Assessing the Impact of Integrating Photovoltaic Systems and Wind Turbines, on Power System Stability and Performance Parameters

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Abstract: This study aims to identify the behavior of parameters in different operating regimes, respectively short circuits in a part of the power system that include renewable sources, respectively wind and photovoltaic (PV) with a combined capacity of 200 MW integrated in a strong 110 kV network. The paper provides an idea for the construction of models of power grid components and a summary of the discussion of their effects on grid nodes, during unanticipated short circuits, according to a bandwidth of fault durations, at the nodes, where wind and PV systems are connected and the rest of the electrical power network. This builds an idea of their stability and the impacts on the stability of the overall operation of the power system. Through the discussed models, the conceptual performance indicators of the operation of wind and PV turbines, in different load regimes, has been built, having a real approach to the construction of concepts for the protection of nodes, busbars and the appropriate measures for action, related to the safety of power systems as a whole. The discussion also includes the characteristics of power flows, currents, load and voltage profiles in lines, busbars, transformers, taking into consideration the topology of the network as part of the analysis. Models of components, such as the wind and solar systems, are used in several simulation test cases. Finally, the results and stability during the testing, according to different cases of short circuits, are discussed through simulations and their analysis.

Keywords: Power system; Wind and PV power integration; Transient processes; Stability and security

1 Introduction and Motivation

Assessing the stability of electrical power systems is crucial, especially with the integration of the renewable resources of wind and solar. This necessitates analyzing their parameters and fluctuations, during relevant operational periods.

However, the issue of incorporating renewable energy sources greatly complicates the operation of current networks. The main renewable energy sources depend on the weather and fluctuate, leading to extreme unpredictability in power generation, causing continuous fluctuations in power output [1]. Synchronous machines serve as the primary source of inertia, affecting system damping and influencing the rate at which the system's frequency responds to disturbances [2]. Furthermore, Energy is an essential sector on the path to prosperity in the future. The value chain of energy generation, distribution, and consumption is crucial for society as a whole. Climate change and sustainability are leading energy systems to a new level of innovation with regard to technology, policy, and societal values [3]. Among various distributed energy resources, the growth of solar photovoltaics (DGPV) has sparked significant interest and led to numerous development projects in integrated transmission (T) and distribution (D) modeling. Bulk system operators often face challenges in gaining sufficient visibility into the amounts and levels of DGPV, which impacts transmission operations and wholesale power markets. Additionally, fluctuations in voltage during the day on the transmission network can influence the performance of distribution systems with high penetrations [4] [5].

PV systems exhibit dynamic behavior distinct from traditional generation units, particularly with large grid penetration. Therefore, finding an appropriate model is crucial for understanding how grid-scale PV-based power generation affects a large power grid's dynamic stability and oscillations. Grid-connected photovoltaic systems commonly rely on core device modeling, which considers the properties of PV modules and inverter control [6].

The integration of large-scale wind generation and PV systems can significantly impact the economics and security of the power grid. It is essential for power grid operations to remain stable, dependable, and cost-effective under extensive use of wind energy and PV systems. Grid connection requirements for wind turbines are specified in grid codes, which typically cover steady-state performance parameters such as frequency, voltage, active and reactive power, and power quality [7].

The primary responsibility of the transmission system operator is to maintain essential electrical parameters, such as frequency and voltages, in compliance with required standards and ENTO-e rules [8].

The study aims to delve into the behavior of parameters across various operational scenarios, particularly focusing on short circuits within a specific segment of the power system incorporating renewable sources—specifically, wind and photovoltaic (PV) systems with a combined capacity of 200 MW, integrated into a robust 110 kV network. It provides insights into the construction of models for power grid components and offers a succinct overview of their impact on grid nodes during unforeseen short circuits, encompassing a range of fault durations at the nodes where wind and PV systems interface with the broader electrical power network. This analysis aims to assess their influence on the stability and overall operational robustness of the power system. By utilizing these models, the study establishes conceptual performance indicators for the operation of wind and PV turbines under varying load regimes, offering a practical framework for formulating strategies to protect nodes, ensure busbar integrity, and implement appropriate safety measures for the comprehensive security of power systems. Furthermore, the discussions encompass the intricacies of power flows, currents, load distribution, and voltage profiles along transmission lines, busbars, and transformers, with due consideration given to the topology of the network as an integral aspect of the analysis. Multiple simulation cases, incorporating models of components such as wind and solar systems, are employed to comprehensively explore various operational scenarios.

2 Renewable Energy Sources and their Penetration in Power System

Frequency disturbances – one of the parameters of primary importance in power system stability, must be considered during fluctuations in the production of renewable resources [9].

The unplanned power flows of electricity pose significant management and operational security challenges to transmission system operators in the region of Central East Europe [6]. The prediction of wind speed is quite challenging because wind and PV generation represent typical non-linear processes due to the influence of meteorological variables [10]. As variable resources are more thoroughly integrated, reserve, demand rises. To maintain long-term reliability, the network must always have greater overall capacity than is required during peak hours. Combining renewable (variable) energy sources with conventional energy sources can balance the energy supply while preserving the same level of supply security [11].

Numerous studies have been conducted on the dynamics and resilience of traditional electricity networks, particularly regarding their resiliency against cascading failures. Cascading failures occur when an initial problem spreads widely throughout a network and causes extensive disruption. Threshold models were used to mathematically represent the cascades, in order to identify key operational regimes when network-wide failures can occur [12] [13].

The following equation sums up the frequency-determining changes in the production-demand balance:

$$\sum_{i=1}^{n} P_p\,(A_1 + \cdots + A_n) + \sum_{i=1}^{n} P_I\,(B_1 + \cdots + B_n) = P_C + \sum_{i=1}^{n} P_E\,(C_1 + \cdots + C_n) \qquad (1)$$

$\sum_{i=1}^{n} P_P$ – production (2)

$A_1 + A_2 + .. + A_n$ – types of production, $\sum_{i=1}^{n} P_I$ – imported power, $\sum_{i=1}^{n} P3_I$ – operators of market trading, $\sum_{i=1}^{n} P_E$ – exported power.

$$\Delta P_{error} = \Delta(P_p + P_I) - \Delta(P_C + P_E) \quad (3)$$

ΔP_{error} – error active power (imbalance) of the power system

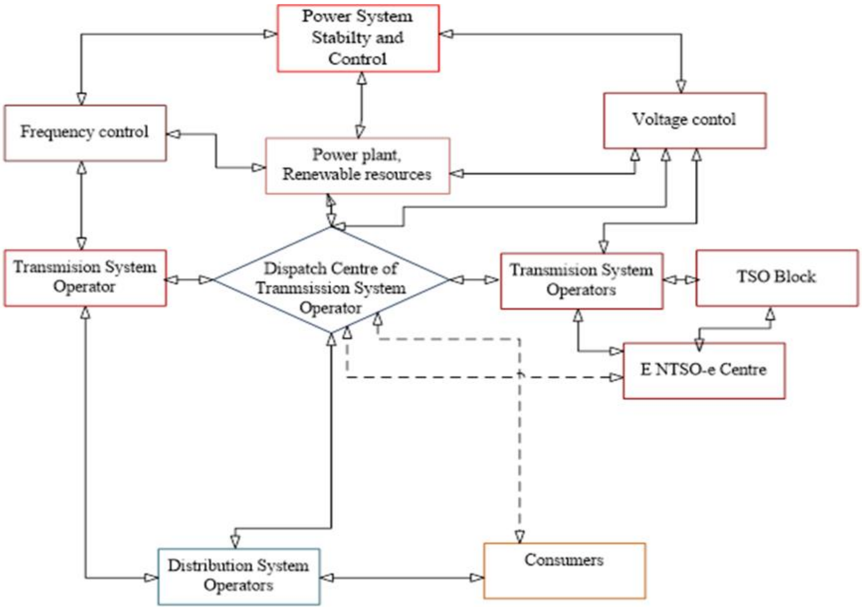

Figure 1
Components hierarchy for adequacy and security of the power system

Development of power plants, including renewable energy sources (RES), is constantly and rapidly rising [14]. Traditional power system stability studies calculate the system's response to a series of significant disruptions, typically a generator failure or a network short circuit, followed by protective branch switching procedures. In the temporal domain, the process is a direct simulation with durations ranging from 1 to at least 20 minutes. The power system's many components have varying impacts on stability, at different stages of the reaction, which is taken into account in system modeling. Short-term models emphasize the electrical components that respond quickly, while long-term models depict the slowly oscillating power balance of the system, assuming that fast electromechanical transients have subsided. Problems in this sector are often categorized by identifying "transient stability" as a short-term issue, covering post-disturbance periods of up to 5–10 seconds [15].

Voltage disturbances—variations in bus voltage magnitude caused by load fluctuations, intermittent generation changes, and potential contingencies that highlight the importance of properly controlling the reactive power supply and voltage magnitude throughout the regular operation of a power network. The key goals often include managing the production and consumption of reactive power and maintaining appropriate bus voltage magnitude levels. For a power system to operate safely and continuously, stability is a crucial component. The ability of the power system to resume a normal operational balance, following a physical disturbance, is what is meant by the term "stability" [16].

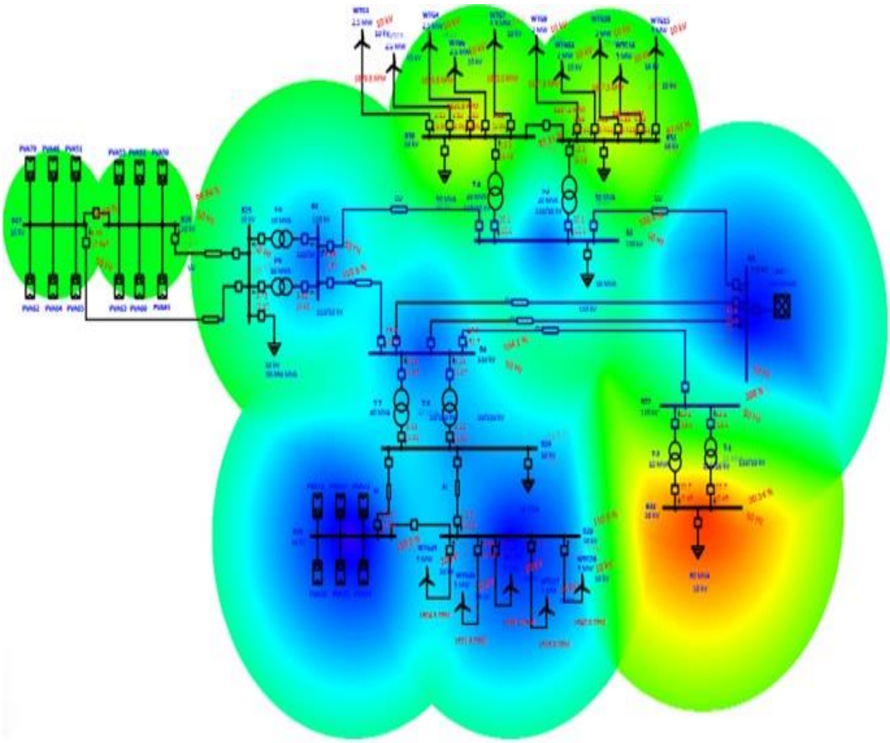

Figure 2
Integration of wind turbines and PV systems (case study)

System inertia is a primary crucial factor in the concurrent operation of power systems. The system is more susceptible to frequency fluctuations and the inertia of the system becomes smaller [17].

3 Modeling of the Components in the Electric Power System and the Use of Methods in the Calculation of Stability Parameters

Control aspects of power systems include a significant number of factors, considering static and dynamic stability. Knowing the problems of static stability constitutes a permanent engineering need, which includes the phenomena of transients, voltage fluctuations and current flows during short transient connections, while dynamic stability includes a deeper range of phenomena that are considered powerful during connections of short in lines, busbars, generators and transformers, where reflections are high in frequency and voltage parameters. Therefore, laying out the problem of control, modeling and combination of participating components and their nature in electroenergetic systems constitutes a necessary element for the recognition and effects of each component in the performance of the respective stability. The computation of control inputs is based on a predictive optimal control strategy which considers previously defined performance specifications [18] [19].

Faults on power lines and other components of power system are the most common cause for the loss of stability of power system. In a typical scenario disconnection of a component is followed by the action of the reclosing system which restores the topology of the system after a fraction of a second. In order to address these consequences are used the model of a power system, where the loads are represented by the static impedances and the n generators have perfect voltage control and are characterized each by the rotor angle δ_k and its angular velocity $\dot{\delta_k}$. When the losses in the high voltage power grid are ignored the resulting system of equation can be represented as [20].

$$m_k\ddot{\delta_k} + d_k\dot{\delta_k} + \sum_j B_{kj}V_kV_j \sin\left(\delta_k - \delta_j\right) - P_k = 0 \tag{4}$$

m_k – dimensionless moment of inertia of the generators

d_k – primary frequency controller action on governor

B_{kj} – is the $n * n$ – reduced susceptance matrix

P_k – is the effective dimensionless mechanical torque acting on the rotor

In normal operating condition the system has many stationary points with at least one stable corresponding to normal operating point. Mathematically, this point characterized by the rotor angles δ_k^* is not unique, as any uniform shift of the rotor angles $\delta_k^* \to \delta_k^* + c$ is also an equilibrium. However, it is unambiguously characterized by the angle differences $\delta_{kj}^* = \delta_k^* - \delta_j^*$ that solve the following system of power flow-like equations:

$$\sum_j B_{kj}V_kV_j \sin\left(\delta_{kj}^*\right) = P_k \tag{5}$$

Formally, the goal of our study is to characterize the “region of attraction” of the equilibrium point δ_k^*, i.e the set of intitial conditons $\{\delta_k(0), \delta_j(0)\}$ from which the system converges to the stable equilibruim δ_k^*. To accomplish this task is used a sequence of techniques originating from nonlinear control theory that are naturally applied in the state space representation of the system [21]. The nonlinear control method is based on the concept of a differential equations that tries to minimize to minimize the system’s objective function and the disturbances and which try to maximize the cost function [22] [23].

Power system stability analysis – the stabilizer component within power systems plays a critical role in managing both steady-state scenarios and disturbances across a broad dynamic spectrum. In practical contexts, events occurring less than 1% of the time are typically deemed low-probability occurrences [24]. Therefore, to ensure adequate damping performance across various operational conditions, system stability can be assessed by ensuring that the one-sided upper confidence limits of a 1% reliability interval for damping coefficients are below zero. Additionally, the one-sided lower reliability limits of a 1% reliability interval for damping ratios should exceed ξ_c, representing the threshold for stable systems. Assuming the one-sided upper reliability limits of a 1% reliability interval for damping coefficients are denoted as a_k'' and the one-sided lower confidence limits of a 1% confidence interval for damping ratios as ξ_k'', can be written as:

$$P\{a_k < a_k'\} = 1 - 1\%$$
$$P\{\xi_k' > \xi_k\} = 1 - 1\% \quad (6)$$

According to the normal distribution characteristics, the a_k'' and ξ_k'' are shown as below:

$$a_k' = \overline{a_k} + 3\sigma_{a_k}$$
$$\xi_k' = \overline{\overline{\xi}}_k - 3\sigma_{\xi_k} \quad (7)$$

So, the conditions of system dynamic stability under multi-operating conditions can be obtained by:

$$a_k' = \overline{\overline{a_k}} + 2\sigma_{a_k} < 0$$
$$\xi_k'' = \overline{\overline{\xi}}_k - 2\sigma_{\xi_k} > \xi_c \quad (8)$$

Transcribing Formula (8) into Formula (9), we get:

$$a_k'' = -\overline{\overline{a_k}}/\sigma_{a_k} \geq 2$$
$$\xi_k'' = (\xi_k - \xi_c)/\sigma_{\xi_k} \geq 2 \quad (9)$$

In this context, a_k'''and ξ_k'''are represent the extended damping coefficient and extended damping ratio, respectively, of the *k*-th oscillation mode. With these parameters, the system ensures dynamic stability across various operating conditions and can be expressed by Formula (10) below:

$$\alpha > \overline{\alpha_k} + 3\sigma_{\alpha_k}$$
$$\xi < \overline{\xi_k} - 3\sigma_{\xi_k} \tag{10}$$

During the operation of the power system, the generators' active power signal under current operating conditions will be gathered, and the algorithm will be able to determine the frequency, damping, and damping ratio. The emergency control will be used when the system's eigenvalues fall into the emergency control range and do not meet the stability conditions. So, when the eigenvalues fall into the emergency control range, Formula (11) is satisfied, and the emergency control will be taken into consideration [16] [25].

$$\alpha > 0$$
$$\xi < \xi_c \tag{11}$$

So, the stabilizer is used in two quantities: active power and frequency. The stabilizer has the same standard transmission function for both channels, but with different parameters:

$$F(p) = K_{ss}\frac{pT_D}{(1+pT_F)(1+pT_D)} \tag{12}$$

Where,

K_ss - gain of the stabilizer per channel

T_F - time constant of the stabilizer (filter)

T_D - time constant of the stabilizer (derivative)

The input signals, such as active power and frequency, undergo filtering processes with predefined time constants. These filtered signals are then subject to further manipulation, where they are multiplied based on the amplification characteristics of individual channels. This amplification depends on whether the signals are fed into the summator before the PI-regulator (designated as index 1) or after it (designated as index 2). The output of the stabilizer assumes the role of PSS1 when the stabilizer signal is retained within the summator before the voltage regulator, and as PSS2 when the stabilizer signal is integrated with the output signal from the voltage regulator. Utilizing logical parameters, it's possible to activate either the active power channel or the frequency channel independently [26].

Power system modeling requires a significant number of component and equipment integration in achieving results. Disturbances are permanent, which can be transitory, but also dynamic with unpredictable impacts. The modeling of the scenarios studied in the paper is based on different cases when breakdowns, short circuits and other transient events occur in the different parts of the electric power system. Important is the response of the resources integrated in the electroenergetic system in relation to the ability of their operational stability, always taking into consideration the stability of the system and the preservation of the parameters according to the allowed band. One of the devices and the application of methods that are taken into consideration for the analysis of stability control and recognition of errors during the operation of components in the electrical network are the types of controllers such as PI and PID. PI and PID controllers have become ubiquitous in industrial control loops, with approximately 90% adoption globally due to their ability to provide satisfactory control system performance at reasonable costs [27].

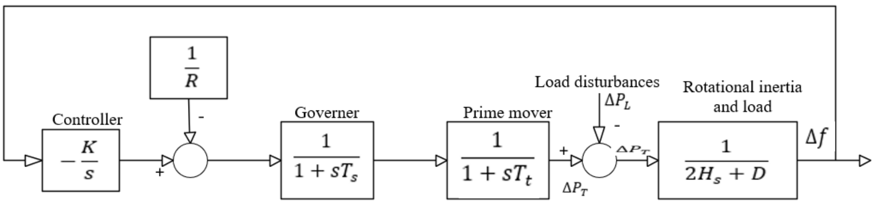

Figure 3

Modeling of power system [27]

The performance metrics delivered by these controllers rely not only on tuning parameters but also on the integration of additional functionalities such as anti-windup, feedforward action, and setpoint filtering [27]. Despite their widespread use, PI and PID controllers face challenges in achieving high-performance setpoint tracking and effective regulation in the presence of disturbances. One common approach to address these challenges is the development of two-degree-of-freedom (2-DOF) controllers, offering advantages over their single-degree-of-freedom counterparts. However, 2-DOF controllers often trade reduced overshoot for slower setpoint response. Another approach gaining prominence is fuzzy control, a specialized branch of fuzzy logic renowned for its cost-effective nonlinear control capabilities [28].

Voltage Control Oscillator Aspects – the analysis of the state-of-the-art indicates quite a number of electronically tunable Quadrature Oscillators (QO) were proposed recently in, where only a few exhibits a linear f_0-tuning law. Some of these are tuned by the device bias current (I_b) or transconductance (g_m). Next, VTI circuit in Fig.1 has been modified as shown in Fig. 3, to implement the VCOs by putting input node-V_i at ground. Here the input impedance (Z_i) at node V_0, derived as:

$$Z_i = {Z_1 Z_3}\Big/{[Z_2 (kV)^2]} \tag{13}$$

The characteristic equation (CE) of these proposed oscillators in Fig. 3 can be obtained as following the continuous time model in terms of:

$$Z_L + Z_i = 0 \tag{14}$$

In (10) choosing $Z_x = {}^{1}/_{sC_0}$ and τ in combionation with $Z_i = s\tilde{L}$ and $1/s^2\tilde{D}$ res[ectively. The CE of LC and rD type voltage Control Oscillators yields:

$$\frac{1}{sC_0} + s\tilde{L} = 0 \text{ and } r + \frac{1}{s^2\tilde{D}} = 0 \quad (15)$$

Hence these frequency of oscillation (f_0), $w_0 L$ and $w_0 D$ for LC-type and rD-type oscillator respectively may be derived using the performance specifications of the oscillation frequencies [29], written as:

$$W_0 L = \frac{1}{\sqrt{\tilde{L}C_0}} approx \frac{kV}{\sqrt{C_0 C R_1 R_3}} \quad (16)$$

Alternatively, data-driven algorithms, which utilize input/output data to adjust controller parameters, offer viable alternatives. Examples include Model-Free Adaptive Control (MFAC), Model-Free Control, Active Disturbance Rejection Control (ADRC), and Virtual Reference Feedback Tuning (VRFT) algorithms. Combining various data-driven algorithms has shown promise in enhancing control system (CS) performance. Notably, the integration of IFT with other data-driven algorithms has yielded significant improvements. For instance, researchers have combined IFT with MFAC for parafoil systems and with ADRC for piezoelectric nano-positioners [30] [31].

The detailed modeling of every component involved in completing a Wind Power Plant (WPP), from each wind turbine generator unit and PV solar panels up to the transmission line system connecting the entire system to the power grid, is required for the use of large-scale wind the power grid, is required for the use of large-scale wind and PV solar simulations in the analysis of power system problems [32].

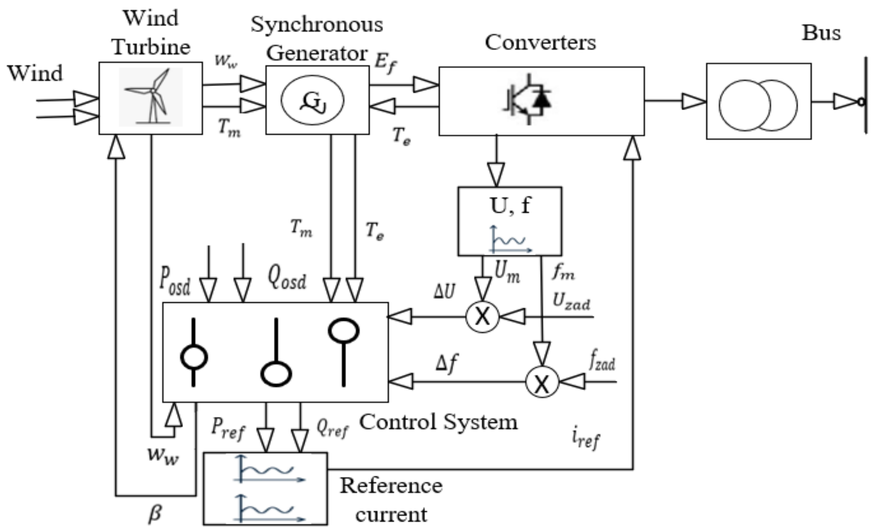

Figure 4
Wind turbine model

Power systems rely on various energy sources, such as sun, wind, water, and others. The effectiveness of these sources and their impacts on the power grid are additional to consider [33].

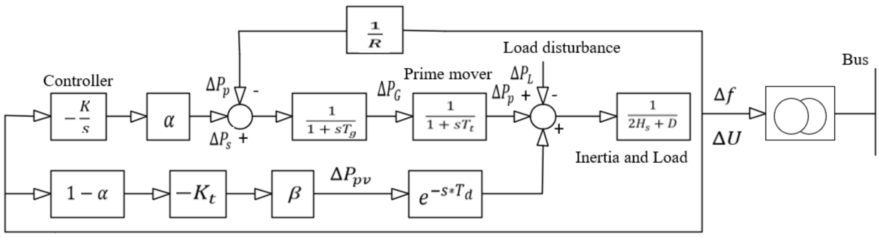

Figure 5

PV model

In order to produce appropriate results, electrical system modeling necessitates designing components with high precision. The modeling includes four substations with an equivalent strong balancing network of 110 kV, two of which incorporate solar PV sources with a combined power of 10.7 MW. Additionally, there are 10 wind turbines with a combined output of 27.5 MW. One substation has a combined system of 15 MW of wind turbine electricity and 5.4 MW of solar PV power. The overall consumption in the scenario is projected to be 220 MVA, and the modeling also includes a distribution substation with consumers connected with a power of 60 MW. The modeling is done using the ETAP software, which considers power transformers, overhead and cable lines, and other components [34].

The goal of the research is to investigate how renewable resource parameters behave when connected to other energy sources for a brief period of time (3 sec) and during other occurrences. The study also provides performance indicators for resources incorporated into substations during pertinent events. Simulated cases include unplanned outages on the busbars (B1, B3, B24, and B31). The simulations are conducted at various times, namely 0.8 sec, 1.5 sec, 2.0 sec, and 2.5 sec, totaling 3 seconds (Fig. 2). Accurate and thorough modeling allows for a more realistic view of the benefits of the results and enables the recognition of parameter behavior for various scenarios, work regimes, and events in the electrical power system.

4 Results and Discussion

The intricate design and configuration of the power system, particularly its integration of PV solar and wind turbines, stand as linchpins for its functionality and reliability. As these components represent the most sensitive elements of power generation, staying abreast of technological advancements in tracking and managing transmission and power system components, as well as in forecasting climate variables and modeling PV systems and wind turbine resources, is imperative. Understanding the evolving trends in power system stability hinges upon robust design, meticulous modeling, and comprehensive analyses that account for a myriad of variables and performance indicators.

This encompasses navigating through transients and dynamic fluctuations across various operational regimes. Whether operating under diverse load conditions or in the midst of designing, modeling, and analyzing power flows, voltages, and disturbances, there lies a distinct and crucial advantage in adhering to standards and codes. Doing so ensures the indispensably reliable and efficient functioning of the electrical system, safeguarding its ability to operate safely and dependably.

The case study scrutinizes several nodes at the 110 kV level within the transmission system, where PV systems and wind turbines are seamlessly integrated. Fig. 6 illustrates the scenario of a short circuit occurring at the B24 busbar, which accommodates renewable energy sources such as PV solar systems and wind turbines. The integration and stability of key parameters, including voltages, currents, and others, are significantly impacted by the unforeseen failure of this bus at a simulation time of 0.8 seconds, followed by a distinct fault at 1 second. Moreover, the scenario also reveals energy losses. During the short circuit at bus B24, discernible voltage fluctuations occur, exerting visible effects on the stability and continuity of wind turbines and, in broader terms, the substations under analysis. Concurrently, the voltage angle experiences marginal fluctuations, which, owing to the influences from other substations, maintain this parameter within acceptable transient conditions.

In Fig. 7, a balancing network is connected at the 110 kV level, simulating an unplanned failure of bus B1. Surprisingly, in the context of frequency and voltage balance, this node is classified as a strong bus. Analyzing the simulation from 1.5 seconds when the event occurs to 1.6 seconds when the fault is cleared, it can be deduced that the most affected parameter influencing the system's balance and stability is the voltage-to-frequency ratio within the turbines (Voltage/Hz).

It can be seen that this parameter, compared to the parameters and cases simulated in other substations, is affected by the main balancing bus B1 of the strong network. As a result, the frequency and voltage fluctuations are significant and directly affect the synchronization of other parts of the substations.

The wind turbines 5 are connected to bus B31, but at the moment of the fault (at 1 sec and clearing the fault at 1.5 sec), there are fluctuations in the parameters, including voltage, voltage angle, and load, while the frequency remains stable due to its consideration as part of a strong equivalent network and its integration in the synchronous area.

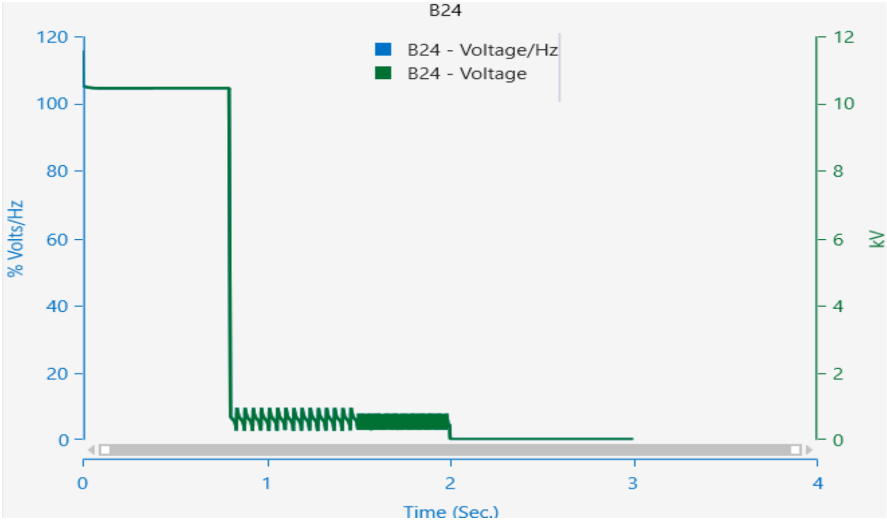

Figure 6

Bus 24, behavioral parameters during faults (connected PV and WT)

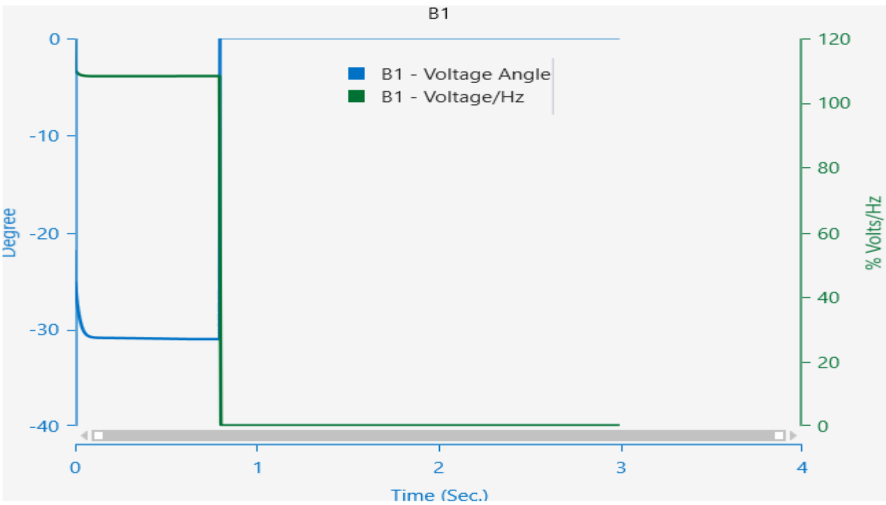

Figure 7

Bus 1, behavior parameters at the time of the fault at the equivalent 100 kV level grid

In such cases, understanding the duration of the transient, the fault's duration cycles, and ensuring that the bus can continue operating without adverse effects on the connected wind turbines (Fig. 8) becomes crucial. While the fluctuations in the voltage/Hz ratio appear smaller than the impact of the small production from the 5 turbines, the distance from the balancing bus of the strong network and the overall topology play decisive roles in the turbulences observed.

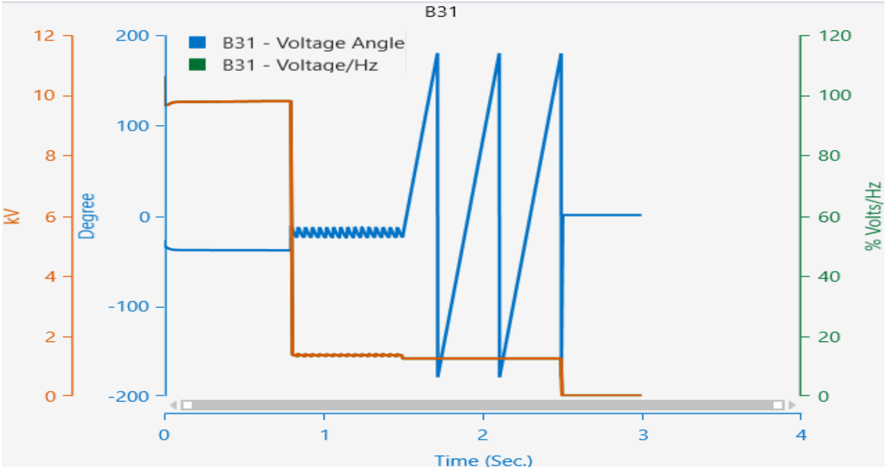

Figure 8

Transient disturbances caused by the wind turbines (5 units) and behavior of the parameters during the fault

The performance of the power system's characteristics and the energy balance are both impacted by the integration of PV solar resources. They have a significant influence on the electrical system and the power and voltages at the busbar where 3they are integrated, depending on their capacity and quantity. As seen in Fig. 9, the voltage angle and voltage exhibit pronounced fluctuations due to the integration of 12 PV systems with a total production of about 10.5 MW into the B3 busbar. These fluctuations have a notable impact on reactive power. Therefore, the analysis should be focused on understanding the effects of voltage fluctuations, among other considerations.

Figures 10 and 11 provide an overview of transient processes and current9 fluctuations in the overhead lines (Lines 14 and 2) connecting the main network to the substations. Simulations were conducted for various cases of failures (0.8, 1.5, 2.0 and 2.5 seconds). Based on the results, it is evident that the flow of currents and apparent power is pronounced, posing a significant threat to the safety of their operation.

Additionally, the relay protections are triggered, leading to disconnections that further endanger the stability and overall safety of the electrical power system, potentially causing cascading failures in its components and substations. The simulation results play a vital role in selecting and prioritizing relevant substations, facilitating the identification and preliminary design of lines, current flows, and their impacts on the power network.

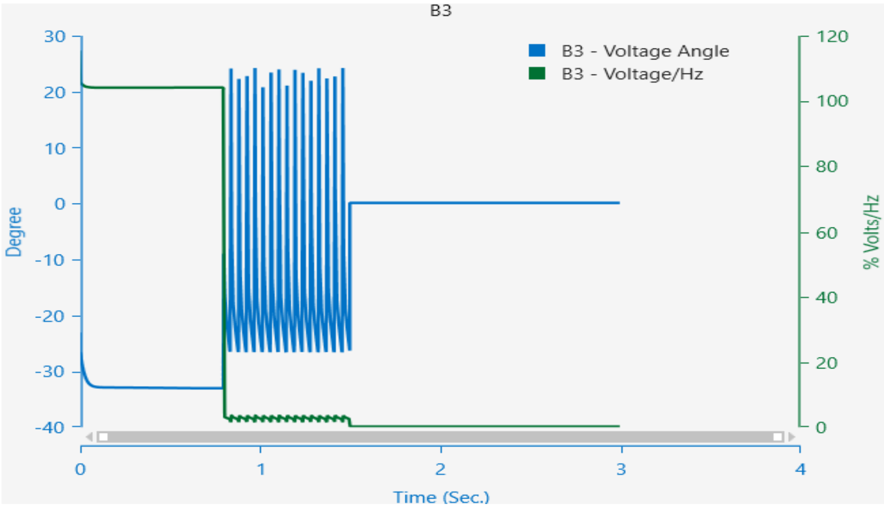

Figure 9

Bus 3, electrical parameter performance (12 PV units integrated)

Given the utmost importance of the safety of the electric energy system, the list should encompass substations, line capacity, consumption, production capacity, and the integration of renewable resources. This approach aims to minimize the impacts in the event of failures, ensuring that stability remains within the allowed limits and complies with the network codes and requirements of the interconnected systems in the relevant synchronous areas.

Depending on the size of the system, production, and consumption, wind turbines can significantly impact the electrical parameters. The scenario under consideration describes the fluctuation of reactive, active, and mechanical power, currents, wind speed, and pitch angle.

The stability and operation of wind turbines can be deduced by observing the influence of pitch angle, active power, and currents. Figs. 12 and 13 provide valuable insights, in this regard. Comparing the parameters in these figures indicates slight differences in currents during the simulated faults. Fig. 12 shows more apparent imbalances compared to Fig. 13. This suggests that various factors, including system topology, loads on the relevant bus, and installed power of the energy sources, contribute to these effects.

The analysis reveals that stability is more threatened when the wind turbines are operating independently (Fig. 12). However, their safety and reliability improve in the case of hybrid work, such as when combined with PV systems, as demonstrated in Fig. 13.

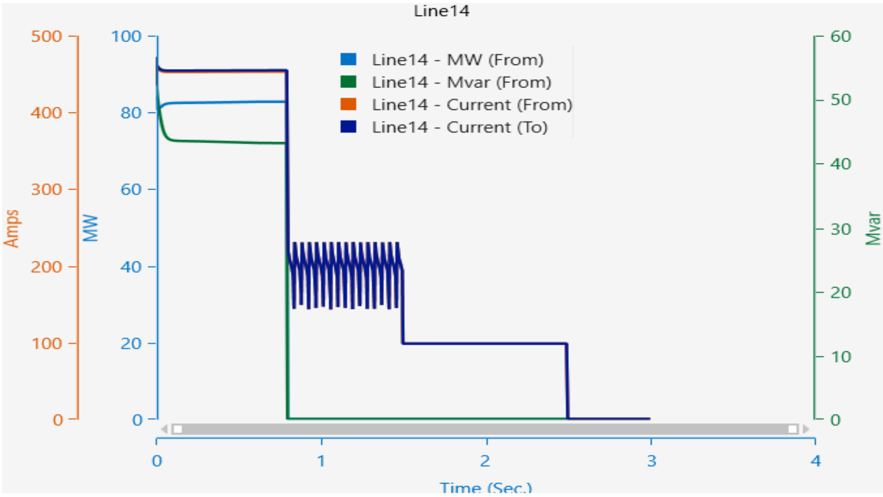

Figure 10
Line 14, the behavior of parameters during failures in bus B1, the apparent power and current turbulence are displayed

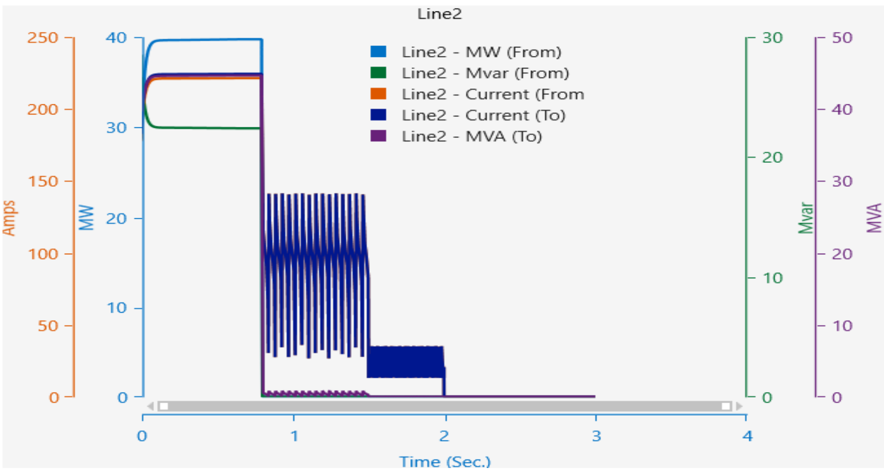

Figure 11
Line 2, the behavior of parameters during faults in bus B1, the turbulence of currents and active power is shown9

The system performance index is an essential parameter considered in all scenarios. Fig. 14 illustrates the performance index of both wind turbines and solar PV systems, where the power parameter is taken into consideration. This index is defined as the measurement or ratio of apparent power, active power, and reactive power as a unit. The results provide valuable insights into the performance index of both wind turbines and PV systems.

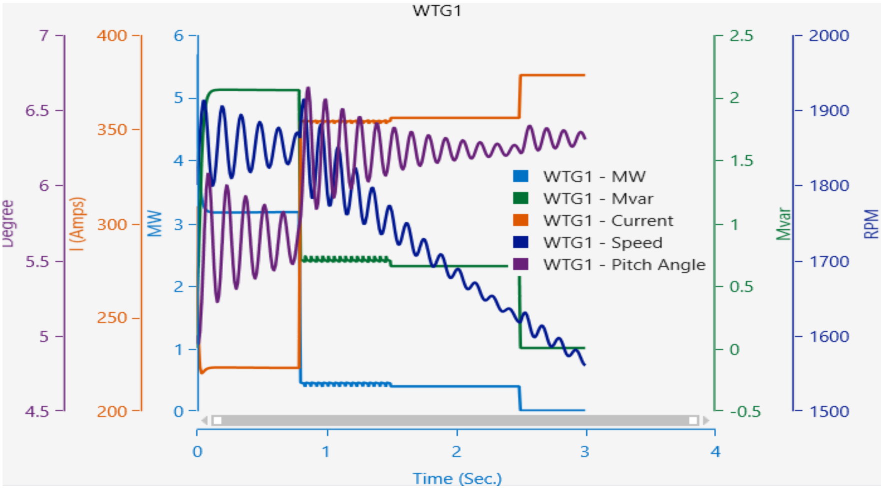

Figure 12

The behavior of the wind turbine WGT1 parameters during a fault (unplanned outages)

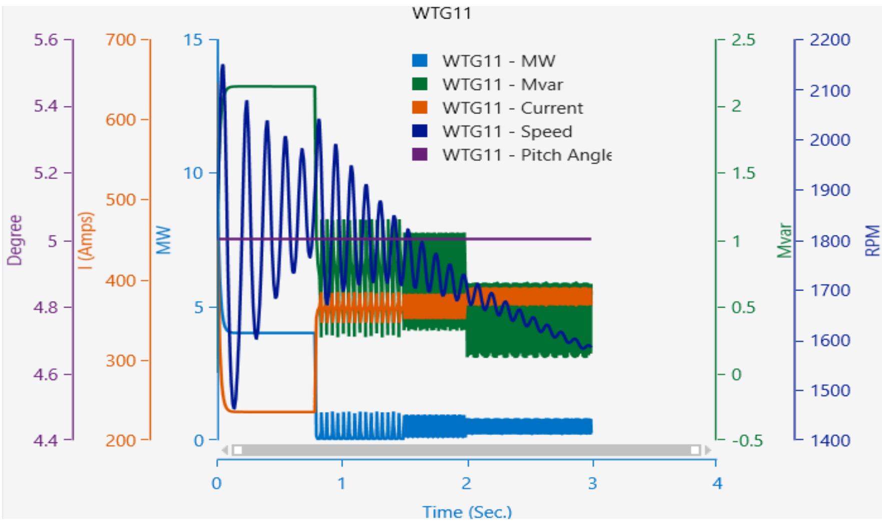

Figure 13

The behavior of the wind turbine WGT11 parameters during a fault (unplanned outages)

The analysis derived from simulated events provides valuable insights into the performance of PV and WT systems amidst system fluctuations. These observations shed light on the repercussions of faults or unexpected outputs from these sources, underscoring their impact on the reliability of both active and reactive power production.

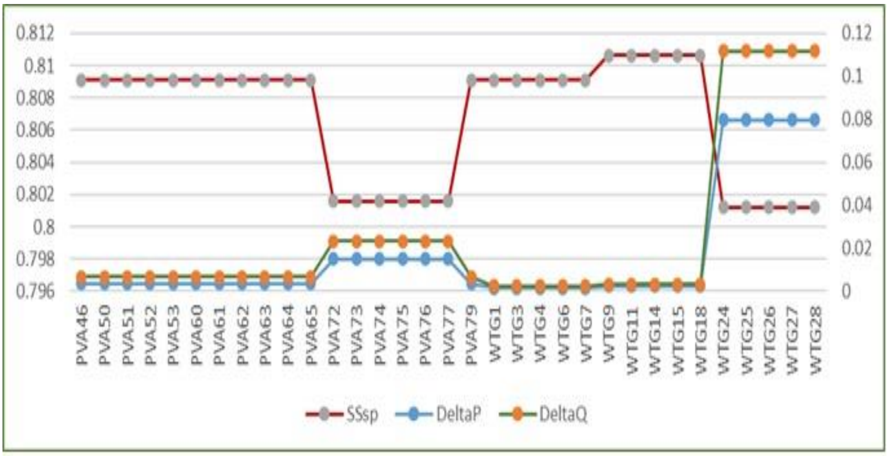

Figure 14

Performance indicators for PV systems and wind turbines in the power system

Figure 15 visually depicts the sensitivity of bus stability to simulated system events. It offers a ranking of bus instability during these occurrences, accompanied by the corresponding percentage of voltage fluctuations. This data serves as a crucial tool for analyzing the power system, facilitating proactive measures to prevent and manage diverse occurrences effectively. Moreover, it underscores the critical importance of maintaining power system stability within the voltage and frequency range stipulated by relevant codes and standards.

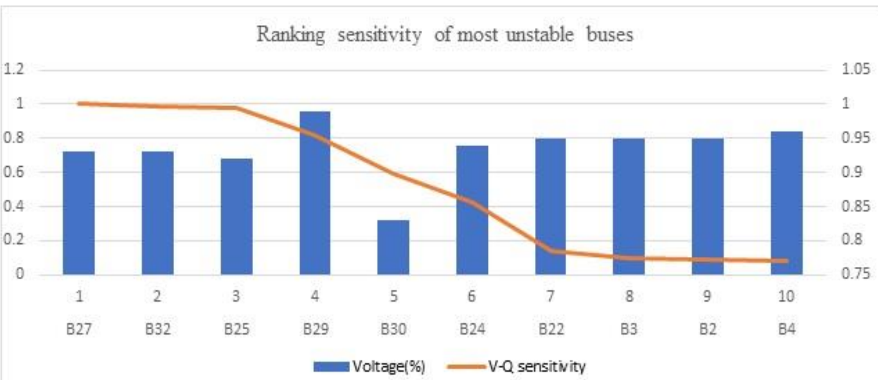

Figure 15

Sensitivity analysis for the most unstable buses during occurrences in the case studies

Conclusions

The integration of renewable resources into a large-scale power system presents both opportunities and challenges, particularly, concerning stability and security parameters. This integration necessitates a careful balance of various components to ensure a safe and reliable operation, within prescribed operational limits. Despite the clear benefits of renewable resources, challenges arise from the dynamic fluctuations, transients, short circuits and synchronization issues.

Maintaining acceptable frequency and voltage levels, in accordance with operational standards, is paramount for the safety and stability of power systems. This paper proposes models for integrating renewable resources into power substations, both individually and in hybrid configurations. These models offer insights into how renewable integration, impacts key parameters of the power system, under different operating condition and fault scenarios.

The study's results indicate that while integrating renewable resources can bring positive outcomes, it also introduces potential problems, due to parameter fluctuations. Analyzing these models provides a realistic understanding of the implications of renewable integration, on energy balance and overall system security.

In synchronous power systems, maintaining consistent frequency and voltage levels, particularly at 110 kV or 400 kV levels, is crucial. Various factors, such as load, production, consumer types, and consumption patterns, influence voltage levels. Understanding the complexity of renewable resource integration aids in managing electric energy systems effectively, minimizing the impacts of production and load fluctuations, and ensuring system stability and sustainability.

In summary, constructing and analyzing models of renewable resource integration are essential for comprehending the impacts on power system operation and security. By doing so, stakeholders can make informed decisions to optimize system performance and resilience, amidst the evolving energy landscape.

It can also be concluded, that it is very important to understand the behavior of the parameters of PV and Wind Turbine systems and their impact on the stability and continuity of the operation. The cases discussed in this paper help in the design, coordination and selectivity for the operation of renewable resources. The recognition of cases during operational failures of PV and Wind Turbines and during their integration in a combined form, is a good reference for designing different network configurations, with a significant impact on increasing the security and reliability of the power system, as a whole, while considering the main parameters, the transmission and distribution systems, as well as continuity and stability of supply to consumers.

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