A deep dive into enhancing frequency stability in integrated photovoltaic power grids

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ABSTRACT

Voltage control strategies (VCS) and frequency stability analysis (FSA) are essential for power system reliability, particularly during high-load periods. Stable voltage and frequency levels prevent malfunction, power quality deterioration, and supply interruptions. Grid operators must skillfully manage VCS and FSA control to ensure system stability. Nonlinear loads, especially under transient conditions, significantly affect voltage stability (VS), introducing harmonics, waveform distortion, and stability complexities. Accurate modeling of these nonlinear loads is vital when traditional static load models fall short. Frequency fluctuations from power generation-demand imbalances require vigilant monitoring and regulation. Effective frequency control mechanisms are indispensable for preserving desired frequencies. Using a Western Algeria case study, this paper underscores FSA's significance in integrating photovoltaic (PV) systems into power grids. It addresses challenges from frequency fluctuations due to dynamic ZIP load profiles, emphasizing the importance of FSA for reliable grid operation. The study offers insights and practical approaches to enhance VS, FSA control, and energy management (EM), improving grid reliability and ensuring uninterrupted power supply. We must look into FSA's benefits in integrating PV systems to improve performance and lower grid interruptions. This includes looking into its control mechanisms and feedback systems.

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1. INTRODUCTION

In the realm of electrical systems operation, voltage stability and frequency control are paramount concerns, especially during high load periods. The reliability and efficiency of power grids depend significantly on the preservation of stable voltage and frequency levels. Variations in these parameters can lead to undesirable consequences, such as equipment malfunctions, diminished power quality, and potential power supply interruptions. Consequently, it is imperative for grid operators and dispatchers to adeptly manage voltage stability and frequency control to ensure system reliability [1]–[3].

Among the key influencers of voltage stability are nonlinear electrical loads operating under critical transient conditions [4], [5]. These nonlinear loads exhibit intricate behaviors that can significantly affect overall system performance, introducing harmonics, distorting voltage waveforms, and displaying dynamic responses that complicate voltage stability [6], [7]. Precisely modeling and comprehending the behavior of these nonlinear loads are essential for formulating control equations and developing effective operational strategies. While static load models serve as a foundational representation of load behavior in electrical systems, they may not fully encapsulate the intricacies and dynamics of real-world load behavior [8]. In scenarios where traditional static load models fall short in accurately depicting load characteristics, alternative dynamic load models, such as frequency-dependent load models, become essential [9], [10]. By accounting for the dynamic responses of loads to frequency variations, a more comprehensive evaluation of load interactions and their impact on system performance is achievable [11], [12]. This knowledge plays a pivotal role in maintaining the reliability, stability, and efficiency of electrical grids. The generalized *z*-impedance, *i*-current, *p*-power (ZIP) model, as expressed in (1), offers a versatile framework for modeling dynamic load behaviors [12].

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

In these equations; P and Q represent the active and reactive powers of the load for the operating voltage V, P_0 and Q_0 denote the active and reactive powers of the load for the nominal voltage V_0, a_p, b_p, c_p, a_q, b_q, and c_q are the coefficients of the ZIP model, k_{pf}, k_{qf} is the sensitivity parameter of the active, reactive power, Δf represents the frequency deviation in p.u.

Frequency fluctuations in electrical systems can result from imbalances between power generation and load demand, potentially leading to synchronization issues among grid-connected devices and undermining system stability [13]–[17]. To maintain the desired frequency levels, grid operators must diligently monitor and regulate system frequency, relying on effective frequency control mechanisms and feedback systems [18]. In the domain of electrical systems modeling and control, addressing the behavior of nonlinear loads under critical transient conditions is imperative [19]. These models are indispensable for comprehending intricate characteristics exhibited by various electrical devices and their interactions within the system, enabling grid operators to develop robust control strategies for mitigating voltage instability and addressing frequency fluctuations [20].

Designing power generation facilities to consider exceptional operating conditions within specified timeframes is vital. For example, in the frequency range of 47.5 to 48 Hz, power generation units must maintain a connection for at least 20 seconds to ensure system stability and safety, while in the range of 48 to 52 Hz, the duration of connection is unlimited. These provisions allow power generation facilities to adapt to a spectrum of operating conditions [1], ensuring that electricity generation units remain connected to the grid during significant frequency deviations from the nominal value, thereby safeguarding system stability and safety. Frequency stability analysis is a key part of understanding and reducing these changes, which helps power systems work at their best [21], [22]. It involves comprehensively examining grid frequency dynamics and the contributing factors to their variations [23]–[26]. Frequency stability analysis is important because it can show how complex the grid works, giving us important information to make good plans for reducing problems. This paper focuses on the importance of frequency stability analysis in the context of integrating photovoltaic (PV) systems into power grids, exemplified through a case study in Western Algeria as depicted in Figure 1. It seeks to elucidate the challenges associated with frequency fluctuations resulting from varying electrical load profiles, emphasizing the crucial role of maintaining frequency stability for reliable and efficient grid operation.

We looked at all of these things in great detail in this study to help dispatchers and system operators who need to monitor voltage stability, frequency control, and energy management when gas turbines and photovoltaic parks are added to electrical systems [27]. By effectively dealing with these problems, power grids can improve their operational reliability, which will not only improve the power quality but also ensure that consumers always have access to electricity [28], [29]. The study aims to give people who work with renewable energy sources and traditional power generation smart ideas for dealing with the complicated problems that come up when these two types of energy are combined. The significance of this study extends beyond theoretical elucidation, aiming to contribute practically applicable methodologies for power grid operators. In doing so, it aspires to foster a resilient and sustainable energy infrastructure capable of meeting the evolving demands of modern society while concurrently advancing the broader goals of energy efficiency and reliability. In Figure 2, the plot illustrates the maximum and minimum average temperatures recorded on May 21, 2023, in El-Abiodh Sidi Cheikh, Algeria. The temperature fluctuations throughout the day are visually represented, displaying the potential impact of weather conditions on energy generation.

By harnessing these factors and implementing best practices in PV system deployment and operation, an exceptionally high effective energy production rate of 64.75% is achievable. Key contributors to this remarkable efficiency include abundant solar energy resources in the El-Abiodh Sidi Cheikh (ESC) region, characterized by high solar irradiation levels and minimal shading or obstructions. Meticulous design and configuration of the ESC PV Park are essential, with factors such as the selection of high-efficiency PV panels and precise installation angles maximizing solar energy conversion. Rigorous operations and maintenance protocols, encompassing regular cleaning, fault detection, and swift issue resolution, minimize energy losses and maximize production.

Figure 1. Geographical locations of the photovoltaic park in the ESC region

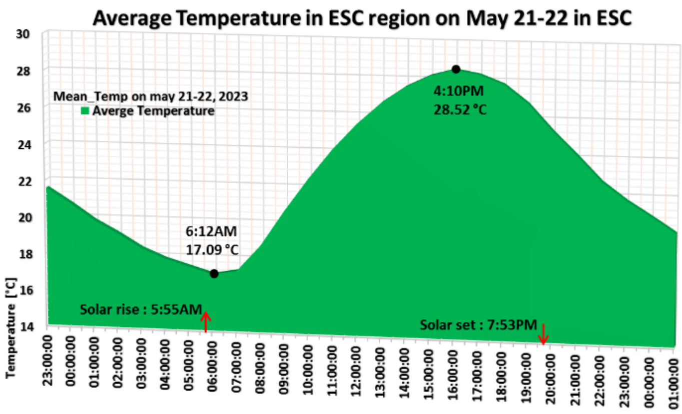


Figure 2. Max and min average temperature on May 21, 2023 in ESC, Algeria

Efficient grid integration and power management systems are pivotal in ensuring optimal utilization of the ESC PV park's output. Technologies like grid-tied inverters, energy storage systems, and advanced control algorithms effectively regulate power flow, manage grid stability, and minimize energy curtailment. This results in the efficient utilization of available solar resources, ultimately enhancing the output and profitability of the PV park while advancing sustainable energy generation [30]. Frequency stability analysis plays a crucial role in the successful integration of PV systems into power grids [31], [32]. Ensuring frequency stability is key to addressing challenges arising from fluctuations in renewable energy generation and maintaining the reliable and efficient operation of electrical grids. Subsequent sections of this paper will delve deeper into the control measures and strategies employed in frequency stability analysis, presenting their potential benefits and practical applications [33]–[36]. Frequency monitoring and control are imperative for upholding grid stability and reliability [37], [38]. This study aims to explore the advantages of frequency stability analysis in the context of PV integration. By understanding the factors influencing frequency variations and implementing control measures, PV system integration can be enhanced, performance optimized, and grid disruptions reduced [39]–[41]. Figure 3 illustrates daily load profiles on active and reactive power (PQ) buses, depicting typical electricity demand patterns with peak hours and lower demand periods, which may vary daily, particularly during morning and evening peaks when residential and commercial activities are most active.

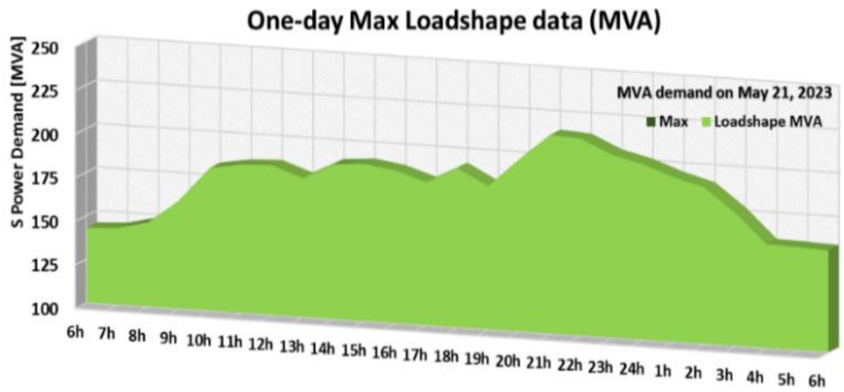


Figure 3. Evolution of the daily load profile in grid study

2. METHOD

The functioning of production generators within the network revolves around the provision of active and reactive power as per demand requirements, all while adhering to strict limits on the generation of reactive power. The complex power at node j is denoted as $\bar{S_i}$, defined by the pair P_i and Q_i, where P_i represents active power and Q_i denotes reactive power at node i. This can be expressed as (2):

$$\begin{cases} \bar{S_i} = P_i + jQ_i \\ \bar{S_i} = \left(P_{G_i} - P_{L_i} - P_{T_i}\right) + j\left(Q_{G_i} - Q_{L_i} - Q_{T_i}\right) \end{cases} \tag{2}$$

where P_i, Q_i is active and reactive power at node i, P_{G_i}, Q_{G_i} is generation active and reactive power at node i, P_{L_i}, Q_{L_i} is active and reactive load power at node i, and P_{T_i}, Q_{T_i} and active and reactive power transmitted.

Efficient management of active and reactive power flow ensures that power demand is met while simultaneously upholding the required voltage and power factor levels within acceptable boundaries. This equilibrium between generation and consumption is vital for the seamless operation of the system. The transportation of these powers occurs via the network through the (3) and (4):

$$\bar{S}_{ij} = |\bar{V}_i|^2.\bar{Y}_{ij}^* - \bar{V}_i.\bar{V}_j^*.\bar{Y}_{ij}^* + |\bar{V}_i|^2.\bar{Y}_{i0}^* \tag{3}$$

$$\bar{S}_{ji} = |\bar{V}_j|^2.\bar{Y}_{ij}^* - \bar{V}_j.\bar{V}_i^*.\bar{Y}_{ij}^* + \left|\bar{V}_j\right|^2.\bar{Y}_{j0}^* \tag{4}$$

where $\bar{S}_{ij}$ is apparent power transited from node i to j, and $\bar{S}_{ji}$ is apparent power transited from node j to i.

During power transmission, managing active and reactive losses is vital for a stable electrical system. Active losses, indicating power dissipation, and reactive losses, affecting voltage levels, necessitate careful monitoring and control to maintain a reliable power transmission network.

$$\begin{cases} \bar{S}_{Loss} = \sum \bar{S}_{Lossij} = \sum(\bar{S}_{ij} + \bar{S}_{ji}) \\ \bar{P}_{Loss} = R\left\{\sum \bar{S}_{Lossij}\right\} \\ \bar{Q}_{Loss} = Imag\left\{\sum \bar{S}_{Lossij}\right\} \end{cases} \tag{5}$$

where $\bar{S}_{Loss}$ is total apparent power lost in the network, $\bar{P}_{Loss}$ is total active power lost in the network, and $\bar{Q}_{Loss}$ is total reactive power lost in the network. To maintain equilibrium within the system, the complex voltage, active power, and reactive power for each PV and PQ bus can be expressed through the following set of equations:

$$\begin{cases} \Delta P_i = P_{is} - P_i = 0 \\ \Delta Q_i = Q_{is} - Q_i = 0 \\ \Delta P_i = P_{is} - V_i \sum_{j=1}^{n} V_j (G_{ij} \cos\theta_{ij} + jB_{ij} \sin\theta_{ij}) = 0 \\ \Delta Q_i = Q_{is} - V_i \sum_{j=1}^{n} V_j (G_{ij} \sin\theta_{ij} - jB_{ij} \cos\theta_{ij}) = 0 \end{cases} \tag{6}$$

where is $\theta_{ij} = \theta_i - \theta_j$, Transport angle between buses i and j.

2.1. System description

Figure 4 illustrates the single-line diagram of the Saida-Naama network topology, highlighting key elements such as the Naama power plant, the ESC photovoltaic park, the static var compensator for transmission network control, and the interconnected electrical loads categorized as residential and industrial. These loads consume electrical power from the generation sources and contribute to the overall power demand. In terms of power generation, the system comprises a 180 MW gas turbine power plant in the Naama region and a 24 MWp photovoltaic park in the El-Abiodh Sidi Cheikh region, Algeria. The transmission network operates at 220 kV, while the distribution network operates at 60 kV. In terms of power generation, it consists of a 180 MW gas turbine power plant located in the Naama region and a 24 MWp photovoltaic park in the El-Abiodh Sidi Cheikh region, Algeria. The electrical loads in the network primarily consist of two types: residential and industrial.

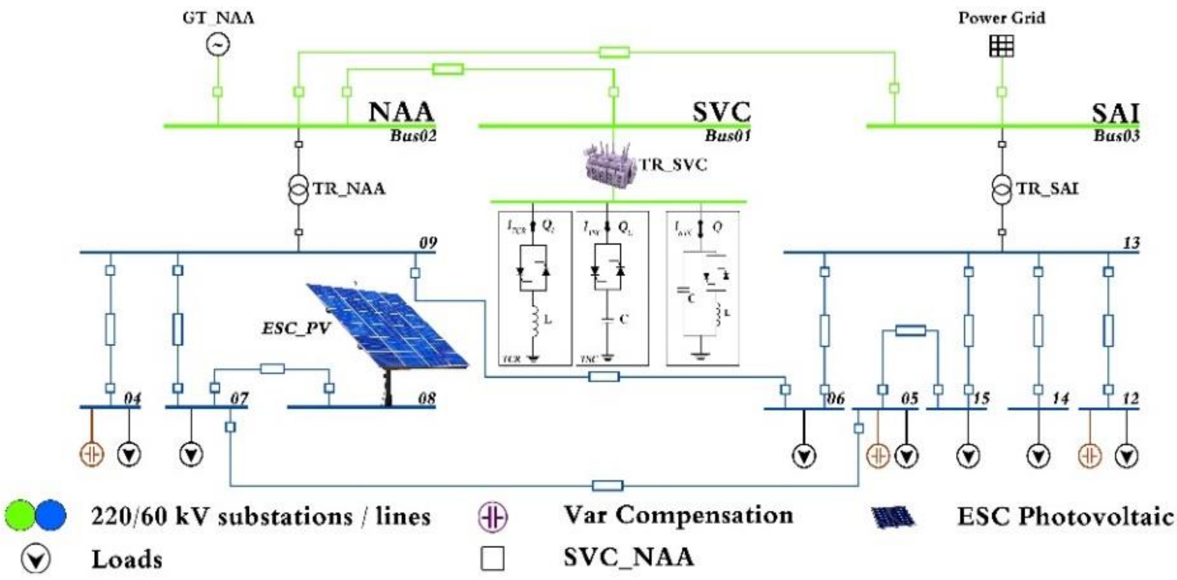


Figure 4. Single-line diagram of the Saida-Naama grid topology

2.2. Voltage control and transit limits

Voltage control in the system is defined by lower and upper voltage level limits of 0.9 and 1.1 p.u, respectively. These boundaries are of utmost importance in upholding the network's stability and dependability. In normal conditions, power transit limits for lines and autotransformers are typically set at 80% of their maximum capacity. This setting allows for a safety margin and ensures the safe operation of components, accounting for factors like load fluctuations, environmental variations, and unforeseen contingencies.

2.3. Real-power frequency control

Figure 5 depicts the closed-loop control system for real-power frequency control. It employs a proportional-integral (PI) controller to monitor and process frequency deviations, adjusting generator set points via the governor control system. This MW load frequency control (LFC) model, with a PI controller, ensures frequency stability by dynamically regulating generator outputs, maintaining system operation within acceptable limits.

For a load change of $\Delta P_L(s) = 0.2\, p.u.$, the integral controller gain is set to $k_I = 4$. The closed-loop transfer function that relates the load change to the frequency deviation $\Delta\Omega(s)$ is expressed by (7).

$$\begin{cases} \frac{\Delta\Omega(s)}{-\Delta P_L(s)} = T(s) = \frac{s(1+\tau_g s)(1+\tau_T s)}{s(D+2Hs)(1+\tau_g s)(1+\tau_T s)+k_I+s/R_g} \\ T(s) = \frac{s^3+7s^2+10s}{50s^4+353.35s^3+523.45s^2+1033.5s+200} \end{cases} \tag{7}$$

This equation characterizes the control system's response to load changes, ensuring frequency stability in the power system.

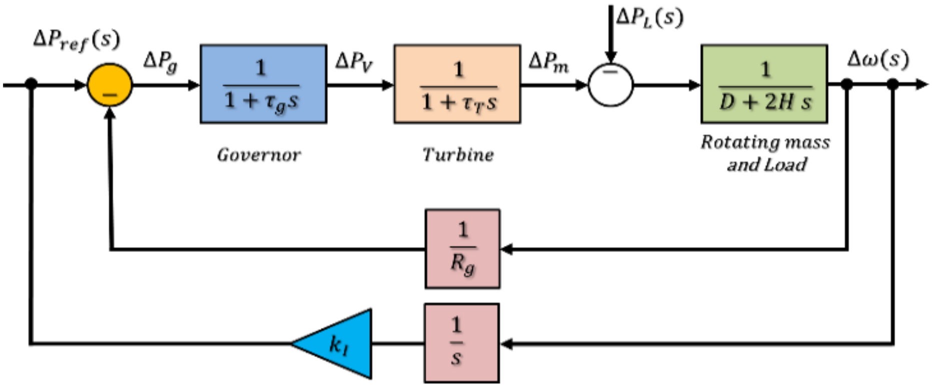


Figure 5. Block diagram of MW load frequency control model (LFC) with PI controller

3. RESULTS AND DISCUSSION

The simulation results underwent comprehensive analysis using various methods. These included the assessment of small signal stability, examination of dynamic voltage behavior in the time domain, and the application of resolution algorithms, such as the fast decoupled load flow (FDLF) method and the multi-objective optimal power flow (MO-OPF) method. These analyses were carried out on the 220 kV transmission electrical network and the 60 kV distribution system within the Saida-Naama region in western Algeria, as illustrated in Figure 4. The data analysis and representation were performed using MATLAB 2021a and ETAP 2019.

3.1. Voltages profiles

Figure 6 depicts the dynamic voltage profile on May 21, 2023, incorporating the integration of the PV in the ESC region. The figure provides a visual representation of the MW production curve alongside the changes in voltage levels, offering insights into the system's response to photovoltaic integration. The integration of photovoltaic energy can significantly influence voltage profiles. During load variations, such as maximum and minimum loads, the presence of photovoltaic energy can enhance voltage stability. Figures 7(a) and 7(b) compare voltage profiles with and without reactive power compensation for maximum and minimum load scenarios.

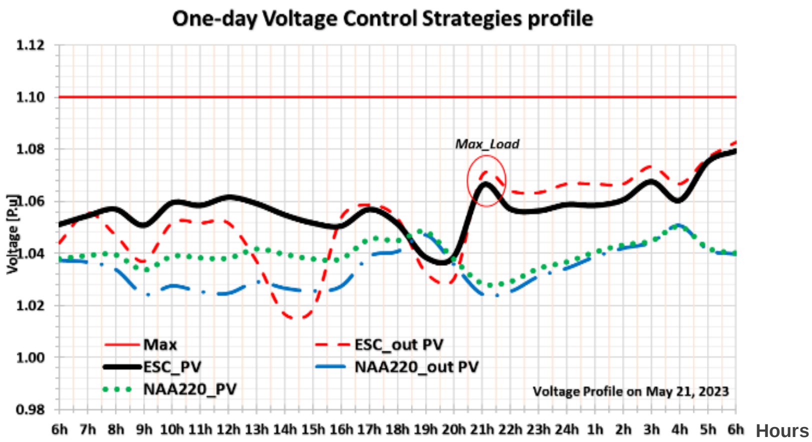
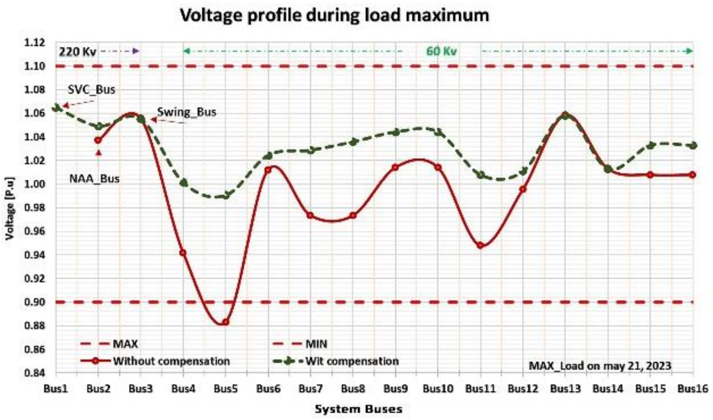
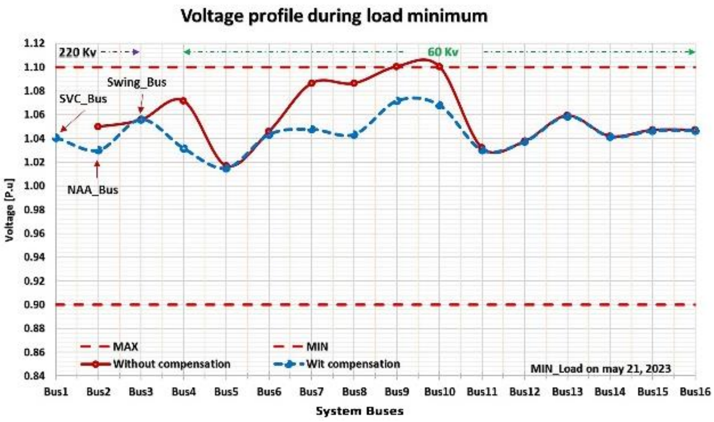


Figure 6. Impact of integrating PV in the ESC Park on the dynamic voltage profile during 24h

Additionally, analyzing the injection bus voltage, *ESC_PV*, and *ESC_out* PV curves reveals a notable improvement in voltage levels resulting from the integration of photovoltaic energy. This improvement signifies the positive impact of renewable energy sources on the overall system performance. Effective management of both local and global reactive power compensation emerges as a critical factor in sustaining and optimizing these enhanced voltage levels.



(a)



(b)

Figure 7. Voltage profiles with and without compensation, (a) load maximum conditions and (b) load minimum conditions

3.2. Frequency control

Ensuring frequency control is imperative for maintaining power system stability. Figure 8 visually presents the dynamic evolution of system frequency on May 21, 2023, incorporating a proportional-integral (PI) regulation model designed for precise frequency correction. This graphical representation offers a clear insight into the system's ability to regulate and stabilize frequency levels over time. While variations in solar energy production can have indirect effects on system frequency, their impact is typically minimal. Robust grid regulation mechanisms are designed to compensate for these variations, ensuring that the overall stability and reliability of the system are maintained even in the face of fluctuations in solar energy generation.

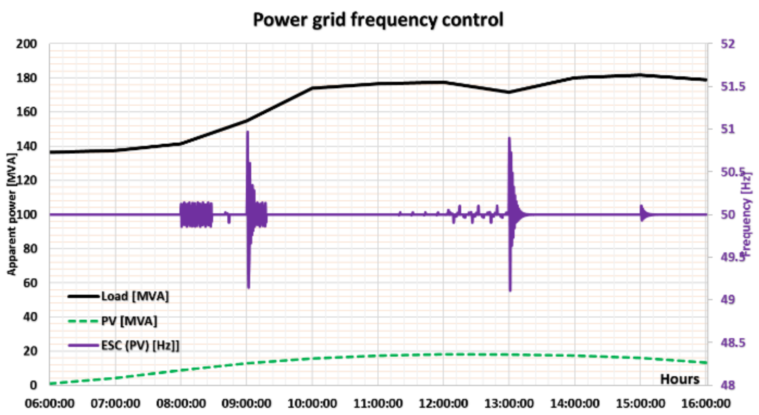
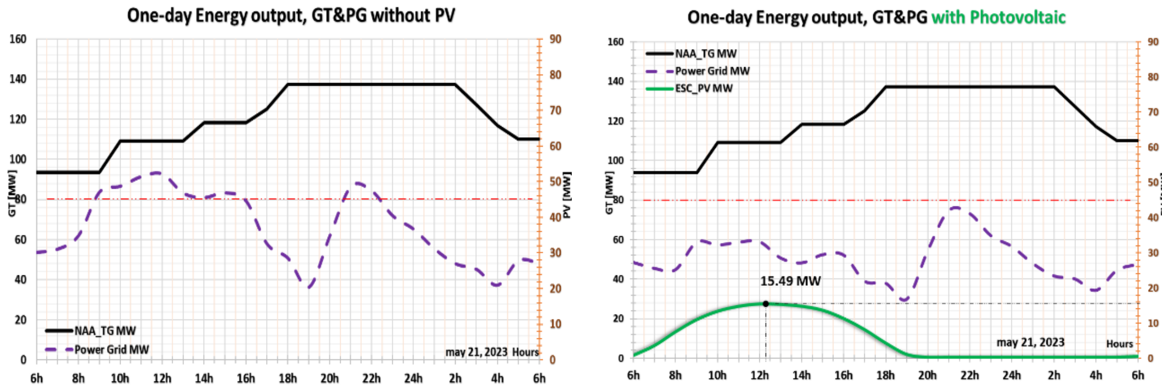


Figure 8. Frequency evolution in grid with PI regulation

3.3. Productions control

Figure 9 depicts the progression of active power production by the Naama gas turbine and the power demand from the electrical grid. Figure 9(a) represents the scenario without the integration of photovoltaic energy from the ESC Park, providing a baseline for comparison. The absence of PV energy is evident in the MW production curve. Figure 9(b) shows the corresponding scenario with the introduction of photovoltaic energy from the ESC Park, illustrating the impact of PV integration on the overall power production dynamics.



(a) (b)

Figure 9. MW Production from gas turbine and power, (a) grid without PV, and (b) grid with PV

3.4. Active losses evolution

Active losses in the power network are substantially impacted by the integration of photovoltaic energy. Figure 10 provides a detailed comparison of power losses in megawatts, emphasizing the significance of var compensation. The subfigures clearly illustrate the contrast between scenarios with and without var compensation, underscoring the effectiveness of compensatory measures in mitigating power losses and enhancing the overall efficiency of the power grid.

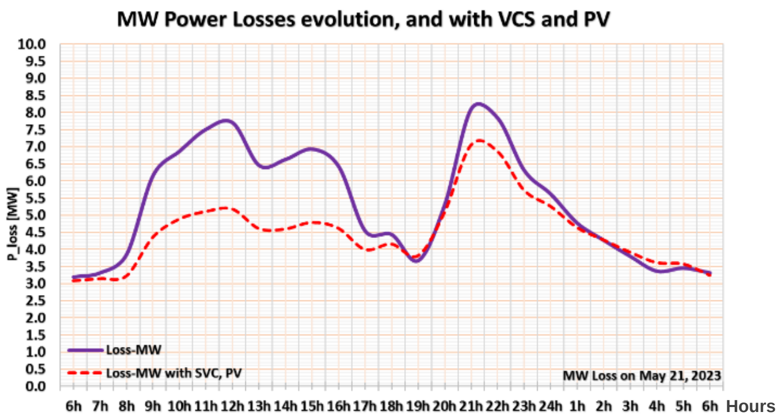


Figure 10. Comparison between evolutions of MW power losses

3.5. Multi-objective optimization algorithm

The optimization of power flow was successfully accomplished through the application of the multi-objective optimal power flow (MO-OPF) method. Figure 11 visually presents the optimal voltage profiles achieved by implementing MO-OPF for both load maximum and minimum scenarios. Notably, the incorporation of static var compensator (SVC) and power factor control is evident in the figure, showcasing the comprehensive nature of the optimization process in maintaining optimal voltage levels under varying load conditions.

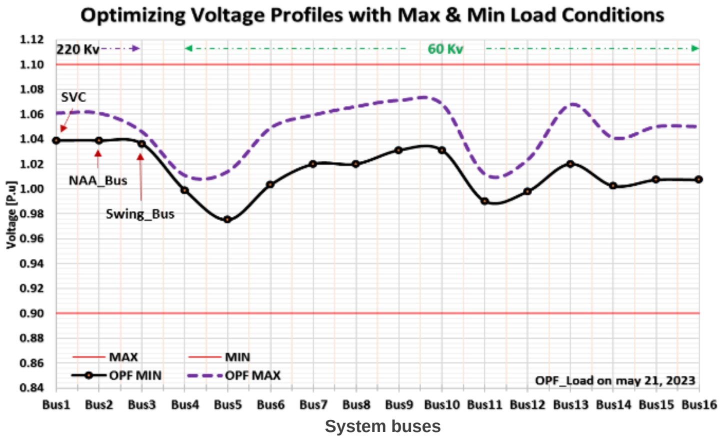


Figure 11. Optimization voltage profiles of load MAX and MIN with MO-OPF methods with SVC and PF control

Table 1 provides a comprehensive summary of the daily power losses and their corresponding reduction rates on May 21, 2023, considering different load scenarios. The results highlight the effectiveness of the multi-objective optimal power flow (MO-OPF) method, highlighting a substantial reduction in power losses. Specifically, there was a noteworthy reduction of 24.72% under maximum load conditions and a commendable 10% reduction under minimum load conditions. Importantly, these improvements were achieved while ensuring optimal voltage adjustments, emphasizing the efficacy of the MO-OPF approach in enhancing the overall efficiency of the power system.

The outcomes emphasize the effectiveness of integrating photovoltaic energy into the system, especially when coupled with sophisticated optimization algorithms. This synergistic approach results in significant improvements in voltage stability and overall power system efficiency. The combination of photovoltaic energy integration and advanced optimization strategies proves instrumental in fostering a more reliable and efficient operation of the grid, highlighting the potential of renewable energy sources and advanced control mechanisms in shaping the future of sustainable power systems.

Table 1. Daily power losses and reduction rates for May 21, 2023

Load	MW_{MAX}	$Mvar_{MAX}$	MW_{MIN}	$Mvar_{MIN}$
Power losses power flow	8.369	-31.542	2.292	-14.976
Power losses optimal power flow	6.300	-31.092	2.064	-9.456
MW reduction %	24.72%		10%	

4. CONCLUSION

The investigation into frequency stability analysis (FSA) and voltage control strategies (VCS) pertaining to the integration of PV systems within the Algerian power grid, particularly exemplified by the case study conducted in Western Algeria, yields significant insights and offers prospective solutions to pertinent challenges. The study successfully addressed the intricate dynamics of frequency fluctuations and voltage stability, two critical elements influencing the robustness and reliability of power grid operations. The research revealed the paramount importance of integrating renewable energy sources, specifically PV systems, into the existing power infrastructure. The analysis of voltage profiles, dynamic frequency control, and power production illustrated the substantial impact of PV system integration on system performance, particularly in augmenting voltage stability during load variations.

Moreover, the application of multi-objective optimization algorithms proved instrumental in enhancing power flow control, significantly reducing active power losses across various load scenarios while maintaining optimal voltage adjustments. This not only demonstrates the effectiveness of advanced control mechanisms but also underscores the potential for improvements in grid stability and efficiency with the amalgamation of PV systems. The results underscore the potential for scaling up the production capacity of PV stations within the region and pave the way for further advancements in sustainable energy production. The study not only contributes to the understanding of PV integration but also supports the broader agenda of renewable energy utilization within Algeria's National Interconnection Grid. The findings and implications of this research are projected to serve as a catalyst for future endeavors in the realm of renewable energy integration, emphasizing the pivotal role of FSA and VCA in ensuring the reliability and efficiency of power grid operations. As such, the work presents an important stride toward fostering sustainable and environmentally friendly energy practices within the Algerian power infrastructure, offering a robust foundation for further exploration and implementation of renewable energy sources (RES).

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