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# VRE Integrating in PIAT grid with Optimal Techniques: A Case Study Kabertene

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## Abstract

The imperative shift to cleaner energy sources is crucial for addressing environmental and economic challenges. However, renewable energy faces grid stability issues due to dynamic electrical demand fluctuations and weather variations have a significant stability impact on the frequency and the dynamic voltage of Algeria's isolated PIAT grid. To maintain stability power supply, it is crucial to keep these quantities close to the nominal values. An Automatic Frequency Restoration Reserve (AFRR) and local reactive compensation are used to regulate real-time frequency fluctuations and voltage drops respectively, caused by integrating Variable Renewable Energy (VRE), specifically wind and solar power. Two capacitor banks with capacity of 5MVAR were installed at the buses of Timimoune and Adrar to supply reactive power to the grid. The study proves the effectiveness of using the MPPT algorithms for PV Park, and PSO for the optimal distribution of VREs. It leads to a significant reduction in active losses, up to 21.83%, while successfully managing frequency fluctuations and voltage, thus improving network stability. In addition, the strategic control of the power factor at the injection buses guarantees optimum power quality and maximizes the use of VRE. This approach reduces reliance on gas turbines, leading to a noteworthy reduction of 15.05% in the overall production of 178.96 MW in the PIAT grid. This reduction in natural gas consumption contributes to lower operational costs and a decreased carbon footprint, promoting a more sustainable and environmentally friendly energy landscape.

**Keywords:** Integration VRE, ZIP dynamic models loads, Automatic Frequency Restoration Reserve, Power System Stabilizers, Maximum Power Point Tracking, Particle Swarm Optimization, PIAT grid

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## 1. Introduction

As Renewable Energy Sources (RES) such as wind and solar power play a larger role in our energy systems, maintaining a stable and resilient power grid in real-time becomes more crucial [1]. Unlike traditional power plants, renewable energy sources are variable, and their output depends on external factors like weather conditions. This variability can introduce challenges for maintaining grid stability, particularly in terms of frequency control [2].

Frequency control is the process of managing the balance between electricity generation and consumption to ensure that the grid operates at a stable frequency. In most power systems, the frequency is kept at a constant level, typically 50 or 60 Hz [3], and any deviations can have detrimental effects on the grid and connected devices [4]. Traditional power plants, which have large rotating masses, provide inherent inertia that helps stabilize the frequency of the grid [5].

However, renewable energy sources, such as solar and wind, do not possess the same level of inherent inertia. Their output fluctuates with changing conditions, which can cause frequency variations if not properly managed [5]. If there is an imbalance between generation and consumption, the

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frequency can deviate from the desired level, leading to grid instability and potential blackouts.

The Algerian Electrical System Operator (AESO) face challenges related to voltage stability and frequency fluctuations, especially during periods of high electrical demand and the integration of Variable Renewable Energy (VRE) sources [6]. To address these issues, the operators employ various strategies, including planning production and power distribution plans based on non-linear ZIP dynamic load models [7].

These non-linear load models take into account the characteristics and behavior of different types of loads, considering their non-linear power consumption patterns. By accurately modeling and forecasting load behavior, the operators can better plan, operate, and maintain the electrical grid of the Pole InSalah-Adrar-Timimoune (PIAT) region [7].

As the penetration of renewable energy sources like solar and wind power increases within the PIAT grid, frequency control becomes increasingly crucial. The average wind speeds in the region range from approximately 3 to 5 m/s, indicating the presence of significant wind potential as shown in Fig. 1. However, the intermittent nature of these energy sources poses unique challenges in maintaining a stable frequency throughout the power system [7].

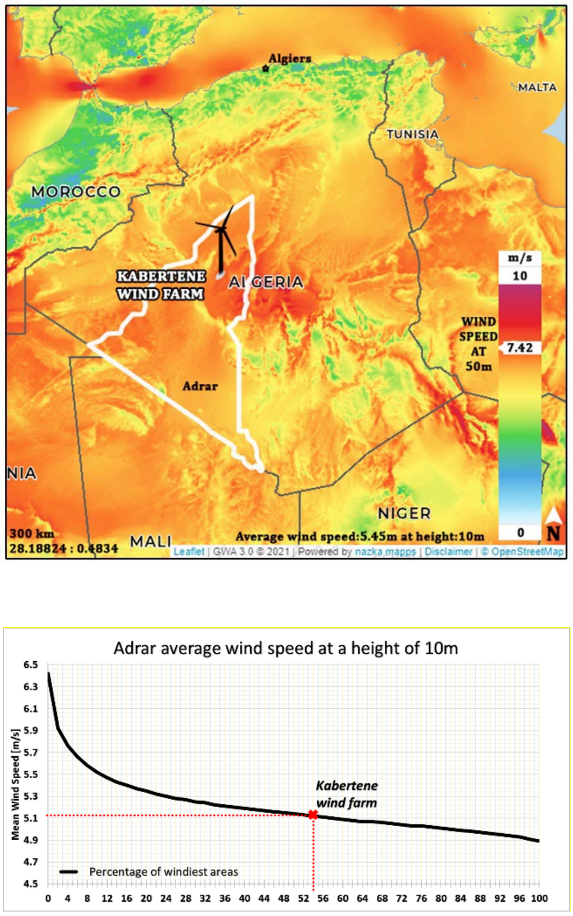


**Figure 1.** (a) Wind Potential in Adrar province, Algeria, (b) The mean wind speed in Kabertene region

Efforts to ensure frequency control in VRE systems revolve around maintaining a balance between electricity supply and demand. Excessive renewable energy generation can result in a surplus of power, causing the frequency to rise and potentially causing instability [8]. Conversely, insufficient generation can result in a frequency drop. Thus, effective frequency control is essential to prevent these deviations and maintain a stable grid [9].

To compensate for the reduced grid inertia resulting from the integration of RES, alternative methods are employed. This may involve the use of virtual inertia systems or synthetic inertia, which simulate the behavior of traditional rotating machines. These technologies help stabilize the grid frequency by providing the necessary resistance to frequency changes [10].

Power system reserves play a vital role in frequency control. These reserves consist of primary and secondary reserves. Primary reserves, which react quickly to frequency deviations [11], usually provide fast-response resources like natural gas-fired power plants or energy storage systems [12]. Secondary reserves offer a longer response time and are dispatched to restore frequency if primary reserves are exhausted [13]. In the interest of conciseness, we have restricted our scope to delineating the five paramount practical techniques utilized for frequency control in power system:

## 1. Grid inertia and frequency response

Keeping grid frequency under control is a new challenge as we enter the era of VRE, however, conventional power plants have been the backbone of power systems that gracefully spin their masses to provide inherent stability. As a result, the network's ability to withstand frequency changes is diminished and maintaining stability becomes more complex [14].

## 2. Primary frequency control

This dynamic technique makes it possible to quickly restore the balance between electricity supply and demand. known as Automatic Generation Control (AGC), essential to keep the network running smoothly. By continuously monitoring frequency deviations, the AGC orchestrates the output of controllable energy sources such as natural gas-fired power plants [15], [16].

## 3. Secondary frequency control

Called automatic load shedding or Automatic Frequency Restoration Reserve (AFRR) comes into play if the AGC are insufficient to restore the grid frequency. It involves larger adjustments, such as shedding predetermined loads in a controlled manner. This control typically relies on sophisticated algorithms and centralized dispatch systems to manage the load shedding process while minimizing disruption to consumers [17], [18].

## 4. Auxiliary Services

These services have indirect and additional functions that contribute to frequency control [19]. These services include reserve regulation, reactive power control, voltage regulation, and blackout start capabilities [20].

## 5. Electrical System Operation (ESO)

The operation of electrical systems also has an impact on frequency control in VRE systems. Network operators should incorporate flexible dispatch strategies and plans that take into account the nature of VREs [21], [22].

Advanced control algorithms and predictive modelling techniques are used to improve dynamic network frequency control in VRE systems, such as frequency control technique by AGC and AFRR. These algorithms use real-time data and forecasts based on actual load curves to anticipate renewable energy production and adjust grid operations accordingly [23]. By coordinating, the production of RES and other grid assets, these algorithms help maintain frequency stability [24].

Demand response programs also play a role in frequency control. By incentivizing consumers to adjust their electricity usage in response to frequency deviations, the demand can be dynamically managed to match the available generation capacity [25]. This active participation of consumers helps to stabilize the PIAT grid frequency [26], [27].

Along with the frequency control in electrical grid stability, the reactive power compensation plays a significant role in maintaining both aspects, which is a key factor in maintaining network stability [28]. The reactive power control is necessary for maintaining the voltage levels within an acceptable range, as it helps balance the reactive power demand and supply in the system. Reactive power compensation devices, such as capacitors, reactors, and Static Var Compensators (SVCs), actively provide or absorb reactive power to regulate voltage levels [29], [30].

The balance between real power and reactive power in the system affects the power factor, which is the ratio of real power to apparent power. By adjusting the reactive power supply, power factor correction improves the overall system efficiency and reduces losses [31].

Additionally, reactive power compensation devices can assist in frequency control by contributing to grid stability. They provide voltage support and help maintain stable voltage levels, which indirectly influence the frequency response of the system. Stable voltage levels contribute to smoother operation and better frequency regulation [32].

Voltage control is necessary to keep it within specified limits, typically around the nominal voltage, in order to meet the requirements of connected electrical devices and loads. Any deviations from the desired voltage can lead to equipment malfunctions, reduced power quality, and inefficient power transfer. By supporting stable voltage levels, it indirectly contributes to frequency control and enhances overall network stability. Proper reactive power compensation ensures efficient power flow, reduces losses, and supports the integration of renewable energy sources [33].

In summary, var compensation plays a vital role in the integration of VRE sources and frequency control [34]. When it comes to VRE integration and frequency control, there are several aspects to consider:

### 1. Voltage Stability

RES have variable and intermittent production, and this can lead to voltage fluctuations on the electrical network. Devices supply or absorb reactive power to keep voltage within acceptable limits, supporting RES and indirectly contributing to frequency control.

### 2. Power Factor Correction

RES often have a variable power factor, influencing the power flow in the grid [35]. Correcting this power factor is crucial to minimize active losses, optimize energy efficiency, improve voltage profiles [36], and plays a significant role in maximizing the benefits of renewable energy integration.

### 3. Grid Codes and Requirements

Grid codes often impose specific requirements on VRE generators regarding reactive power control [37]. These codes define the necessary standards and limits for reactive power compensation to ensure stable and reliable operation of the grid, aiding in maintaining voltage and frequency stability [38].

### 4. Voltage Control and Ancillary Services

Voltage control is closely linked to frequency control in power systems. Reactive power compensation devices and control strategies can actively regulate voltage, thereby influencing the frequency response [32]. Voltage control schemes, such as Automatic Voltage Regulators (AVRs) and SVCs [33]-[35], work in conjunction with frequency control mechanisms to maintain grid stability [36]. These devices provide reactive power support to manage voltage fluctuations [37] and contribute to frequency control as a part of ancillary services.

### 5. Coordination with Frequency Control

Reactive power compensation devices need to be coordinated with frequency control mechanisms to respond to deviations effectively [38]. This coordination helps maintain proper voltage levels, support system reliability, and contribute to overall frequency stability [39].

### 6. Integration of VRE

Efficient management of renewable energy sources is crucial to optimize their contribution to the grid and to meet electricity needs sustainably [40]. To address these constraints, minimize the utilization of natural gas in the Adrar and Timimoune gas turbines while maximizing the utilization of the Kabertene photovoltaic, and wind park, we used the results of the works by Professor Yassine Kebbati on the Maximum Power Point Tracking (MPPT) technique [41].

In the literature, MPPT is a high-performance technology that regulates the output current and voltage of photovoltaic panels [42]. It estimates the optimal global electrical power point in real-time to efficiently transfer power to the battery or grid working with programmable device controls [43],[44].

Various MPPT algorithms are used for photovoltaic and wind systems control, such as the imperialist competitive algorithm and artificial neural networks [45], [46], and other studies based on MPPT control [47, 48].

These advanced algorithms contribute to enhancing the performance and efficiency of renewable energy integration into the electrical grid.

## 1.1. Followed methods and strategies

For electrical grid managers, a photovoltaic plant or wind farm is viewed as a generator of active power $P_{Gi}$ and reactive power $Q_{Gi}$ that are injected into the electrical grid. These active and reactive powers contribute to the integration and balance of the electrical grid, ensuring a stable and reliable power supply for consumers while minimizing costs and environmental impacts.

Our research strategy is focused on achieving a harmonious balance between the powers transported, the production of electricity (including gas turbine and RES) and the energy consumption (D-ZIP dynamic loads) within the PIAT network. In this article, we present an exhaustive study of frequency and voltage stabilization for all buses in the PIAT network, taking into account the integration of renewable energy resources.

The dynamic characteristics of electrical loads and renewable energy resources can cause grid instability, which can lead to critical scenarios and outages. To remedy this problem, we used specific frequency regulation and voltage correction techniques.

In particular, we focus on the implementation of AFRR technique to correct frequency deviations through active control of power generation. In addition, for voltage correction, we adopt the local reactive power compensation approach.

The fusion of AFRR for frequency control and local reactive power compensation for voltage control is the primary purpose of the Power System Stabilizer (PSS).

In addition, we use the meta-heuristic algorithm Particle Swarm Optimization (PSO) to optimize the power distribution of PV generation integration and effectively regulate power consumption. PSO is instrumental in finding optimal solutions to the energy allocation problem, ensuring the efficient use of renewable energy resources while improving grid stability.

Our research delves into the intricate realm of dynamic integration of RES within the PIAT grid, illuminating the diverse challenges and promising opportunities embedded within this complex domain.

### 1. Technical Challenges

Through detailed analysis, we shed light on the complex technical challenges associated with integrating VRE into the grid. Our focus on the impact of such integration on network stability and control provides valuable insights for AESO.

### 2. AFRR Control Strategy

One of our key achievements is the successful development and implementation of a control strategy based on the AFRR mechanism. This approach ensures efficient utilization of VRE generation while upholding grid stability through real-time frequency regulation.

### 3. OPF Techniques for Optimization

By integrating Optimal Power Flow (OPF) techniques, we optimize the allocation of energy resources, including dynamic PV generation and conventional power production. This optimization minimizes system costs and significantly enhances overall network performance.

### 4. Practical Validation

Our proposed approach has been practically validated using real-world data from the Kabertene region. The results demonstrate the effectiveness of our strategy in enhancing grid control and improving energy quality, reaffirming its suitability for real-world applications.

## 1.2. Polynomial Load Model ZIP

Conversely, the static load models have a deficiency in capturing the intricacies of load behavior, forcing the exploration of alternative dynamic load models. The examination of these models allows a global understanding of the dynamics of networks in real time. In this context, particular attention is devoted to frequency-dependent dynamic load models [37]-[40]. For our study, we chose to adopt the dynamic ZIP polynomial model, which efficiently adapts to frequency fluctuations and guarantees an accurate representation of load characteristics in real-time scenarios.

This model represents the relationship between the voltage magnitudes and power in a polynomial equation that combines constant impedance (Z), current (I), and power (P) components.

$$\begin{cases} P_{sched} = P_0\left[a_p\left(\frac{V}{V_0}\right)^2 + b_p\left(\frac{V}{V_0}\right) + c_p\right]\left[1 - k_{pf}\Delta f\right] \\ \mathrm{Q}_{sched} = Q_0\left[a_q\left(\frac{V}{V_0}\right)^2 + b_q\left(\frac{V}{V_0}\right) + c_q\right]\left[1 - k_{qf}\Delta f\right] \end{cases} \quad (1)$$

Where, the equations (1) revolve around power scheduling and sensitivity settings in power systems. $P_{sched}$ and $Q_{sched}$ represent the desired active and reactive powers at an operating voltage $V$, while $P_0$ and $Q_0$ are real powers at the nominal voltage $V_0$. The coefficients $a_p, b_p, c_p, a_q, b_q$ and $c_q$ determine the relationship between voltage and power outputs in polynomial model. The $k_{pf}$ and $k_{qf}$ parameters indicate the sensitivity to variations in active and reactive powers with respect to voltage variations, typically within specific ranges. $\Delta f$ Represents the frequency deviation, influencing the dynamic behavior of the system in response to frequency fluctuations.

## 1.3. Power station load control with frequency

The damaging effect of turbine power withdrawal during frequency dips can be alleviated. The redefined scheduled power target, considering the desired frequency, ensures that power plant control systems respond appropriately. The introduction of a frequency bias enables the power plant to make corrective adjustments and contribute to grid frequency control, minimizing the impact of frequency deviations.

These strategies enhance the stability and reliability of the power grid, as power plants play a crucial role in maintaining grid frequency within acceptable limits. By aligning power plant operations $P_{set}$ with the desired frequency and applying appropriate control measures, the overall grid frequency control can be improved, ensuring the efficient and reliable operation of the power system becomes:

$$P_{set}(f) = P_{sched} + B_f\,(\Delta f) \tag{2}$$

Where,
$B_f$, The model coefficient

The relationship between power grid load and frequency has typically been regarded as beneficial for system control. In other words, it has been commonly assumed that as the frequency decreases, the overall system load also decreases. The load's comportment is often approximated by equation 2:

$$P_{laod}(f) = P_0(f_{nom}) * \left(1 + m(\Delta f)\right) \tag{3}$$

Where,
$m$, The load-damping factor.

## 1.4. Dynamic loads model

Figure 2 presents the evolution of the global loads in all the PQ buses over a span of 1000 cycles. The graph would show how the loads at these buses change over time in the initial case. This information is valuable for understanding the load dynamics and characteristics of the system, which can aid in planning and optimizing the operation of the electrical grid.

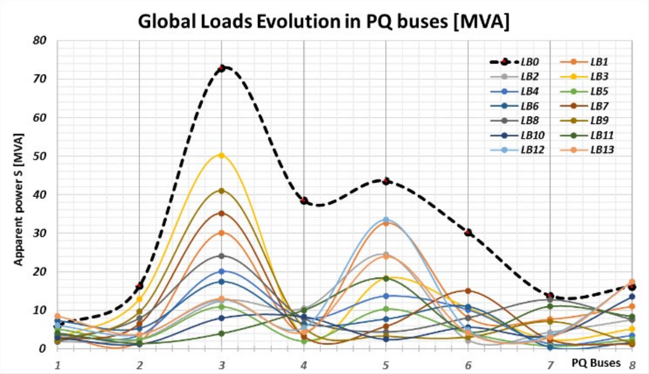


**Figure 2.** Global loads evolution in PQ buses over a period of 1000 cycles

The graph depicts the changes in distribution load values buses during the simulation period. Figure 3 presents the evolutions of the partial loads over a span of 1000 cycles.

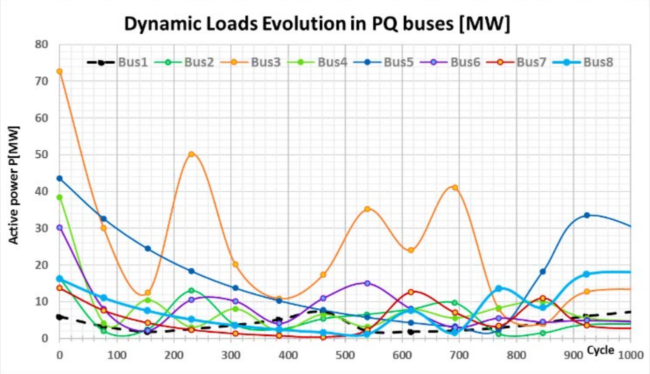


**Figure 3.** Changes in the partial loads of the distribution buses over a period of 1000 cycles.

## 2. Materials and mathematical formulation

The production generators provide the necessary active and reactive powers according to demand while respecting the limitations of the reactive power generated.

$$\bar{S}_i = P_i + jQ_i = \left(P_{G_i} - P_{L_i} - P_{T_i}\right) + j\left(Q_{G_i} - Q_{L_i} - Q_{T_i}\right) \tag{4}$$

Where,
$i$, the number associated with each bus.
$P_i$ & $Q_i$, Active and reactive power at bus $i$.
$P_{G_i}$& $Q_{Gi}$, power generation at the production bus.
$P_{L_i}$& $Q_{L_i}$, Active and reactive load power at node $i$.
$P_{T_{ij}}$& $Q_{T_{ij}}$, Power transmitted from bus $i$ to bus $j$.

These powers are transmitted via the transport network.

$$\bar{S}_{ij} = |\bar{V}_i|^2.\,\bar{Y}_{ij}^* - \bar{V}_i.\bar{V}_j^*.\bar{Y}_{ij}^* + |\bar{V}_i|^2.\bar{Y}_{i0}^* \tag{5}$$
$$\bar{S}_{ji} = |\bar{V}_j|^2.\,\bar{Y}_{ij}^* - \bar{V}_j.\bar{V}_i^*.\bar{Y}_{ij}^* + \left|\bar{V}_j\right|^2.\bar{Y}_{j0}^* \tag{6}$$

Where,
$\bar{S}_{ij}$, Apparent power transmitted from bus $i$ to bus $j$,
$\bar{S}_{ji}$, Apparent power transmitted from bus $j$ to bus $i$.

Active and reactive losses are involved during power transmission.

$$\begin{cases} \bar{S}_{Loss} = \sum \bar{S}_{Lossij} = \sum(\bar{S}_{ij} + \bar{S}_{ji}) \\ \bar{P}_{Loss} = R\{\sum \bar{S}_{Lossij}\} \\ \bar{Q}_{Loss} = Imag\{\sum \bar{S}_{Lossij}\} \end{cases} \tag{7}$$

Where,
$\bar{S}_{Loss}$ : Total apparent power lost in the network.
$\bar{P}_{Loss}$ : Total active power lost in the network.
$\bar{Q}_{Loss}$ : Total reactive power lost in the network.

The complex voltage and the active and reactive powers, for each PV bus and PQ bus, we have the following equation can be written as follows:

$$\begin{cases}\Delta P_i = P_{is} - P_i = P_{is} - V_i \sum_{j=1}^{n} V_j \left(G_{ij}\cos\theta_{ij} + jB_{ij}\sin\theta_{ij}\right) = 0 \\ \Delta Q_i = Q_{is} - Q_i = Q_{is} - V_i \sum_{j=1}^{n} V_j \left(G_{ij}\sin\theta_{ij} - jB_{ij}\cos\theta_{ij}\right) = 0\end{cases} \quad (8)$$

Where,
$\theta_{ij} = \theta_i - \theta_j$, Transport angle between bus $i$ and $j$.

The production generators are controlled synchronously with load variations, taking into account all the constraints and limits of the subsystems. The main control lines are summarized in the following Fig. 4. Traditional and effective ways to reduce these problems are to derive additional signals for generator excitation systems and to compensate for fluctuations in power flow through transmission networks.

Figure 4 shows the Flowchart of OPF dynamic ZIP loads with evaluation methods.

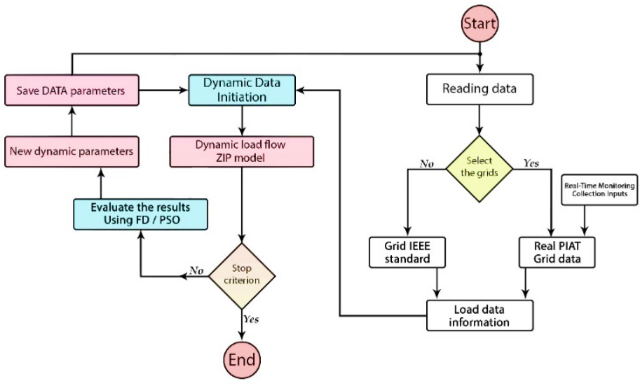


**Figure 4.** Flowchart of OPF dynamic ZIP loads with evaluation methods

## 2.1. System Description

The one-line diagram of Kabertene PV/WF section of PIAT electrical grid is shown in Fig. 5.

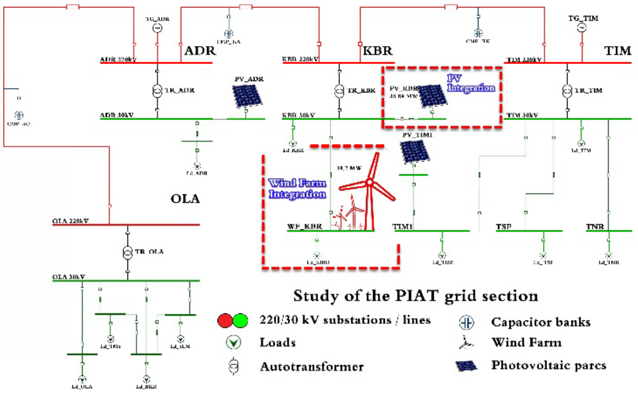


**Figure 5.** Kabertene PV/WF section study of PIAT grid

The electrical grid section studied is composed as indicated in Table 1 below:

Table 1. Description of the study system

| System characteristics | | Number |
|---|---|---|
| Buses | Slack bus | 1 |
| | PV bus | 05 |
| | PQ bus | 08 |
| branches | | 13 |
| Generators | Gaz Turbine | 10 |
| | Wind Farm | 01 |
| | PV parcs | 03 |
| Autotransformers | | 08 |
| Shunts | | 03 |

In Fig. 6, the maps depicting the geographic locations of renewable energy installations of the Kabertene photovoltaic and wind farm parks in south of Algeria.

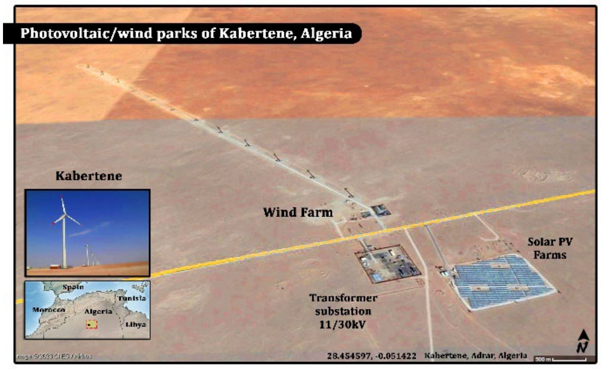


**Figure 6.** Kabertene maps geographic with PV/WF parks

## 3. Results and discussion

The stability of the PIAT grid is a fundamental and crucial aspect to ensure the capacity of the network to maintain its balance and to restore its stable state after internal or external disturbances. To ensure this stability, AESO use control and protection devices, such as voltage regulators and AFRR systems, to maintain the balance between generation and electricity consumption and to ensure the safe and efficient operation of the electricity grid.

Our study was conducted on the 220KV transmission electrical network and the 60KV distribution system of the PIAT grid in Adrar province, southern Algeria, as shown in Fig 5 & Fig 6. The software tools utilized for analyzing and representing the results were MATLAB 2021a and ETAP 2019.

The simulation results were analyzed and interpreted using transient stability analysis of small signals for frequency correction through the AFRR controller.

To achieve voltage level adjustments, it is imperative to monitor real-time dynamic voltage violations at the buses. For this purpose, two algorithms, namely the Fast Decoupled Load Flow (FDLF) method and for the optimal power flow Particle Swarm Optimization (PSO) method, were employed.

Subsequently, dynamic voltage regulation was accomplished through several methodologies, with a primary focus on local reactive power compensation and decentralized production control by power factor control at injection buses. To improve the efficiency of the study, the Maximum Power Point Tracking (MPPT) technique to maximize the production of photovoltaic energy at Kabertene Park, ensuring optimal use of the capacity of the park.

## 3.2. Frequency grid evolution synchronization

Figure 7 shows the evolution of the synchronism frequency correction ($f_r$) with FDLF at the integration point of Kabertene (bus 4) with the frequency prediction ($f_p$) model.

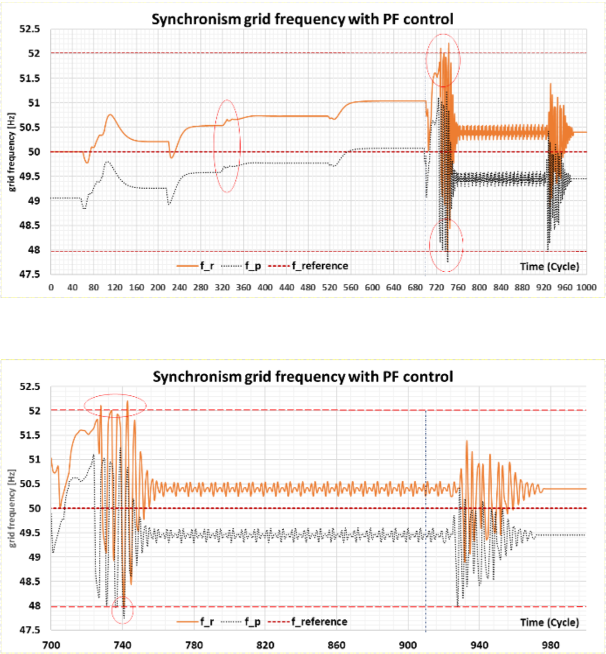


**Figure 7.** (a) Frequency synchronization with FDLF (b) Zoom-in 700-1000 cycles frequency synchronization

In Fig. 8, the graph displays the evolution of the optimal synchronism frequency correction ($f_{OPF}$) with PSO at the integration point of Kabertene (bus 4) using the frequency prediction ($f_p$) model.

The graph illustrates how the $f_{OPF}$ value changes over time based on the predictions made by the $f_p$ model. The $f_{OPF}$ represents the desired frequency correction required to maintain optimal synchronism at the integration point. By comparing the predicted frequency ($f_p$) with the actual frequency, the model calculates the appropriate $f_{OPF}$ value to ensure synchronization and stability in the system.

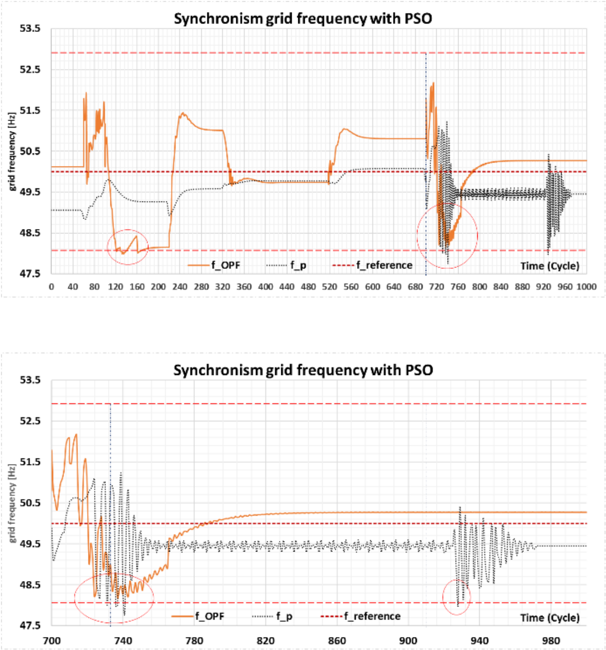
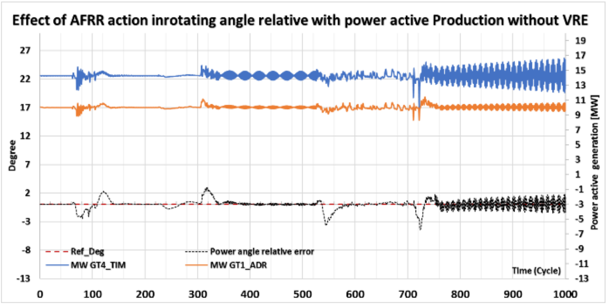


**Figure 8.** (a) Frequency grid evolution synchronization with OPF (PSO method) (b) Zoom-in 700-1000 cycles PSO frequency synchronization

This graph provides insights into the effectiveness of the frequency prediction model in accurately estimating the necessary correction to maintain optimal synchronism at the integration point of Kabertene. It helps operators and system planners make informed decisions and adjustments to ensure reliable and stable operation of the electrical grid.

Figure 9 depicts the correction made using the Automatic Frequency Restoration Reserve (AFRR) at the integration point of Kabertene (bus 4). It highlights the evolution of active power production $P_{G1}$ & $P_{G14}$ at the gas turbine buses of GT1_ADR and GT4_TIM.



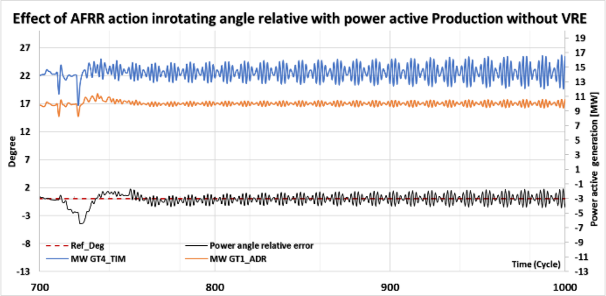


**Figure 9.** (a) AFRR correction evolution with power active generation, action on angle relative, (b) Zoom-in 700-900 cycles AFRR correction

The graph illustrates how the AFRR system adjusts and regulates the power active generation of the gas turbines in response to changes in frequency fluctuations. This correction mechanism ensures that the power generation from these gas turbines aligns with the required frequency and maintains the stability of the electrical grid at the integration point of Kabertene.

Figure 10 presents the maximum voltages observed in the 220KV transmission and 30KV distribution buses using frequency control measures without VRE sources.

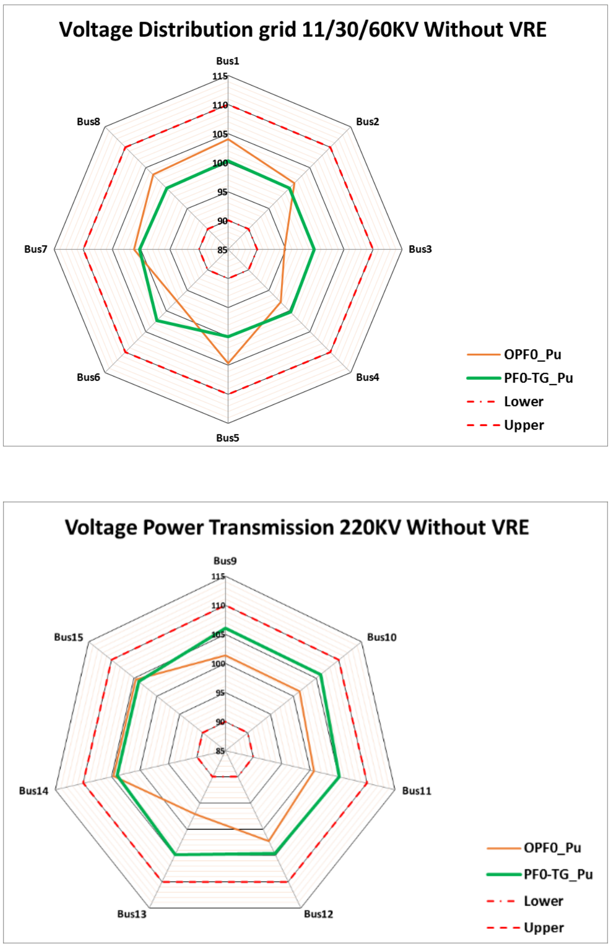


**Figure 10.** (a) Maximum voltages in the distribution grid without VRE sources (b) Maximum voltages in the transmission system without VRE sources

The graph displays the highest voltage levels recorded at the specified buses, indicating the peak voltages experienced during the operation of the electrical system. Frequency control mechanisms, such as automatic voltage regulation and reactive power compensation, are employed to maintain voltage stability within acceptable limits.

Monitoring and controlling voltage levels is crucial to ensure the safe and efficient operation of the transmission and distribution networks. The graph provides valuable information on the maximum voltages observed, enabling operators and system planners to assess the effectiveness of frequency control measures in maintaining voltage stability and taking necessary actions to mitigate any voltage-related issues that may arise.

Figure 11 illustrates the maximum voltages observed in the 220KV transmission and 30KV distribution buses when integrating VRE sources and employing frequency control measures.

The graph displays the highest voltage levels recorded at the specified buses during the operation of the electrical system with the presence of VRE sources.

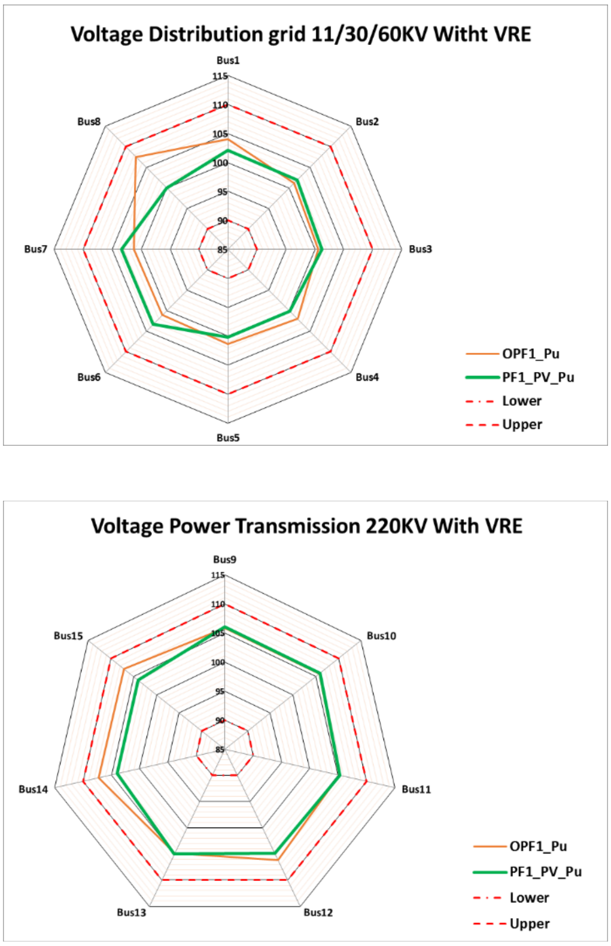


**Figure 11.** (a) Maximum voltages in the distribution grid with VRE sources (b) Maximum voltages in the transmission system with VRE sources

The graph provides insights into the impact of VRE integration on voltage levels and the effectiveness of frequency control measures in managing voltage stability. It helps operators and system planners assess the performance of the system under varying renewable energy conditions and make informed decisions to ensure reliable and stable operation of the transmission and distribution networks.

## 3.2. Generator productions

Figure 12 illustrates the evolution of the maximum total production in terms of active power (MW) and reactive power (Mvar) with the optimal setting of the power factor, both without and with the integration of Variable Renewable Energy (VRE) sources.

The graph displays how the maximum total production changes over time in two scenarios. The first scenario represents the maximum total production without the integration of VRE sources, while the second scenario includes the presence of VRE in the system.

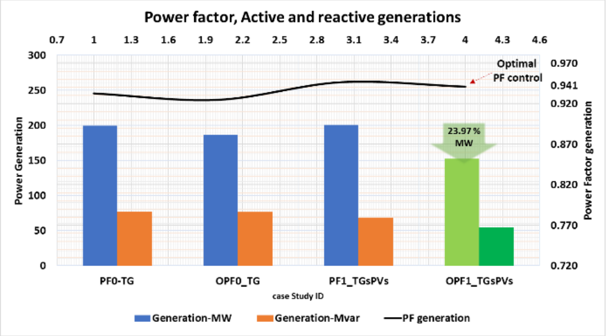


**Figure 12.** Power factor, active and reactive generations with different scenario case

By optimizing the power factor, the system aims to achieve efficient utilization of electrical power and minimize losses. The graph showcases the impact of the optimal power factor setting on the total production of both active and reactive power under different conditions, considering the presence of VRE.

The fluctuation of VRE introduces variability into the overall maximum total output of production in the PIAT grid. The representation in Fig. 9, and Fig. 11b, facilitates a visual understanding of changes in output production by regulation in the power factor.

The graph provides valuable insights into the effects of VRE integration on the maximum total production of active and reactive power and highlights the importance of optimizing the power factor to ensure efficient and sustainable energy utilization.

Figure 13 provides a visual representation of the variations and relationships between the PF1 and PF0 power factors throughout the cycle, offering an overview of the system's power factor performance. This enables operators and planners to make informed decisions regarding power factor optimization and overall management of electrical energy within the system. The graph depicts the variations in power factors over the entire cycle, focusing on two important elements. Firstly, the specific control factor PF1 for Kabertene Wind represents the desired optimal power factor for this specific wind energy source. It illustrates how the power factor varies based on the needs and production conditions of Kabertene Wind.

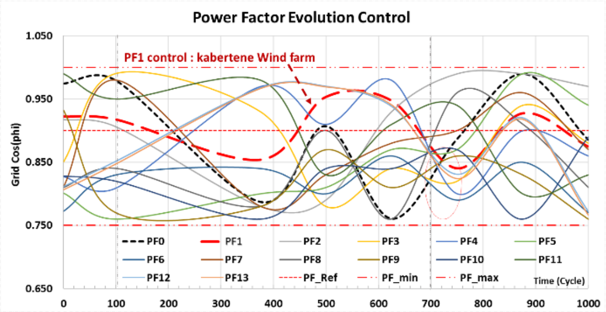


**Figure 13.** Global power factors per cycle with VRE sources.

Secondly, the overall system power factor PF0 represents the average or global power factor of the entire electrical system. This global power factor is influenced by various factors, including the contribution of Kabertene Wind and other energy sources present in the system.

## 3.3. Active losses of the system

Figure 14 presents the results of the total active losses in the system without and with the presence of VRE in the system in PF and OPF control.

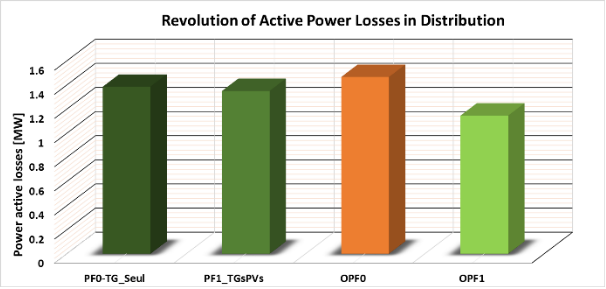


**Figure 14.** The total active losses of the PIAT system in different scenario

By utilizing these results, decision-makers can respond appropriately to optimize the performance of the electrical system and minimize active losses, thereby contributing to a more efficient and sustainable utilization of energy.

Table 2 presents a comparison between different scenarios or interventions aimed at reducing active losses in the system. It shows the percentage by which active losses are reduced in each case, indicating the effectiveness of the respective measures or conditions.

Table 2. Reduction in percentage of active losses of the PIAT system.

| | Without VRE | | With VRE | |
|---|---|---|---|---|
| Study ID | PF0-TG_Seul | OPF0 | PF1_T GsPVs | OPF1 |
| Loss-MW | 1.39 | 1.47 | 1.35 | 1.15 |
| Reduction % | 5.53 | | 7.91 | **21.83** |

The percentage reduction in active losses provides valuable insight into the impact of various factors, such as the integration of renewable energy sources, optimization strategies, or technological improvements, on the overall efficiency of the system. It helps evaluate the success and effectiveness of different approaches in minimizing energy losses and improving system performance.

By analyzing the data presented in Table 2 and Fig. 14, operators, planners, and decision-makers can identify the most effective measures for reducing active losses and prioritize interventions that offer the highest percentage reduction. This information facilitates informed decision-making and allows for the implementation of strategies that enhance the efficiency and sustainability of the electrical system by minimizing active losses.

## 3. Conclusion

Integrating VRE sources, such as the Kabertene wind and photovoltaic farm, into Algeria's isolated PIAT power grid poses challenges regarding maintaining stable frequency and voltage levels. However, regulation measures have been identified to address these challenges. Among these measures, the establishment of an AFRR system, as it plays a crucial role in the regulation of frequency deviations in real-time. In addition, dynamic voltage regulation is used to effectively counter fluctuations resulting from the integration of Kabertene's 28.3 MWp photovoltaic system and 10.2 MWp wind power. This voltage regulation strategy ensures the system's ability to withstand and adapt to varying power inputs, enhancing the stability and reliability of the PIAT network.

Efficient energy extraction from solar panels is achieved through MPPT techniques, optimizing the utilization of power production in PV Park. PSO algorithm, considering the intermittent nature of renewable sources, facilitates the scheduling and dispatching of VRE generation.

The study demonstrates the effectiveness of these techniques in enhancing network stability, reducing frequency deviations, and facilitating VRE integration. Incorporating ZIP dynamic load models and Optimal Power Flow (OPF) results in a significant reduction in active power losses, ensuring stable voltage levels. Comparing optimization methods, the study highlights PSO's superior performance in limiting network frequency deviations during VRE integration.

In summary, the study provides valuable insights into the practical implementation of AFRR, voltage regulation, MPPT, and PSO-based algorithms. These techniques enhance network stability, optimize energy utilization, and enable seamless VRE integration. The findings contribute to developing a cleaner and more sustainable energy system, offering guidance for similar power grids seeking stability improvement and increased VRE integration.

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