Transient stability investigation of a grid integrating solar and wind energies: a case study of southern Algeria

Investigação da estabilidade transitória de uma rede que integra as energias solar e eólica: um estudo de caso do sul da Argélia

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ABSTRACT
The primary goal of electricity producers is to ensure the efficient operation of the electrical grid and the reliable delivery of electricity to individual households. Strengthening the electricity network with the integration of micro-power plants such as wind farms and photovoltaic power plants, as in the case of Algeria, contributes to improving the quality of electricity supplied to consumers. This work presents a simulation study of the electrical network of the Adrar region using ETAP program, to show the influence of the insertion of photovoltaic and wind power plants on the electrical network. The results showed good tolerance of the grid to the integration of wind energy, while the integration of photovoltaic energy needs more requirements and technical challenges to overcome, because, as shown by the results of simulations, the integration of photovoltaic energy makes the network more vulnerable to disturbances. The primary reason for this phenomenon is the lack of mechanical inertia, enabling the system to minimize perturbations. Where wind turbines are unique in their ability to withstand load variations and respond quickly to disruptions. They return to their initial value in 20 seconds, while solar power systems signal return to their initial value after 45 seconds due to their lack of mechanical inertia. Owing to the limitations of the electrical network, the majority of test scenarios demonstrate that wind farm structures can sustain a steady voltage and frequency of 50 Hz. On the other hand, there are momentary fluctuations in voltage and frequency in structures that have photovoltaic systems installed.
Keywords: electricity network, photovoltaic generator, wind turbine, ETAP.

RESUMO
O principal objetivo dos produtores de eletricidade é garantir a operação eficiente da rede elétrica e o fornecimento confiável de eletricidade a residências individuais. O fortalecimento da rede elétrica com a integração de usinas de microgeração, como parques eólicos e usinas fotovoltaicas, como no caso da Argélia, contribui para melhorar a qualidade da eletricidade fornecida aos consumidores. Este trabalho apresenta um estudo de simulação da rede elétrica da região de Adrar usando o programa ETAP, para mostrar a influência da inserção de usinas fotovoltaicas e eólicas na rede elétrica. Os resultados mostraram uma boa tolerância da rede à integração da energia eólica, enquanto a integração da energia fotovoltaica precisa de mais requisitos e desafios técnicos para ser superada, pois, conforme mostrado pelos resultados das simulações, a integração da energia fotovoltaica torna a rede mais vulnerável a distúrbios. O principal motivo desse fenômeno é a falta de inércia mecânica, o que permite que o sistema minimize as perturbações. As turbinas eólicas são únicas em sua capacidade de suportar variações de carga e responder rapidamente a perturbações. Elas retornam ao seu valor inicial em 20 segundos, enquanto o sinal dos sistemas de energia solar retorna ao seu valor inicial após 45 segundos devido à falta de inércia mecânica. Devido às limitações da rede elétrica, a maioria dos cenários de teste demonstra que as estruturas dos parques eólicos podem sustentar uma tensão e uma frequência constantes de 50 Hz. Por outro lado, há flutuações momentâneas na tensão e na frequência em estruturas que têm sistemas fotovoltaicos instalados.

Palavras-chave: rede elétrica, gerador fotovoltaico, turbina eólica, ETAP.

1 INTRODUCTION
On a global scale, various sectors, such as agriculture, power, and diverse architectural structures, are progressing. The observed increase aligns with the growth of the population, which has a direct impact on the energy demand [1]. Moreover, electricity generation is mainly facilitated by conventional power plants that primarily rely on the combustion of fossil fuels inside traditional power systems [2]. The presence of elevated levels of carbon dioxide (CO2) in the atmosphere, coupled with the persistent dependence on fossil fuels, necessitates the development of novel technological interventions [3]. Renewable energy sources, including hydro, solar, wind, biomass, geothermal, and marine energy, have the potential to satisfy the world’s rising energy needs while also significantly lowering CO2 emissions [4,5]. Currently, the adoption of renewable energy sources is considered an essential tool in the efforts to boost sustainability in the power sector...
and address the adverse impacts of climate change. Solar photovoltaics (PV) and wind power have experienced significant growth in recent decades, with global installed capacity percentages of 4% and 7%, respectively. These technologies have demonstrated average annual growth rates of 27% and 13% over the preceding years [6,7]. The capacity of installed renewable energy reached 295 GW for the first time in 2021. Between 2020 and 2021, solar photovoltaics grew from 134 GW to 151 GW, mainly at the expense of wind, which dropped from 113.3 GW to 94.3 GW [8]. The complexity of existing energy systems poses challenges to the programming and integration of renewable energy sources and to ensuring the efficient control of energy operations. It is more challenging to include renewable energy sources and increase energy production since they are unpredictable and changeable, particularly wind and solar energy [9]. Thus, integrating renewable energy-based power plants into the conventional power system leads to power and voltage fluctuations, owing to the inherent variability of wind and solar power sources. Furthermore, the photovoltaic (PV) system lacks any mechanical components, hence lacking inertia. Therefore, more devices are necessary to uphold the frequency [10,11]. The stability and dependability of power systems will be more vulnerable to renewable energy power plants due to the rise of green power generation. Regarding structure, the growing utilization of renewable energy makes the system’s power structure more complicated, which might pose greater running risks; the elevated use of renewable energy will raise the network's rate of interruption and increase the susceptibility of the power grid to risks. [12,13]. Algeria exhibits considerable potential for producing renewable energy, particularly in the domains of solar and wind energy. [14]. The government launched a national renewable energy program (PNER) which is set to be implemented from 2015 to 2030. It plans to install 22,000 MW, i.e., 27% of the overall energy mix by 2030. Photovoltaic has the largest share with 13,750 MW, followed by wind power (5,000 MW), 2,000 MW of CSP (Concentrated Solar Power), biomass (1,000 MW) and 400 MW in cogeneration [15].

Several researches on the subject of this paper have been presented in the literature.

The authors in [16] investigate the problems, prospects, and future trends of inverter-based distributed energy resources (IBDER) integrated distribution
grids. Control and protection solutions have been developed. Reference [17] presents the simulation of influence of renewable sources on the grid, using a PSS®E software simulation tool. Furthermore, a contingency analysis is performed to determine their influence on supply dependability and security. Finally, this article suggests ways to strengthen the transmission system.

Authors in [18] compared grid codes from Germany, the United States, Puerto Rico, Romania, China, and South Africa in terms of fault ride through capabilities, frequency and voltage management, and active and reactive power assistance. Furthermore, a wide overview of the obstacles that large-scale solar power plants must solve, as well as compliance technologies and future trends, is presented.

The research published by the authors in reference [19] investigates the modelling, simulation, and control strategies employed in a grid-connected hybrid solar-wind system. The system incorporates two tiers of energy storage and is evaluated across diverse climatic conditions. The Particle Swarm Optimization (PSO) method, which creates the ideal PV system current, is used to optimize the power of the PV system using MatLab-Simulink.

The authors in [20] analyzed the documented issues produced by wind energy integration as well as the offered solutions techniques. Many of the solutions utilized and suggested to minimize the impact of these difficulties, such as energy storage devices, wind energy policies, and grid regulations, are analyzed and explored.

The research in [21] presented the influence of integrating a large-scale Doubly-Fed Induction Generator (DFIG)-based wind energy conversion system (WECS) on the voltage stability of Nigeria’s 52-bus, 330 kV power grid. Indices derived from Active Power-Voltage (PV) and Reactive Power-Voltage (QV) analyses were used to determine the voltage stability limits in terms of the system’s maximum active power margin (APM) and minimum reactive power margin (RPM), as well as the system buses’ critical voltage-reactive power ratio (CVQR).

The authors in [13] conducted an analysis on the dynamic and steady-state implications of intermittent renewable energy generators (IREGs) on the electricity system of Lesotho. The study examined the responses of frequency, voltage, and rotor angle under different degrees of solar PV and wind power penetration. These
responses appeared when a fault occurred at the substation with the shortest critical clearance time (CCT). The DigSILENT Power Factory program was used to conduct the impact studies. The integration of a 36 MW solar farm into the power grid at a voltage level of 132 kV resulted in grid instability due to the presence of rotor angle instability. Similarly, the connection of a 52 MW wind farm at an 88 kV voltage level created grid instability due to an excessive voltage of 1.051 (p.u.) at the adjacent 33 kV Tlokoen substation.

This research aims to determine and suggest the best practices for efficiently integrating renewable energy sources into the electrical grid. Establishing a dependable and sustainable energy network that optimizes wind farms and solar fields potential while providing effective operation, low environmental impact, and long-term energy security is the ultimate goal.

Due to the introduction of renewable energy sources to the Adrar region (Algeria) electrical network [22], this study wants to emphasize how these various components affect the behaviour of the actual electrical system of this region by analyzing its performance both with and without the addition of PV power systems and wind farms. To demonstrate the influence of integrating PV plants on voltage levels, network frequency, and operation, as well as the consequential consequences on network stability, a series of scenarios and architectures were simulated.

2 AN OVERVIEW OF ALGERIA’S ADRAR WILAYA ELECTRICAL NETWORK

The power network of the Pole InSalah-Adrar-Timimoun (PIAT) [23] serves as a representative illustration of the inclusion of renewable energies inside the framework of the National Renewable Energy Programme (PNER), where the strongest wind and solar potential in Algeria are located. Two photovoltaic power systems (20 MWp and 3 MWc) and one wind farm (10.2 MWc) make up the system. The autonomous Adrar electrical network consists of four (4) THT transmission lines, seven (7) THT/MT transformer stations, and seven (7) production facilities, including gas-fired power plants, portable generators, and renewable energy-powered structures. These massive production facilities are dispersed along the PIAT pole (Table.1). The SKTM 20MWc Adrar plant[24], the
SKTM 3MWc plant, and the 10.2 MWc wind power plant will be the three production facilities that we will concentrate on[25].

Figure 1. Electrical energy production and evacuation system of the ADRAR power plant

Table 1. PIAT Adrar conventional production plant

<table>
<thead>
<tr>
<th>Identity of the central</th>
<th>Power</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adrar TG plant</td>
<td>4*25 Mw</td>
<td>5001 PA Nuovo Pignone (Italy)</td>
</tr>
<tr>
<td>TG Asea</td>
<td>2*6 MW</td>
<td>ASEA Brown Boveri B.V.50Mw</td>
</tr>
<tr>
<td>XD Adrar</td>
<td>2*20 Mw</td>
<td>TG type Of JOHN BROWN</td>
</tr>
</tbody>
</table>

Source: Authors.

3 SYSTEM MODELLING
3.1 WIND TURBINE MATHEMATICAL MODEL

As production costs decline, it will be possible to integrate wind energy into a sustainable energy production system that can participate in the power generation sector [26]. Energy systems with constant or variable speeds are used to generate wind power. As a result, there is a connection between the rotor's power, torque, rotational speed and wind speed. The mechanical components of
a wind turbine that convert wind energy into electrical energy are the generator and rotor assembly [27]. The following formula determines the mechanical power that can be obtained from the wind [28,29]:

\[
P_w = \frac{1}{2} \rho R^2 V^3 \pi C_p(\lambda, \beta)
\]  

The power generated by the wind turbine's rotor is given by the following relation

\[
P = C_p \cdot \frac{\rho \cdot S \cdot V^3}{2}
\]  

With:

\( \rho \) is the air density, which is around 1.2 kg/m³.
The blade's length is represented by \( R \).
Where \( C_p \) is the wind turbine's coefficient of power, it is dependent upon the tip-speed ratio \( \lambda \) and pitch angle \( \beta \). The value of coefficient power is expressed as:

\[
C_p(\lambda, \beta) = 0.5 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}}
\]

\[
\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^2 + 1}
\]  

The torque generated on the wind turbine's rotor is explained as below:

\[
T = \frac{P}{\omega}
\]  

Where:

\[
T = \frac{\rho \cdot S \cdot V^3}{2 \omega}
\]  

3.2 PHOTOVOLTAIC MODULE MATHEMATICAL MODEL

The equivalent circuit description of the cell is used to make the physical models, which simulate the whole \( I - V \) curve as a continuous function for a given set of operating conditions. The most widely used physical models, referred to as
diode models, benefit from the similarities between diodes and solar cells. However, numerical fitting of device measurements usually yields empirical models that only estimate important spots on the $I$-$V$ curve [30, 31, 32]. The equation that determines the output current of the PV array is [33]:

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{V + IR_s}{aV_t} \right) - 1 \right] - \frac{V + IR_s}{R_p}$$

(6)

The value of the thermal voltage is:

$$V_t = \frac{N_s kT}{q}$$

(7)

$I$ is the module’s output current.

$V$ is the module’s output voltage.

$a$ is the ideality factor of a diode.

The characters $I_0$, $R_s$, $R_p$, $I_{ph}$, and stand for the diode saturation current, series and shunt resistances, and photocurrent, respectively.

4 SIMULATION DESCRIPTION

The joint IEEE/CIGRE working group defines the stability of the electrical system as follows: "It is the ability of the electrical system to return to a position of stable equilibrium, after a sudden disturbance of high amplitude, this disturbance can considerably deviate the network from its initial position". The electrical system contains various components, including transmission lines, generators, loads, and more elements, which collectively contribute to the occurrence of instability. These conditions generate continuous changes in response to disturbances, regardless of their magnitude. The disturbances in question can manifest as either a load rise or a fault. The presence of numerous uncertainties impacts the operational parameters, hence giving rise to equilibrium challenges within the production process. The stability of power systems can be broadly categorised into three basic classifications: power stability, rotor angle stability, and voltage and frequency stability [34].

In our case, the analysis of transient stability was employed. Transient stability refers to the ability of an electrical system to preserve the synchronism of its machines following temporary disturbances, such as line faults or the loss of a
power station, etc. The simulation duration is 60 s, in order to reach the steady state and have a precise analysis. To carry out this study, we used the ETAP software (Electrical Transient Analyzer Program) as a means of simulation. It is a simulation and modeling software that electrical systems engineers use to process and calculate the dynamic, transient and protection of electrical power system. The "Adaptive Newton-Raphson" method is selected as the calculation method.

Figure 2 shows the studied system under the ETAP software environment; it is composed of:

- three (03) classic power stations based on eight (08) electrical generators of power between 6 and 25 Mw, connected to the 30 Kv busbar through power transformers;
- a wind farm with a power equal to 10.2 Mw, a photovoltaic power plant with a power of 20 Mw and one of 3 Mw, they are inserted into the 30 Kv busbar;
- 30 Electrical different loads connected to busbar1, varying between 0.69 (minimum) and 5.92 MVA (maximum) with a total of 630 Kva.

In this context of our simulation, the studied system is affected by a three-phase fault that appears at time 1.0 seconds and is erased at time 1.083 seconds. The behavior of the electrical generators and the influence on the main busbars 30 kV and 220 KV have been analyzed, by observing the following parameters (power angle, electric power, reactive power, electric current). Different possible scenarios that show the operation and stability of the electrical network have been studied. In addition, we studied the influence of the penetration rate of renewable energies on the operation of the electrical network, for several proposed electrical architectures.
5 RESULTS AND DISCUSSIONS

5.1 SCENARIO 1 – ALL PLANTS

In this case, we have simulated the entire electrical system, which is composed of the elements shown in Figure 2. Figure 3 and Figure 4, shows an amplitude peak during the fault, and then it is reduced after its elimination. Subsequently, significant oscillations were observed and progressively attenuated towards their initial position following the rectification of the fault. In the context of the present analysis, it is observed that both the current and active power exhibit a series of oscillations, which eventually achieve a state of stability after the removal of the fault. The frequency and the amplitude of the voltage mark a drop in the moment of the fault; they oscillate until they return to the nominal value.

Figure 3. Simulation of transient stability analysis of scenario 1 (Electric generator)

a. Relative power angle of generator  b. Electrical power of the generator
c. Reactive power  d. Generator current
5.2 SCENARIO 2- ALL PLANTS WITHOUT WIND TURBINES

In this case (Figure 5 and Figure 6), we have isolated the wind farm and kept all the other plants at their full capacities, to see the reaction of our system and its influence on the electrical generators. In this situation, the operation of the system is affected by the integration of photovoltaic power plants and synchronous machine power plants. Like the previous scenario, we see the appearance of the same amplitude peak behaviors, but this time we noticed that the oscillations continued after the elimination of the fault for a longer duration than in the previous case. Voltage and frequency show a drop in amplitude, and current and active power show a significant increase in amplitude.
Figure 5. Simulation of transient stability analysis of scenario 2 (Electric generator)

- Relative power angle of generators
- Electrical power of the generator
- Reactive power
- Generator current

Source: Authors.

Figure 6. Simulation of transient stability analysis of scenario 2 (220 Kv and 30 Kv bus bar)

- Voltage angle
- Frequency
5.3 SCENARIO 3 – ALL PLANTS WITHOUT PHOTOVOLTAIC PLANTS

In this scenario (Figure 7 and Figure 8), the simulation of our system is carried out without the insertion of the photovoltaic power plants (20 Mw of Adrar zone and 3 Mw of kabarten). We notice that there is a peak of amplitude appearing in the moment of the fault for all the curves and after its elimination, the various curves present small oscillations appearing in a short time and the stable state of the system is reached after a few seconds.

Figure 7. Simulation of transient stability analysis of scenario 3 (Electric generator)
   a. Relative power angle of generator
   b. Electrical power of the generator
c. Reactive power  

d. Generator current  

Source: Authors.

Figure 8. Simulation of transient stability analysis of scenario 3 (220 Kv and 30 Kv bus bar)  
a. Voltage angle  

b. Frequency  

c. Voltage  

Source: Authors.
5.4 SCENARIO 4 – CONVENTIONAL POWER PLANTS WITHOUT RENEWABLE ENERGIES

For this case, we launched the simulation of the electricity network without the integration of power plants based on renewable energies (Figure 9 and Figure 10). To see how these affect the electrical generators and the main buses of our system. The following figures show fewer oscillations, which last only 5 seconds, and a stable state after the elimination of the fault.

Figure 9. Simulation of transient stability analysis of scenario 4(Electric generator)
\[\text{a. Relative power angle of generators} \quad \text{b. Electrical power of the generator} \]

\[\text{c. Reactive power} \quad \text{d. Generator current} \]

\[\text{e. Voltage angle} \quad \text{f. Frequency} \]

Source: Authors.
5.5 SCENARIO 5 – ALL CONVENTIONAL PLANTS + 5MW PV-

This scenario aims to show the influence of the rate of penetration of photovoltaic power plants in the electrical network; we have integrated only 5 Mw of the total PV power (20 Mw), associated with conventional generators. We see after the elimination of the fault the presence of small oscillations during all the time of the simulation (Figure 11 and Figure 12).
Figure 11. Simulation of transient stability analysis of scenario 5 (Electric generator)
a. Relative power angle of generator   b. Electrical power of the generator

c. Reactive power
d. Generator current

Source: Authors.

Figure 12. Simulation of transient stability analysis of scenario 5 (220 Kv and 30 Kv bus bar)
a. Voltage angle   b. Frequency
c. Voltage

![Graph showing voltage over time]

Source: Authors.

The graphs mentioned previously show the active and reactive power generated by various sources, including wind and solar energy. Additionally, they depict the power angle, electric current, voltage, and frequency of the primary buses operating at 30 Kv and 220 Kv. After eliminating the fault, one notices in the scenarios in which injected productions based on wind turbines a resemblance consisting of short-term oscillations, which have been weakened towards the stable state quickly. This is due to the mechanical inertia of wind turbines, which quickly dampens the disturbances that appear following the application of faults.

- the presence of the production generated from the wind farm contributes to the stability of the electrical system because of the inertia, which will dampen the various oscillations and compensate for the imbalance between production and consumption;
- according to the results of the preceding simulation and the various scenarios proposed for the case of insertion of the solar power stations, we note that the addition of these power stations to our electrical system causes oscillations of different amplitudes according to the percentage of the PV systems in the total output. These oscillations are caused by the intrinsic characteristics of PV systems consisting of the absence of mechanical inertia. Even inverters that are tied into the PV system can produce less precise control characteristics that can exhibit large swings in voltage and power. Thus, a significant penetration of PV-based production can disturb the impedance of the network;
• mixing between two or more renewable-based productions, like our case where there is a combination of two PV and wind sources, may introduce additional oscillations;
• the integration rate directly influences the frequency of the system when we have injected the total capacity produced by the PV and wind power plants, noticing that the frequency exceeds its nominal value and the reverse in the case where we have inserted a lower rate of power.

6 CONCLUSION

The simulation study in this work showed the behaviour of the electricity network, and in particular that of ADRAR (Algeria) faced with the integration of renewable energies. The results showed good tolerance of the grid to the integration of wind energy. In contrast, the integration of photovoltaic energy needs more requirements and technical challenges to overcome because, as shown by the results of simulations. The integration of photovoltaic energy into the network increases its susceptibility to perturbations. The main reason for this behaviour is the absence of mechanical inertia, which allows the system to dampen concerns effectively. The capacity of wind turbines to tolerate fluctuations in load and react rapidly to disturbances makes them unique in this regard. While solar power systems signals recover to their initial value after 45 seconds due to mechanical inertia, wind turbines take a mere 20 seconds to recover to the same level. Most of the test scenarios show structures that are integrated by wind farms can maintain a constant voltage and frequency of 50 Hz. However, in structures where photovoltaic systems are installed, there are brief variations in frequency and voltage. This study's findings have significant implications for academia and society. It suggests that understanding the different capacities of wind and solar electricity can improve policy decisions and grid planning initiatives, leading to a shift towards a more sustainable energy system, enhancing grid stability and resilience through strategic deployment of renewable energy sources. This study contributes to the understanding of technical difficulties and system-level effects of combining renewable energy sources. Wind turbines recover faster than solar PV, highlighting the need for ongoing research in energy storage and grid-interactive controls. The findings can guide the development of advanced grid modeling and
optimization methods, encouraging interdisciplinary cooperation in energy policy, renewable energy, and power systems engineering. This will help develop more sustainable ways to integrate renewable energy, meet society's energy needs, and advance scholarly knowledge.
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