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Study of the *N* – 1 Criterion (Loss of Power Plants) of Burkina Faso's Interconnected Electrical Network Following the Injection of Energy from Photovoltaic Solar Power Plants

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Abstract

The study analyzes the resilience of Burkina Faso's electrical network against failures, using the *N* – 1 security criterion. A network modeling for the 2021 horizon was carried out using Digsilent Power Factory software, incorporating planned solar installations. The simulations tested different failure scenarios to evaluate their impacts on voltage levels and short-circuit currents. The results show that the majority of simulated failures do not cause major problems, although the loss of interconnections is identified as the most critical scenario, causing overloads. Based on these conclusions, several recommendations were made: readjusting the protection devices, improving the network structure, and reinforcing points with overloads. This study takes place in a context of continuous expansion of Burkina Faso's electrical network, driven by increasing energy demand due to economic development and industrialization of the country.

Keywords

N – 1 Criterion, Voltage, Current, Short-Circuit, Network, Solar, Overload

1. Introduction

To ensure the proper functioning of an electrical network in the event of a failure or malfunction of one of its components, it is essential to comply with the $N-1$ security criterion, which guarantees network continuity despite the loss of a single element [1]. This study aims to analyze the resilience of Burkina Faso's National Interconnected Network (RNI) by simulating various scenarios using Digsilent Power Factory. The objective is to assess the levels of voltage degradation and the additional short-circuit current contribution in case of a network element failure.

Our approach is structured in three steps:

- Modeling of the RNI for the 2021 horizon, incorporating the necessary reinforcements to ensure its static stability.
- Simulation of constraining scenarios to identify the impacts of losing critical elements.
- Analysis of the obtained results and proposal of improvements.

This approach will enable the anticipation of network vulnerabilities and the proposal of tailored solutions to enhance its reliability [2].

2. Materials and Methods

The $N-1$ safety criterion refers to the requirements of the operation of the electrical system of the synchronous area in order to maintain the entire interconnected network at any time during the operating preparation phase and in real time. In this part, we will present the tools and methods used to carry out the study of the $N-1$ security criterion of the network.

2.1. Digsilent Power Factory Software

Digsilent Power Factory is a robust tool for the static and dynamic analysis of electrical networks. Used here to model the RNI and simulate failures, it relies on validated calculation methods [3].

2.2. Mathematical Model

2.2.1. Power Flow Calculation Equation

The study of power flow is fundamental to the planning and management of electrical networks, which are characterized by three types of nodes (load, generator, slack) represented in **Figure 1**. Each node is defined by four variables (P, Q, V, ρ), of which two are generally known. The Burkina Faso National Interconnected Network (RNI) follows this configuration with a meshed structure.

The power flow is calculated to assess the network's stability. For a node i, the apparent power is given by the following equations [5]:

$$S_i = I_i^* V_i \tag{1}$$

$$S_i = S_{Gi} - S_{Di} = \left(P_{Gi} - P_{Di}\right) + j\left(Q_{Gi} - Q_{Di}\right) \tag{2}$$

With:

S_{Gi}: Apparent power generated at node i,

S_{Di}: Apparent power demanded at node i,

P_{Gi}: Active power generated at node i,

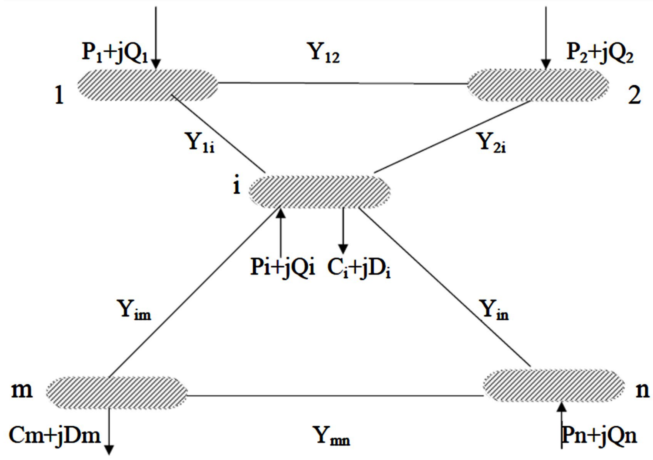

Figure 1. Network with n nodes [4].

P_{Di}: Active power demanded at node *i*,

Q_{Gi}: Reactive power generated at node *i*,

Q_{Di}: Reactive power demanded at node *i*.

The voltages at nodes V_i and V_m are represented in trigonometric form with their respective amplitudes and phase angles. They are given by Equations (3) and (4) [6].

$$V_i = |V_i| e^{j\delta_i} \tag{3}$$

$$V_m = |V_m| e^{j\delta_m} \tag{4}$$

The current at node "*i*" is calculated as the sum of the products of the mutual admittances with the voltages of the connected nodes.

$$I_i^* = \sum_{m=1}^{n} Y_{im}^* V_m^* \tag{5}$$

The admittance of the branch *i*-*m* is given by the expression:

$$Y_{im} = \rho_{im} + j\beta_{im} \tag{6}$$

These relationships lead to a system of nonlinear equations for the active and reactive powers:

$$\begin{cases} P_{Gi} - P_{Di} = V_i \sum_{m=1}^{n} V_m \left[\rho_{im} \cos(\delta_i - \delta_m) + \beta_{im} \sin(\delta_i - \delta_m) \right] \\ Q_{Gi} - Q_{Di} = V_i \sum_{m=1}^{n} V_m \left[\rho_{im} \sin(\delta_i - \delta_m) - \beta_{im} \cos(\delta_i - \delta_m) \right] \end{cases} \tag{7}$$

The active power losses P_L and reactive power losses Q_L are defined as the sum of the differences between the generated and demanded powers across the entire network [7].

$$\begin{cases} P_L = \sum_{i \neq m}^{n} \left[(P_{Gi} + P_{Gm}) - (P_{Di} + P_{Dm}) \right] \\ Q_L = \sum_{i \neq m}^{n} \left[(Q_{Gi} + Q_{Gm}) - (Q_{Di} + Q_{Dm}) \right] \end{cases} \tag{8}$$

With:

P_{Gm} and Q_{Gm}: active and reactive powers generated at node *m*,

P_{Dm} and Q_{Dm}: active and reactive powers demanded at node *m*.

This mathematical formulation enables a precise analysis of power flow in complex electrical networks.

The resolution of this system employs the Newton-Raphson method, selected for its rapid convergence even in complex networks.

Solving Power Flow Calculation Equations: Newton-Raphson Method.

Principle of the Newton-Raphson Method [8].

The method involves introducing a sequence (x_n) of successive approximations to solve the equation $f(x) = 0$.

- We start with an initial guess x_0 close to the solution.
- From x_0, a new term x_1 is calculated as follows: we draw the tangent to the curve C_f at x_0. This tangent intersects the x-axis at x_1, as shown in **Figure 2**.

The process is repeated by calculating x_2 by replacing x_0 with x_1, then x_3 by replacing x_1 with x_2, and so on…

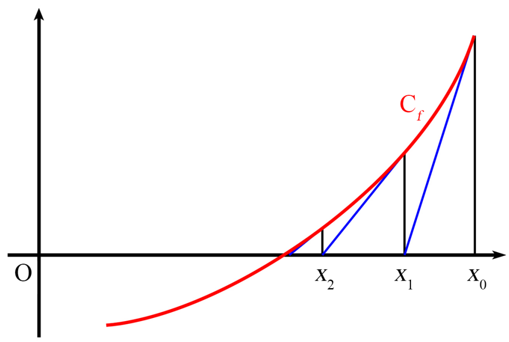

Figure 2. Illustration of the Newton-Raphson method.

Conditions for Applying the Newton-Raphson Method

For the sequence (x_n) to exist:

- The function fff must be differentiable at each of the points considered. In practice, the function must be differentiable in an interval centered at a that contains x_0.
- The derivative must not be zero over this interval.

For the sequence (x_n) to be convergent, the conditions go beyond the scope of a high school curriculum, but in practice, it is necessary to choose an x_0 sufficiently close to the value a that makes the function zero. This is determined using the Intermediate Value Theorem.

To enable the use of the Newton-Raphson method, we will reformulate Equation (6) into a form relating voltage and power. Starting from Equation (9), and defining:

$$\begin{cases} e_i = V_i \cos \delta_i \\ f_i = V_i \sin \delta_i \\ e_m = V_m \cos \delta_m \\ f_m = V_m \sin \delta_m \end{cases} \tag{9}$$

We obtain:

$$\begin{cases} P_i = \sum_{m=1}^{n}\left[e_i\left(e_m\rho_{im} + f_m\beta_{im}\right) + f_i\left(f_m\rho_{im} - e_m\beta_{im}\right)\right] \\ Q_i = \sum_{m=1}^{n}\left[f_i\left(e_m\rho_{im} + f_m\beta_{im}\right) + e_i\left(f_m\rho_{im} - e_m\beta_{im}\right)\right] \end{cases} \tag{10}$$

This system of equations is nonlinear. The active power P_i and reactive power Q_i are known, while the real and imaginary components of the voltage e_i et f_i are unknown for all buses except the reference bus, where the voltage is specified and fixed.

The method transforms the equations using the real e_i and imaginary f_i components of the voltages, resulting in a matrix formulation with the Jacobian [J], given by Equation (11).

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_{n-1} \\ \hline \Delta Q_1 \\ \vdots \\ \Delta Q_{n-1} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_1}{\partial e_1} & \cdots & \frac{\partial P_1}{\partial e_{n-1}} & \frac{\partial P_1}{\partial f_1} & \cdots & \frac{\partial P_1}{\partial f_{n-1}} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_{n-1}}{\partial e_1} & \cdots & \frac{\partial P_{n-1}}{\partial e_{n-1}} & \frac{\partial P_{n-1}}{\partial f_1} & \cdots & \frac{\partial P_{n-1}}{\partial f_{n-1}} \\ \hline \frac{\partial Q_1}{\partial e_1} & \cdots & \frac{\partial Q_1}{\partial e_{n-1}} & \frac{\partial Q_1}{\partial f_1} & \cdots & \frac{\partial Q_1}{\partial f_{n-1}} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_{n-1}}{\partial e_1} & \cdots & \frac{\partial Q_{n-1}}{\partial e_{n-1}} & \frac{\partial Q_{n-1}}{\partial f_1} & \cdots & \frac{\partial Q_{n-1}}{\partial f_{n-1}} \end{array}\right] \begin{bmatrix} \Delta e_1 \\ \vdots \\ \Delta e_{n-1} \\ \hline \Delta f_1 \\ \vdots \\ \Delta f_{n-1} \end{bmatrix} \tag{11}$$

where the last busbar is the reference busbar. The form of the matrix is therefore:

$$\begin{bmatrix} \Delta P \\ \hline \Delta Q \end{bmatrix} = \left[\begin{array}{c|c} J_1 & J_3 \\ \hline J_2 & J_4 \end{array}\right] \begin{bmatrix} \Delta e \\ \hline \Delta f \end{bmatrix} \tag{12}$$

Or alternatively:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix} \tag{13}$$

$[J]$: is the Jacobian of the matrix

ΔP and ΔQ: are the differences between the planned values and the calculated values of the active and reactive powers, respectively.

2.2.2. Short-Circuit Currents

The sizing of an electrical installation and the equipment to be implemented, as well as the determination of protections for people and property, require the calculation of short-circuit currents at every point in the network. The method for calculating short-circuit currents applied in the software is the one proposed by the IEC 60909 standard. It addresses both radial and meshed circuits, covering LV—Low Voltage and HV—High Voltage. This standard is based on Thévenin's theorem and involves calculating an equivalent voltage source at the short-circuit point.

The calculation of short-circuit currents enables the sizing and securing of electrical installations. It is expressed by [9]:

$$I_{cc} = \frac{U}{Z_i + \sum Z_l + \sum Z_a} \tag{14}$$

With:

U: network voltage (phase-to-neutral),

Z_i: internal impedance of the source,

Z_l: impedance of the traversed line sections,

Z_a: impedance of the encountered equipment.

The main types of short-circuits are:

- Three-phase short-circuit: $I_{cc3} = c\dfrac{U_n}{Z_{cc}\cdot\sqrt{3}}$ (15)
- Isolated two-phase fault: $I_{cc2} = c\dfrac{U_n}{2\cdot Z_{cc}}$ (16)
- Two-phase-to-ground short-circuit: $I_{cc2} = c\dfrac{U_n\cdot\sqrt{3}}{Z_{cc}+2\cdot Z_0}$ (17)
- Single-phase short-circuit: $I_{cc} = c\dfrac{U_n\cdot\sqrt{3}}{2\cdot Z_{cc}+Z_0}$ (18)

In these formulas, Z_{cc} represents the direct impedance of the circuit traversed, and Z_0 the zero-sequence impedance related to the neutral or ground line. The voltage factor ccc, according to the CEI 60909 standard, ranges between 0.95 and 1.1, with a default value of 1.1 in the software [10].

2.3. Simulation Hypotheses

For these simulations, the National Interconnected Network (RNI) of Burkina Faso, having received the injection of energy produced by the planned solar power plants up to 2021, has undergone the necessary reinforcements to ensure its static stability.

Note that this initial situation of network, also integrates interconnections with Ghana and Cote d'Ivoire.

Next, we will simulate the loss of critical elements of the electrical network (particularly power plants with significant capacity), and then observe the impact of these losses on the RNI in terms of power flow and short-circuit currents. To do this, we will carry out the following scenarios:

- **Scenario 1**: Network in its initial state, including all solar power plants planned up to the 2021 horizon, thermal power plants, hydroelectric plants, and interconnections. In this reference case, all reinforcements necessary for the static stability of the network are already integrated.
- **Scenario 2**: We will simulate the loss of the 106 MW Kossodo thermal power plant (the Komsilga plant being already offline in the reference network) using the reference network. The power of this power plant represents ¼ of RNI load point.
- **Scenario 3**: In this scenario, we will simulate the loss of the 50 MWp Zagtouli photovoltaic solar power plant using the reference network. The power of this power plant represents 8% of RNI load point during the day.
- **Scenario 4**: In this scenario, we will simulate the loss of the 55 MW Bobo2 thermal power plant using the reference network. The power of this power

plant represents 1/8 of RNI load point.

3. Results and Discussion

3.1. Power Flow Analysis

The network has been modeled, and all equipment has been represented. The power flow calculations (in steady-state conditions) were performed by the software using the Newton-Raphson iteration method. The purpose of these calculations is to determine:

- The voltages at the various nodes and their phase shifts relative to the current;
- The active and reactive powers of the different branches;
- The currents in the different branches.

These power flow analyses were conducted for all the scenarios we described to observe variations in voltage, currents, and power flows.

- The upper voltage limit permitted for the network equipment is 1.07 pu.
- The lower voltage limit permitted for the network equipment is 0.93 pu.

The upper admissible load range is 90%.

These tension and load range are those used by the National Electricity Company (SONABEL). The higher 90% load beach avoids overloading network equipment.

Scenario 1. In this reference scenario (year 2021), no elements are overloaded, and the network remains stable with all power plants and interconnections operational.

Figure 3 presents the simulation diagram of Scenario 1.

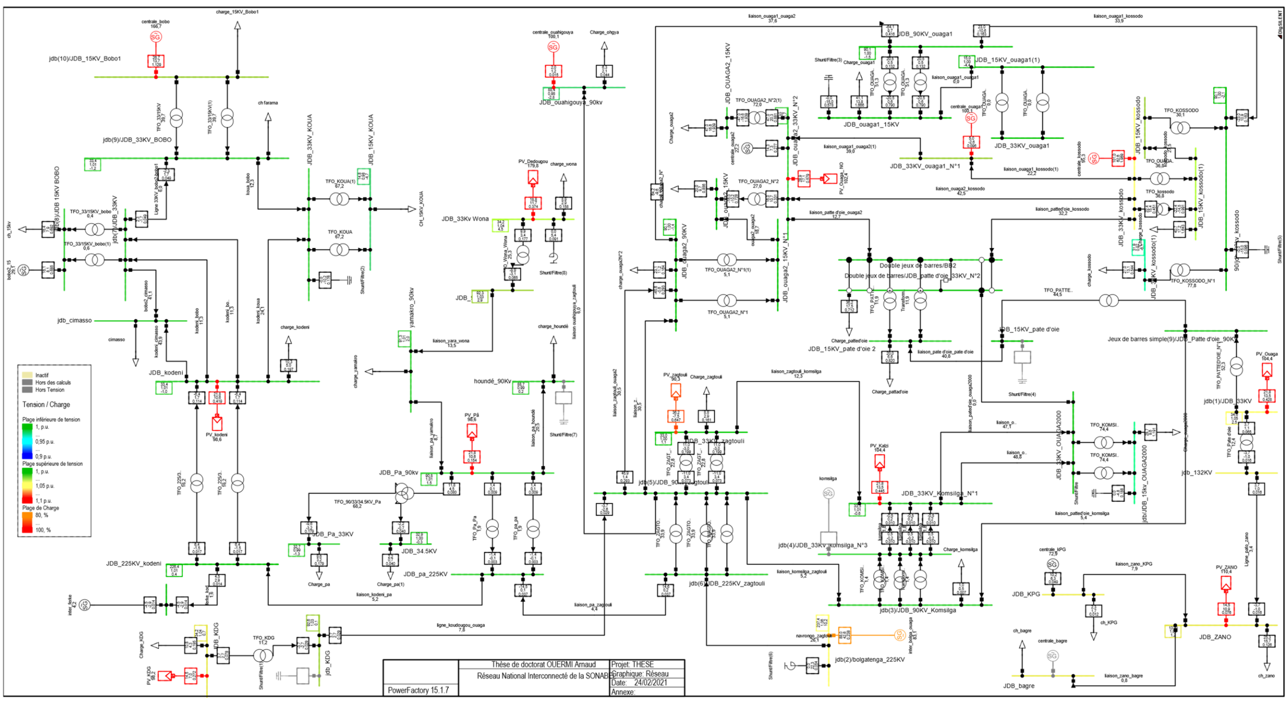

Figure 3. National Interconnected Network in the initial state (reference state).

Scenario 2 (Loss of Kossodo): Notable overloads: Kossodo 15/90 kV transformer (114.43%), Kossodo line (104.87%), Kossodo power plant (132.61%). The $N-1$ criterion is not met.

Figure 4 provides the schematic of the simulation for Scenario 2 (loss of Kossodo).

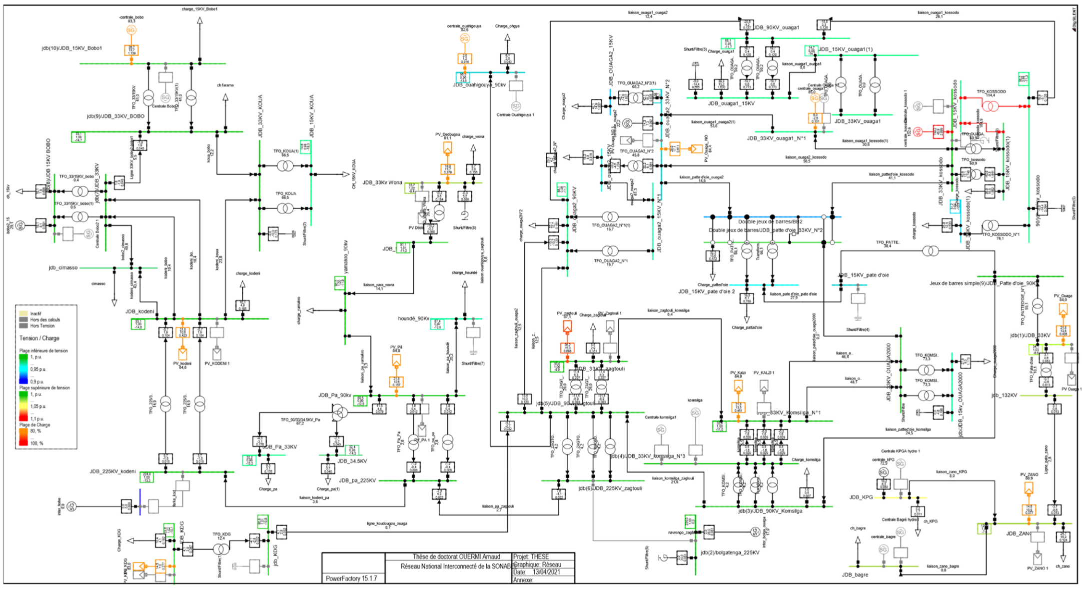

Figure 4. National Interconnected Network after the loss of interconnections.

Scenario 3 (Loss of Zagtouli): No overloads, the network remains stable, $N-1$ criterion met.

Figure 5 provides the schematic of the simulation for Scenario 3 (loss of Zagtouli).

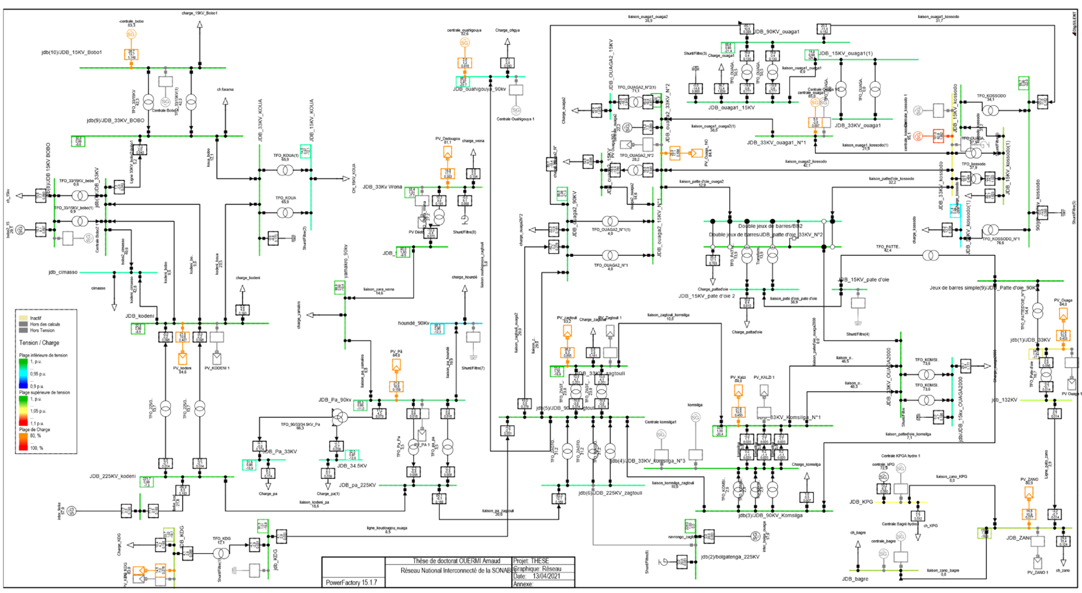

Figure 5. National Interconnected Network after the loss of the Bolgatenga line.

Scenario 4 (Loss of Bobo2): No overloads, $N-1$ criterion met.

Figure 6 provides the schematic of the simulation for Scenario (loss of Bobo2).

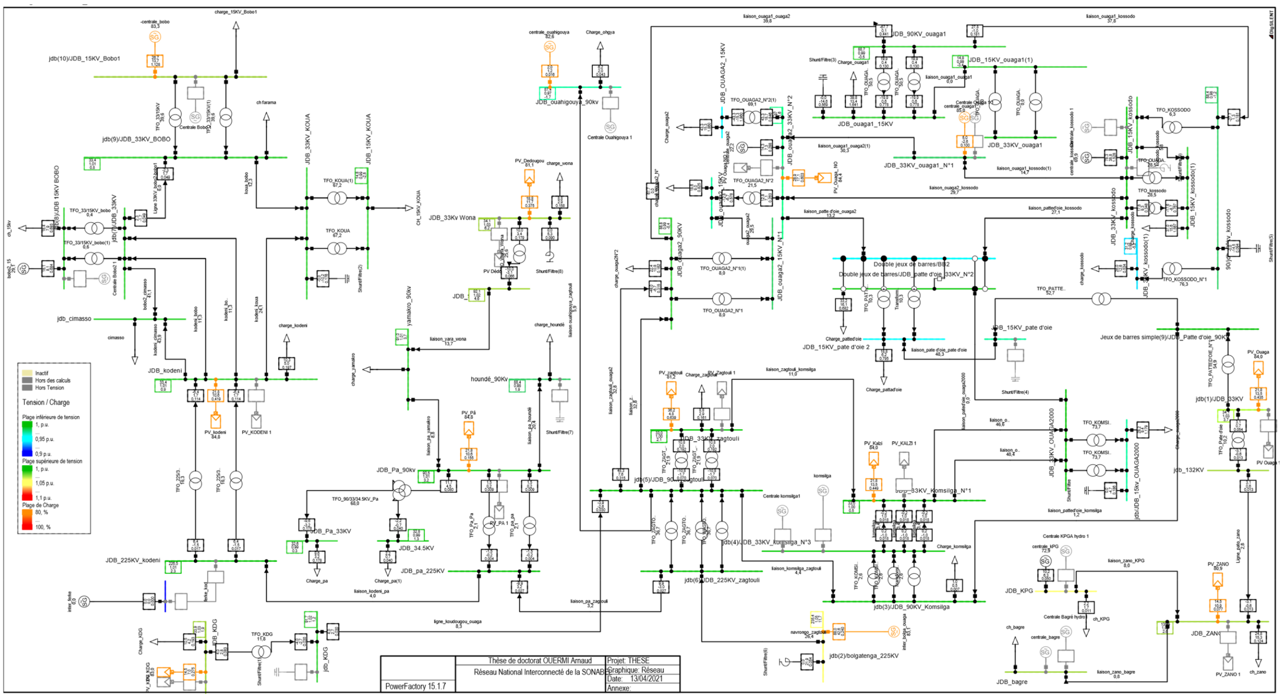

Figure 6. National Interconnected Network after the loss of the Ferké line.

3.2. Short-Circuit Current Analysis

Figure 7 shows the variation in short-circuit power after the loss of interconnections, and **Figure 8** shows the variation in short-circuit current after the loss of interconnections.

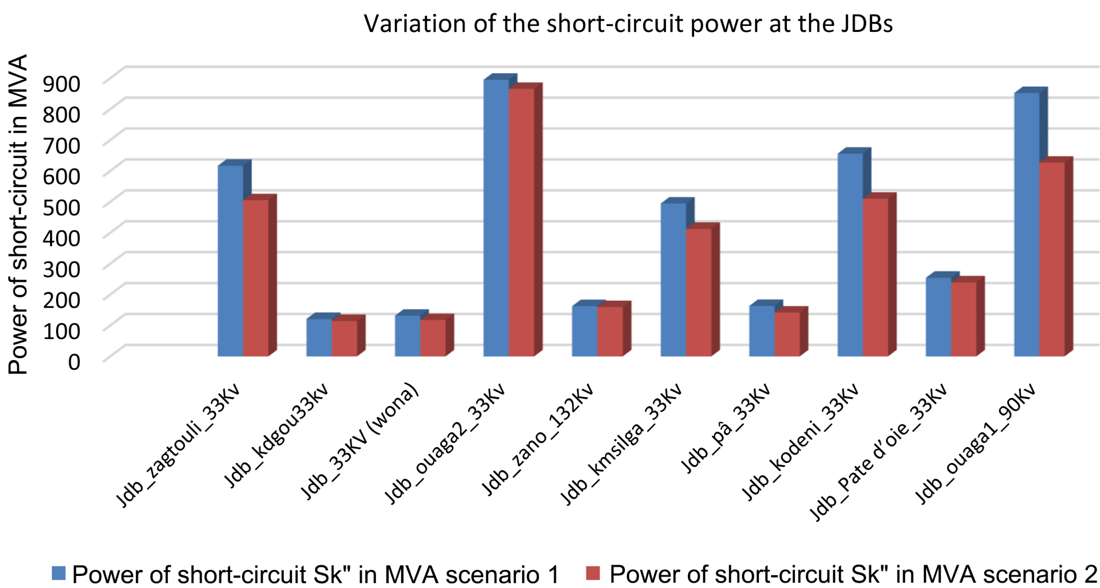

Figure 7. Variation in short-circuit power after the loss of interconnections.

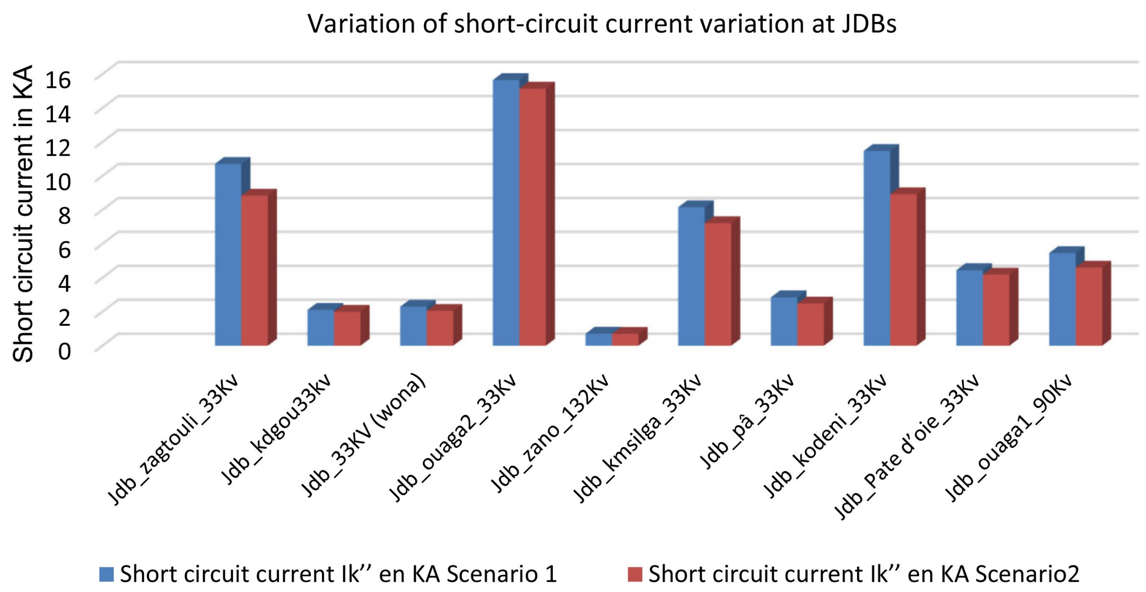

Figure 8. Variation in short-circuit current after the loss of interconnections.

Short-circuit currents vary with the loss of elements. For example, at the Zagtouli JDB (33 kV), the short-circuit power decreases from 616.71 MVA (Scenario 1) to 505.08 MVA (Scenario 2), affecting protections calibrated for higher initial values.

3.3. Proposed Solutions

The results of the various scenarios we executed indicate that the current SONABEL network will experience instabilities following the loss of network elements carrying significant power, such as the interconnections with Côte d'Ivoire and Ghana.

Therefore, reinforcements are necessary to ensure the stability and continuity ($N-1$ security criterion) of the network's operation.

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Therefore, reinforcements are necessary to ensure the stability and continuity ($N-1$ security criterion) of the network's operation.

To comply with the $N-1$ criterion, the following is required:

- Increase the capacity of overloaded equipment (transformers, lines).
- Add a surplus of 50% of the production capacity (gradually depending on the means available).
- Convert lines to double circuits or closed-loop configurations.
- Adapt protections to the new short-circuit currents.
- Transition to a smart grid with reinforced interconnections and FACTS devices for dynamic stability.

4. Conclusion and Perspectives

The study demonstrates that Burkina Faso's National Interconnected Network (RNI) remains stable in most failure scenarios, meeting the $N-1$ criterion, except during the loss of interconnections, where critical overloads occur. These results, obtained using Digsilent Power Factory for the 2021 horizon, highlight the network's overall resilience to the integration of solar power plants. However, the interconnection scenario reveals vulnerabilities requiring targeted reinforcements. Solutions such as capacity increases, protection readaptation, and a shift to a smart grid are proposed to ensure continuity. A complementary dynamic study is recommended to further the analysis. This approach aligns with Burkina Faso's context of growing energy demand.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

Symbol	Designation	Unit
S_i	Apparent power at node *i*	Megavolt-Ampere (MVA)
P_i	Active power at node *i*	Megawatt (MW)
Q_i	Reactive power at node *i*	Megavolt-Ampere Reactive (MVAR)
S_{Gi}	Apparent power generated at node *i*	Megavolt-Ampere (MVA)
S_{Di}	Apparent power demanded at node *i*	Megavolt-Ampere (MVA)
P_{Gi}	Active power generated at node *i*	Megawatt (MW)
P_{Di}	Active power demanded at node *i*	Megawatt (MW)
Q_{Gi}	Reactive power generated at node *i*	Megavolt-Ampere Reactive (MVAR)
Q_{Di}	Reactive power demanded at node *i*	Megavolt-Ampere Reactive (MVAR)
e_i	Real part of the voltage at busbar *i*	Kilovolt (kV)
f_i	Imaginary part of the voltage at busbar *i*	Kilovolt (kV)
e_m	Real part of the voltage at busbar *m*	Kilovolt (kV)
f_m	Imaginary part of the voltage at busbar *m*	Kilovolt (kV)
Z_i	Internal impedance of the source	Ohm (Ω)
Z_l	Impedance of the traversed line sections	Ohm (Ω)
Z_a	Impedance of the encountered equipment	Ohm (Ω)
I_{cc3}	Three-phase short-circuit current	Kiloampere (kA)
I_{cc2}	Two-phase short-circuit current	Kiloampere (kA)
I_{cc}	Single-phase short-circuit current	Kiloampere (kA)

List of Acronyms and Abbreviations

P.u	Per unit
RNI	National Interconnected Network
JDB	Busbar