CURRENT STATE OF ANTSIRANANA'S ELECTRICITY NETWORK AND PROPOSED SOLUTIONS

M.M. Inès MANAMIHANTA [1], Dominique G.M.B. RAKOTO [2], Liva F. RAFANOTSIMIVA[3], Nirinarison Jean RAZAFINJAKA[4], Virgil DUMBRAVĂ[5]

This article describes the current state of the Antsiranana power grid, incorporating a photovoltaic power plant. Unlike in industrialized countries, where grids are interconnected and can be considered to have infinite capacity, those in developing countries are often standalone and have limited capacity. Based on various grid parameters and the assumptions made, simulations were conducted with and without the photovoltaic power plant. The results indicate that the grid operates satisfactorily under steady-state conditions, although localized voltage drops and relatively high line loads persist on feeder N3. The main contribution of this work lies in the technical evaluation of photovoltaic integration and its impact on the operation of the Antsiranana power grid.

Keywords: Power grid, Photovoltaic solar, Stability, Penetration

1. Introduction: Madagascar's general energy situation and its electricity network

Madagascar is an island in the Indian Ocean, divided administratively into 6 provinces, 24 regions and 120 districts. Antsiranana, located in the north of the country, is one of these 6 provinces. Currently, Madagascar's total population is estimated at 30 million, with a surface area of 587,000 km^2 [1-2].

Electricity supply in Madagascar is ensured by the network of the state company JIRAMA (JIro sy RAno MAlagasy) created in 1975 for urban areas, and by the ADER agency created in 2002 for rural areas. ADER is part of the Ministry of Energy. The average electrification rate is 36%, 15% of which is in rural areas, although many private initiatives have developed in recent years outside the grid [2-3-4-6].

[1] Eng., Ecole Doctorale Thématique Energies Renouvelables et Environnement, University of Antsiranana, Madagascar, e-mail: manamihanta.minosoa@gmail.com
[2] DR., GR3D, Institut Supérieur de Technologie D'Antsiranana, Madagascar, e-mail: rakoto.dominique@gmail.com
[3] Prof., GR3D, Institut Supérieur de Technologie D'Antsiranana, Madagascar, e-mail: liva.rafanotsimiva@gmail.com
[4] Prof., Ecole Doctorale Thématique Energies Renouvelables et Environnement, University of Antsiranana, Madagascar, e-mail: razafinjaka@gmail.com
[5] Prof., University POLITEHNICA Bucharest, Romania, e-mail: v_dumbrava@yahoo.com

Since 2001, electrical energy production and demand have continued to grow. Although the private sector is beginning to get involved, the state company JIRAMA is still the main supplier, with 119 stand-alone thermal power plants: one in each district. The installed capacity is currently around 869.67 MW. Thermal power is still very important, accounting for 75.18%. The rural share is very low, with only 5.13MW installed [4-5].

The Antananarivo-Antsirabe interconnected network (RIA), which encompasses the Atsinanana, Analamanga and Vakinankaratra regions, concentrates a large proportion of Madagascar's electrical energy production. Outside the interconnected grids, thermal power plants generally operate independently and are intended to supply a limited area, essentially their towns of installation and the surrounding area [3-4-5-6]. Fig. 1 shows the distribution of production centers in Madagascar [6].

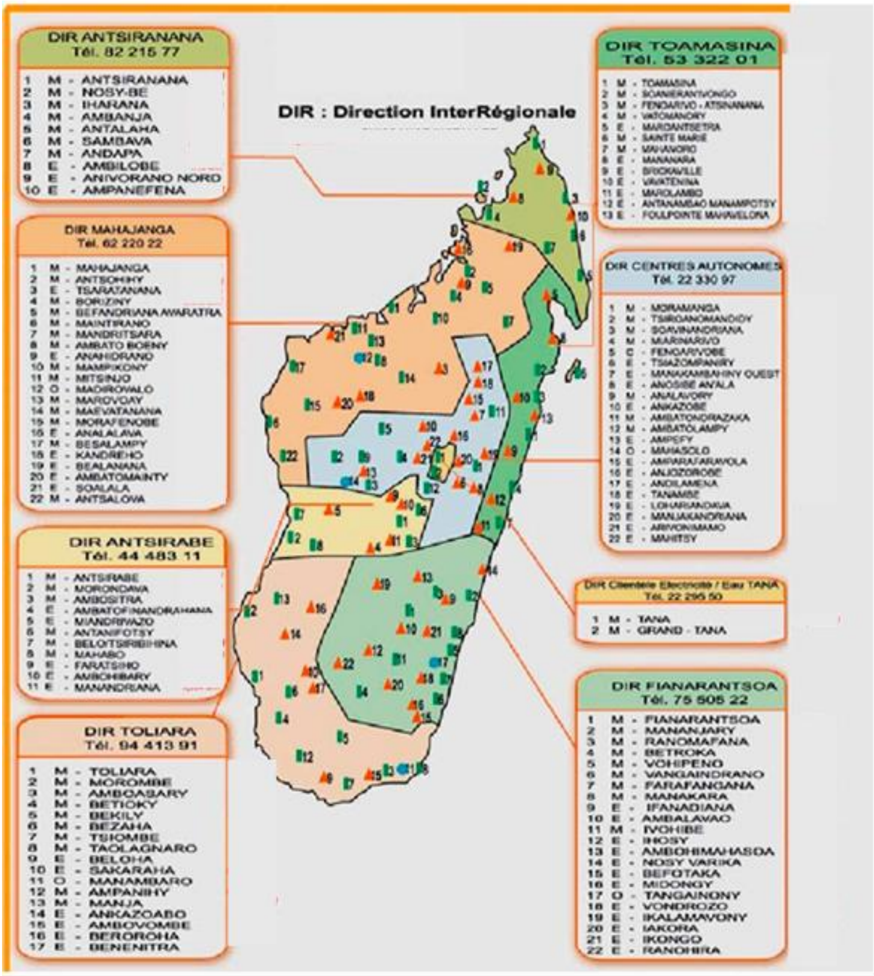

Fig. 1. Power generation centers in Madagascar

At present, 30-35% of the electricity generated is lost before it reaches consumers, due to an ageing network and massive fraud [2].

2. Problems on the Antsiranana distribution network

JIRAMA of Antsiranana, in partnership with ENELEC (ENergie ELECtrique, a private company), operates 2 thermal power plants: Centrale Thermique Amporaha (CTA) and ENELEC. The total installed capacity is 30.66 MVA, for an active power offered to users of 24.53 MW, assuming an average power factor of 0.8 [7-8]. Energy demand, meanwhile, is estimated at 30.42 MVA, according to calculations made on the basis of the network diagram given before 2020.

As Madagascar has no petroleum products, the impact of petroleum product costs weighs heavily on the operation and running of power plants. In 2021, the company also commissioned a 2.4 MW solar power plant, a project carried out by LIDERA Green Power, a subsidiary of the Filatex Group (like ENELEC), with a view to achieving 10MW by 2030. In August 2022, the solar power plant was operational with a maximum output of 1.7 MW between 11:30 and 12:30 [7-9]. It is located 10km from the town of Antsiranana. The two thermal power plants, the solar power plant and the feeder lines are in a closed system.

The integration of the solar power plant means that one or more thermal units can be shut down, resulting in average monthly fuel savings of around 150,000 liters under good operating conditions. Operating equipment costs are also reduced [7].

From a health perspective, the integration of this photovoltaic power plant contributes to improving air quality and, consequently, the health of local populations. Reducing diesel fuel combustion significantly cuts emissions of air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter, which are responsible for many respiratory and cardiovascular diseases. According to ADEME (the French Environment and Energy Management Agency), burning one liter of diesel fuel emits approximately 2.67 kg of CO_2 [12]. Thus, a monthly saving of 150,000 liters of fuel corresponds to approximately 402 tons of CO_2 avoided each month, which also translates into a significant reduction in pollutant emissions that are harmful to human health.

Most installations are ageing. Electrical equipment such as transformers, lines and protection devices no longer complies with recommended standards: transformers are outdated, generators are ageing and wearing out, lines have not been reinforced for years, and subscribers often make unauthorized connections. For example, power transformers account for up to 60% of the investment cost of a power station. Their failure causes interruptions in the supply of electrical power to consumers and significant economic losses [13].

The available power injected into the grid is no longer equal to the installed power, currently around 25.5 MVA, plus the power injected by the PV plant. Yet the demand for electricity is increasing with population growth, and more and more every year. Supply remains lower than demand when all neighborhoods are connected: the network is overloaded.

Power cuts are unavoidable in many neighborhoods, when consumption peaks between 6.30pm and 8pm. The photovoltaic power plant is disconnected from the grid at 4 p.m., as solar production declines rapidly at this time of day in Madagascar, where sunset generally occurs between 4 p.m. and 5 p.m., depending on the season. This early drop in production is exacerbated by the fact that the photovoltaic panels installed are fixed, i.e., they do not have a solar tracking system. As a result, the installation is no longer able to capture solar energy efficiently in the late afternoon and therefore no longer contributes to production during peak evening hours, when electricity demand remains high.

By way of illustration, Table 1 below highlights the frequency of various types of faults recorded during the year 2021, the period corresponding to the grid situation prior to the integration of the photovoltaic system in the city.

Table 1

Frequency of faults detected on the power grid in 2021 (before integration of the photovoltaic system) [7].

Year	**General triggering (Black-out)**				**Departure opening**				
	Line, phase	Overloaded group	Ground fault	Mini frequency unknown	Line, phase	Overloaded group	Ground fault	Mini frequency unknown	Fire
2021	26	10	1	8	53	25	6	4	2

This table shows that MV line/phase faults and generator overloads are the cause of many black-outs and automatic feeder openings.

Other tripping factors, although less frequent, are also observed on the JIRAMA Antsiranana network, such as faults in damaged transformers and insulators, which can lead to short-circuits and black-outs [7].

Before the solar power plant was added, the grid was already very unstable. After the installation and operation of the solar power plant, the grid is still disturbed, despite expectations. In principle, the energy produced by a photovoltaic solar power plant fluctuates according to weather conditions and the time of day. When there's shade on the panels, or as the day progresses, the power injected varies. This can lead to power cuts or even blackouts. ENELEC and CTA power plants are not yet equipped with automatic generator management systems.

Grid behavior remains dependent on the power injected by the solar power plant. A penetration of 1.7 MW in front of the 25 MW grid remains minimal.

So, even if the integration of a PV power plant is a very good idea from the outset, it requires a stable grid to be fully effective. After all, the integration of renewable energies requires rigorous technical preparation, and can not be considered a miracle solution [17].

3. Description of Antsiranana's electricity network

The two thermal power plants are linked by a 20kV transmission line. ENELEC has three feeders: N1, N2 and N3, while CTA has five: Grand Hôtel feeder, Tanambao feeder, PFOI feeder, Hôpital Be feeder and Marne feeder [7]. The network schematic diagram is shown in Fig. 2 (Before injection):

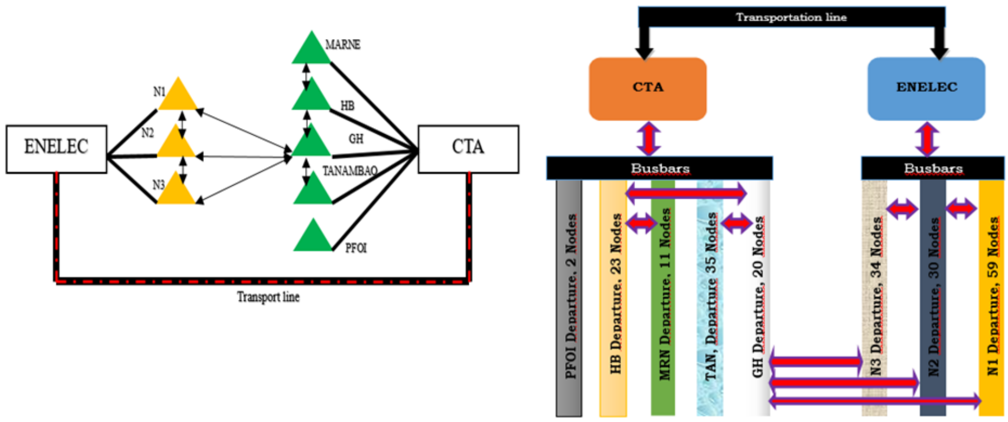

Fig. 2. Schematic Diagram of the Antsiaranana power grid

The Antsiranana grid uses three-phase voltages of 20 kV for transmission and 380V for distribution at a frequency of 50 Hz [7-8].

The busbars at JIRAMA's PK7 substation (ENELEC) support a maximum power of 16 MW [7]. At the output of the power stations, transformers raise the production voltage to 20 kV for economic power transmission. This voltage must be lowered again for distribution networks. The types of cable used are shown in Table 2 [7].

Table 2

Type of cables used

Cable type	**Section [mm²]**			**Resistivity [Ω.mm²/m]**
Copper	34.4	117	148	0.0225
Almelec	29.3	29		0.036

In terms of network synoptic diagrams, we found that the cable dimensions used were not graduated in relation to the distance of users from power stations or transformers. Constrained by growing demand and difficulties in obtaining cables, the company often connected cables available from stock. Details in Table 3 illustrate the total length of lines for each production departure in the city [7].

Three types of poles are used [7-8]:

- Concrete poles for 20 kV lines;
- Metal and wooden poles for LV 380V networks.

Protection devices for the entire network include circuit breakers, surge arresters, relays, BPNs, current and voltage transformers (CTs and VTs).

Table 3

Total length of lines for each departure

Source plant	Overhead power line	Underground power line
ENELEC thermal power plant	- Departure N1: 27,661 m - Departure N2: 7,643 m - Departure N3: 32,852 m **Total: 68 156** m	**Total: 80** m
Amporaha thermal power plant (C.T.A)	- Departure hôpital: 5,203 m - Departure Tanambao: 10,230 m - Departure Marne: 2,204 m - Departure Grand hôtel: 7,326 m - Departure P.F.O.I: 1,073 m **Total :25,165**m	- Departure hôpital: 45 m - Departure Tanambao: 129 m - Departure Marne: 65m - Departure Grand hôtel: 40 m **Total: 279** m

At present, there are no longer any HTA medium-voltage subscribers in Antsiranana and the surrounding area. They are classified as B1 or BTA for customers using 220 V single-phase networks, and B2 or BTB for large companies such as PFOI, STAR, etc., using 380 V three-phase networks.

The solar power plant has a capacity of 2 MW, with 4,240 photovoltaic panels rated at 400 W each currently in operation. It features 24 three-phase inverters with a power of 100kW each, 2 weather stations, 2 HTA transformers and an auxiliary transformer.

Electrical energy from the solar power plant is injected directly into the JIRAMA power grid without the use of a storage battery on the N1 feeder line. Fig. 3 shows the location of the solar power plant.

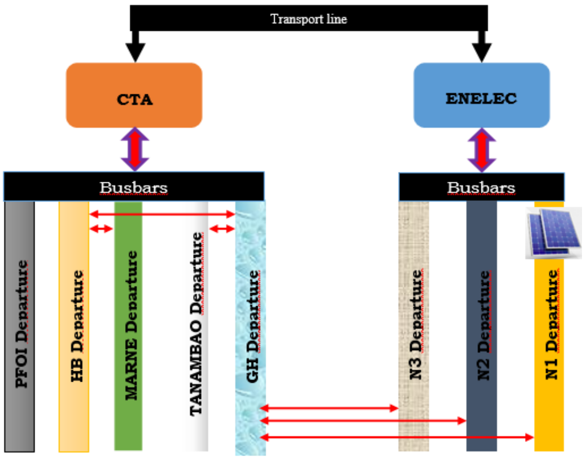

Fig. 3. Location of the PV power plant

4. Network performance analysis results

For our study, we set all parameters at 20kV using the reported values method.

4.1. Calculation of network parameters according to the synoptic plan

The electrical parameters required for modeling the power system in NEPLAN were determined based on the technical specifications of the transformers and lines shown on the synoptic diagram. The calculations were used to estimate the impedances, transformation ratios, rated currents, and electrical parameters of the lines used in the power flow simulations. The calculation formulas selected are those commonly used in power system analysis and were applied to ensure the consistency of the model under study.

4.1.1. Transformers

The transformer parameters were determined based on their rated characteristics (apparent power, primary and secondary voltages, short-circuit impedance, and turns ratio). These data were used to calculate the parameters required for modeling in NEPLAN.

4.1.2. Calculations on lines

The line parameters were evaluated based on their length and the characteristics of the conductors used. The corresponding resistances, reactances, and impedances were determined in order to model the electrical behavior of the feeder lines under study and to evaluate the losses associated with power transmission.

4.2. Application results

Note that the results presented below are obtained from the exact nominal values of each piece of equipment:

- Total installed power of units, taken from nameplates;
- Line and transformer characteristics, taken from the pre-2020 network synoptic diagram

The analysis is based on the assumption that all equipment is in perfect working order, with no ageing or loss of performance. The simulations were performed using NEPLAN software, based on network parameters derived from the schematic diagram and available technical data.

4.2.1. Steady-state network behavior without the solar power plant

a. Voltage at each network node:

For information purposes, JIRAMA relies mainly on the technical standards it applies to MV distribution networks [11]:

- Nominal voltage: 20 kV (MV);
- Permissible tolerance: implicitly ±7% (18.6 kV to 21.4 kV).

Results:

All points comply with the voltage range defined by the permitted tolerances. The values observed remain close to the nominal voltage. No starting node has a voltage higher than 21.4 kV or lower than 18.6 kV. Slight voltage drops below 19.5 kV are observed on feeder N3, but these remain within the tolerance range (see Tables 2. and 3.). Fig. 4 below shows the voltages at each node on the N3 feeder.

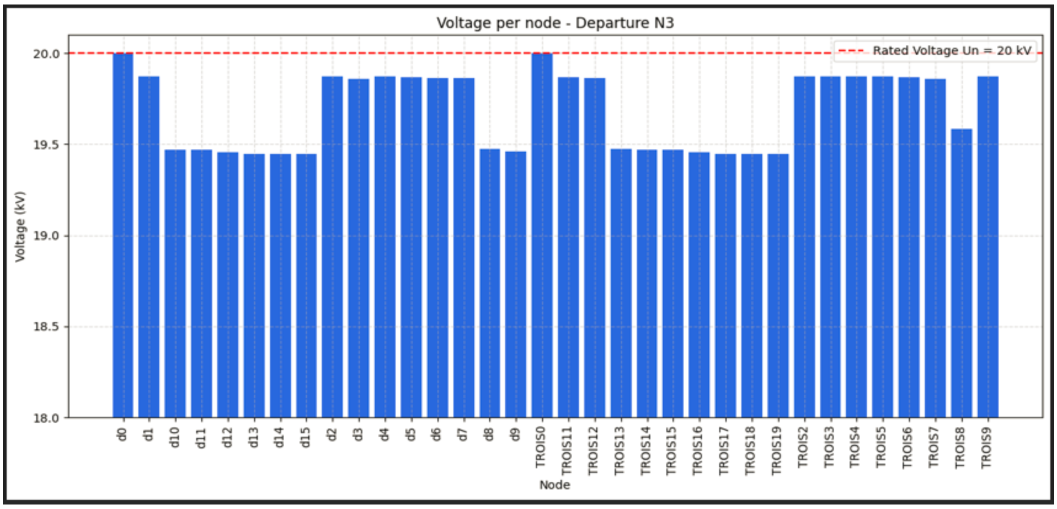

Fig. 4. Voltage at each N3 feeder node

These drops may be due to:
- Long line lengths (resistance or impedance effect).
- High local load (active and/or reactive power).
- Poor load balancing or lack of compensation.

Recommended solutions:

It might be useful to identify the nodes where voltage drops the most, and analyze:
- The length and type of the lines connected to it.
- Active and reactive power consumed by local loads in MW and MVAR.

Example: In feeder N3:
- Line lengths between 1,715m and 11,750m;
- Different cable cross-sections 34.4 mm2 and 117mm2 in the same line;
- Loads between 0.05 MVA and 1.6 MVA (Node TROIS 16 for example).

Table 4

Problems observed and solutions proposed for N3 departure

Problem observed	Possible solutions
Voltage drops at remote or heavily loaded nodes.	Reduce the length of the lines if possible. Use larger cross-section or lower impedance conductors. Double certain critical lines (paralleling).
Load imbalance between different branches or departures.	Reconfigure loads between phases or nodes, for example by moving certain consumption items. Implement a load management system to optimise distribution.

b. Distribution of network power:

P: Active power, expressed in kW or MW;
Q: Reactive power, expressed in kVAr or MVAr.

i. Active and reactive losses:

The levels of active and reactive losses per node can be direct indicators of network efficiency: too many losses means poor efficiency or overloading.

Results:

The network components connected to most nodes have low active and reactive losses, which are even negligible in some cases.

The analysis also shows that active and reactive losses on each outlet remain very low. Losses are highest at one point on feeder N3, while losses on the other feeders range from 0.0005 MW/MVAr (0.5 kW/kVAr) to 0.025 MW/MVAr (250 kW/kVAr). This corresponds to levels generally considered acceptable for MV or LV distribution networks. Fig. 5 opposite shows the distribution of active and reactive losses on feeder N3.

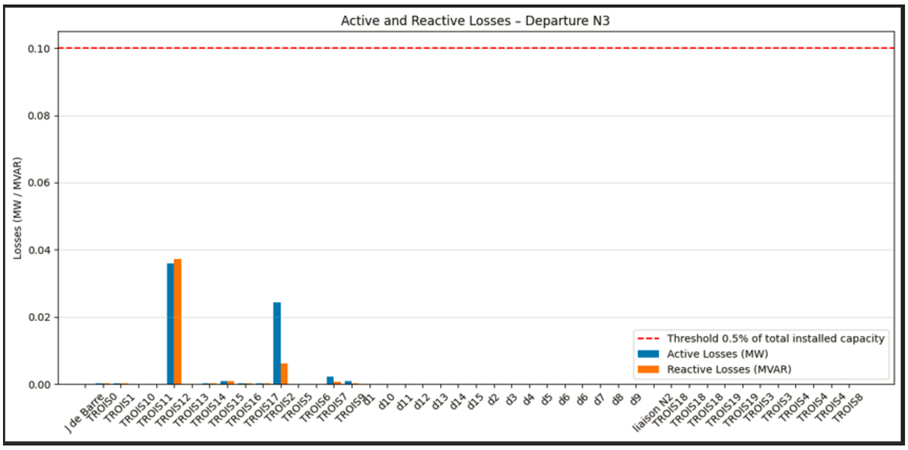

Fig. 5. Active and reactive losses on N3 feeder

The losses observed are mainly due to line charges, line lengths, and insufficient reactive compensation. These factors reflect possible network overloading or poor flow distribution.

The analysis also shows that peaks in active and reactive losses generally coincide, indicating strong current flow. However, a predominance of reactive losses may reveal a capacitive/inductive imbalance, linked to a low power factor or an overload of inductive loads.

Solution:

- Analyze the network configuration around areas with high losses (line length, cross-section, impedances,...).
- Partially rebalance loads on feeder N3 by switching the network, using the nearest feeders and available coupling points.
- Reinforce the network at the relevant points (larger conductors, doubled lines).
- Add reactive compensation (capacitors) to reduce reactive losses.
- Reconfigure power flows through dispatching adjustments.

ii. Distributed line loads (P line load and Q line load):

The purpose of monitoring line loads is to check not only their thermal capacity but also compliance with permissible voltage drop limits, which is essential for ensuring the quality of service of the network.

Results:

Calculations indicate that the majority of lines from the eight feeders have active and reactive powers below 0.25 MW/MVAr (250 kW/kVAr). This suggests a good distribution of transit over a large part of the network. However, there are still relatively high loads on some lines, particularly on feeder N3. This indicates either a local imbalance (heavy load), or a concentration of transit. The figures below show the distribution of active and reactive power on the lines of feeders N2 (associated with an average load level) and N3 (reflecting a high load level).

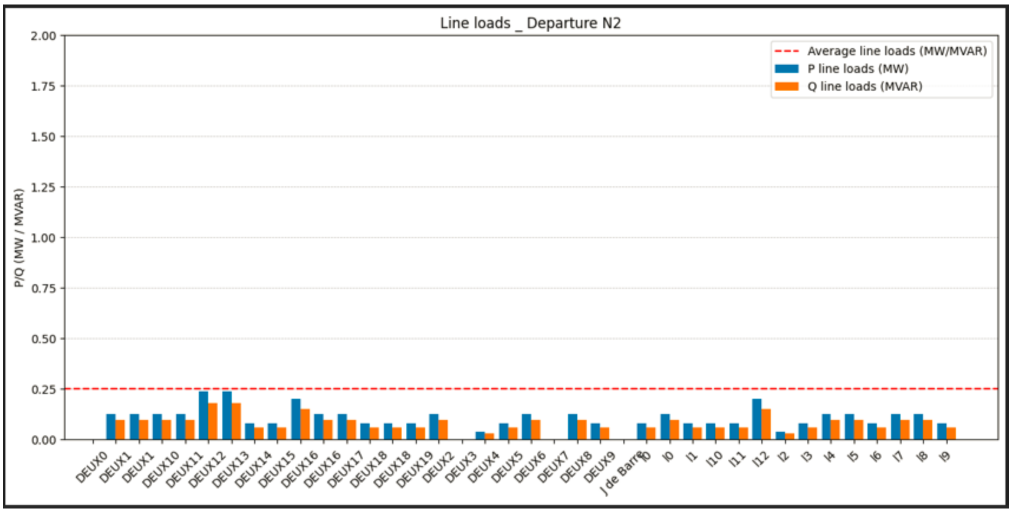

Fig. 6. Line loads on N2 feeder

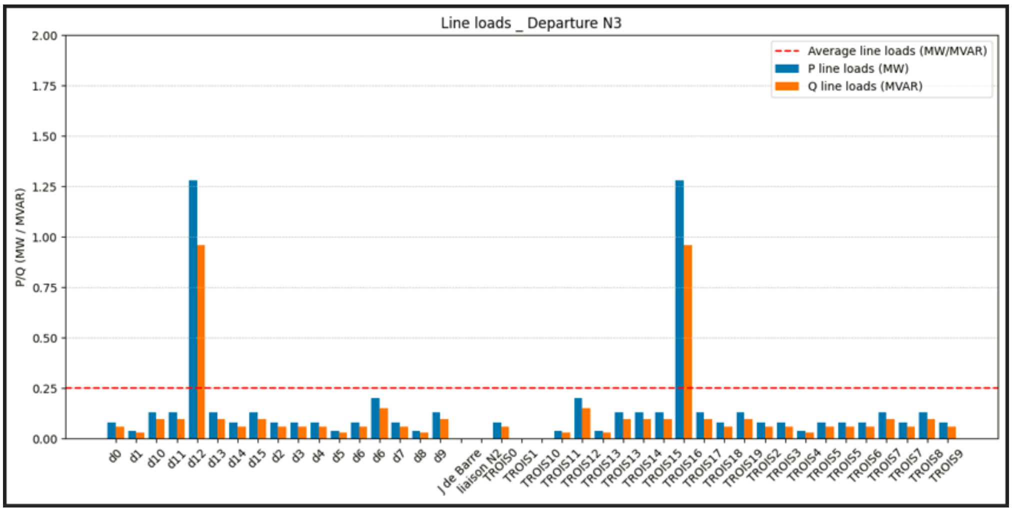

Fig. 7. Line loads on N3 feeder

<u>Solution</u>:

The lines to be monitored are those attached to nodes with high peaks (risk of thermal overload or excessive voltage drop): length, capacity, neighboring loads, etc.

Network optimization is recommended: redistribute loads via topology adjustment (line switching) or add compensators or additional sections if permanent overloads occur.

In short, overall, the network presents no major malfunctions, assuming that all equipment is in perfect working order, with no ageing or performance degradation. However, a few localized signals on feeder N3, such as voltage dips, relatively high line loads and slightly increased active and reactive losses, merit particular attention. It can be said that these anomalies are mainly due to ageing installations and obsolete equipment, aggravated by irregular connections.

4.2.2. Steady-state behavior of the grid with the solar power plant

A 1.7 MW injection, representing only 6.67% of the grid's total capacity (25.5 MW), has a limited impact on grid operation. The voltage variations observed at the various nodes before and after the injection remain small, indicating that grid operating conditions are largely unaffected [15-16-17-18-19].

One of the major problems is the absence of automatic generator management systems for both plants, which limits their responsiveness in the event of production fluctuations. In addition, solar production is highly dependent on weather conditions. The presence of shadows on the panels or variations in sunshine levels over the course of the day lead to fluctuations in the power injected. These uncontrolled variations can lead to untimely power cuts, and sometimes even blackouts.

Solution:

A program to renew and modernize the power grid, including replacing obsolete equipment, rehabilitating infrastructure and bringing installations up to standard, is essential to guarantee system reliability and safety before injecting PV power [17]. The table below shows the variations in active and reactive losses in the grid obtained from the simulation results for each PV system penetration rate in relation to the entire grid.

Table 5

Active and reactive grid losses at each PV system penetration rate

Penetration rate	Active network losses (MW)	Reactive network losses (MVAr)
0% (Without PV injection)	0,118141 (+ 0%)	0,092935 (+ 0%)
6,67% (1,7MW)	0,120238 (+ 1,77%)	0,103236 (+ 11,08%)
39,22% (10MW)	0,120849 (+ 2,29%)	0,154441 (+ 68,33%)
50% (12,75MW)	0,121059 (+ 2,47%)	0,171366 (+ 84,39%)

It has been observed that as the penetration rate increases, so do total grid losses, with a notable predominance of reactive losses. This increase can be explained by the fact that, although modern photovoltaic inverters allow the power factor to be adjusted, their contribution to compensating for reactive power in the grid generally remains limited under operating conditions. This leads to overloading of the lines with reactive power, thus increasing the associated losses. The intermittent and unpredictable nature of renewable energy production poses new challenges to grid stability, particularly by exacerbating imbalances in the distribution of reactive power flows [14]. On the other hand, the impact on active losses remains marginal, with only a negligible variation despite the increase in injected power.

5. Improving the operation of the N3 start by integrating a PV power plant

As a solution, and with the aim of attenuating the signals observed on feeder N3, one possible option is to reconfigure the injection point of the photovoltaic plant currently connected to feeder N1, to inject it directly into feeder N3. This reallocation would provide local voltage support, reduce technical losses and lighten the load on certain lines, thus contributing to improved network performance in this sector. Fig. 8 below shows the new location of the PV power plant, now connected to feeder N3 in order to optimize grid performance locally.

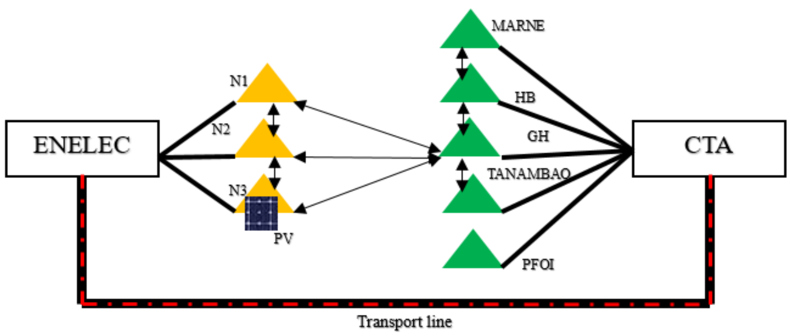

Fig. 8. Proposed location for PV power plant

Result:

Most points are within the acceptable voltage range, and no node exceeds the nominal value of 20 kV. The figure below shows the new bar graph of the voltages recorded at each node of feeder N3, after the PV plant has injected power into the feeder.

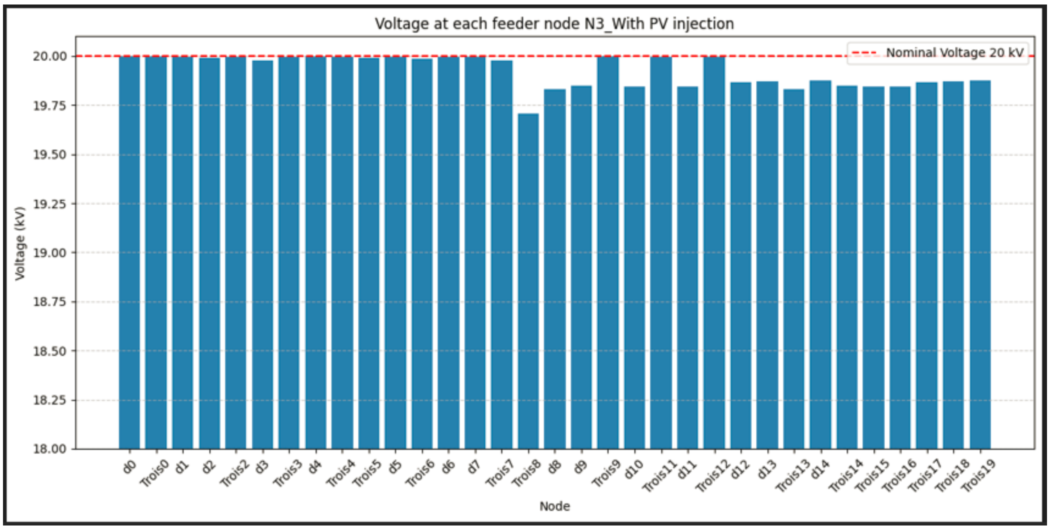

Fig. 9. Voltage at each node of the N3 feed, with direct PV injection

The comparative analysis highlights the beneficial effect of changing the photovoltaic power plant's injection point. Indeed, when the plant was connected to feeder N1, some of the voltages measured on the nodes of feeder N3 fell below 19.5 kV, reflecting localized voltage dips. By contrast, with the direct injection of generation into feeder N3, voltages stabilize around the nominal value of 20 kV, improving quality of service and voltage withstand across the entire feeder.

To further this study, it would be helpful to know the voltage levels at end-user delivery points in order to confirm the quality of the power supply across the entire grid. Another approach would be to analyze the grid's behavior over a one-year period, taking into account variations in load and photovoltaic generation, which would allow for a more accurate assessment of the impact of integrating the PV plant under different operating conditions.

6. Conclusion

The smooth operation of an electrical network depends on compliance with a number of technical constraints. The simulations carried out have enabled us to assess the state of the network, identify any malfunctions and suggest ways of improving it. The network functions normally if the equipment is in perfect condition. However, a few localized anomalies on the N3 feeder, such as voltage dips, high loads and increased losses, call for particular vigilance.

The study showed that direct connection of the photovoltaic power plant to feeder N3, replacing its initial injection on feeder N1, led to a significant improvement in voltage profiles, with values now stabilized at around 20 kV, compared with drops of up to 19.5 kV previously observed.

The stability of a power grid to which photovoltaic sources are added is highly dependent on the initial state of the grid prior to injection. It is therefore essential to guarantee the stability of the power grid prior to any integration of solar generation. This implies the implementation of a renewal and modernization program, including the replacement of obsolete equipment, the rehabilitation of existing infrastructures, and the compliance of installations with current standards.

The increase in the photovoltaic penetration rate increases losses, mainly reactive, in the network, which can compromise its stability and lead to a deterioration in the power factor in the absence of appropriate compensation. It is therefore necessary to support this integration with suitable compensation devices, such as capacitor banks, etc., strategically installed within the network to preserve its performance.

REFERENCES

[1]. Vincent Garruchet (France Volontaires), Pierre-Marie Bosc (Cirad), Isabelle Mialet-Serra (Cirad), L'Agriculture à Madagascar: Évolution, chiffres clés et défis Janvier 2023, Prépad Océan Indien

[2]. Comprendre la situation énergétique de Madagascar, Février 2025, Diapason Think Tank Madagascar

[3]. Projet de renforcement et d'interconnexion des réseaux de transport d'énergie électrique à Madagascar (prirtem), Septembre 2017, Groupe de la banque africaine de développement

[4]. Diagnostic du secteur énergie à Madagascar, Septembre 2012, WWF à Madagascar et dans l'Océan Indien Occidental, Ministère de l'Energie

[5]. Hydroélectricité, ORE

[6]. Small Hydro Resource Mapping in Madagascar, August 2014, World Bank Group and ESMAP

[7]. Andriantsoa Franc Dolly, « Etude, modélisation et simulation du réseau électrique de Diégo-Suarez suite à l'implantation de centrale PV », Décembre 2022, Mémoire d'ingénieur de l'IST-Diego

[8]. Code de Réseau de Transport d'Energie Electrique à Madagascar Règlements Techniques de Planification, de Raccordement et d'Exploitation, Mars 2020

[9]. Transition énergétique: une centrale solaire inaugurée à Antsiranana, 14 Août 2023, NewMada

[10]. https://www.a-eberle.de/fr/savoir/mesure-de-la-chute-de-tension/

[11]. Standards techniques et normes en vigueur à Madagascar, ORE

[12]. https://www.futura-sciences.com/planete/questions-reponses/automobile-carburant-emet-plus-co2-essence-gasoil-947/

[13]. Maaya I. BEY, Cristina STANCU, Petru V. NOTINGHER, « Calculation of the used and remaining lifespan of power transformers in countries with a dry tropical climate », vol. 87, Iss. 2, 2025

[14]. Lishi LUO, Bo ZHAO, Hongliang HE, Yiwei LI, Weijiang LI, Jiansong WU, Dan LI, « Three-level automatic voltage control strategy considering the operational balance of reactive power compensation devices », vol. 87, Iss. 2, 2025

[15]. Toussaint Tilado Guingane, Zacharie Koalaga, Cedric Beogo, Eric Simonguy, Nogma Ouiya, Dominique Bonkoungou, François Zougmore, « impact de la pénétration du photovoltaïque sur le réseau électrique »

[16]. Jacques Percebois, Stanislas Pommeret, « Injection massive d'électricité renouvelable intermittente et fatale dans un réseau interconnecte : effets d'éviction et besoins de stockage », juillet 2017
[17]. Dr. Andreas Beer, Dr. Maurus Bachmann, « Limitation de la puissance d'injection photovoltaïque », Août 2020
[18]. Maliki G., Binkou A., Sidibe K., Coulibaly D., « Analyse des impacts d'une pénétration accrue des réseaux Electriques par les Générateurs Photovoltaïques »
[11] Karima Kadda Touati-Bergheul, Mohamed Boudour, Amar Hadj Arab, Ali Malek, « Etude de faisabilité de l'insertion d'une centrale photovoltaïque raccordée au réseau de distribution de Ghardaïa »