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Voltage Stability Evaluation using Modal Analysis and Deep Learning Technique for the Tunisian Power System Integrating Large-Scale RES Power Plants

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Abstract: - The voltage stability of the Tunisian power system, which includes 1750 MW of renewable energy resources power plants, is evaluated and analyzed. The study is based on a developed stability analysis tool based on an eigen-analysis approach and employs the concept of mode stability. The system model is the Tunisian 225 kV system, which a 23-bus equivalent model represents. The base case and the case of increased renewable energy resource power penetration are presented, compared, and predicted using Recurrent Neural Networks (RNNs). The main focus here is on the unavoidable consequences of the latter case on overall voltage decrease or increase. Each case study presents the critical mode's characterizations, the power system element's participation in each mode, and the generator PV-PQ state transitions.

Keywords: Renewable Energy Sources, Tunisian Transmission Power System, Voltage Stability, Modal Analysis, Deep Learning Technique.

I. Introduction

Energy consumption in Tunisia is proliferating. Fossil fuels currently dominate the total primary energy supply. But with climate change and global warming, this is changing. This shift brings many new and exciting opportunities to Tunisia. Tunisian's renewable power capacity is expanding faster than ever before. Tunis's green energy capacity expanded by 12 % in 2022. In 2022, $ billion was invested in renewable energy projects. In 2023, renewable energy saw its fastest growth in 2 decades, with solar PV playing a starring role. Tunisia is now on course to deliver more renewable energy in the coming years. The massive expansion puts the local goal of increasing renewable power within reach. However, emerging and developing economies need access to affordable financing to achieve this. Besides, policies must support urgent planning and investment in grids [1,2]. The Tunisian government adapts to current challenges for investors financing renewable projects; the government encourages researchers by providing insights on overcoming challenges and mitigating risks. The Tunisia government helps build the foundations of a renewable energy future by improving power quality and capacity transmission. Thus, accelerating toward a carbon-neutral energy system. Championing Tunisians' transition to renewable energy through power quality solutions. The government is Accelerating a resilient and zero net carbon future by enhancing grid resilience, security, and safety with reliable space, making the power grid more sustainable, flexible, and secure. Hence, renewable energy needs intense transmission rate action and struggling to integrate this renewable energy. As power plants grew more extensive, the need for ways to efficiently transmit electrical power over long distances became more critical. Transmitting electrical power is a significant endeavor in the flex industrial process that requires substantial capital investments and ongoing operation and maintenance costs [3,4].

The main attributes concerning the transmission system are reliability of power supply, survivability in case of man-made or natural disasters such as earthquakes, resiliency, the ability to rebound after a major catastrophic event, and safety, in addition to the cost. The immense power stations traditionally are a mixture of baseload power

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stations that supply energy 24/7 throughout the day. These power stations are very efficient and economical. They produced power throughout the day as the demand picked up and the requirement for more energy increased, which helped balance the network. The transmission system operator undertakes all that control and the operation of those power stations. They ensure enough generation on the network to balance with the demand. A significant amount of embedded generation, particularly renewable resources, is intermittent. So, because of all the changes in the distribution network, it is a more challenging job to balance electricity. It conventionally happens at a transmission level on a national basis; the regional electricity companies that operate the distribution networks must take up their responsibility and play an active part in managing those networks. It is increasingly becoming an active operation, so balancing the generation on a local level and demand to make sure that forecasting and predicting the energy needs for local users and making sure that to have generation in the area, and to be able to fulfill those needs as much as possible.

Consequently, voltage instability eases stress on the grid by operating existing distributed generators closer to their limits and accommodating diverse load models [5, 6, 7]. As a result, incentives promoting compliance with voltage control standards in renewable energy power generation systems are relatively limited compared to traditional power systems [8, 9]. Additionally, transmission system operators face challenges in controlling voltage stability due to factors such as the thermal limitations of the power system and the characteristics of control generators. Renewable energy sources (RES) exhibit variations in static and dynamic performances, as well as voltage reactive power control capabilities, differing from traditional synchronous generators. Therefore, the impact of distributed generation on the system's voltage stability necessitates comprehensive layout studies [2, 3, 4, 10].

IEEE defines the point of common coupling (PCC) as the interface point between the customer and the electric utility in the power system. Positioned at the revenue meter on the customer side, the PCC facilitates an intermediate disconnection between RES and the main power grid, allowing for independent operation and isolation from the main grid during significant disturbances [2]. Numerous stability issues may arise during grid maintenance and operation, particularly concerning the stability of voltages at buses and feeders under normal operation and during contingencies.

Voltage stability is achieved when the power system's buses maintain a consistent voltage magnitude in a steady-state condition following perturbations caused by disturbances from a specified initial operating state [7]. Fig. 1 illustrates the categorizations of methods employed in voltage stability analysis, distinguishing between static and dynamic analyses. The static analysis relies on the grid's operating parameters to identify pivotal factors influencing static stability, commonly employing load-flow analyses like V–Q analysis and sensitivity and the P–V curve [11]. Conversely, dynamic analysis is valuable for testing the application effect of control strategies and assessing voltage collapse. Dynamic analysis methods closely resemble transient analyses of the power system, employing sets of differential equations to model the system. In these studies, dynamic changes related to system stability are relatively small, and most dynamic voltage stability analyses still leverage the system's static operating parameters.

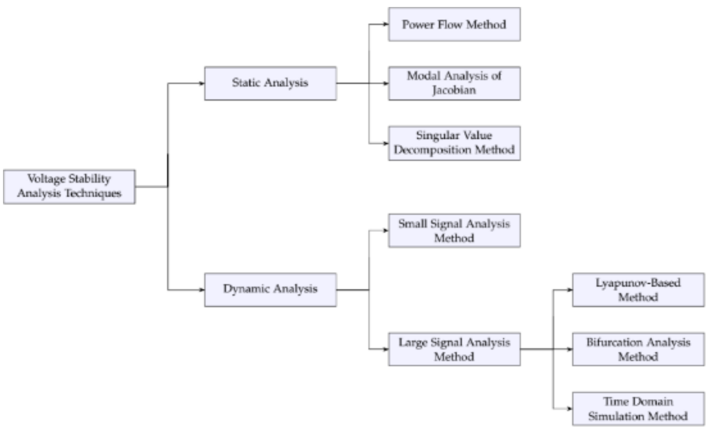

Figure 1. Classification of voltage stability analysis techniques.

The modal approach of voltage stability evaluation of large power systems is among the most effective ways of determining voltage collapse zones and the causal factors of the problem [12, 13, 14]. This technique is based on the eigen-analysis approach, where the notion of stability of modes is used to assess voltage stability. The reduced system has eigenvalues of the Jacobian matrix that define the system modes, and voltage stability requires all modes to be positive. Moreover, to better understand the instability problem, participation factors for buses, generators, and branches are computed. This information model may reveal the instability mechanism and its causes and extent. This article aims to determine the voltage stability analysis of the Tunisian Power system designed for renewable-dominated power systems. To our knowledge, this work is the first on the Tunisian 23-bus HV system vision 2025. It investigates, analyzes, and verifies voltage stability research based on RES. In addition, this work classifies and compares analysis methods based on different grid operation modes and types of distributed RES. It evaluates techniques and conducts a simulation demonstration to verify the optimal configuration with varying grid settings.

This paper performs a voltage stability analysis on the Tunisian power system, including 950 MW of Solar Photovoltaic Power Plant (SPVPPs) and 765 MW Wind Farms (WFs). Two cases are presented and compared: the base case with no renewable penetration and the other case with RES power penetration. The proposed comprehensive analysis is a valuable guide for evaluating the maximum solar power penetration using a bifurcation diagram, considering the enormous potential need for SPVPP penetration into the transmission network. The smallest eigenvalue defines a saddle-node bifurcation (SNB) point observation. Hence, monitoring the proximity to voltage collapse. The advent of Artificial Intelligence (AI) in power systems engineering has heralded a new era of analytical precision and predictive capability. At the vanguard of this revolution is integrating renewable energy resources, presenting complex operational challenges due to their inherent intermittent and variability. Also, this work addresses these challenges by examining the voltage stability of the Tunisian power system under a significant renewable energy contribution.

The paper is organized as follows: Section 2 presents the literature review related to the work. Then, voltage stability analysis methods of the Tunisian grid analysis with RES integration are discussed. Section 4 introduces the model analysis technique. The generic model for RES is presented in Section 5, followed by the system under study. Section 7 presents the simulation results, and the paper's conclusion and findings are presented in Section 8.

II. LITERATURE REVIEW RELATED TO THE WORK

Several studies have conducted modal analyses to explore the impact of Solar Photovoltaic Power Plant penetration on the small-signal voltage stability of power systems. These investigations analyze a small-signal Photovoltaic (PV) generation model connected to a vulnerable AC grid. The stability of PV power generation is examined under varying power grid strengths and control parameters through eigenvalue analysis [15]. The influence of photovoltaic power plants on the northern Chilean power system is examined through modal analysis and time-domain simulations involving substantial disturbances. The assessment focuses on the impact of these plants, particularly those utilizing a conventional converter controller for photovoltaic (PV) generation [16]. The findings demonstrate that power plants comprised of virtually synchronous power converters have the potential to enhance the stability of power systems. They achieve this by constraining frequency excursions caused by substantial power imbalances and alleviating power oscillations in the synchronous machines within the system. To facilitate the modeling and integration of renewable energy resources into the grid, an open-source program is created using Matlab/Simulink. This model can simulate large-scale dynamic modern power systems, including the IEEE 68-bus test system [17]. The program covers various crucial subjects, encompassing modal analysis, participation factor analysis, optimal controller placement using frequency response analysis, and modal residue analysis. It is characterized by its speed and efficiency; it just takes few seconds to simulate the test system using intricate machine and controller models. The study investigates the influence of SPVPP penetration on the static voltage stability of the IEEE-14 bus test system [18]. Various performance metrics, such as the bus participation factor, critical eigenvalues of the Q-V modal matrix, and loading margin, are employed in the assessment. The simulation results reveal that the location, sizes, and integration patterns of photovoltaic (PV) installations—whether concentrated or scattered—have a profound and significant impact. The study applies this understanding to investigate the influence of integrating SPVPPs on the voltage stability of the IEEE 30 bus test system. Modal analysis is conducted under scenarios without PV generation, with collective PV generation, and with scattered PV generation at different rates. The outcomes indicate a positive impact on power system voltage stability with increased penetration of the PV system [19]. The effect of micro-grid (MG) operations on the voltage stability of the IEEE 14 bus benchmark system is assessed. Utilizing eigenvalue and modal analysis methods, the findings indicate a positive influence of the MG on the power system. It demonstrates healing effects, particularly in mitigating instability at the critical bus distance [20].

The model analysis identifies the weakest bus in a separate analysis focused on the Nigeria 44 bus grid. The study reveals that Gombe, Damaturu, and Yola buses exhibit vulnerability, with their voltage profiles dropping below the acceptable level of 0.95 p.u. Yola bus emerges as the weakest, determined through participating factors analysis. The network is unstable, as modal analysis exposes the presence of eigenvalues with negative real parts [21]. On the other hand, the investigation of WF penetration on the power system's small-signal voltage stability is analyzed broadly [22, 23, 24, 25, 26]. Several aspects can affect stability, such as peaking and frequency modulation, frequency fluctuations, harmonics pollution, and the economical dispatch of power systems. The voltage stability characteristics of WF under different control strategies are compared and analyzed as a survey [22]. The paper examines the active power dynamic characteristics of a grid under voltage control during extensive wind farm penetration, systematically analyzing the impact of grid stability characteristics. Numerous studies indicate that voltage stability features indicate operational safety and can enhance voltage stability. One such improvement is demonstrated through a proposed control strategy utilizing TCSC–STATCOM [24]. The study introduces a novel voltage stability-constrained wind energy planning (VSC-WEP) model applied to the IEEE New England 39-bus test system. This model adapts the optimal platform for WF penetration based on voltage stability. The outcomes provide insights into identifying the optimal access point and optimizing the capacity of the connected WF [25]. A small-signal reduced-order --analysis framework with several micro sources was suggested for an islanded microgrid. The obtained eigenvalues are calculated by linearizing around the operation point with the system matrix. The results are validated and compared with the PSCAD platform [26]. On the other hand, the increasing WF penetration on power systems requires adequate development models to represent dynamic behavior. Modeling and simulation for power system small-signal stability with WF integration are conducted [27, 28, 29, 30, 31]. The prediction of the power system's dynamic behavior and energy sustainability with the application of DFIGs is proposed [32, 33, 34]. The paper discusses the impact of a large-scale WF on small-signal stability and presents corresponding control strategies to mitigate the adverse effects [34]. Utilizing the Lyapunov stability criterion, the study analyzes the stability of an integrated hybrid system comprising a WF, SPVPP, and micro hydropower [35]. However, the introduced perturbed power system neglects its involvement in frequency regulation, rendering the method ineffective for stability analysis. Eigenvalue analysis is employed to explore small-signal behavior, determining participation factors to identify participation states in the variations of different mode shapes. Variations, such as oscillatory modes, are illustrated to observe damping performance at various WF penetration levels [36]. Additionally, eigenvalue analysis is investigated to identify critical oscillation modes and participation factors [37], pinpointing potential problematic areas in the Integrated Nepal Power System (INPS) concerning small-signal stability. The study also conducts transient stability analysis through time domain analysis, revealing both beneficial and detrimental effects of integrating a Doubly-Fed Induction Generator (DFIG) into the INPS.

III. Energy transition in Tunisia

A massive investment in renewable energy resources follows the vision to decarbonize the power system grid to stabilize the grid. Modern grid technologies can support the smooth transition to adopting renewable energy resources that are cleaner, more secure, resilient, and distributed. On the other hand, there is increased complexity, changing structure, and penetration by various renewable energy resources of modern power grids, such as the Tunisian power system. The Tunisian government has outlined plans for significant industrial development expansion in the upcoming years. The national power grid in Tunisia is undergoing substantial expansion to meet the rising energy demand, attributed to the ongoing growth of industrial regions and the increasing population density in new cities [38-40]. Hence, more analysis is necessary to evaluate the grid voltage stability and determine the requirements to interconnect new large-scale solar photovoltaic power plants and wind farms with the Tunisian National grid [41-49]. Hence, harvesting more renewable energy dictated researchers to evaluate the impact of these renewable energy expansions on Tunisia's power system stability. Some of these studies determined the stability issues of Tunisian power system interconnection [50-54], and others explored the transient stability and reactive power problems [55-59]. Whereas the integration of WFs is discussed in [45, 60-62], the integration of SPVPPs in the Tunisian system is presented in [41-44], respectively.

Voltage stability, a key determinant in the reliability of power systems, can be quantified through a robust eigen-analysis. This involves the formulation of the power system's state matrix A, whose eigenvalues λ reveal critical stability insights. Specifically, the Jacobian matrix J, derived from the power flow equations $P(V, \Theta)$, where V and

Θ represent the voltage magnitudes and angles, respectively, is critical. The eigenvalues of J, obtained from det($J - \lambda I$)=0, must have negative real parts to ensure system stability.

In this study, the feature selection for input into our AI models was conducted using a quantitative approach that assesses feature variance. The principle behind this selection is that features contributing minimal variance offer limited predictive power and may be excluded. Mathematically, this involves calculating the variance σ^2 for each feature and comparing it against a predetermined threshold θ, thus retaining features where $\sigma^2 > \theta$.

IV. THE MODAL ANALYSIS TECHNIQUE

In 1992, a modal analysis approach was introduced to assess voltage stability in large power systems [12]. This method relies on investigating the eigenvalues of the matrix associated with the linearized steady-state power system model. The eigenvalues of the reduced Jacobian matrix directly indicate the power system's degree of steady-state stability [50, 51]. Expressly, these eigenvalues represent the V-Q sensitivity for the load bus.

In voltage stability, modal analysis can anticipate potential voltage collapse in power system networks. The process primarily involves computing the smallest eigenvalues and their corresponding eigenvectors from the reduced Jacobian matrix obtained through the load-flow solution [63]. The static voltage stability margin is quantitatively measured based on the magnitude of the eigenvalue. Identifying weak areas in the system can be achieved by calculating eigenvectors and bus participation factors.

The eigenvalues associated with voltage and reactive power variation modes offer a relative assessment of voltage instability. Consequently, participation factors become a valuable tool for identifying the weakest nodes or buses in the system, with their values derived from the eigenvectors of eigenvalues. This information proves helpful in power flow modeling, typically represented by the active and reactive power mismatch (1)-(2):

$$\Delta P = \Delta P(\alpha, V) \quad (1)$$

$$\Delta Q = \Delta Q(\alpha, V) \quad (2)$$

The Jacobian matrix J contains the first derivatives of the mismatch equations concerning voltage magnitudes and angles, evaluated at equilibrium (operating) points, giving the linearized steady-state power flow model:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{p\alpha} & J_{pv} \\ J_{q\alpha} & J_{qv} \end{bmatrix} \begin{bmatrix} \Delta \alpha \\ \Delta V \end{bmatrix} \quad (3)$$

where ΔP, ΔQ, $\Delta\alpha$, and ΔV are the incremental adjustment made to the bus's real power injection, to the bus's reactive power injection, to the bus's voltage angle, and to the bus's voltage magnitude, respectively. Also, for voltage stability studies, it is practically helpful to neglect the incremental change in active power [64], i.e., we let $\Delta P = 0$, then (3) has the following form:

$$\Delta Q = J_R \Delta V \quad (4)$$

where

$$J_R = \left\lfloor J_{qv} - J_{qa} J_{pa}^{-1} J_{pv} \right\rfloor \quad (5)$$

J_R is the reduced Jacobian matrix of the system relating the bus voltage magnitude and bus reactive power injection. The system is voltage stable if all the eigenvalues of J_R are positive, and each eigenvalue defines a mode of the system. Moreover, each mode may be treated separately, as can be seen from the decomposition of J_R as the following equation:

$$J_R = \Phi \Lambda \Gamma \quad (6)$$

Its inverse is expressed as:

$$J_R^{-1} = \Phi \Lambda^{-1} \Gamma \quad (7)$$

where, Φ and Γ are the right and left eigenvector matrix of J_R, respectively, and Λ = diagonal eigenvalue matrix J_R. From (5) to (7), we can express the voltage variation ΔV as:

$$\Delta V = \sum_i \frac{\phi_i \Gamma_i}{\lambda_i} \Delta Q \quad (8)$$

where ϕ_i is the i^{th} column right eigenvector, and Γ_i is J_R's i^{th} row left eigenvector. Each eigenvalue λ_i, and the corresponding right and left eigenvectors ϕ_i and Γ_i, define the i^{th} mode of the system. The i^{th} modal reactive power variation is given in (9):

$$\Delta Q_{mi} = K_i \phi_i \quad (9)$$

where, $K_i^2 \sum \phi_{ji}^2 = 1$ and ϕ_{ji} the j^{th} element of ϕ.

The corresponding modal voltage variation is

$$\Delta V_{mi} = \frac{1}{\lambda_i} \Delta Q_{mi} \tag{10}$$

The system is deemed voltage stable when all eigenvalues of the Jacobian matrix, denoted as J_R, are positive. Conversely, it is considered voltage unstable if at least one eigenvalue is negative [12]. The magnitude of the eigenvalue indicates the proximity of the corresponding modal voltage to voltage instability, with a smaller magnitude suggesting closer instability. When the eigenvalue is zero, the system is at the limit of voltage instability [50, 51]. The incremental change in voltage magnitude is inversely proportional to the magnitude of the eigenvalue (λ_i), multiplied by the incremental change in reactive power injection. A smaller positive λi implies that a slight adjustment in reactive power injection could lead to a significantly substantial change in voltage magnitude. Therefore, a larger λ_i signifies a more stable system. A λ_i value of zero signifies a voltage collapse, as any variation in reactive power injection results in an infinite change in voltage magnitude.

Participation factors for power system components are coefficients specially defined to indicate the degree of the component involvement being affected or causing the weakness of the specific mode. The participation factor of bus k to mode i is defined as

$$P_{ki} = \phi_{ik} \Gamma_{ki} \tag{11}$$

Bus participation factors are based on the right and left eigenvectors of J_R. Buses with close participation may determine the collapse zone for a specific zone [12].

V. GENERIC MODEL FOR RES

The initial generation of generic models for renewable energy systems surfaced between 2010 and 2013, followed by the development of second-generation models by EPRI [65]. These models can represent various types of wind turbine generators (WTG) (Type 1–4), solar PV, and battery charging. The generic model utilized in this study is based on Type 4 WTG, as depicted in Fig. 2, and is proficient in simulating WF, solar PV plants, and batteries. The main goal is to closely examine the system's dynamic behavior. The following elements make up this model's structure [65-66]:

(a) *Converter*: this component has two inputs, the active command currents (I_{pcmd}) and the reactive command currents (I_{qcmd}), respectively. And two output: p-axis current injections into the grid (I_p) and q-axis current injections into the grid (I_q). Two low-pass filters that are mathematically equivalent and have quick temporal constants (0.01 to 0.02 s).

(b) *Currents set point controller*: It has two inputs, the command active power (P_{cmd}) and the command reactive power (Q_{cmd}), and two outputs: the x-axis command current (I_{pcmd}) and the y-axis command currents (I_{qcmd}), respectively. They can be computed using the following equation:

$$\begin{bmatrix} I_{pcom} \\ I_{qcom} \end{bmatrix} = \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix}^{-1} \begin{bmatrix} P_{cmd} \\ Q_{cmd} \end{bmatrix} \tag{12}$$

where V_d and V_q are the dq-components of the terminal voltage (V), I_{dcmd} and I_{qcmd} are the dq-components of the produced command currents that the converter uses as signal inputs, and P_{cmd} and Q_{cmd} are the command power signals, which correspond to the produced RES active and reactive powers, respectively.

(c) *Voltage regulator*: This model segment represents the plant controller, featuring two paths. The first path utilizes the input active power reference, with the option to use the nominal frequency as a reference signal in this loop [65]. Conversely, the second path is the input reactive power or voltage reference. Depending on the loop control and its main goal, either the terminal voltage or the active/reactive power of the grid might serve as the plant's feedback. [67]. Mathematically, one or two Proportional-Integral (PI) controllers generate active and reactive power commands [66], while others adopt a two-loop control scheme [68]. An extra damping controller can be added to one of the loops to improve system stability [69]. Reactive power loop management can be utilized to regulate the terminal voltage of the plant or to maintain a constant power factor [70].

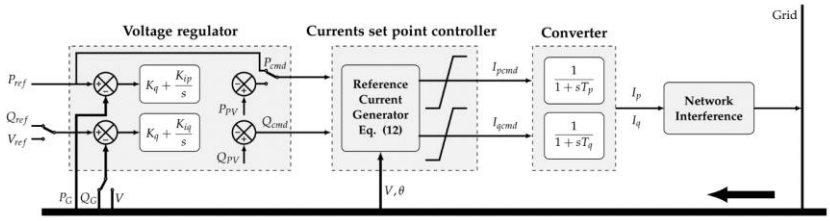

Figure 2. The generic model of RES [65, 70].

A simplified flowchart for defining the steps followed in the modal/eigenvalue analysis of the power system network is shown in Fig. 3.

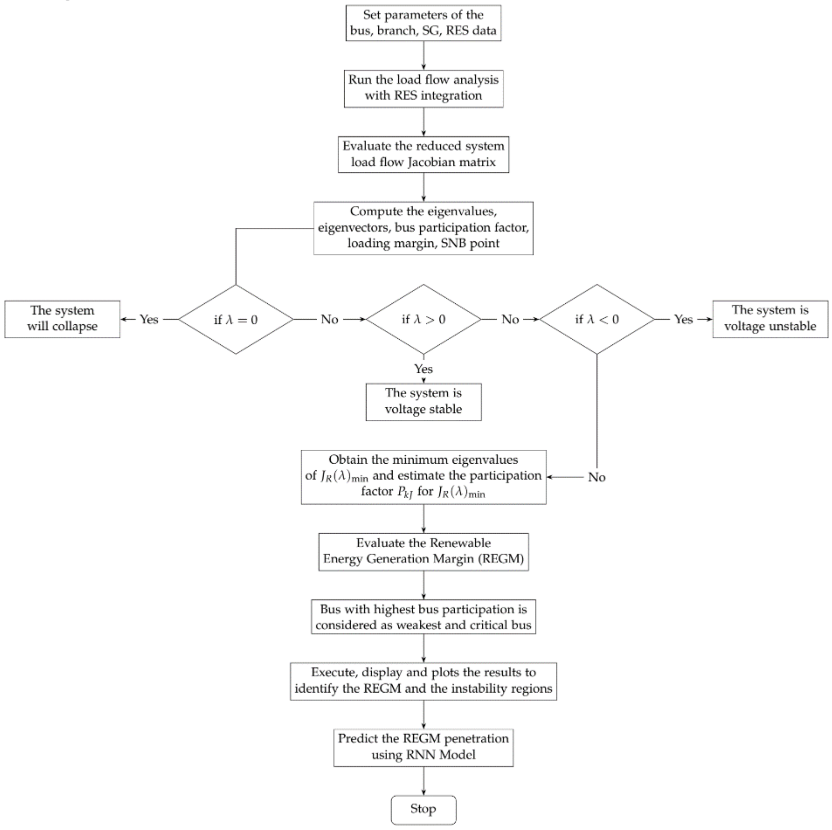

Figure 3. A flowchart for the modal analysis of stability analysis.

VI. SYSTEM UNDER STUDY

A. Tunisian's Electrical Power System: Transition Towards RES

Investing in RES projects is no longer a choice. It is a necessity. RES is a strategic choice in Tunisia [71, 72]. It is necessary to guarantee energy security at an affordable price. The dependence on gas and fuel is more expensive. The instability of the International Energy market shows that the state needs to yield 35% of its electricity from RES by 2023 and 80% by 2050. Accordingly, the energy sector plan in Tunisia is divided into three stages; the first immediate stage started in 2020. It is characterized by launching RES projects and setting a regulation. It is an action horizon. Followed by an intermediate horizon. This stage can be marked by upgrading and developing the RES project structure to enhance renewable energy production by 2030. The final stage can be distinguished by convergence towards advanced technological RES projects by 2050 [73-76].

North Africa aims to put clean and sustainable production and consumption systems for energy in place. The desert in the South is an endless source of clean energy. However, most African countries need to mobilize additional funds from the public and private sectors and international financial institutions. Africa Visibility Hospital Tunisia's 2035 strategic vision prioritizes the green economy to fight against pollution and promote energy management and control. The Tunisian government has to reinvent how the state produces new energy; new ideas, technologies, and energy sources are needed—an annual investment of $300 million towards the rules for renewable energy projects. Tunisia has a vast solar power potential. The state will invest massively in this field to provide reasonably priced electricity everywhere in the country. Furthermore, dozens of solar energy projects and wind farms have been created and financed in partnership between this state, the private sector, and foreign partners. Tunisia is investing in RES for environmental and economic reasons. Experts maintain that solar energy can be deployed in regions without access to alternative electricity sources, and the availability of sunshine becomes exceptionally valuable. Tunisian authorities have estimated that the energy compensation will exceed the forecasted $ 620 million from the state budget. Energy experts maintain that the continuous rise in a barrel of oil has forced the government to revise prices. The Tunisian minister of energy announced that this state has opted for renewable energy instead of oil as an effective solution to reduce oil consumption. The value of state energy subsidy was set at 2.5% of GDP or about $1 billion to preserve the balance of the state budget, but it has become a real burden. Tunisia has different clean energy sources, representing only 3% of the energy circulating in the national power grid [39]. Clean energy production plays a vital role in the decarbonization scenario. The pillar of Tunisia's green project is supporting the private sector in producing clean energy and boosting economic development while respecting the environment. To draw the road for the energy transition, the 2022 state budget introduced several fiscal incentives. According to the International Renewable Energy Agency, many projects will be developed nationwide.

Tunisia started implementing clean energy in the early 90s, making the country the leader in North Africa regarding clean energy production. Indeed, the efforts of the Tunisian government began in 1990 to study wind energy production in Tunisia, leading the government to build the first wind farm in Tunisia in Sidi Daoud in Haouaria, 140 km from Tunis, the capital. Tunisia has two mainly vital wind farms—one in Sidi Daoud and the other in Bizerte, respectively. Sidi Daoud Wind Farm comprises 71 wind turbines that face the Mediterranean and produce clean and renewable electricity. These turbines of different sizes range from 330 kW/unit- to 1.32 MW, which generates a total power of 550 MW. The annual production is 150 GWh/year. Meanwhile, the Bizerte wind farm is rated at 190 MW and comprises 143 wind turbines with 1.32 MW/ unit and an annual production of 600 GWh /year. The yearly total energy produced is 750 GWh/ year. This power allows the country to save 153000 tons of equivalent oil annually [38].

Tunisian authorities assert that the state is moving forward with renewable energy projects. The Energy Department has launched calls for tenders to promote investment in the renewable energy sector. Electricity and gas companies (STEG) have completed several projects, including installing a capacity of 5547 MW distributed across 25 power plants, resulting in 22,093 GWh in 2022 [77]. STEG is responsible for over 91.5% of the installed capacity and contributes to 91% of the electricity output. The remaining 9% is attributed to Independent Power Producers (IPPs) [77, 78]. The recent installations have made it possible to obtain very competitive rates ranging between 18 and 20 US cents/ kWh. Stack says this is the lowest price compared to similar projects in Africa and the Arab region. Most renewable energy projects are developed and implemented in partnership with the German cooperation agency in Tunisia Jay-Z. This close collaboration has led to good results in the RES sector.

Fig. 4 shows the distribution of the national installed capacity for electricity generation in Tunisia during 2022. The energy scenario is marked by a substantial reliance on thermal plants fueled by natural gas, accounting for an estimated 98% of the energy mix in 2022 [77]. A significant portion of Tunisia's electricity power plant installations, approximately 73.5%, is fueled by natural gas [78]. The peak summer electricity demand in 2022 was 4677 MW while it was 4472 MW in 2021 [79].

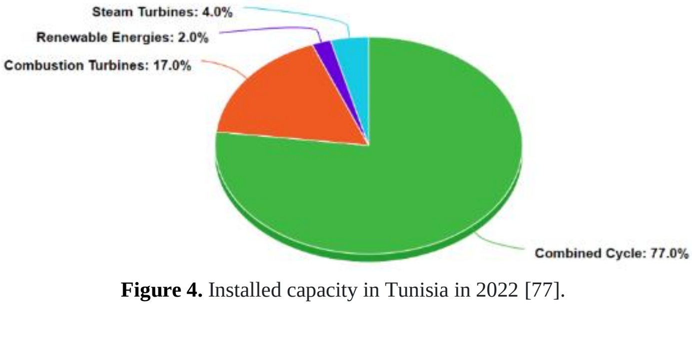

Figure 4. Installed capacity in Tunisia in 2022 [77].

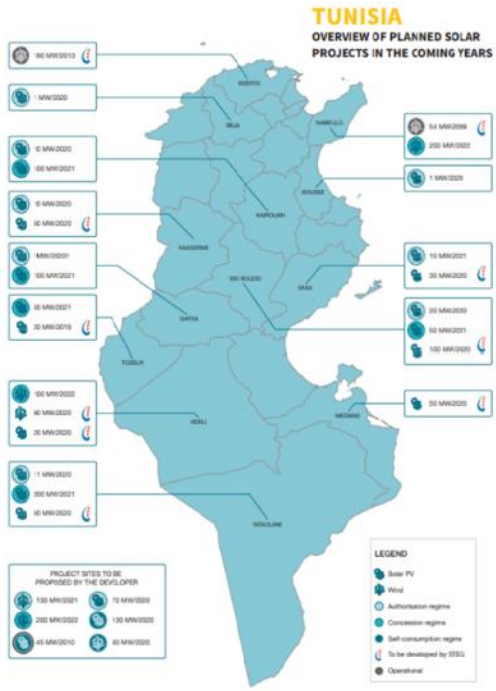

Figure 5. Overview of Tunisia Planned solar projects. Source: Solar Power Europe, 2020

B. National and International Electricity Transmission Grid of Tunisia

Tunisia has a big chance for the country to take the profit out of RES for future investors (Fig. 5). Specialists and government representatives agree that further green energy implementation requires vital political decisions. In addition to the benefits of RES for the environment in Tunisia, exporting energy to foreign markets could be a substantial added value for the Tunisian economy. Indeed, two critical challenges are the exports, namely the high cost of the installations and the establishment of a transparent judicial framework that regulates energy exports. Tunisia can benefit from markets that are ready to pay high prices for clean energy. Thus, investing in new technologies. Tunisia has approximately 20 % better radiation than most European sites.

An ambitious plan of proactive decarbonization scenario based on the transport of the RES based on a reliable transmission network. A transmission network has taken a sensible approach in responding to the growth of RES in safe, secure, and reliable network operations that never experience a power cut due to a fault on the transmission network. So, replacing lines and infrastructure is vital to introducing new technologies for digitizing the network by giving information and real-time fault trends and usage trends to make investment decisions. According to [80-81], STEG installed around 170000 km of medium voltage lines, 65000 km of low voltage, and 6985 km of high voltage transmission lines. The transmission network voltages are 90 kV, 150 kV, 225 kV, and 400 kV, as shown in Fig. 6 (a) and (b) [82-84].

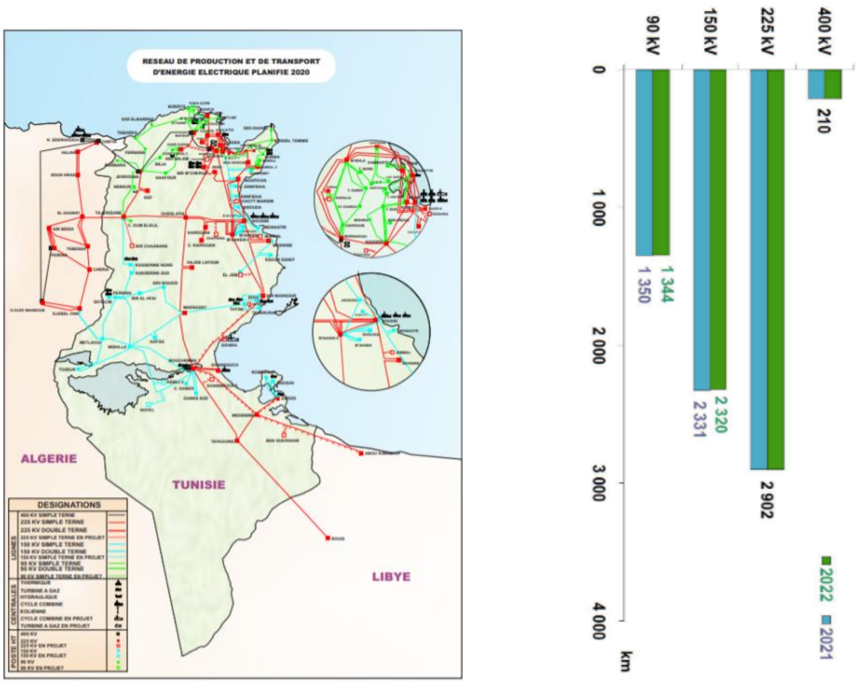

Figure 6. (a) Electrical grid map (b) Accumulative Length of the electricity transmission network between 2021 and 2022 [77].

The Saharan desert and North Africa are among the world's most incredible untapped energy resources. The blazing sun of these deserted lands could now finance an industrial revolution for these countries and draw a drastic new vision for them and a plan to turn this dream into reality. Tunisia is well-positioned to lead by example, benefiting from its proximity to Europe and relatively stable government, indicated by a political stability index of -0.65 compared to its North African counterparts. With abundant Renewable Energy Sources (RES) and consistent desert winds along its coast, Tunisia can potentially meet its energy needs and export surplus to Europe, focusing on enhancing local electrical infrastructure for the benefit of its residents. Tunisia's strategic use of resources underscores its commitment to self-benefit. The undeniable potential of solar energy is complemented by existing technologies supporting cross-border energy trading, with ongoing investments aimed at expanding trade capacity by reducing the problem of balancing demand and supply across borders [85-87].

Many interconnections link North Africa to Europe. The earlier two interconnections are between Morocco and Spain's 2700 MW interconnections. The first was completed in 1998, followed by the second in 2006. The third connection between the two countries is anticipated to be finalized by 2030, collectively transporting 2100 MW of power. These connections represent the shortest route from North Africa to Europe as shown in Fig. 7.

Figure 7. North Africa grid interconnections.

Simultaneously, the proliferation of electric interconnections between countries remains a consistent trend. Fig. 7 visually delineates the existing and planned electrical interconnections among nations. The interconnections extend from Tunisia to Sicily (200 km), Algeria to Sardinia, Tunisia to northern Italy, Libya to Greece, Italy to Greece and Turkey. The interconnection will be expanded across the Middle East network. These efforts aim to establish sufficient internal interconnections between nations, facilitating solar energy transmission. Tunisia will have two green corridors of 400 kV between the state and (i) Algeria (220 km) and (ii) Libya (210 km). Political leaders have devised plans to connect North Africa to Europe and the Middle East, confident in the swift recovery of costs. Investments would focus on high voltage alternating current transmission for shorter gaps, like from

Morocco to Spain, and high voltage direct current for longer distances. Utilize HVAC transmission for shorter spans, such as the connection between Morocco and Spain, and opt for HVDC for longer distances.

High voltage direct current (HVDC) is favored due to lower power loss per kilometer than alternating current (AC) (Fig. 8-a). However, converting North Africa's regional AC grid power to DC for long-distance transmission involves costly transformers and converters. The cost versus distance graph (Fig. 8-b) indicates a crossover around 500 to 800 km, where DC becomes more cost-effective. Consequently, shorter connections like Morocco to Spain may not be suitable for high-voltage DC. At the same time, longer lines, such as Tunisia to Italy, are better suited for HVDC transmission, with losses of around 3% per 1000 km. Since Germany's capital is merely 1800 km from Tunisia, transmitting power with such investment is reasonable.

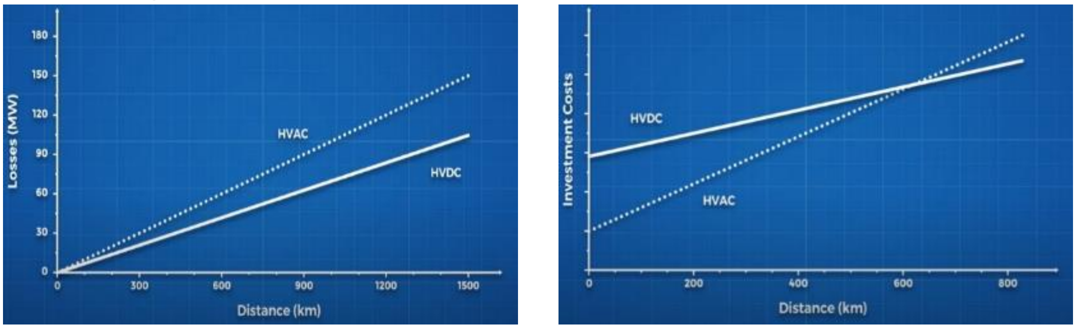

Figure 8. (a) High voltage transmission losses (b) Cost curves for high voltage lines.

C. *System Simulation*

The electrical grid and its topologies are major spatial flexibility options. The system energy is modeled, allowing us to see the impact on the energy system regarding the overlay grid border interconnections transmission and distribution grid—besides the integration of dispatchable solar power. The expansion of the Tunisian electrical grid is analyzed and evaluated with different shares of fluctuating and dispatchable RES. The electrical grid topologies with an energy mix include transferring dispatchable solar power for a future energy system. The scenario adopted is based on sensitivities of technical economic assumptions. The energy system is represented in Fig. 9, including spatial distribution effects such as the transmission and distribution grid inside the region. A model is a representation of an already existing past or future original characteristics.

As shown in Fig. 9, the system under study presents an equivalent model for the 225 kV high-voltage Tunisian power transmission system. The system base values are 100 MVA, 225 kV, and 50 Hz. The branch and bus data are summarized in Fig. 10. It encompasses 23 busbars, 18 generators, 17 loads, 5 transformers, and 47 branches. In the base case, the active and reactive power generating systems are 5046.6 MW and 1451.1 MVAR, respectively. The transmission system is rated at two voltage levels, 400 kV and 225 kV. The swing bus is chosen to be number 1003, which is attached to the SKHIRA power station. Bus 1001 (Jendouba) assures connection respectively to the Algeria system, while buses 715 (Tataouine) and 730 (Tataouine) assure connections to the Libyan grid. Note that these buses are modeled as PV buses with zero active power generation, thus ensuring voltage control at these nodes.

The SPVPPs connected to buses 701, 702, 706, 708, 712, 715, 718, 730, and 741 with the maximum installed PV power of 950 MW. Each SPVPP comprises several PV generators operating with homogeneous temperature and solar radiation distribution. They are identified by a single equivalent SPVPP at their shared point, presuming a 0.95 leading and 0.95 lagging power factor during operation.

The WFs denoted as WF1, WF2, WF3, WF4, and WF5, are linked to buses 701, 705, 716, 719, and 728, contributing to a maximum installed wind power of 765 MW. Every wind farm has several wind generators, each represented by a comparable wind turbine at the PCC. The assumption is a uniform wind speed distribution within the WF [86, 87], and these turbines operate with a power factor ranging from 0.95 lagging to 0.95 leading. The complete scheme, structure, and simulation are analyzed using MATLAB/ PSAT toolbox and Matpower software [88, 89].

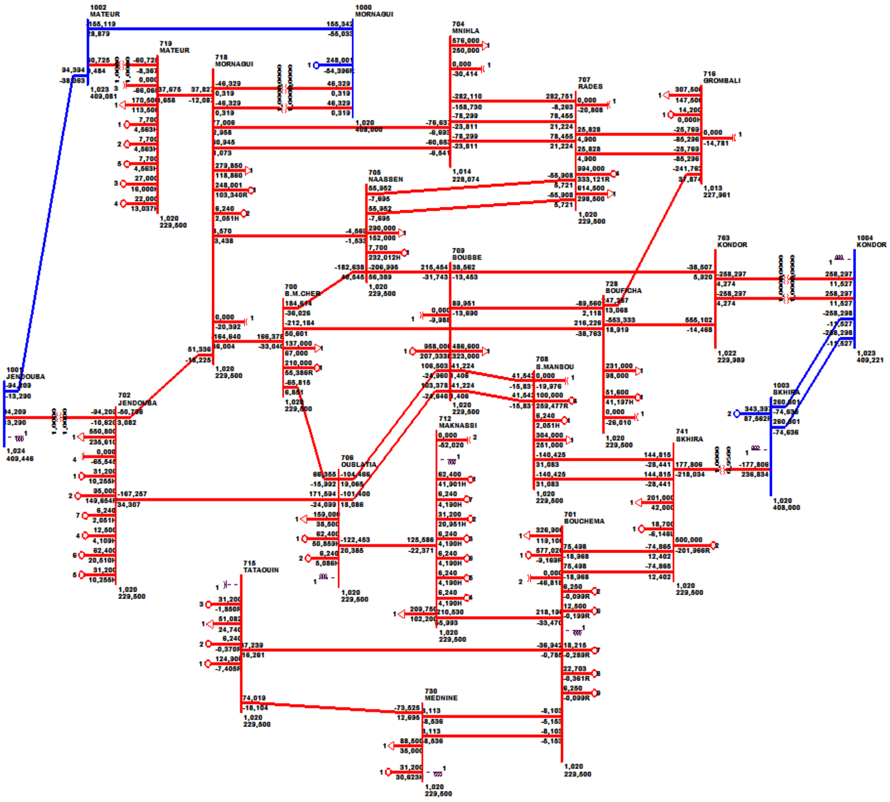

Figure 9. Single line diagram of the existing transmission grid showing the interconnection points of the RES power plants.

VII. Simulation Results

A. *Base case*

During load-flow analysis, RES generators are typically incorporated into the PV bus of the generator type due to their voltage control capabilities and active power generation. Conversely, RES are treated as load buses once they reach their reactive generation limits. Based on this assumption, the power network has characterized each SPVPP and WF. The network's voltage profile under peak load conditions has been examined with and without RES power generation, considering both with and without reactive power limitation. Fig. 10 and Fig. 12 illustrate the impact of reactive power limitation and RES integration on the voltage profile during peak load conditions; in scenarios where RES power is zero and there is a reactive power limitation, the voltage at buses 763, 1003, and 1004 varied from 0.75 p.u to 0.95 p.u. These bus locations are situated within the southern and western transmission grids, interlinked with the Libyan and Algerian transmission grids, as illustrated in Fig. 7 and Fig. 9, respectively. It is important to highlight that the Libyan and Algerian system grids do not provide reactive power support because tie-connections to neighboring networks are not taken into account in these simulations. These buses thus run at lower voltage levels.

Solar PV generators at buses 706, 712, and 741, wind generators at buses 716 and 728, and Synchronous Generators at buses 763, 1003, and 1004 are initially categorized as PV type. When they reach their upper reactive limit (Q_{gmax}), they can no longer maintain the required voltage at their terminal bus, as illustrated in Fig. 11 and Fig. 13, respectively. The exhaustion of conventional generator buses precedes solar and wind farm generators. This trend suggests that these connection buses experience insufficient reactive support due to their small size and limited reactive control capability. As a result, when all SPVPP and WF inject their maximum power, voltage levels increase at the connection buses under peak load conditions, and there are no instances of over-voltages, as demonstrated in Fig. 10. The voltage profile of the grid and PV buses exhibits an increase, with voltages across multiple buses within the acceptable 10% tolerance range.

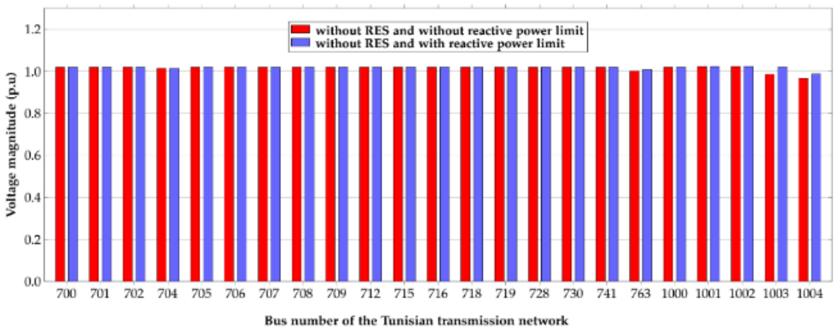

Figure 10. Voltage magnitude profile of the Tunisian transmission network with RES and with and without reactive limit in peak load conditions.

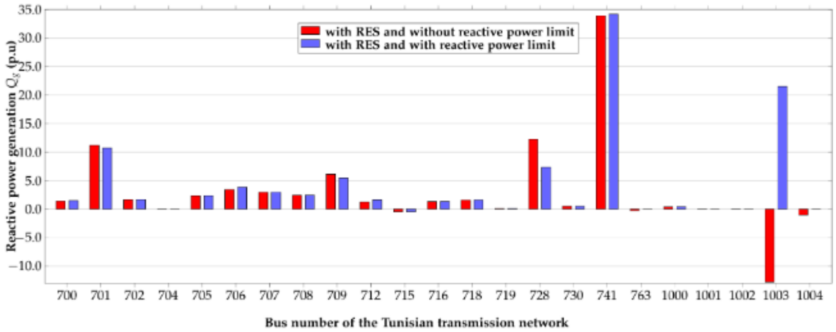

Figure 11. Reactive power generation profile of the Tunisian transmission network with and without reactive limit in peak load conditions.

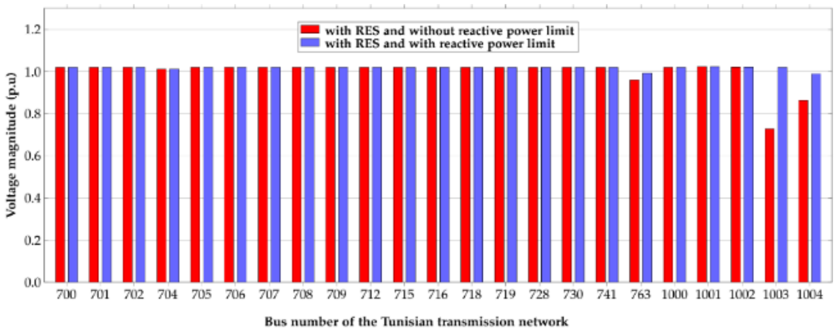

Figure 12. Voltage magnitude profile of the Tunisian transmission network without RES and with and without reactive limit in peak load conditions.

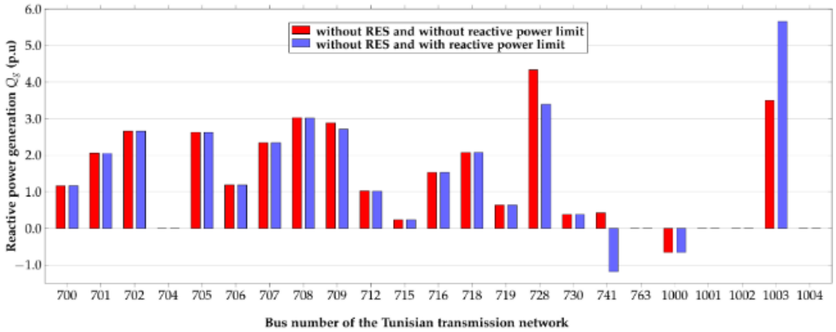

Figure 13. Reactive power generation profile of the Tunisian transmission network without RES and with and without reactive limit in peak load conditions.

Table 1 shows the minimum eigenvalues of the load-flow Jacobian matrix computed in the base case with and without RES and with and without reactive power limits. It can be observed that the system doesn't present any critical modes close to zero. This indicates that the system is maintaining its stability. Further, the system without RES is more stable than the one with RES because integrating RES into the grid affects the transmission line losses and overall system performance in the static base case.

Table 1. Minimum eigenvalues locus of the Load flow Jacobian matrix J_{LF}

Without RES and with a reactive power limit	Without RES and without reactive power limit	With RES and a reactive power limit	With RES and without reactive power limit
7.7356	5.1848	2.6876	3.6654

B. RES power transfer case

Modal analysis is carried out on the system described in Fig. 9 in the presence of high-RES penetration levels. The RES penetration level is the relative amount of PV solar and wind power injected into the grid. There are three common classifications to describe the contribution of solar power penetration level to the power grid: instantaneous, energy, and capacity penetration [90-92].

The Instantaneous penetration expresses the ratio of total RES generated to the total load at a particular time because of the variable natures of the RES system and load. Energy penetration is the energy ratio from the RES system to the load energy over a certain period. Capacity penetration refers to the ratio of the RES capacity to the system's peak load. In this study, the calculation of the RES penetration percentages is carried out based on the following equation:

$$\text{PV Penetration (\%)} = \frac{\text{Total PV generation (MW)}}{\text{Total generation (MW)}} \qquad (13)$$

As the penetration level of RES generation increases, more traditional generators are evacuated to account for the load balance and generation. An adequate reactive power margin is considered in selecting the displaced generators. Hence, the crucial generators involved in reactive power generation have not been disconnected from the system.

Fig. 14 shows the bifurcation voltage diagram at system buses under different RES penetration levels. It reveals the behavior of the steady-state bus voltages with the increase of the RES generation but at slightly different voltage levels. When the renewable energy generation margin (REGM) increases, the distribution feeder reduces its power injection into the network, which causes the voltage to increase in the first half of the curve. The second half of the curve shows a voltage drop that is ascribed to a power transfer constraint issue.

At the REGM generation margin value of 0.01453 pu, the bifurcation takes place. At a certain SNB, the system breaks down. This is one of the main causes of voltage instability. For increased transmission capacity, the transmission system has been improved. The system's loading state determines the maximum margin for RES generation. With the increased RES power penetration, the voltage decreases catastrophically at the most critical buses, 763 and 1004, until the SNB point at 0.82 pu and 0.65 pu, respectively. This is because the RES location is geographically close to these buses.

The bifurcation technique examines qualitative shifts in the system dynamics that occur during gradual variations in distinct system parameters. These changes are assessed based on factors such as stability loss, initiation or alteration of oscillations, transition from periodic to chaotic solutions, or vice versa. The use of bifurcation techniques aids in predicting the potential instability of the system and provides insights into when and how such instability may manifest [43].

The eigenvalue-locus depicted in Fig. 15, which illustrates how the minor eigenvalues' locus for the load-flow Jacobian matrix J_{LF} changes as the RES generation parameter increases, verifies the bifurcation point. The rest of the eigenvalue's locus for J_{LF} is ignored, taking only a loose value. Meanwhile, the min eigenvalues of J_{LF} at the SNB point equal 0.01702. The critical real eigenvalue reaches the origin, and SNB happens. Thus, the RES generation margin affects the system eigenvalues in the s-plane.

Fig. 16 shows that the determinant of the load-flow Jacobian matrix JLF verifies this point. It is equal to 0 at the SNB point. Thus, showing the singularity of the load-flow Jacobian matrix JLF. After the SNB point, the system becomes unstable, as plotted in Fig. 17, and the system stability is completely lost with continuous parameter variations. The system encounters a static voltage collapse. When the RES penetration is at its maximum, voltage levels at bifurcation points are relatively higher in some busses, as shown in Fig. 14. Fig. 18 shows that on buses 1001, 1002, 701, 712, 716, and 728, the voltages are close to 1.00 pu. This implies that the voltage collapse cannot be forecasted based only on voltage measures. This phenomenon is further prominent in the off-peak-load case. It is essential to consider that the buses in the north and center have taken advantage of their proximity to the RES power injection.

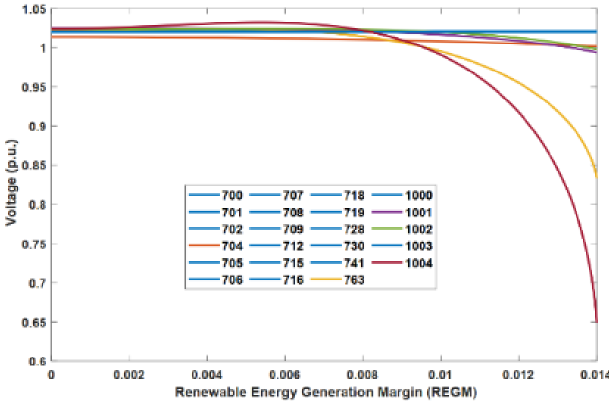

Figure 14. Bifurcation diagram of voltage at all buses of the Tunisian transmission network with RES and with a reactive limit in peak load conditions.

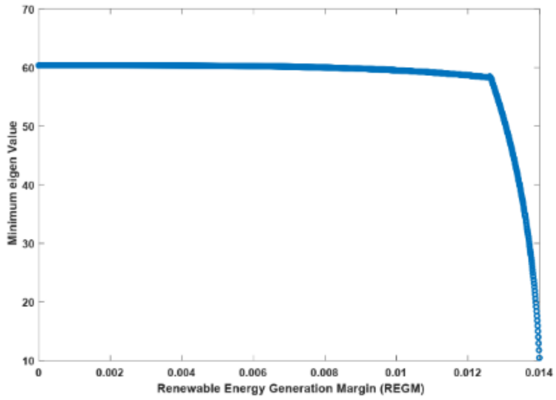

Figure 15. Minimum-eigenvalues locus for the system state load flow Jacobian matrix J_{LF} for increasing renewable energy generation margin.

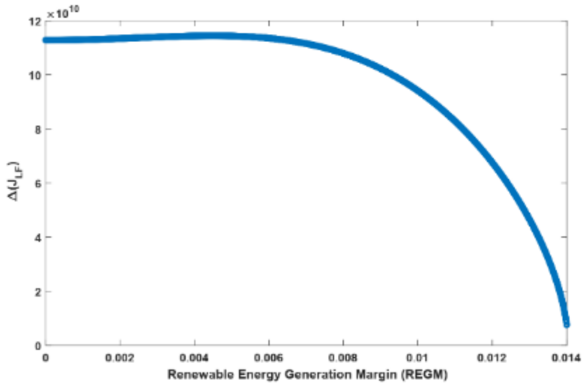

Figure 16. The determinant of the system state Load Flow Jacobian matrix J_{LF} for increasing renewable energy generation margin.

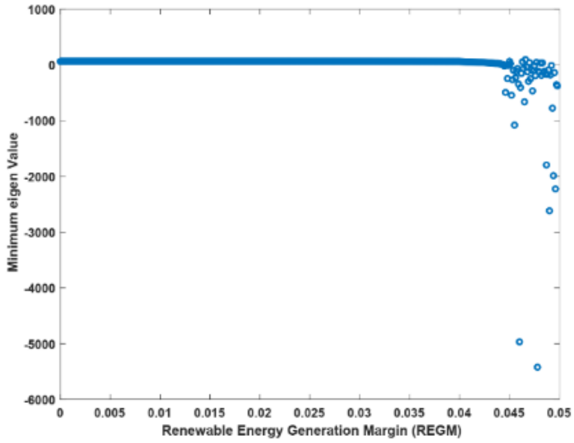

Figure 17. Critical eigenvalue trajectory under increasing RES generation margin.

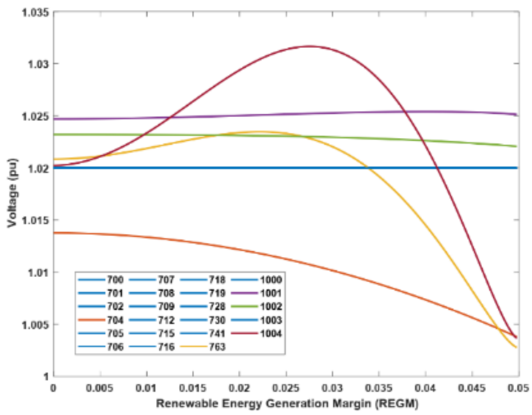

Figure 18. Bifurcation diagram of voltage at maximum RES penetration.

The simulation results obtained from the application of Recurrent Neural Networks (RNNs) provide a critical evaluation of the model's predictive accuracy [93]. RNNs are particularly adept at capturing temporal dependencies through their hidden states h_t, which are updated at each time step by:

$$h_t = \mathrm{ReLU}(W_{hh}h_{t-1} + W_{xh}x_t + b_h) \quad (14)$$

$$y_t = \mathrm{softmax}(W_{hy}h_t + b_y) \quad (15)$$

where W_{hh}, W_{xh}, and W_{hy} are the weight matrices, b_h and by are bias vectors, ReLU is the Rectified Linear Activation Function, and softmax is the softmax function for the output layer.

The evaluation of our RNN model's performance was quantitatively conducted using error metrics such as Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE). The MAPE is defined by:

$$\text{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{y_t - \hat{y}_t}{y_t}\right| \times 100\% \tag{16}$$

where y_t is the actual value, $\hat{y}_t$ is the predicted value by the model, and n is the number of observations. The RMSE is computed by:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(y_t - \hat{y}_t\right)^2} \tag{17}$$

The obtained MAPE of 22.77% and RMSE of 0.03749 indicate a moderate level of prediction error, which suggests that while the model can capture the general trend, it requires further optimization to reduce these errors. These results indicate the necessity for a comprehensive analysis of model architecture, selection of input features, and hyperparameter tuning.

The forecast plot shows a divergence from the actual values, particularly during periods of peak variability. This divergence might indicate the model's sensitivity to the non-linear and stochastic nature of renewable energy outputs, suggesting that including additional layers or alternative architectures, such as LSTM units, could potentially enhance the model's ability to model complex dependencies.

In conclusion, while our RNN model demonstrates an inherent capability to predict voltage stability within the power grid, the simulation results underscore the need for further refinement. This refinement could involve exploring more sophisticated deep learning architectures, more granular feature selection, or advanced training methodologies to improve the accuracy of voltage stability predictions in the presence of RES.

Recurrent neural networks (RNNs) are the most practical algorithms because they are the only neural network (NN) with internal memory. Hence, they are considered a robust NN. RNNs are ancient, like many other techniques in deep learning. They were founded in the 1980s, though we have seen their actual possibility exclusively in recent years. RNNs are now more popular than ever thanks to advances in computing power, massive data sets that require processing, and the development of long short-term memory (LSTM) in the 1990s. But because RNNs have internal memories, they can identify important details in the information they receive, making precise predictions about what will happen next. In addition, the RNN Model has a recurrent encoder stage, which encodes its input, and a fully connected NN decoder stage, which produces a prediction of the output chunk length established on the last hidden state of the encoder set. Thus, the model delivers blocks of forecasts and is confined to looking at covariates simultaneously as the input target, as shown in Fig. 20.

Fig. 19 compares the predicted and estimated bifurcation diagram of voltage stability on bus 1 with real voltage measurements. The estimated values significantly improve over the predicted values, showing settlement with the actual values.

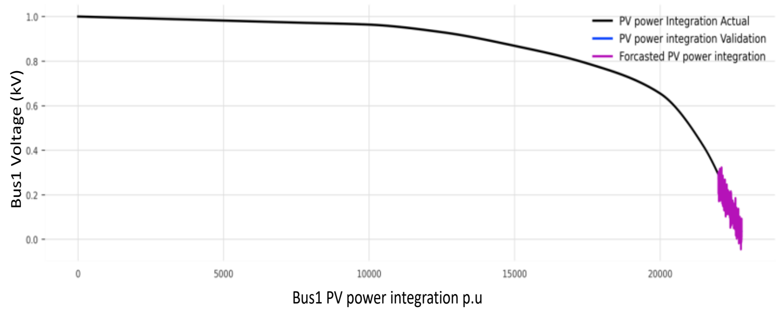

Figure 19. Prediction of PV power penetration using RNN Model.

Fig. 20 and Fig. 21 show the modes that appear in two extreme cases of RES power penetration at maximum and zero REGM. The simulation shows that the number of modes changes when the RES penetration level increases, according to the bifurcation diagram of the voltage in Fig. 15. It indicates that some synchronous generators and RES power plants have reached their maximum reactive power limits and transferred to PQ loads. Here, the system presents two critical modes when the penetration level is at its maximum power, namely modes 18 and 23, which are close to zero. This indicates that the system is close to voltage instability. This result confirms the result in Fig. 15. The simulations also show that the system is more stable in the case of zero penetration level, i.e., in the base case.

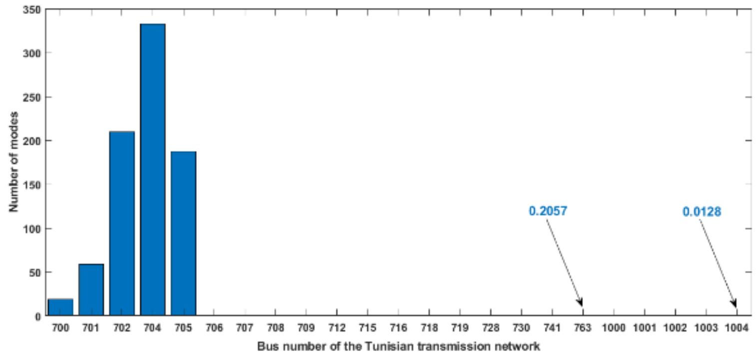

Figure 19. Number of modes of the system in case of max renewable energy generation margin.

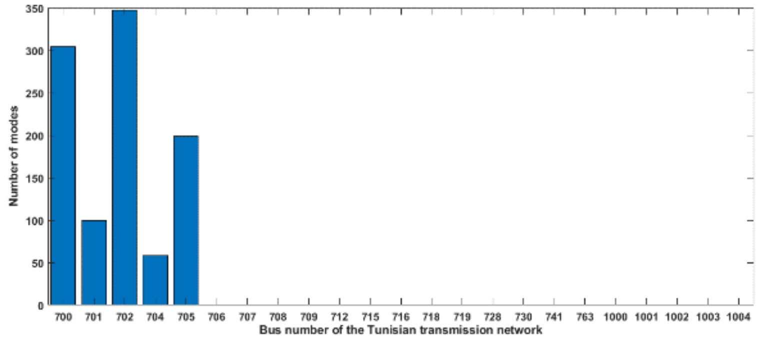

Figure 20. Number of modes of the system in case of zero renewable energy generation margin.

The left and right eigenvectors correspond to the system's minor (critical mode) eigenvalue. They offer insights into the mechanism of voltage instability by identifying the elements involved in the respective mode. The bus participation factor, indicating the contribution of the k^{th} bus to the i^{th} mode, is defined in (11).

Bus participation factors associated with critical modes can forecast regions or nodes in the power system prone to voltage instability. Buses with significant participation factors in the governing mode represent either the most vital or weakest system bus. The vicinity where the top-ranked weak buses are concentrated is the system's weak area. Fig. 22 depicts the participation factor of different buses about the critical eigenvalue. From the figure, buses 701, 704, 705, 707, 709, 712, 715, and 716 are the most contributing buses in this mode, which implies the weak areas of the system are in the center and south region. The simulation has shown these modes are localized, i.e., the modes 2, 4, 5, 7, 9, 10, 11, and 12, which only dominate bus participation, whereas the rest of the buses have participation close to zero.

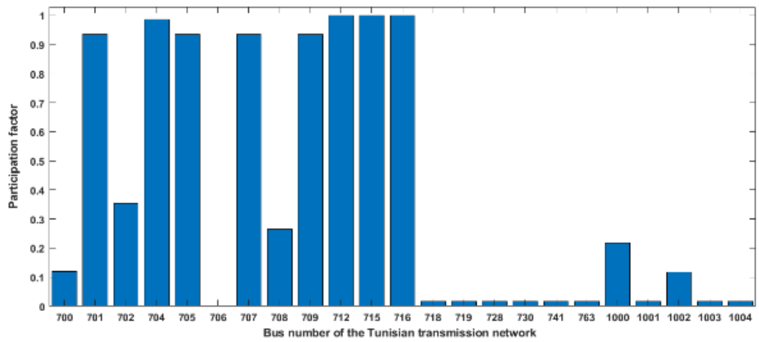

Figure 42. Participation of system buses on the critical eigenvalue.

VIII. CONCLUSION

The investigation of the critical modes independently is made possible by the impact of 1750 MW renewable energy resource power plants on the voltage stability analysis of the HV linked Tunisian power system using the modal analysis approach. The results for the studied power system prove that the voltage collapse during various contingencies can predict the maximum RES penetration level that a system can securely handle for any operating conditions.

The participation factor of the power system devices is determined to analyze the leading causes of voltage instability. The branches with high participation in a mode are those linked to main production sources and the branches ensuring inter-regional connection. Enhancing the performance of the branches directly connected to the effective operation of the power system. Thus, deficient performance harms a significant section of the tie-connections between the Tunisian linked power system and the bordering networks in Algeria and Libya. In addition, RES have had a beneficial impact on the power system, introducing mitigating effects on the distance of the critical bus to instability. The grid has played a constructive role in enhancing the overall stability of the power system. Current research emphasizes the significance of refining small signal characteristics in power systems with RES integration, with a primary focus on control strategies for supplementary damping controllers. This includes aspects such as controller design, parameter optimization for coordinated tuning of diverse controllers, damping controller considerations, eigenvalue sensitivities, input signal selection, Power System Stabilizers, and related factors.

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