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Enhancing network resilience and energy efficiency in the El Abiodh Sidi Cheikh grid through load flow analysis

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ABSTRACT

This study investigates the performance of the El Abiodh Sidi Cheikh (ESC) electrical grid, focusing on energy efficiency, system stability, and the integration of renewable energy sources. Numerical methods, including the Newton-Raphson (NR), accelerated Newton-Raphson (ANR), and fast decoupled (FD) load flow methods, were employed to evaluate power flow, voltage stability, and active power losses. Key results reveal that the NR method achieves the lowest power loss, with a minimal value of 2.32 MW, while voltage violations at specific nodes, such as buses 4 and 13, emphasize the necessity for voltage regulation. Analysis of the sun trajectory and temperature profiles highlights correlations between climatic conditions and energy demand, aiding renewable energy optimization. Additionally, photovoltaic (PV) measurements demonstrate diurnal variations in energy output, critical for enhancing renewable energy integration. These findings underscore the importance of advanced power flow analysis and strategic planning to ensure network resilience, energy efficiency, and reliability in the ESC region.

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1. INTRODUCTION

One essential piece of infrastructure that makes it easier to move electricity from power plants to consumers is the distribution electrical network [1], [2]. Nevertheless, many of the distribution systems in place today were built to satisfy the requirements of bygone eras, and they currently struggle to adjust to rising energy demands and changing operating environments [3]–[5]. The challenges of updating outdated infrastructure to meet modern energy demands [6], [7] are shown by the 30 kV distribution network of El Abiodh Sidi Cheikh (ESC), a region in southwest Algeria as shown in Figure 1.

Originally intended for far simpler energy needs, the ESC 30 kV grid was put into use prior to 2,000. However, as economic activity soars and power needs in the area rise, the network has simply pushed itself beyond its capacity over the years. The particular local conditions (extreme heat and very dry air) make things much more difficult. These severe external conditions truly affect the functioning of the Almelec-conducted overhead lines. Regrettably, this results in increased energy waste and shorter lifespans for important tools.

The network's simple "radial" design makes it particularly susceptible to power cuts. Take El-Bnoud, for instance, which is about 90 kilometers from the main ESC substation as shown in Figure 1. People there typically struggle with obvious voltage drops, which seriously compromise their power quality as shown in Figure 2. Active and reactive power losses over those long transmission lines, exacerbated by the age of the equipment, produce these reductions [8]. Conversely, other parts of the grid may experience overvoltage problems, which often start when demand and power generation vary [9], [10]. These swings compromise the stability of the system and can damage linked electrical equipment [11], [12].

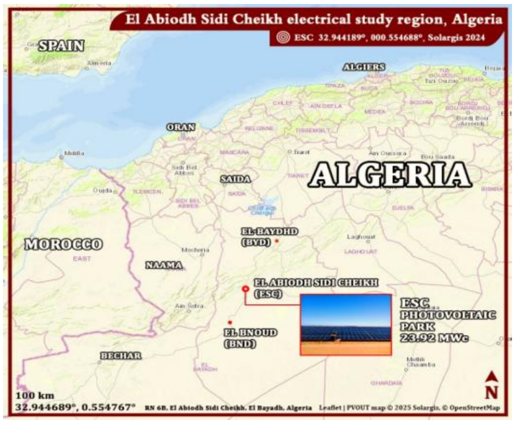

Figure 1. El-Abiodh Sidi Cheikh (ESC) map

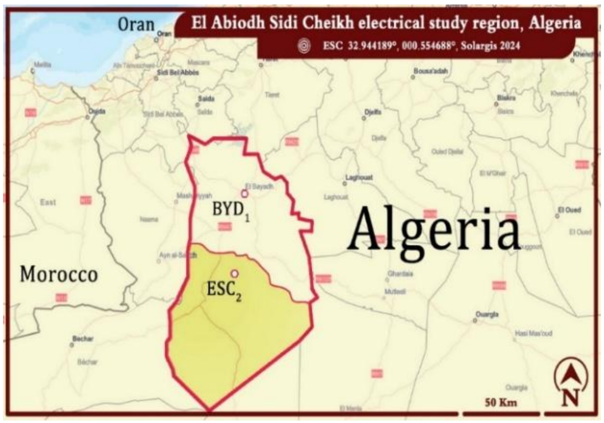

Figure 2. ESC distribution electrical grid (Area 2)

In addition to these operational challenges, the region's extreme temperatures create further difficulties. High temperatures increase the resistance in the conductors, therefore reducing their capacity to carry power and causing more losses that are technical [13], [14]. This raises important questions about the suitability of materials like Almelec conductors for long-term use in extreme weather, thereby adding another layer of fragility to the network [15], [16].

Including a 24 MWc solar (PV) plant in the system has clearly complicated things. This renewable energy project presents difficulties maintaining voltage stability and guaranteeing general network dependability even if it exactly corresponds with the objectives of the area for an energy transition. With an estimated 1885.3 kWh/kWp shown in Figure 3, the ESC region really has amazing solar potential and is obviously strategically important for solar energy harnessing. But power from these distributed PV (sources especially during low demand and peak sunshine) may generate localized overvoltage issues. The initial design of the infrastructure for a more centralized power system makes grid management considerably more difficult.

Besides that, the area has unrealized wind energy potential in Figure 4. Integrating wind energy might greatly increase the current renewable mix in some areas, where the average wind speed at 50 meters is 9.80 m/s. However, adding wind power would require major technical adjustments to guarantee it runs well with the current infrastructure and does not further aggravate already existing issues.

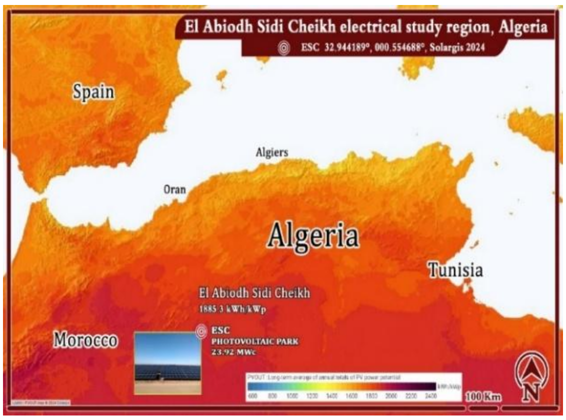

Figure 3. ESC PV potential: 1885.3 kWh/kWp

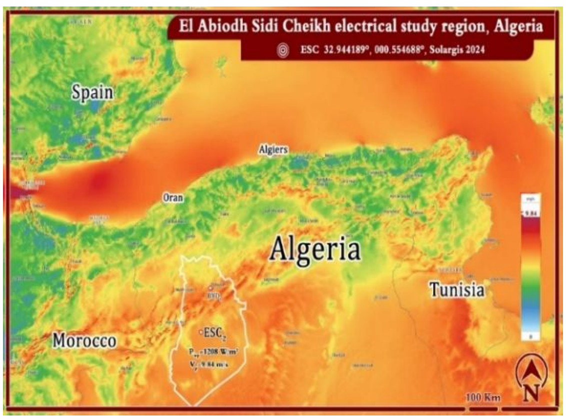

Figure 4. ESC average wind: 1200 W/m² at 50 m

These all point clearly to the multi-layered challenges invading the ESC network: Technical challenges include addressing voltage problems (both drops and surges), optimizing current from existing infrastructure, and managing the impact of climate on energy systems [14], [17], [18]. Related to energy: It is about minimizing technical losses, improving network efficiency, and seamlessly introducing renewable energy sources [2], [7], [19].

This effort focuses especially on the ESC 30 kV network and is all about carefully assessing these problems. We intend to do here: Particularly for those far-off loads like El-Bnoud, pinpoint voltage violations present challenges, find precisely how local climate variables influence overhead line performance, considering the new PV systems, compare the total energy losses of the network to its production, and provide doable technological fixes that increase the dependability, robustness, and energy efficiency of the network.

The results of this study should truly help maximize the performance of the current network and provide specific advice on improved integration of renewable energy sources. Emphasizing sustainable and financially wise solutions, this work should also contribute to a better understanding of how to modernize distribution networks under such conditions. To get all this, the work employs three well-known numerical calculation techniques selected for their accuracy and efficiency in power flow analysis: Newton-Raphson (NR), adaptive Newton-Raphson (ANR), and fast decoupled (FD).

2. MATHEMATICAL FORMULATION

We truly depend on sophisticated modelling tools to tackle those challenging, complicated equations and large system computations. They are necessary for ensuring our analysis is accurate and spot-on. These advanced computer tools were crucial for our work. They guided us in exploring the several configurations of the ESC distribution network and determining the optimal approaches to improve its performance in Figure 5. Consider the single-line figure as our grid map. It lets us examine how energy moves, how to reduce losses, and how to maintain voltage stability by precisely showing us how everything is linked. Look at the single-line diagram for the first zone of the ESC distribution network in Figure 6.

Here are some salient features it emphasizes: simply said, radial arrangement is the way the medium-voltage wires branch from the main substation to every other distribution point, components of a network: It shows visually all the important parts: transformers, transmission lines, and where all the power is being consumed, and particularly in heavy demand, we can quickly identify places experiencing voltage drops or loss of electricity.

To address the stability and efficiency problems in the ESC distribution network, our research followed a quite regimented route. Here is our approach: We compiled comprehensive data on the features of the network, normal usage patterns, and potential generating capacity. This clarified just what was impeding its functioning [20], [21]. Constructing models and running simulations: We developed models of every network component with accepted techniques including FD, ANR, and NR. Key in determining voltage issues, power loss, and network general health was these simulations.

Finding solutions: We focused especially on places with dubious voltage levels and important electricity distribution points. We proposed and implemented methods to offset reactive power in order to resolve voltage problems and get the network working as intended. This methodical methodology guarantees not only identification of actual issues but also generates useful, doable suggestions to guarantee everyone's dependability and efficiency of the ESC distribution network.

Particularly for the behavior of loads, dynamic load models (that which take frequency changes) are very vital when we require an accurate analysis. These models enable us to precisely see how frequency changes the consumption of electricity. This provides us with a far more realistic view of how loads interact with the complete system and their general effect on performance. Maintaining a dependability, stability, and seamless operation of the network depends on this degree of detail [22], [23].

Common and efficient for both static and dynamic load behavior representation is the ZIP model:

$$\begin{cases} S_i^*(t) = P_i(t) - jQ_i(t) = V_i^* * I_i \\ P_i(\mathrm{t}) = P_{\mathrm{i0}}\left[a_p\left(\frac{V_i}{V_0}\right)^2 + b_p\left(\frac{V_i}{V_0}\right) + c_p\right] \\ \mathrm{Q_i(t)} = Q_{\mathrm{i0}}\left[a_q\left(\frac{V_i}{V_0}\right)^2 + b_q\left(\frac{V_i}{V_0}\right) + c_q\right] \end{cases} \tag{1}$$

In these equations, P_i and $\mathrm{Q_i}$ represent the active and reactive power of the load at the operating voltage V, while P_{i0} and Q_{i0} represent the active and reactive power of the load at the nominal voltage. The coefficients of the ZIP model are a_p, b_p, c_p, a_q, b_q, and c_q in per unit (P.u.).

Emphasizing how closely generation, transmission, and consumption are all interconnected inside the distribution network, this model really highlights the dynamic character of energy flow. Finding the intricate nodal voltages is the primary objective of this whole method. Once we have those, we can figure out everything else including line power flow, currents, and even energy losses. Simply said, it all comes down to solving a series of challenging equations in which our major unknowns are the real and imaginary components of those nodal voltages.

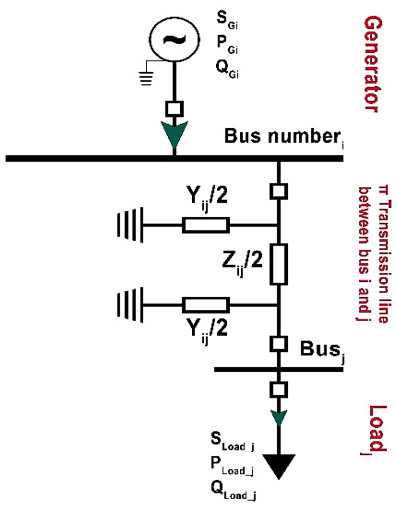

Figure 5. Bus i with production, transmission, and load in bus j

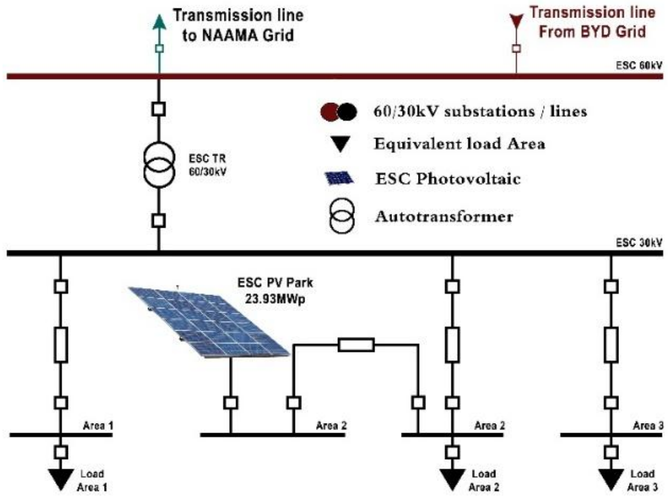

Figure 6. ESC Single-line diagram (Area 2)

2.1. Power flow analysis

Power flow analysis provides operators and planners with critical information, including line loads, bus voltages, generated power, losses and powers optimizations [24], [25]. This information highlights constraints and helps identify areas where limits are exceeded. Modern computational tools make power flow calculations feasible for networks of virtually any size [26], [27]. Each $bus\ i$ is characterized by six variables: $V_i, \delta_i, P_{Gi}, Q_{Gi}, P_{Li}$, and Q_{Li}. For a system with n nodes, this results in $6n$ variables [28]. To ensure the system is solvable, $2n$ unknowns and $4n$ known parameters must be defined.

a. Non-generating busses, $P_{\{Gi\}} = Q_{\{Gi\}} = 0$, and V_i and δ_i are unknown. The Table 1 present the constraints with formulation mathematical.

Table 1. Constraints with formulation mathematical

Constraints	Mathematical formulation	
Generation and load balance:	$\begin{cases} \sum_{i=1}^{N} P_{Gi} - (\sum_{i=1}^{N} P_{Li} + P_{ri}) = 0 \\ \sum_{i=1}^{N} Q_{Gi} - (\sum_{i=1}^{N} Q_{Li} + Q_{ri}) = 0 \end{cases}$	(2)
Generation limits:	$\begin{cases} P_{Gi}^{min} \leq P_i \leq P_{Gi}^{max} \\ Q_{Gi}^{min} \leq Q_i \leq Q_{Gi}^{max} \end{cases}$	(3)
Voltage constraints:	$V_i^{min} \leq V_i \leq V_i^{max}$	(4)
Angle constraints:	$\theta_{ij}^{min} \leq (\theta_i - \theta_j) \leq \theta_i^{max}$	(5)

b. Generating busses: for generating nodes, the following relationships apply:

$$\begin{cases} I_i = \sum_{i=m}^{n} Y_{im} V_m \\ S_i^* = V_i^* * (\sum_{i=m}^{n} Y_{im} V_m) \end{cases} \quad (6)$$

c. The active and reactive power injected at a node are defined as:

$$\begin{cases} P_i = (\sum_{i=m}^{n} Y_{im} V_m V_i) * cos(\delta m - \delta i + \theta im) \\ Q_i = (\sum_{i=m}^{n} Y_{im} V_m V_i) * sin(\delta m - \delta i + \theta im) \end{cases} \quad (7)$$

2.2. Power flow in transmission lines

Once the iterative voltage solution is complete, line flows can be calculated. The current between nodes ii and k is:

$$\begin{cases} I_{ik} = (V_i - V_k) * Y_{ik} + V_i * ({Y'_{ik}}/{2}) \\ S^*_{ik} = P_{ik} - jQ_{ik} = V^*_{ik} * (V_i - V_k) * Y_{ik} + V_i * (\frac{Y'_{ik}}{2}) \end{cases} \quad (8)$$

Where Y_{ik} is line admittance and Y'_{ik} is shunt admittance. System losses are represented as:

$$\begin{cases} S_{ri} = (\sum_{i=0}^{n} S_{Gi}) - (\sum_{i=0}^{n} S_{Li}) \\ P_{ri} = (\sum_{i=0}^{n} P_{Gi}) - (\sum_{i=0}^{n} P_{Li}) \\ Q_{ri} = (\sum_{i=0}^{n} Q_{Gi}) - (\sum_{i=0}^{n} Q_{Li}) \end{cases} \quad (9)$$

Where S_r represents total network losses.

These constraints ensure that the system operates safely, avoiding damage, instability, or insecurity. Figure 7 outlines the process of evaluating power flow results, which are applied in investment planning and operational. The Figure 7 illustrates the step-by-step process for evaluating power flow results, highlighting the sequence of data input, computation, and analysis phases. It is a critical tool for understanding the integration of power flow computations into system planning, including the identification of constraints, optimization of network operations, and assessment of reliability and efficiency.

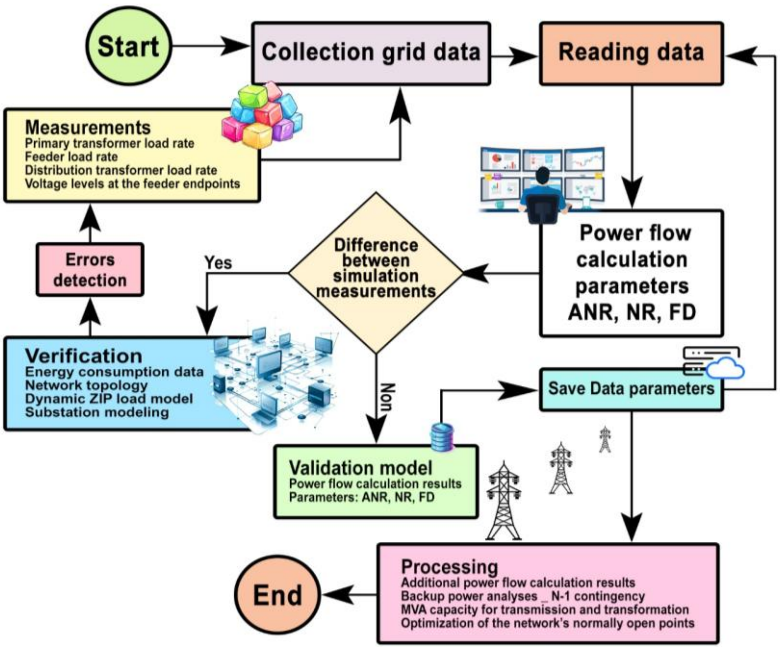

Figure 1. Flowchart of power flow result evaluation process

The lower at 0.9 p.u. and upper at 1.1 p.u. voltage limits are used in our study. The Newton-Raphson (NR) method is widely used for solving nonlinear power flow problems due to its efficiency and fast convergence [27]–[29]. Below is a detailed explanation of the mathematical process.

To solve a nonlinear equation $f(x) = 0$, the Newton-Raphson method relies on successive approximations of the solution x. If Δx^0 is the correction applied to the initial value x^0, the solution is expressed as:

$$x = x^0 + \Delta x^0 \quad (10)$$

Using the Taylor series expansion around x^0, the equation $f(x) = 0$ becomes:

$$f(x^0 + \Delta x^0) = f(x^0) + f'(x^0)\Delta x^0 = 0 \quad (11)$$

Neglecting higher-order derivative terms (since Δx^0 is assumed small), we obtain: $\Delta x^0 = -\frac{f(x^0)}{f'(x^0)}$.

The updated solution and the general iterative form is:

$$\begin{cases} x^1 = x^0 + \Delta x^0 = x^0 - \frac{f(x^0)}{f'(x^0)} \\ x^{k+1} = x^k - \frac{f(x^k)}{f'(x^k)} \end{cases} \quad (12)$$

Convergence criteria: The iterations stop when the following conditions are satisfied:

$$|\Delta x^k| < \varepsilon_1 \; and \; f(x^k)| < \varepsilon_2 \quad (13)$$

where: ε_1 and ε_2 are small positive numbers representing the desired accuracy.

Extension to systems of nonlinear equations: For a system of n nonlinear equations:

$$\begin{cases} f_1(x_1, x_2, \dots, x_n) = 0 \\ f_2(x_1, x_2, \dots, x_n) = 0 \\ \vdots \\ f_n(x_1, x_2, \dots, x_n) = 0 \end{cases} \quad (14)$$

The method is extended to calculate corrections $\Delta x_1^0, \Delta x_2^0, \dots, \Delta x_n^0$. Using the Taylor expansion and neglecting higher-order terms, the system can be written in matrix form as:

$$F(x^k) = -J^k \Delta x^k \quad (15)$$

where: F is the vector of functions $[f_1, f_2, \dots, f_n]^T$, J is the Jacobian matrix containing partial derivatives:

$$J = \begin{bmatrix} \left.\frac{\partial f_1}{\partial x_1}\right|_{x_1^0} & \left.\frac{\partial f_1}{\partial x_2}\right|_{x_2^0} & \cdots & \left.\frac{\partial f_1}{\partial x_n}\right|_{x_n^0} \\ \left.\frac{\partial f_2}{\partial x_1}\right|_{x_1^0} & \left.\frac{\partial f_2}{\partial x_2}\right|_{x_2^0} & \cdots & \left.\frac{\partial f_2}{\partial x_n}\right|_{x_n^0} \\ & \vdots & & \\ \left.\frac{\partial f_n}{\partial x_1}\right|_{x_1^0} & \left.\frac{\partial f_n}{\partial x_2}\right|_{x_2^0} & \cdots & \left.\frac{\partial f_n}{\partial x_n}\right|_{x_n^0} \end{bmatrix} \quad (16)$$

Iterative solution: The iterative update equations are:

$$\begin{cases} \Delta x^{k+1} = -(\mathrm{J}^k)^{-1} \mathrm{F}(x^k) \\ x^{k+1} = x^k + \Delta x^k \end{cases} \quad (17)$$

here, x^k represents the solution vector at iteration k, and J^k is the Jacobian matrix evaluated at x^k.

3. RESULTS (ESC GRID AREA 2)

The results obtained from the ESC network demonstrate the effectiveness of the three applied numerical methods and the identification strategies employed. Thus, providing important information to improve the energy efficiency and resilience of the ESC network. Improving network performance relies in particular on the identification of active power losses and the accurate detection of bus voltage fluctuations, ranging from slight to significant.

3.1. One-hours evolution load shape peak

Analysis of ESC's secondary grid sector reveals substantial demand variance in Figure 8, with Bus 12 (industrial/residential hybrid) drawing 15.71 MW versus Bus 15's minimal 0.87 MW residential load, demonstrating the critical balancing challenge between heavy industrial and light domestic loads within a unified distribution network.

3.2. ESC average temperature

Figure 9 presents the hourly variation in average temperature throughout the study day for the ESC region. This profile helps establish potential correlations between climatic conditions and energy consumption patterns. The average temperature measured on November 5, 2024, is 14.98 °C.

3.3. ESC Trajectory of the Sun

Figure 10 depicts the sun's trajectory in the ESC region, providing essential data on solar angles critical for evaluating solar energy potential. The sun path aligns well with global benchmarks for June and December, confirming the suitability of the measurements for optimizing PV installations and solar trackers.

3.4. ESC park photovoltaic analysis

Figure 11 tracks 24-hour PV generation in area 2 of ESC park (November 05, 2024), showing characteristic daytime production curves. These diurnal patterns are key for predicting renewable contribution and planning storage/grid compensation strategies.

3.5. ESC voltages profiles

Three load-flow methods (NR, ANR, FD) were applied to analyze grid voltages as shown in Figure 12. Consistent violations detected at Bus 4 and 13.

3.6. ESC gain and losses

Figures 13 analyze active power gains and losses within the ESC electrical grid using the NR, ANR, and FD methods. The NR method exhibits the lowest power loss, with a minimal loss of 2.32 MW, highlighting its effectiveness.

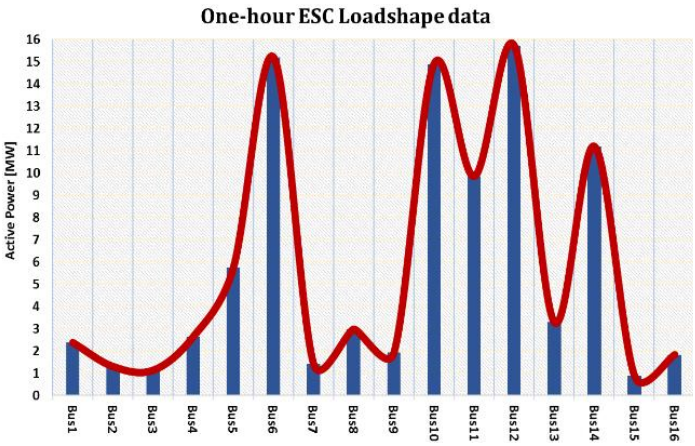

Figure 8. One-hour ESC load curve (MW)

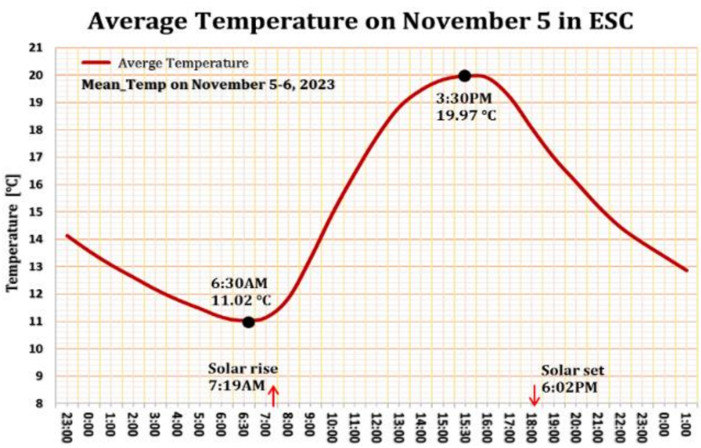

Figure 9. ESC average temperature over the study day

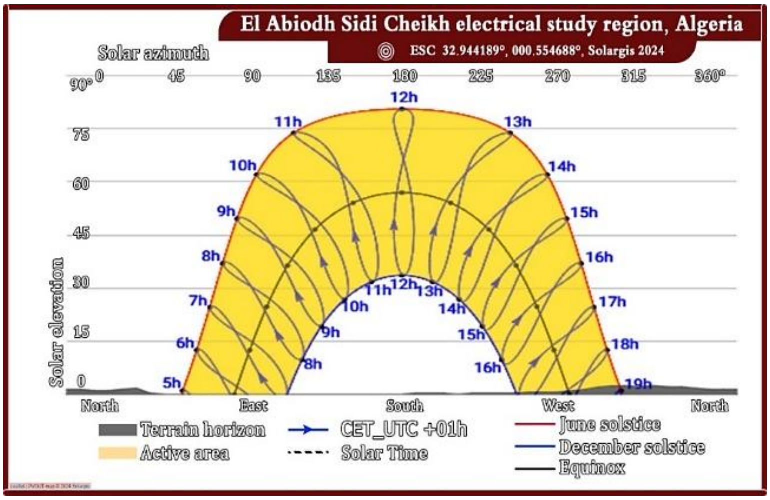

Figure 10. Horizon and sun path diagram in the ESC region

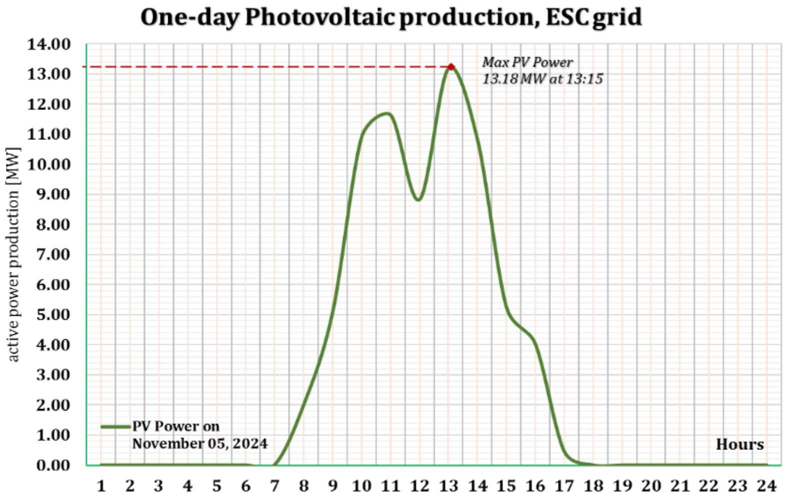

Figure 2. Daily PV output (Area 2, ESC Park)

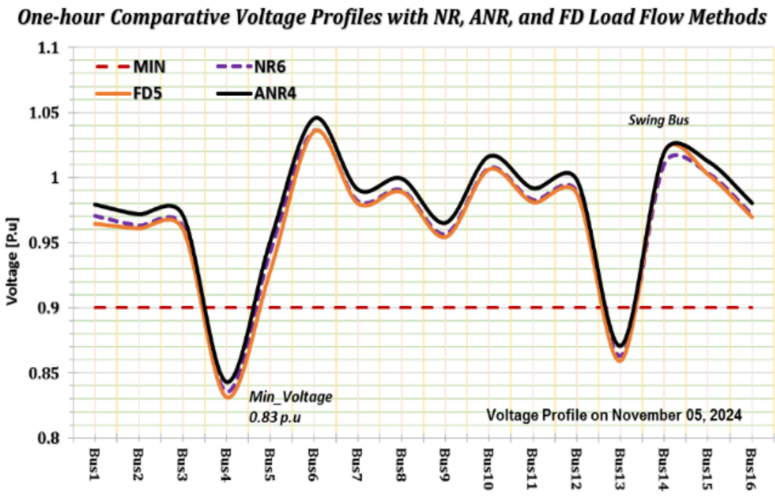

Figure 12. Voltage comparison with NR/ANR/FD methods

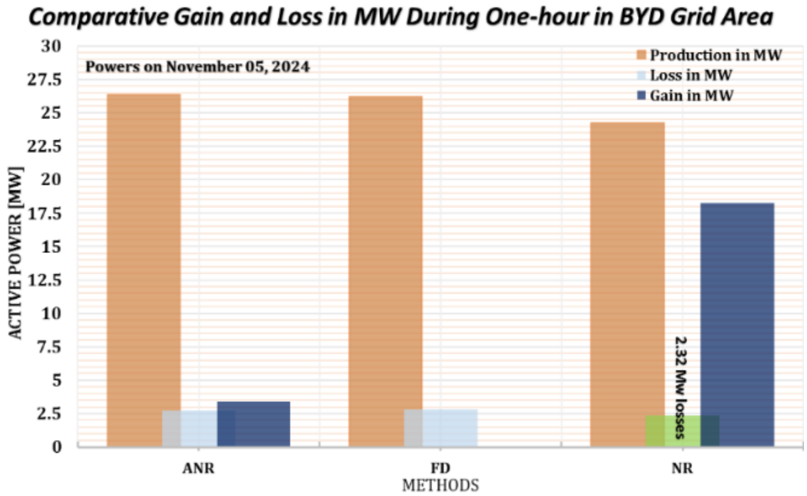

Figure 13. Comparative analysis of power gains and losses for NR, ANR, and FD methods

4. CONCLUSION

This paper assessed the electricity grid in area 2, using three load flow methodologies NR, ANR, and FD by an in-depth examination in ESC, Algeria. The NR technique proved best with low active power losses of 2.32 MW, therefore verifying its better power flow management capacity than the ANR and FD techniques. Significant deviations at busbars 4 and 13 were found by voltage stability analysis over the sixteen buses of the grid, therefore indicating important buses needing quick voltage fixes. These findings suggest that either through transformer Tap changes (TLC) or reactive power compensation, voltage correction determines dependability of grid operation.

During the investigation of environmental impacts on grid functioning, close linkages between temperature oscillations, solar irradiation patterns, and load demand fluctuations were also underlined. Particularly these connections determine the optimization of renewable energy integration strategies. Furthermore, the analysis of the energy generation of PV systems indicated normal diurnal production patterns, which provide required data for enhancing storage capacity and solar energy resource management.

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