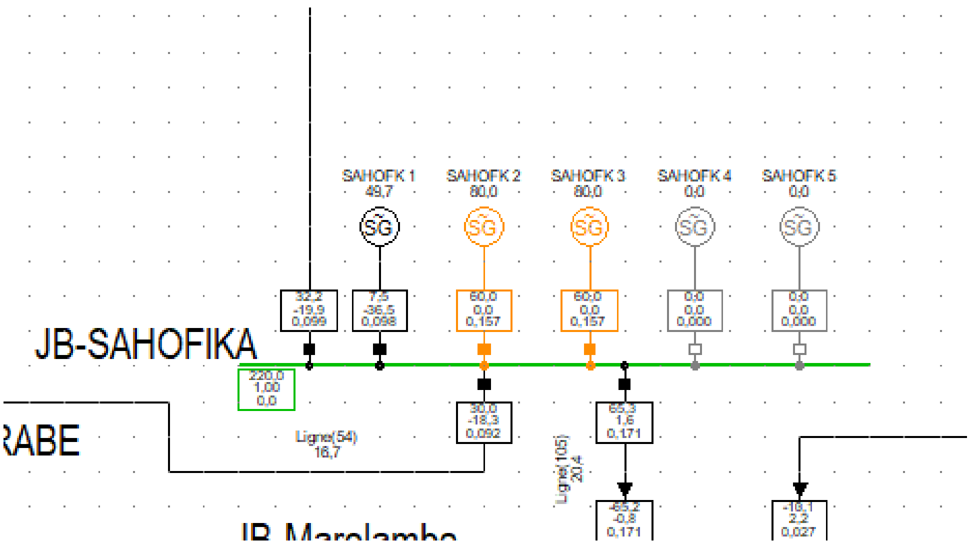


Figure 12. *State of load of the Sahofika reference hydropower plant.*

```
DIgSI/info - Elément ' SAHOFK 1' est référence dans région isolée de ' JB-SAHOFIKA'
DIgSI/wrng -    4 région(s) non alimentées(s).
DIgSI/info - Réseau divisé en 9 régions isolées
DIgSI/info - Calcul du Flux de puissance…
DIgSI/info - ---------------------------------------------------------------------------------------
DIgSI/info - Démarrer algorithme Newton-Raphson…
DIgSI/info - itération du Flux de puissance: 1
DIgSI/info - itération du Flux de puissance: 2
DIgSI/info - itération du Flux de puissance: 3
DIgSI/info - itération du Flux de puissance: 4
DIgSI/info - itération du Flux de puissance: 5
DIgSI/info - itération du Flux de puissance: 6
DIgSI/info - Newton-Raphson converge en 6 itérations.
DIgSI/info - Flux de puissance calculé avec succès.
DIgSI/info - ---------------------------------------------------------------------------------------
DIgSI/info -    Rapport des conditions de contrôle pour les régulateurs relevants
DIgSI/info - ---------------------------------------------------------------------------------------
DIgSI/info - Les conditions de contrôles de tous les régulateurs d'intérêt sont remplies.
```

Figure 13. *Outcomes of a computational process on PowerFactory.*

```
----------------------------------------------------------------------------------------------------------------------------------
|                |                                                           |  DIgSILENT    | Projet:                          |
|                |                                                           | PowerFactory  |----------------------------------|
|                |                                                           |   15.1.7      | Date:  01/07/2025                |
----------------------------------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------------------------------
| Calcul Flux de puissance                            Rapport Complet du système: Postes, Profiles de tension, Grid Interchange |
----------------------------------------------------------------------------------------------------------------------------------
|     Flux de puissance AC, équilibré, régime directe           |   Adaptation automatique du modèle pour convergence      Non   |
|     Réglage auto. des prises des transformateurs      Non     |   Erreur de flux de puissance max. acceptable pour             |
|     Considérer les limites de puissance réactive      Non     |      Noeuds                                         1,00 kVA   |
|                                                               |      Equations du modèle                            0,10 %     |
----------------------------------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------------------------------
| Résumé système complet                                        | Cas d'Étude: Cas d'étude          | Annex:                / 19 |
----------------------------------------------------------------------------------------------------------------------------------
|          Production   Puissance Charge    Compen-  Alimentation                  Flux        Perdes     Perdes    Perdes         |
|                        Moteur             sation    externe                  d'exchanges    Total                à vide         |
|              [MW]/      [MW]/     [MW]/    [MW]/     [MW]/                       [MW]/      [MW]/      [MW]/     [MW]/          |
|             [Mvar]     [Mvar]    [Mvar]   [Mvar]    [Mvar]                      [Mvar]     [Mvar]     [Mvar]    [Mvar]         |
----------------------------------------------------------------------------------------------------------------------------------
| \User\TOPOLOGIE 8 vf\Modèle du réseau\Données du réseau\topologie 8 vf                                                         |
|            1453,96       0,00   1344,45    43,55      0,00                       0,00      65,96      62,86      3,10         |
|             -36,51       0,00     -0,00  -375,38      0,00                       0,00     338,87     319,54     19,33         |
----------------------------------------------------------------------------------------------------------------------------------
| Total:                                                                                                                         |
|            1453,96       0,00   1344,45    43,55      0,00                                  65,96      62,86      3,10         |
|             -36,51       0,00     -0,00  -375,38      0,00                                 338,87     319,54     19,33         |
----------------------------------------------------------------------------------------------------------------------------------
```

Figure 14. *System report summary.*

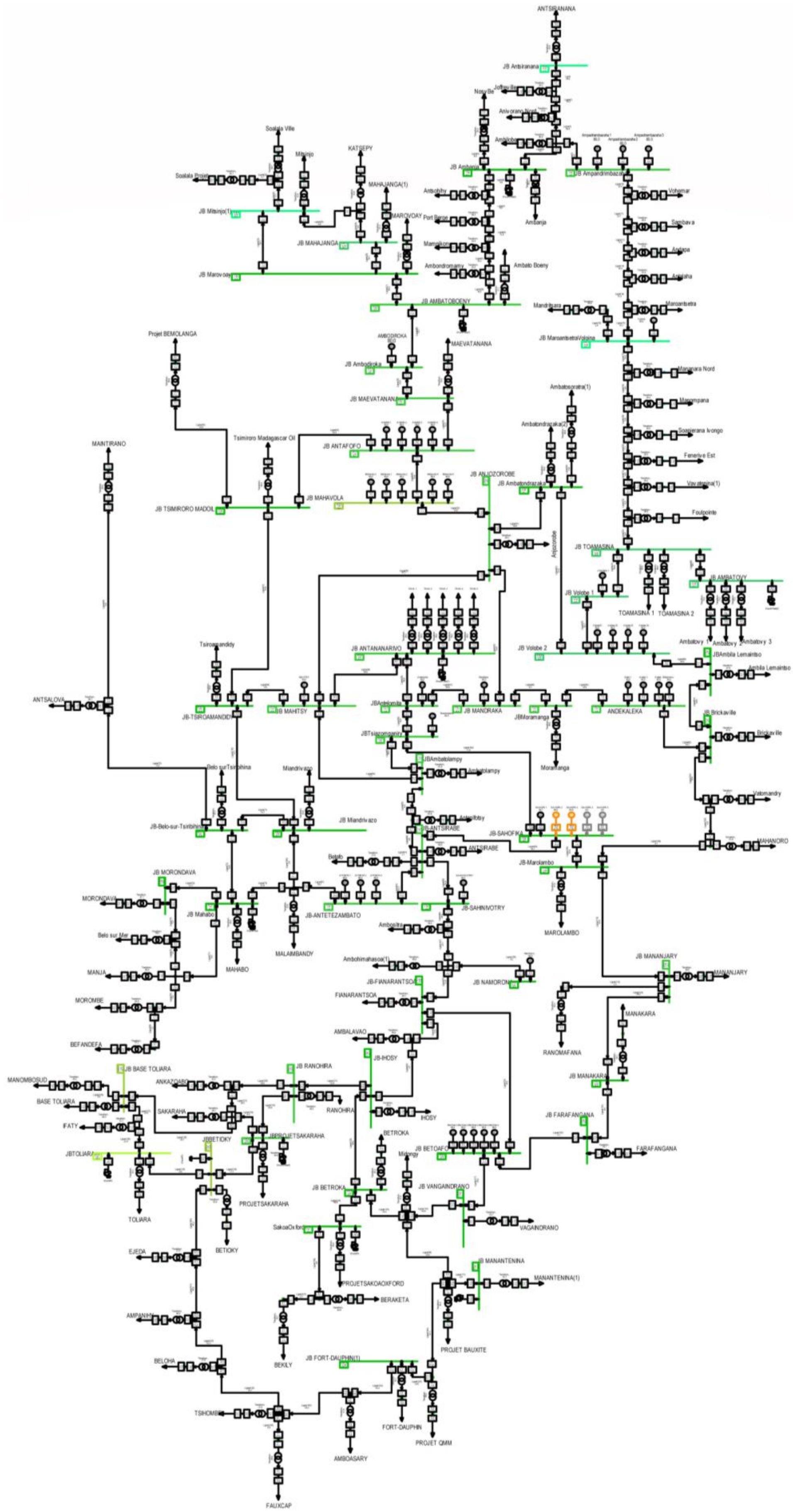


Figure 15. *PF from the 220 kV of MIN.*

```
| DIgSILENT    | Projet:
| PowerFactory |
|   15.1.7     | Date:  01/07/2025

| Calcul Flux de puissance          Rapport Complet du système: Postes, Profiles de tension, Grid Interchange |

|   Flux de puissance AC, équilibré, régime directe        |  Adaptation automatique du modèle pour convergence    Non
|   Réglage auto. des prises des transformateurs    Non    |  Erreur de flux de puissance max. acceptable pour
|   Considérer les limites de puissance réactive    Non    |     Noeuds                                            1,00 kVA
|                                                          |     Equations du modèle                               0,10 %

| Réseau: topologie 8 vf      Phase d'expansion: topologie 8 vfas d'étude: Cas d'étude        | Annex:         / 14 |
```

	Tension nom. [kV]	[p.u.]	Tension-JB [kV]	[deg]
JB Ampandrimbazaha	220,00	1,017	223,76	1,50
JB Ambanja	220,00	1,000	220,06	-0,23
JB Antsiranana	220,00	0,975	214,49	-1,52
JB Volobe 1	220,00	0,982	216,09	-3,01
JB Volobe 2	220,00	0,984	216,49	-1,51
JB Marovoay	220,00	0,997	219,28	0,85
JB AMBATOBOENY	220,00	1,016	223,59	2,07
JB Ambodiroka	220,00	1,015	223,24	4,52
JB ANTAFOFO	220,00	1,015	223,33	6,66
Ambatondrazaka	220,00	0,000	0,00	0,00
JB TOAMASINA	220,00	0,981	215,77	-5,00
ANDEKALEKA	220,00	1,011	222,39	1,83
JBAntelomita	220,00	1,009	221,93	-1,41
JBTsiazompaniry	220,00	1,009	221,98	-1,16
JBAmbila Lemaintso	220,00	1,001	220,26	-0,11
JBAmbatolampy	220,00	1,008	221,66	-1,64
JBMoramanga	220,00	1,009	222,01	0,82
JB-ANTSIRABE	220,00	1,009	222,04	-1,82
JB Mahabo	220,00	1,007	221,45	-8,71
JB Miandrivazo	220,00	1,001	220,29	-5,69
JB-Belo-sur-Tsiribihina	220,00	1,005	221,14	-7,76
JB-TSIROAMANDIDY	220,00	0,998	219,53	-2,91
JB-ANTETEZAMBATO	220,00	1,015	223,32	-1,60
JB-SAHINIVOTRY	220,00	0,997	219,38	-2,84
JB-FIANARANTSOA	220,00	0,992	218,20	-7,89
JB-IHOSY	220,00	0,996	219,05	-25,72
JB-SAHOFIKA	220,00	1,000	220,00	0,00
JB-Marolambo	220,00	0,998	219,55	-0,71
JB MANDRAKA	220,00	1,010	222,10	0,50
JB MAEVATANANA	220,00	1,017	223,70	4,84
JB NAMORONA	220,00	0,993	218,42	-6,52
JB MANANJARY	220,00	0,991	218,09	-5,22
JB BETOAFO	220,00	1,002	220,48	-11,15
JB VANGAINDRANO	220,00	1,002	220,44	-11,29

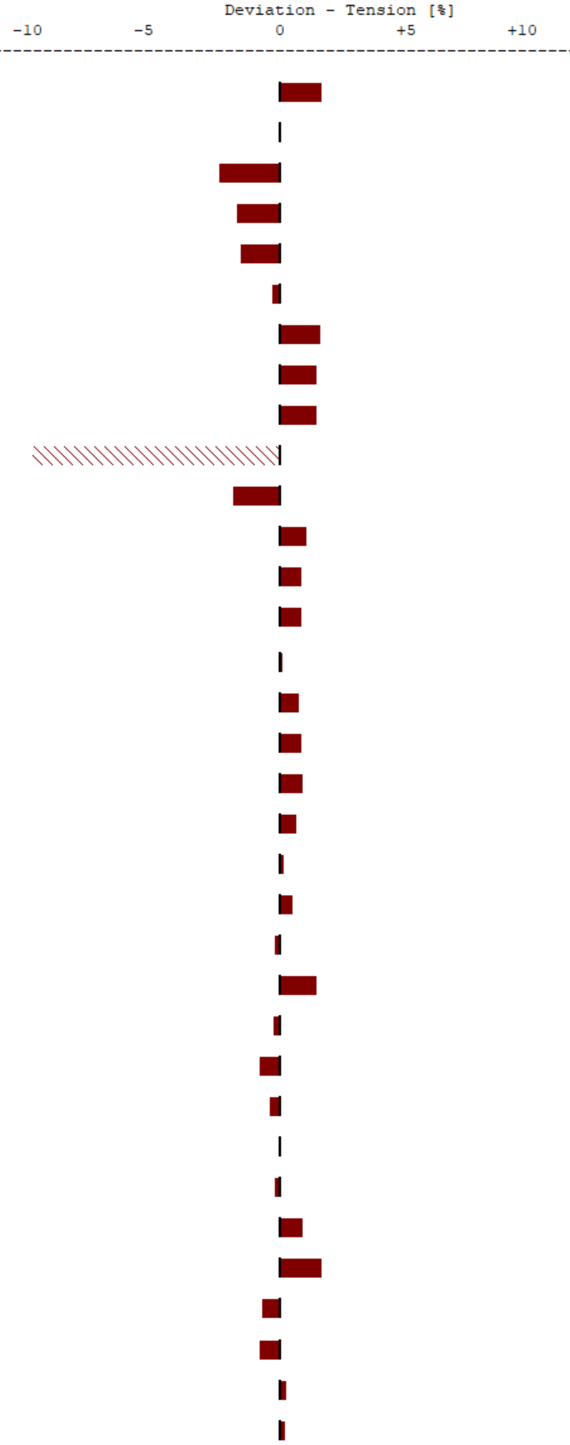
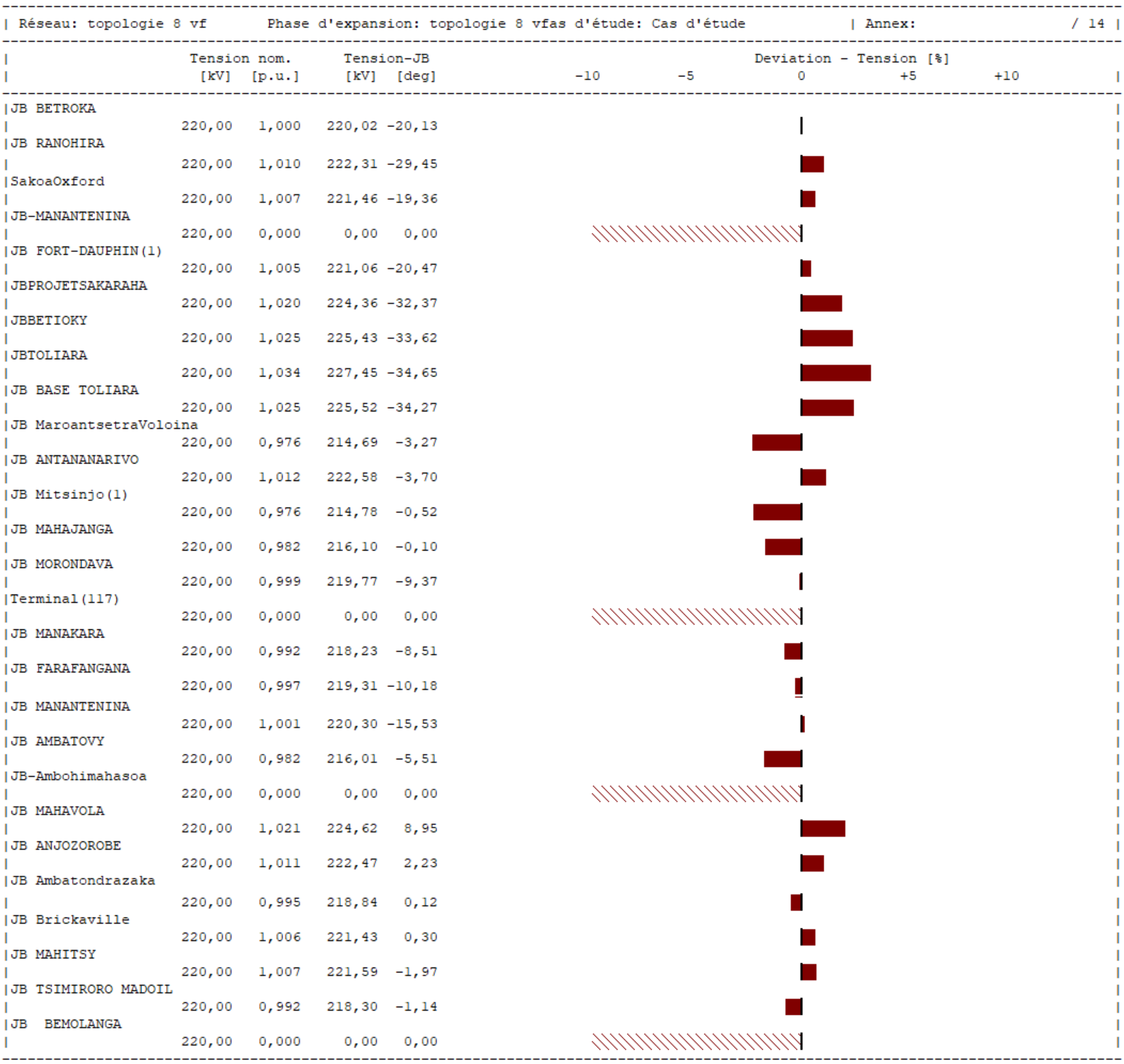


Figure 16. Voltage drops in rectified topology 8 for the MIN (part 1).



Réseau: topologie 8 vf	Phase d'expansion: topologie 8 vfas d'étude: Cas d'étude				Annex: / 14
	Tension nom. [kV]	[p.u.]	Tension-JB [kV]	[deg]	Deviation - Tension [%]
JB BETROKA	220,00	1,000	220,02	-20,13	
JB RANOHIRA	220,00	1,010	222,31	-29,45	
SakoaOxford	220,00	1,007	221,46	-19,36	
JB-MANANTENINA	220,00	0,000	0,00	0,00	
JB FORT-DAUPHIN(1)	220,00	1,005	221,06	-20,47	
JBPROJETSAKARAHA	220,00	1,020	224,36	-32,37	
JBBETIOKY	220,00	1,025	225,43	-33,62	
JBTOLIARA	220,00	1,034	227,45	-34,65	
JB BASE TOLIARA	220,00	1,025	225,52	-34,27	
JB MaroantsetraVoloina	220,00	0,976	214,69	-3,27	
JB ANTANANARIVO	220,00	1,012	222,58	-3,70	
JB Mitsinjo(1)	220,00	0,976	214,78	-0,52	
JB MAHAJANGA	220,00	0,982	216,10	-0,10	
JB MORONDAVA	220,00	0,999	219,77	-9,37	
Terminal(117)	220,00	0,000	0,00	0,00	
JB MANAKARA	220,00	0,992	218,23	-8,51	
JB FARAFANGANA	220,00	0,997	219,31	-10,18	
JB MANANTENINA	220,00	1,001	220,30	-15,53	
JB AMBATOVY	220,00	0,982	216,01	-5,51	
JB-Ambohimahasoa	220,00	0,000	0,00	0,00	
JB MAHAVOLA	220,00	1,021	224,62	8,95	
JB ANJOZOROBE	220,00	1,011	222,47	2,23	
JB Ambatondrazaka	220,00	0,995	218,84	0,12	
JB Brickaville	220,00	1,006	221,43	0,30	
JB MAHITSY	220,00	1,007	221,59	-1,97	
JB TSIMIRORO MADOIL	220,00	0,992	218,30	-1,14	
JB BEMOLANGA	220,00	0,000	0,00	0,00	

Figure 17. *Voltage drops in rectified topology 8 for the MIN (part 2).*

This topology, shown in Figure 18, represents Madagascar's Interprovincial Network obtained by graph theory and power flow throughout the 17 source nodes and 94 load nodes. From this topology, we can see that the Sahofika 300 MW supplies the provinces of Toliara and Fianarantsoa. The Sahofika 300MW and Antetezambato 120 MW plants work for the province of Antananarivo. The Volobe 120MW and Andekaleka 112 MW plants give their power for the province of Toamasina. The Mahavola 300 MW, Antafofo 160 MW and Ambodiroka 42 MW plants will supply the provinces of Mahajanga and Antananarivo. The 90 MW Ampandriambazaha power station works for the province of Antsiranana. The total length of the line is estimated as 7613 km.

Figure 18. *Topology of MIN simulated by GT and PF.*

3.3. Cost Implications of Implementing MIN

The economic evaluation of the MIN depends on several factors: the length of the line, topographical and environmental constraints, the number of transformer stations and logistical conditions. We have established a rough estimate of the cost of the MIN based on the PRIRTEM projects [4, 24] (Project to Reinforce and Interconnect Power Transmission Networks in Madagascar) in the following table.

Table 9. *Cost of the implications of MIN [4, 24].*

Designation	Approximate cost USD/km	Number	Unit	Montant
Cables and Pylognes double-circuit 220 kV	400 000	7613	km	3 045 200 000
Transformer substation < 5MW	1 200 000	30	unit	36 000 000
Transformer substation between 5MW and 10MW	2 000 000	27	unit	54 000 000
Transformer substation between 10MW and 25MW	5 000 000	17	unit	85 000 000
Transformer substation between 25MW and 50MW	10 000 000	12	unit	120 000 000
Transformer substation between 50MW and 90MW	15 000 000	14	unit	210 000 000
Dispositif de compensation entre 10 Mvar et 30 Mvar	1 000 000	4	Unit	4 000 000
Dispositif de compensation entre 30 Mvar et 90 Mvar	5 000 000	3	Unit	15 000 000
Civil engineering and implementation	200 000	7613	km	1 522 600 000
Technical studies	100 000	7613	km	761 300 000
TOTAL in USD				5 853 100 000

The success of this large-scale project of MIN requires close collaboration between the Malagasy Government and Technical and Financial Partners, in exchange for the exploitation of Madagascar's abundant mineral resources.

4. Conclusions

The electrification plays an important role in improving the living conditions of the Malagasy population. We propose to make the most of our natural resources to ensure carbon-free and sustainable energy development. This is the major challenge facing the development of Madagascar Interprovincial Electrical Network (MIN).

Reducing the all distances between loads and electric sources which are dispersed throughout various regions is the primary problem. Graph theory (GT) was used to design the MIN. The graph is made up of 111 vertexes, including 17 source vertexes and 94 load vertexes, which can be found on the map of Madagascar with scale and their res- pective geographic coordinates.

The problem with this work lies in modeling the shorter distances between electrical loads and hydroelectric power sources, as the latter are scattered in various locations. The programming required to design the topologies is carried out using the Python language, which is simple, intuitive, powerful and open source. The objective of this initiative is to establish optimal connections between 94 load nodes and 17 source nodes. The first step in our algorithm is to connect source nodes to load nodes with minimum distances and to connect as many load nodes as possible. The second stage of our algorithm consists of deleting triangular meshes deemed unnecessary, the third stage involves prioritizing load nodes around a source node and the fourth stage involves deleting superfluous meshes and applying the (n-k) rule.

Following a series of calculation stages, eight distinct topologies of MIN were obtained. The final topology, designated as number 8, is identified as the optimal topology. From this last topology, we carried out simulations of Power Flow (PF) in the static regime across the different busbars of the different provinces and the major mining projects of Madagascar by the PowerFactory software using the Newton-Raphson method. In the transmission line, we used the THTB 220 kV voltage.

According to the simulation results and taking into account the Madagascar grid code regarding long-term planning 2030-2040, we find the Madagascar Interprovincial Network in an optimal distance 7613 km. The capacity of hydroelectric plants installed is estimated at 1454 MW, the total load is estimated at 1344,5 MW, and the total losses are calculated at 66 MW, or 4.5% of total production. The estimated cost of constructing the MIN is approximately 5.86 billion dollars.

The stability of the MIN also needs to be studied, both in terms of small disturbances and large disturbances in dynamic regimes. It will also be necessary to examine the applicability of emerging technologies to interconnected power systems. Economic and financial studies will enable MIN to be built at lower cost. The study of environmental impacts occupies an important place.

Abbreviations

JIRAMA	JIro sy RAno Malagasy (National Electricity and Water Company of Madagascar)
NPE	New Energy Policies
SDG	Sustainable Development Goal
MIN	Madagascar's Interprovincial Network

EITI	Extractive Industries Transparency Initiative
GT	Graph Theory
PF	Power Flow
PDMC	Plan de Développement au Moindre Coût (Least Cost Development Plan)
PRIRTEM	Projet de Renforcement et d'Interconnexion des Réseaux de Transport d'Energie électrique à Madagascar.
THTB	Très Haute Tension classe B

Author Contributions

Solofo Hery Rakotoniaina: Conceptualization, Methodology, Supervision, Validation, Writing - review & editing
Olivier Mickael Ranarison: Software, Writing - original draft
Rajo Harivelo Randriamboavonjy: Data curation
Mamy Prudence Rakotondrainitsimba: Resources, Software, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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