Impact of large photovoltaic power penetration on the voltage regulation and dynamic performance of the Tunisian power system

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Abstract
By the year 2023, the Tunisian power transmission grid has been projected to include photovoltaic pool of power of 937 MW, scattered throughout the whole landscape of the nation. This paper investigates high photovoltaic energy penetration impacts voltage regulation and dynamic performance of the grid. Load flow analysis is implemented to investigate the power system capability for the case of incorporating the desired photovoltaic power. Computer-based simulations have been used for evaluating the upgradation of the grid. Moreover, the study is based on bifurcation diagrams taking the photovoltaic generation as a bifurcation parameter and time response simulations to grid disturbances. Professional PSAT simulation toolbox has been used for the power flow simulation studies. Network-related faults like outage of photovoltaic farm event, three-phase short-circuit at a conventional bus, and voltage dip at the largest photovoltaic station have been considered. It is hoped that the results of the presented study would benefit Tunisian's utility's policies on integration of PV systems. Moreover, this comprehensive analysis and study will be a valuable guide for assessing and improving the performance of national grid systems of any other countries also, that gives the huge potential and need for solar energy penetration into the grid systems.

Keywords
Photovoltaic generation margin, Tunisian power system, bifurcation analysis, grid connection requirements, voltage regulation

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Introduction

Nowadays, Renewable Energy Sources (RES) has become a significantly propitious aspect in the domain of energy systems globally and many nations are building policies and regulations for it. During the last decades, among the various RES, the solar photovoltaic generation plants (SPVGPs) have attained a spectacular upsurge (Gul et al., 2016). This growth of SPVGPs can be seen for applications ranging from smaller domestic, house-hold applications to even larger scale commercial projects connected to the grid with varying power capacities. According to the renewables global status report, approximately 505 GW of SPVGPs had been commissioned globally by the end of year 2018 (REN21, 2019).

Power systems are predicted to experience alteration in their steady-state and also dynamic performances due to the swift upsurge in penetration levels of SPVGPs and trends that aim at dispensing with traditional power generation plants. Assimilating large generation from symmetrical SPVGPs creates accompanying challenges in supporting stability of transmission networks, during normal operation modes as well as during occurrence of irregular disturbances (Qutaishat et al., 2016). Such irregular conditions comprises of faults of diverse nature, such as the bus bar or a transmission line getting exposed to three-phase to ground fault, phase to phase fault, single-phase to ground fault and so on. These irregular conditions may also lead to tripping of the transmission line, disruption in the performance of the larger conventional types of generating stations and substantial load change. Consequently, to sustain the stability of the transmission network and to maintain the reliability of the power supply throughout day and night, the projected operational scenarios should be identified and analyzed beforehand.

Stability and reliability are very much correlated with the specified technical boundary requirements related to active power control, reactive power supply, voltage control, power factor requirements, frequency requirements, fault-behavior, and protection concepts. A grid code (GC), issued by the Transmission System Operators, is set and also implemented in order to ensure the stability and reliability of such a system operation with the rapid incorporation of SPVGPs in power system networks. For stable and reliable power system operation, solar energy sources should not to be disconnected from the grid at the time of temporary voltage drop due to the fault at transmission line or load switch over operation. If most of photovoltaic (PV) systems are disconnected from the grid under such conditions, it leads to failure of large-scale power supply and thus unstable power system. Studies have shown that stability may be significantly affected with large PV power penetration taking into regard the total power rating, fault analysis, transient stability, and voltage drop (Daniel et al., 2017). Therefore, a high penetration of PV systems is required. This results fault ride-through (FRT) capability, which is an essential requirement for solar energy source to ensure the stability of power system.

Power system stability has been variously studied (Feilat et al., 2018; Gobind and Naser, 2017; Hamdy et al., 2019; Kawabe and Tanaka, 2015; Khan Mohammed et al., 2013; Rakibuzzaman et al., 2012; Schinke and Erlich, 2018; Tamimi et al., 2013) to demonstrate the impact of SPVGPs with high penetrations. To study the voltage and frequency stability during normal and transient conditions of operation, DiGSIENT PowerFactory simulation package has been used in (Hamdy et al., 2019). The study demonstrates the impact of integrating high penetration levels of PV plants into the national grid of Egypt. In Feilat et al. (2018), the impact of integrating wind power generation and large PV plants with national grid on the performance of the Jordan’s national grid have been examined by...
computer simulations on DIgSILENT software platform. Simulation results demonstrate that the penetration level of the RES should not be increased beyond 10% of the annual peak demand of Jordan in order to avoid line congestions. The impact of integrating a 1 MW PV plant to the power network of Bahrain has been examined by means of a systematic modeling and analysis using PVsyst and PSSE in (Gobind and Naser, 2017). Results are focused to illustrate how advantage provided by the weather of Bahrain can be exploited by PV systems to meet the peak demand. The stability of frequency and voltage of the larger inter-connected system has been dealt in (Schinke and Erlich, 2018) by quantitative assessment of the impact of high penetration of small PV units that are embedded in the distribution networks. Specifically, the effect of the several provisions related to active power control, frequency control, and voltage control during exigency situations has been analyzed by means of a fully integrated EMT-type model for the PV power plant. A broad study illustrating the impact of low and high levels of PV generation on the stability of the power system, employing an equivalent model of the Ontario utility grid, eigenvalues and voltage stability, has been presented in (Tamimi et al., 2013). The influence of the solar PV power on the short-term voltage stability is studied in (Kawabe and Tanaka, 2015). It shows that short-term stability of voltage is strongly impaired by voltage sag and interruption of the solar PV power. On the other hand, Rakibuzzaman et al. (2012) presents the static voltage stability of a power system with large-scale PV penetration. The results in this study shows that system static voltage stability has been significantly influenced by the PV size, locations, and the method used to integrate them, whether concentrated or dispersed. The effect of PV generation on the Bangladeshi power system stability has been depicted in (Khan Mohammed et al., 2013). Simulation results illustrates an improvement in voltage collapse point near the bus and load margin for static voltage stability in the Bangladeshi power system by injecting PV generation with different sizes located at different zones.

In brief, larger PV power plants should remain connected with the power grid throughout large grid voltage disturbances because the disconnection of this large PV power may further deteriorate voltage recovery during the disturbance and after fault recovery (Kim et al., 2013). This phenomenon attracts the attention of many researchers towards the low-voltage ride-through (LVRT) competency of PV solar plants with higher levels of generation (Daniel et al., 2017; Moursi et al., 2013; Saïdi et al., 2018a). Since the LVRT capability of PV power generators supports the grid voltage recovery, the integration of PV power plants with a varied range of generation capacity, have been studied (Ruiz, 2011; Tamimi et al., 2011).

Effects of high penetration of PV generation on power grid frequency, power and voltage have been explored by the researchers Feilat et al. (2018), Olusayo et al. (2019), Rahmann and Castillo (2014), Sk et al. (2020), and Widén et al. (2010). The influence of ambient conditions, i.e. temperature and solar radiation level, on the grid voltage, power, and frequency at the switching-in instance of large-scale PV power plant with the grid have been evaluated in (Ana and Oriol, 2016; Saïdi et al., 2018a, 2018b). Moreover, the techniques of integrating SPVGPs with large power generation with the power transmission and distribution networks have been presented in (Delille et al., 2012; Eftekharnejad et al., 2013; Khan Mohammed et al., 2013). Their effect on the frequency of the transmission grid has also been scrutinized.

A stability analysis for the Tunisian grid is done in (Abdelaziz and Helmy, 2019; Abdelaziz et al., 2005, 2011, 2019; Saïdi et al., 2016). This analysis does not consider the PV systems and its impact on the grid. Saïdi et al. (2011) have presented and discussed the
stability analysis of Tunisian grid with wind energy plant constituting five wind farms. Since the presented stability study has not considered the integration of PV systems with the power grid and its effect on the grid variables, the effect of integrating small PV plants on the performance and stability of the Tunisian radial distribution networks has been introduced in (Saïdi et al., 2014; 2016). With this beginning, increased complexity and changing structure of the Tunisian power system, more analysis is necessary for evaluating voltage and frequency stability along with determining the requirements to interconnect new large-scale SPVGPs with the Tunisian National grid.

Owing to the increasing population density in new cities, and developing industrial areas, the Tunisian national power grid has been facing huge expansion with growing additional energy demand. Since the government has planned for industrial development expansion during years to come, there will be sustained growth in energy demand. In view of meeting this growth in energy demand, Tunisian government has focused to harvest renewable energy available in abundance in nature. This paper presents stability analysis study about the integration of planned SPVGPs with national grid of Tunisia. This work is an extension to a previously mentioned research. The objective of the presented work is to assess the dynamic performance and voltage regulation of the Tunisian power system by integrating 14 distributed PV farms with a total capacity 937 MW. The presented voltage stability assessment is as mentioned before, based on bifurcation diagrams with PV generation used as a bifurcation parameter. The impact of the PV generation parameter on the grid voltage profile has been simulated for the peak-load event duration. Network faults that are simulated for the PV farms are three-phase short-circuits located at conventional buses, withdrawal events, and voltage-dip faults occurring at the buses near the largest SPVGPs. The outcomes are discussed in terms of dynamic performance and voltage regulation capability at PV connection buses in complying with the standards for grid connection requirements.

Tunisian’s national electric network integrated with proposed SPVGPs has been simulated and tested on PSAT software platform (Milano, 2005). During the last two decades, PSAT has a history of establishing trends and standards for modeling, simulation, and analysis of power systems. PSAT software has applicability for modeling of generation, transmission, distribution, and industrial power systems. It has proven advantages of overall functional integration, and the examination of these transmission systems interfaces. It is being considered as a versatile and powerful engineering services providing tool in the domain of electrical power systems and also has a specific applicability for the simulation of power system incorporation of RES. It also identifies automatically the over-loading or under-loading elements that are in the power grid. In turns, it can assist in exactly identifying exactly the appropriate bus for connecting new load.

The presented paper is as a part of a planned project and based on the study to evaluate the impact of integration with increasing level of renewable energy generation obtained from SPVGPs on performance of national grid.

The main objectives of this paper are: (i) observing the actual solar PV generation plants power effect on the GCs, (ii) giving a comprehensive and categorized point of view for the FRT regulations, and (iii) presenting a useful reference of a widespread GC’s FRT capabilities to be utilized and referred. To fulfill the above-mentioned objectives, this paper presents an extensive review of fault ride through in the Tunisian GC with a prominence on solar energy sources including low-voltage ride through and high-voltage ride through (HVRT). Tunisia has established its GC for fulfilling the minimum required technical
criteria and revised it regularly to cope with new modifications of the utility. Increasing the penetration PV sources have impacted many operational features of the power system such as protection, power quality, reliability, and stability. There upon, regulations must safeguard the power system’s security and controllable operation of solar energy sources. Analysis of voltage stability reveals that the dynamic behavior of the voltage depends unusually on the short circuit capacity of the grid at the point of integrating the PVPs. The main part of this paper is to study the impact of the PV plants on the performance of the national utility grid. The validated model has been used to study and analyze the influence of the strategic PV power plants on the voltage and frequency stability of the national power system.

The first step in the process of achieving the goal is collecting the real data of the constituents of high voltage (225 kV) transmission networks, and the data from the transformers, substations, and loads. These data have been obtained for the identified areas with higher PV power capacity from selected regions by the TCEG and the division for transport and production of electricity and mentioned in the next section.

Next step is the analysis and structuring of the obtained data. In step 3, a full model of the national utility grid of Tunisia is developed and validated on PSAT platform depending on the assessed parameters of system components from data. After that, selection of the appropriate locations for deployment of large-scale PV power plants throughout all the territories of the country has been accomplished. For installing SPVGPs systems, on the basis of our previous study and consulting the plan of the Ministry of Electricity and Energy, 14 locations have proposed. The capacity of each SPVGPs has been estimated by evaluating the allowable bus capacity margin for integrating the SPVGPs at the proposed location with the national grid. After this, the impact of the planned SPVGPs on the stability of frequency and voltage of the national grid have been studied and analyzed using the validated model.

Existing status and future plan of renewable energy in Tunisia

Tunisia is a country with meager energy production, with a steady production of energy despite a sharply increasing rise in demand. A discrepancy in the primary energy balance has been shaped due to the disparity between energy generation and the national demand for hydrocarbons, reaching to 49% in the year 2018 compared to just 15% in 2010 (Tractebel, 2019). When the year 2018 came to a close, the magnitude of the commissioned power generation has spanned to the capacity of 5476 MW. Tunisian Company of Electricity and Gas (TCEG) had a share of 5005 MW in this and 471 MW was produced by Carthage Power Company, which is a private venture. Electricity generation has been raised to 18,988 GWh in 2018 from 12,091 GWh in 2005, resulting in an average annual growth rate of 4% (Tractebel, 2019). To reach the renewable energy development strategy targets in Tunisia, a national program known as the Tunisian Solar Plan (TSP) has been established. The TSP aims at commissioning an added installed capacity for renewable energy of 3815 MW by 2030. The objective is to enhance the total stake of RES in electric power generation from the current 3% to 30% by the year 2030. The targeted share from each technology has been illustrated in the chart given as Figure 1. In order to achieve the intermediary targets for 2020, Figure 2 projects the targets to be achieved in the installed capacity during 2017–2020 contributed by different technologies and the regulatory scheme. It is published by the Tunisian Government in Renewable Energy Generation Notice,
The notice exhibits targets of 650 MW for SPVGPs and 350 MW for Wind energy, making a total RES installed capacity of 1000 MW (MESIA, 2019).

The Tunisian Government had come to a decision for updating the objectives mentioned in the 01/2016 Notice after considering the recommendations from the Conference in December 7 and 8 on the issue of accelerating the development of the renewable energy project. The updated total installed capacity target has been set to 1860 MW by 2022. Consequently, after following the revision for the targets for 2017–2020, a substantial increase during the 2021–2025 for the total targeted installed capacity has been established (UNDP, 2018).

Since Tunisia is a country located geographically in the solar belt region, there is abundance of unharvested solar energy. Therefore, it is of utmost importance for Tunisia to deploy solar energy harvesting schemes. Tunisia is a country in North Africa, bordering the Mediterranean Sea in the north and east, Libya in the south-east, and Algeria in the west. It covers an area of 163,610 km². In its national energy planning, Tunisia has accorded solar energy a place of priority (RES4MED, 2016; Tractebel, 2019). For evaluating the performance of the proposed methodology in this paper, Tunisia is taken as the case study with the locally available amount of solar energy and its distribution across the whole country.
According to Atlas Tunisia, average values of global horizontal irradiation for the duration of 1994–2015 (last 21 years) over the territory of Tunisia is shown in Figure 3. There is large variation of global horizontal solar irradiation from north to south during winter and summer. During December in the North of Tunisia, the daily average solar radiation is about 6.9 MJ/m²/day, while in July in the South East of Tunisia (surroundings of the Gulf) it is 28 MJ/m²/day (UNDP, 2018). It is inferred from Figure 3 that the average solar radiation varies between 1600 and 2200 kWh/(m²/year) from North to south. Figure 4 presents the mean of the annual diurnal sunshine time duration map (Chelbi et al., 2015). The duration of annual average daily sunshine hours fluctuates between 6.7 and 9 h/day over the Tunisian Land. These inferences help to develop prospective opportunities for investing in diverse solar energy–related domains.

The correlation of renewable energy plants with higher scales of generation is not a new issue in many developed countries (Afonaa-Mensah et al., 2019; Qian et al., 2019, 2020a, 2020b). According to the reports published in 2014 by the International Energy Agency there are around 20 renewable energy generation plants on the globe with a total generation of more than 100 MW, mostly in China and the USA. A considerable number of corporates are participating in the advancement of this technology to harvest the unutilized energy from sunlight and wind in to the form of usable electrical energy (IEA, 2014). Therefore, both supplier as well as the operator of the grid have to safeguard the linking aptness of RES with the electrical consumer. The TCEG and the Ministry in charge of Energy in Tunisia have stipulated the technical requirements to be complied by all renewable energy project intending for integration with the grid, as defined in the GC (JORT, 2017). In order to avoid expensive design changes after installation it is therefore essential to ensure and comply with the technical requirements as are applicable at the design as well as pre-design stage by simulation, evaluation and examination of the performance of these plants prior to testing on-site during the commissioning. To inspect the plant’s performance beforehand specialized simulators are used to model the RES as well as the electrical utility grid.

**GC requirements capabilities by PV systems**

Since the unexpected increase in renewable energy integration has not been presumed during the planning phase of conventional grid, the GCs require modification when new RES are going to be integrated with the grid. The LVRT capability plays its role to sustain the operation of solar power generation without sudden tripping of solar generation to the grid during transient conditions. Eventually this evades the sudden loss of power during transient conditions and also support the grid by providing reactive power (Maha et al., 2018; Mehrdad and Tohid, 2018).

According to the TCEG stipulation, single generating units having capacity of 10 MVA or more, when connected to the transmission system through a step-up transformer, should be modeled as distinct generators. Besides, it states that collector-based systems like the solar plants while connected to the transmission grid shall be represented as a single-machine equivalent circuit comprising of an equivalent generator. Figure 5 shows a typical connection diagram for the HV grid network of a PV generator with a power more than 10 MW along with a low to intermediate voltage transformer, equivalent collector circuit, and station transformer (WECC, 2014).
Interval-specified normal and critical frequencies in Tunisian GCs

Even in the case of frequency deviations, each generating unit should essentially deliver a specified level of power output. For supplying rated MW, all onshore synchronous generating units must have the capability for continuous operation for any operating point between limits of a power factor (PF) lag of 0.85 and PF lead of 0.95. Also, all on-shore synchronous generation units should have the capability for operating continuously at any point between the limits of the reactive power capability, as mentioned in the Generator Performance Chart (SRF, 2014).

Figure 3. Global horizontal irradiance over Tunisia’s landscape.
The Tunisian GC specified that the generating units connected to the grid should have the capability for operation on a continuous basis with constant active power output around the normal frequency condition (49.5–50.5 Hz). While operating in the broader critical range of frequency (47.5–49.5 Hz and 50.5–52.0 Hz), the active power outputs from the generating units should be sustained within a certain specified range. To give an example, as is depicted in Figure 6 (JORT, 2017), it could not be lesser than the limiting range corresponding with the system frequency fluctuation in the range of 49.5–47.5 Hz. Also, a generating unit connected for operation in the Tunisian grid should obey the duration requirements mentioned in Table 1.

A frequency control system must be coupled to the PV power plants with a nominal power greater than 10 MW. The purpose of frequency control system is to add the capability
of frequency adjustment to PV plants, in case of rise or fall in frequency due to load variation. This frequency control system permits the PV power plant to participate in primary and secondary frequency adjustment by injecting active and reactive power to the grid in the same way as conventional power plants. The rate of change of power per minute shall be

Figure 5. Typical connection diagram for the HV grid network of a PV generator with a power more than 10 MW.
HV: high voltage; MV: medium voltage; PV: photovoltaic.

Figure 6. Active power output requirements for Tunisian grid-connected generation units versus frequency change in the range of 47.5–50.5 Hz.

Table 1. The requirements for generating units corresponding to variations in grid frequency of Tunisia (JORT, 2017).

| Frequency ranges | Requirements |
|------------------|--------------|
| 51 Hz–52 Hz      | Operation for a period at least 15 mn is permitted one to five times a year |
| 50.5 Hz–51 Hz    | Operation for a period 60 mn continuously is permitted and 15 h cumulative during lifetime of the installation. |
| 49.5 Hz–50.5 Hz  | Continuous operation is permitted |
| 48.5 Hz–49.5 Hz  | Operation for a period 5 h continuously is permitted and 100 h cumulative during lifetime of the installation. |
| 47.5 Hz–48.5 Hz  | Operation for a period at least 15 mn cumulative is permitted during lifetime of the installation. |
adjustable within a range of 10% of the installed power and the maximum permitted rate indicated by the manufacturer.

In order to sustain the system voltage during the faults, conventional synchronous generators increase its excitation during disturbance via automatic voltage regulator action. This increase in excitation means reactive power injection. Tunisian Grid Codes (TGC) enact that the reactive current generated by PV plant must be increase during the faults. TGC also enact the active power regulation capability that is affected by amount of active power supplied at a particular power factor. Figure 7 explains the typical requirements for power factor variation with respect to active power of PV farm (JORT, 2017).

**Fault ride-through.** According to TGC, the minimum voltage requirements that PV farms should withstand is as shown in Figure 8 (JORT, 2017). It illustrates that each PV farm with transient stability remains connected with the power system without failing with an overall fault clearance time of 250 ms. Within the operating range of the PV farms, such faults should not lead to isolation or instability from the grid. In addition, Figure 8 shows that PV generator should have the capability for continuous operation for a voltage drop up to zero for duration of 0.250 s. Followed by voltage recovery up to the 85% of the nominal grid voltage at the point of common coupling (PCC) with voltage recovery duration of 30 mn. The LVRT capability in solar inverters is necessary to maintain the stability of the grid.

Figure 9 exhibits HVRT requirements according to TGC. This needs PV farms to withstand faults and continue to be connected to the system within 250 ms when the grid voltage at connection point of PV system increase to 120%. This is followed by the voltage recovery down to 110% from the rated voltage at PCC with voltage recovery duration of 15 mn (JORT, 2017).
Recovery duration of the PV generating unit under abnormal operation is listed in Table 2. The grid voltages ranges are expressed in per unit.

**Required dynamic reactive current injection for voltage support**

For obtaining faster recovery of grid voltage, when the voltage dip occurs at PCC, the grid-connected PV power station essentially increases its reactive current output to inject a higher reactive power to the grid. The TGC demands that the PV power station should be capable of withdrawing reactive power from the grid and in turn reactive current when there is occurrence of overvoltage. The reactive current injection requirement is shown in Figure 10 (JORT, 2017). In this GC a deadband of $\Delta U_t = \pm 10\% \ Un$ is defined around $Un$, which is permissible rated voltage. It means 10% variation in grid voltage does not require any injection or absorption of reactive current injection. When voltage drops below 0.9 p.u., the PV power station connected to the grid is required to inject a reactive current to the grid proportional to the voltage deviation according to the following equation

$$\Delta I_q = k\Delta U_t$$  \hspace{1cm} (1)

$\Delta I_q$ is the reactive current variation before and after disturbances.

$k$ is the slope or also known as droop, with requirement of $0 \leq k \leq 10$ p.u.

The permissible tolerance for the injected or absorbed reactive current is $\Delta I_q = \pm 20\% \ In$, where $In$ is the rated current. On the other hand, as the voltage exceeds beyond the
deadband region, the PV generator must supply reactive current by satisfying the droop $k$. It must be noted that, for voltage drop of more than 50%, the reactive current is required to supply at least 100% of the rated current.

**Requirements for the supply and absorption of the reactive power.** Around the allowable steady-state voltage range (i.e. $93\% Un < U < 107\% Un$), any PV power plant, connected to the TCEG HV network, should have the ability for supplying and absorbing reactive power corresponding to an over-excited and under-excited power factor $\leq 0.95$ at the connection point of the PV plant. Outside of the allowable steady state voltage range, a voltage higher than 107% Un or below 93% Un the limits of the reactive power can be summarized according to Figure 11.

| Voltage ranges       | Requirements |
|----------------------|--------------|
| 0.8 Un–0.85 Un       | 30 mn        |
| 0.85 Un–0.95 Un      | 3 h          |
| 0.95 Un–1.05 Un      | Unlimited    |
| 1.05 Un–1.1 Un       | 1 h          |
| 1.1 Un–1.2 Un        | 15 mn        |

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Figure 10. Required dynamic reactive current injection for voltage support during LVRT/HVRT. HVRT: high-voltage ride through; LVRT: low-voltage ride through.

Figure 11. The limits in reactive power range as function of voltage \( (P = P_n) \) at the connection point for PV plants with an HV connection point.
For a power generation less than the nominal power but greater than 20% of the nominal power, the limits for the reactive power are abridged in proportion to the active power (see Figure 12). There is no reactive power supply requirement for the power generation $P < 5\%$ of rated power. The requirements for supply/absorption limits of reactive power as a function of active power ($U = U_n$) for PV power plants connected to the HV grid of TCEG are shown in Figure 12.

System modeling

Power system model

Since the transmission lines are long, they are considered using an equivalent $\pi$-network model. At the $i$th bus, the resulting injected active and reactive power balance equations can be expressed as follows (Abdelaziz, 2017)

$$P_i = \sum_{j=1}^{N} Y_{ij} V_i V_j \cos(\alpha_i - \alpha_j - \theta_{ij}) = P_{gi} - P_{Li}$$

$$Q_i = \sum_{j=1}^{N} Y_{ij} V_i V_j \sin(\alpha_i - \alpha_j - \theta_{ij}) = Q_{gi} - Q_{Li}$$

Figure 12. The reactive power range limits as function of active power ($U = U_n$) at the connection point for PV plants with HV connection points.

where $-V_i = V_i \angle \alpha_i$ is the complex voltage at the $i$th bus, $-Y_{ij} = Y_{ij} \angle \theta_{ij}$ are the $(i,j)$ elements of the admittance matrix of the grid, $P_i$, $P_{gi}$, and $P_{Li}$ denote injected active, generated,
and consumed power at \( i \)th bus, \( Q_i, Q_{gi}, \) and \( Q_{Li} \) denote injected reactive, generated, and consumed power at \( i \)th bus, and \( N \) is the entire number of the power system buses.

**Static load models**

The load modeling for stability studies in power system network is a complex problem due to the uncertain nature of the aggregated loads. These load models are typically classified into two broad categories, i.e. static and dynamic (WECC, 2014). For active and reactive power, common static load models are expressed in an exponential form (Milano, 2005). These static loads can be modeled by means of constant impedance, constant current, and constant power load models. For the constant impedance load model, real, and reactive power are proportional to the square of the magnitude of the voltage. In the case of the constant current load model, the real and reactive power are proportional to the voltage magnitude. Whereas, for constant power load model the real and reactive powers have no relation to the voltage magnitude. It is also referred as constant MVA load model. All of these load models can be described by the following polynomial equations (Milano, 2005)

\[
P_{Li} = P_o \left( \frac{V_i}{V_o} \right)^\alpha
\]

\[
Q_{Li} = Q_o \left( \frac{V_i}{V_o} \right)^\beta
\]

where \( P_o \) and \( Q_o \) are the real and reactive powers at a reference voltage, \( V_o \). The exponents \( \alpha \) and \( \beta \) depend on the type of the load. For constant power load models, \( \alpha = \beta = 0 \), for constant current load models \( \alpha = \beta = 1 \), and for constant impedance load models, \( \alpha = \beta = 2 \).

**Dynamic models for a solar PV unit.** PV generator constitutes of semiconductor devices and also solid-state synchronous voltage source converter, i.e. DC-AC converter. Voltage source converter in the PV generator has the function of converting an input DC input to an output AC output voltage and supplying the active as well as reactive power into the system. It generates a balance set of sinusoidal voltage at the fundamental frequency with rapidly controllable amplitude and phase angle. It is analogous to a synchronous machine except the rotating part. A typical example of a grid-connected PV generator is depicted in Figure 13.

Figure 14 shows the block diagram for Dynamic PV Model of SPVGP. The reactive and active power controls have been included in the inverter control module. The basic structure of the reactive power controller is presented in Figure 14. This controller comprised of two major parts, i.e. the voltage regulator and the power factor controller depending on the required control task. In this work, voltage regulation has been selected for the controller options. The reactive current command for the remote bus voltage control has been calculated by the reactive controller. The reference power has been controlled by the amount of DC power coming from the panel module. The SPVGPs possessing dynamic components as expressed below

\[
\frac{di_d}{dt} = \frac{(Q_{ref} \cdot \cos(t) - P_{ref} \cdot \sin(t)) / V - i_d}{T_p}
\]
According to Figure 14, the current set points has been established on the basis of selected reactive powers, active powers and measured terminal voltages in the dq reference frame as shown below

\[
\frac{di_q}{dt} = \frac{(P_{\text{ref}} \cos(t) + Q_{\text{ref}} \sin(t))}{V - i_q} + \frac{1}{1 + sT_p} - \frac{1}{1 + sT_q}
\]  

(7)

where the notations carry their standard meanings as in (Tamimi et al., 2013). In Figure 14, the reference value for the reactive power has been founded by a PI controller on the basis of the set-point and actual voltage values.

The case study. Model description. The single line diagram of Tunisian transmission network under study has been illustrated in Figure 15. It encompasses 225 bus-bars,
67 generators, 97 loads, 119 transformers, and 220 branches. The entire loading system for active and reactive power, in the base case, are 5181.01 MW and 2162.43 MVAR, respectively. The transmission system functions at four voltage levels 400 kV, 225 kV, 150 kV, and 90 kV. Table 3 presents the capacity specifications of the each generating stations included in this study. The synchronous generator buses are considered as Gi, i is the number assigned to generators in service, the missing i’s are the numbers assigned to generators not in service. Each synchronous generator is fitted with an Automatic Voltage Regulator and a Turbine

Figure 15. Single line diagram of the existing transmission grid.
Governor. The central power station of “Sousse” (470 MVA) is chosen as the slack bus (G25).

The SPVGPs connected to buses 49 to 62 are labeled as CPV_i, where i is the name of SPVGP with the maximum installed PV power 937 MW. Table 4 represents the SPVGPs parameters. Each SPVGPs consists of a number of PV generators and designated by one single equivalent PV farm at their common point, assuming homogeneous temperature and solar radiation distribution in the PV farm with operating at power factor between 0.95 lagging and 0.95 leading. The complete scheme/structure has been realized using MATLAB/PSAT toolbox (Milano, 2005). The system base values are 100 MVA, 30 kV, and 50 Hz.

| Bus number | Bus code | Rating of each unit (MVA) | $P_{Gen}$ (MW) | $Q_{Gen}$ (Mvar) | Voltage level (kV)
|------------|----------|--------------------------|---------------|-----------------|----------------|
| G3         | TV3 RD   | 232                      | 120           | 105.572         | 15.5           |
| G4         | TV4 RD   | 232                      | 120           | 88.227          | 15.5           |
| G5         | RADES2   | 165.30                   | 108           | 89.145          | 15.5           |
| G6         | RADES2   | 165.30                   | 108           | 25.446          | 15.5           |
| G7         | RADES2   | 303                      | 219           | 136.408         | 18.0           |
| G8         | TG RDC   | 345                      | 280           | 47.006          | 17.0           |
| G9         | TV RDC   | 201.3                    | 130           | 22.888          | 15.5           |
| G10        | TG1 MOG  | 345                      | 280           | 141.674         | 17.0           |
| G11        | TG2 MOG  | 345                      | 280           | 156.827         | 17.0           |
| G14        | TG3 BMC  | 166                      | 100           | 81.151          | 15.5           |
| G15        | TG4 BMC  | 166                      | 100           | 81.151          | 15.5           |
| G16        | TG GL    | 149.25                   | 100           | 25.146          | 14.0           |
| G25        | CC SSC   | 470                      | 347.69        | 207.38          | 20.0           |
| G26        | CC SSD   | 470                      | 350           | 215.928         | 20.0           |
| G27        | TG1 THYN | 149.25                   | 100           | 62.561          | 14.0           |
| G28        | TG2 THYN | 149.25                   | 100           | 62.561          | 14.0           |
| G32        | TG1 CC SK| 470                      | 380           | 131.408         | 17.0           |
| G33        | TV1 CC SK| 200                      | 160           | 64.618          | 15.5           |
| G34        | TG2 SKHI | 470                      | 380           | 111.281         | 17.5           |
| G35        | TV2 SKHI | 200                      | 160           | 45.251          | 15.5           |
| G36        | TG1 FRI  | 149.25                   | 100           | 51.751          | 14.0           |
| G47        | CC GHNCH | 500                      | 350           | 108.044         | 21.0           |

Steady state voltage. In load flow analysis, solar PV generators are usually integrated to the generator type PV bus because of their voltage control capability and also due to the active power generation. On the other side, SPVGPs are considered as load buses after achieving their reactive generation limits. Each SPVGPs have been characterized in the power network on the basis of above hypothesis. The network voltage profile for peak load conditions have been tested with and without PV power generation. These characteristic has been shown in Figures 16 and 17.

It has been noted that without PV power, the PV generator connection buses operate at low voltages. It goes down to 0.9 p.u for bus 60 “CPV_Tozeur.” Further, it slipped to 0.88 p. u at buses 144 “Tozeur” and 154 “CPV_IPP.” These low voltage buses (buses 144 and 154) are located in the southern transmission grid which is connected to Libyan and Algerian...
transmission grid (see Figure 18). As the tie-connections to neighboring Libyan and Algerian networks have not been considered in these simulations, there is no reactive support from the Libyan and Algerian system grids. As a consequence, these buses operate at lower voltages.

The voltage levels at connection buses for the peak load condition have improved without over-voltage, by injecting the generated maximum solar power of 14 PV farms. It has improved the voltage profile throughout the network within the acceptable tolerances limit of 10%, according to the TGC, in general and more particularly at the PV buses.

Table 4. PV specifications.

| Bus number | Bus code | Sbase (MVA) | PGen (MW) | QGen (Mvar) | Voltage at PCC (kV) | Voltage at PCC (kV) | Bus number at HV/TCEG |
|------------|----------|-------------|-----------|-------------|---------------------|---------------------|----------------------|
| 49         | CPV_BIR3 | 105         | 74        | 20.478      | 30                  | 225                 | 197                  |
| 50         | CPV_HAJE | 55          | 37        | 10.362      | 30                  | 225                 | 201                  |
| 51         | CPV_BMHI | 55          | 38        | 2.598       | 30                  | 225                 | 218                  |
| 52         | CPV_BOUS | 35          | 30        | 1.388       | 30                  | 225                 | 219                  |
| 53         | CPV_MAZZ | 105         | 100       | 16.01       | 30                  | 30                  | 220                  |
| 54         | CPV_LABB | 55          | 50        | 15.472      | 30                  | 225                 | 221                  |
| 55         | CPV_IPP  | 55          | 50        | 8.237       | 30                  | 225                 | 223                  |
| 56         | CPV_IPP  | 210         | 200       | 11.817      | 30                  | 225                 | 224                  |
| 57         | CPV_IPP  | 105         | 100       | 18.43       | 30                  | 30                  | 225                  |
| 58         | CPV_KEBE | 85          | 50        | 14.017      | 30                  | 150                 | 123                  |
| 59         | CPV_IPP  | 105         | 100       | 4.042       | 30                  | 150                 | 155                  |
| 60         | CPV_TZR  | 25          | 20        | 4.136       | 30                  | 30                  | 157                  |
| 61         | CPV_OUDD | 55          | 38        | 11.733      | 30                  | 150                 | 159                  |
| 62         | CPV_IPP  | 55          | 50        | 9.458       | 30                  | 30                  | 156                  |

Figure 16. Voltage profile for all buses in the case of static analysis with all PV power plant in peak load.
Formulation of PV generation margin in the continuation form. For applying the local continuation technique to the power flow problem, a parameter should be inserted which represents the SPVGP. Standard power flow models have been described as constant PV or PQ generators with reactive power limits, and static PQ or voltage dependent loads. Since the static
continuation power flow technique takes into account standard power flow models, the obtained stability information is typically related to the maximum loading margin of the system. However, since the presented study has emphasis on the PV active power penetration, the stability margin, $\lambda$ is defined as a measure of the maximum level of PV generation margin (PGM)

$$P_{PV}^i = \lambda P_{max,PV}^i$$  \hspace{1cm} (9)

where $P_{PV}^i$ is the power generation by the solar farms. In this case, a simple SPVGP model is considered. Let us assume that the value of $\lambda$ lies in the interval $0 \leq \lambda \leq \lambda_{\text{critical}}$ where $\lambda = 0$ corresponds to base-case solution and $\lambda = \lambda_{\text{critical}}$ corresponds to critical SPVGP.

Introducing the equations (4), (5), and (9) in the equations (2) and (3) the resulting power flow model at the SPVG bus will be

$$0 = \sum_{j=1}^{N} Y_{ij} V_i V_j \cos(\alpha_i - \alpha_j - \theta_{ij}) - \lambda P_{max,PV}^i + P_o \left( \frac{V_i}{V_o} \right)^{\alpha}$$  \hspace{1cm} (10)

$$0 = \sum_{j=1}^{N} Y_{ij} V_i V_j \sin(\alpha_i - \alpha_j - \theta_{ij}) - Q_o \left( \frac{V_i}{V_o} \right)^{\beta}$$  \hspace{1cm} (11)

Thus, it can be seen that the power flow equations are modified to accommodate the parameter $\lambda$.

The voltage stability limit at all the 14 sites is assessed throughout steady-state normal operation of PV power plants. While carrying out simulation and analyzing behavior of P-V curves, the real power generated at all these 14 buses $P_{PV}^i$ was gradually increased until the bus voltage reached to collapse.

This margin has been restricted by stability limits for voltage (saddle-node bifurcation or limit-induced bifurcation) or security-related limits (voltage limits, transmission line thermal limits). Saddle-node bifurcation (SNB) is understood as one of the most important static factors responsible for voltage instability problems in power systems. Mathematically, an SNB point can be solved by the following set of equations (Dobson et al., 2002)

$$g(y, \lambda) = 0$$

$$\nabla_y g(y, \lambda)v = 0$$  \hspace{1cm} (12)

$$|v| = 1$$

$$g(y, \lambda) = 0$$

$$\nabla_y g(y, \lambda)^T w = 0$$  \hspace{1cm} (13)

$|v| = 1$ where “w” and “v” are respectively, the left and right eigenvectors.
In practice, SNB occurs at the merger of two equilibrium points, typically one of which is stable and the other unstable to appear as the parameter $\lambda$. The PV curves are depicted in Figure 19(a) and (b) with slow change in $\lambda$, where $V_{Gi}$ stands for the $i$th generator terminal voltage magnitude and $Q_{Gi}$ for the reactive power.

To solve the above-mentioned problem, a pseudo-arclength continuation strategy (Hill and Mareels, 1990) for continuation algorithms applied to algebro-differential equations has been implemented to investigate the effect of the smooth parameter variations on stability properties. It comprises of a number of routines used for detecting limit points and bifurcations as functions of a system parameter. To determine the series of solutions, continuously from $y_0$ and using appropriate increments of $\lambda$, we proceed with the help of a predictor-corrector. The local continuation algorithm is illustrated in the form of a flow chart in Figure 20. The proposed algorithm is used to trace the solutions of the power flow problem when $\lambda$ varies in a continuous manner. This gives a faster way for estimating the next equilibrium point on the bifurcation diagram by making modifications to the predictor-corrector. It is possible to take larger step lengths near the nose point and divergence is not encountered. The objective of bifurcation method is to examine qualitative changes in the system dynamics under slow variations of distinct system parameters. These qualitative changes can be evaluated in terms of loss of stability, start or seize of oscillations, change-over from periodic to chaotic solutions or vice versa, etc. Bifurcation analysis helps to forecast how and when the system may become unstable. Moreover, detailed deliberations on the stability of power systems DAE model are elaborated in (Cutsem and Vournas, 1998).

Since the buses, TG Zarsis, Robbana, Djerba, and CPV_LABB numbered as 48, 128, 149, and 219, respectively, have been experiencing the lowest voltage in the network, they are selected for the bifurcation study. For the peak-load case the bifurcation diagram of voltage at buses TG Zarsis, Robbana, Djerba, and CPV_LABB (i.e. buses 48, 128, 149, and 219) as function of PV generation margin has shown in Figure 21. It has been observed that bifurcation occurs at a PGM value of $\lambda = 2.5818$ p.u. at above mentioned buses, but at slightly different voltage levels. With SN bifurcation, the collapse voltage for all the network buses has been shown in Figure 22. With maximum solar penetration, it is clear from Figure 22, the collapse voltage levels for bifurcation points at selected four buses are the lowest.

![Figure 19. Main bifurcations observed in PV curves: (a) SNB without $Q_{Gi}$ limits; (b) LIDB followed by an SNB.](image)

LIDB: limit-induced bifurcation; SNB: saddle-node bifurcation.
For example, the voltage profile at Bus 128 close to the saddle node bifurcation is lower than 0.70 p.u. It indicates that the voltage collapse can be predicted only on the basis of measured voltage. It is concluded that the SNB is related to maximum PGM in the power flow models. From Figure 23, it is observed that the operating point at vertical tangent to the system PV curve lead to the voltage instability and corresponds to the singularity of the system Jacobian matrix. It is the foremost causal aspect to voltage instability. It is further inferred that for increased high transmission capability the transmission system must be upgraded. Figure 23 shows the eigenvalue-locus for the selected critical buses. The bifurcation point is substantiated by the eigenvalue-locus, which represents the variation in minimum eigenvalues of the power flow Jacobian with the increase in solar generation parameter. These eigenvalue crosses the imaginary axis for $\lambda = 2.5818$ p.u., thus leading to a SNB point. The maximum capacity contributed by each SPVGs are shown in Figure 24. In totality,
the maximum capacity supported by all the 14 SPVGs connected to the network is 2185 MW.

**Dynamic performance.** The transient responses of grid-connected PV generators and the networked synchronous generators, during the occurrence of grid faults are presented and examined in this section. The performance of the system is analyzed in compliance with the Tunisian grid requirement codes. In this regard, worst-case scenarios have been

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**Figure 21.** Bifurcation diagram of voltage at buses TG Zarsis, Robbana, Djerba, and CPV_LABB.

**Figure 22.** Voltage levels for all buses at SN bifurcation points with all PV power plant in peak load.
considered. Initially, the transient response of the system has been tested for a sudden PV power loss, i.e. the case of disconnection of all PV farms. Next, a three-phase short circuit fault has been applied at a regular transmission network bus (bus 48 “Zarzis”). Lastly, faulted voltage profiles have been applied at the connection bus of the largest PV farm, i.e. CPV_IPP “bus 56.” In all the simulations, the initial conditions have been set for 100% power output of the PV nominal power. For example, 25°C and 1000 Wb/m² corresponding to a PV temperature and irradiance, respectively.

**Figure 23.** Eigenvalue-locus of the power flow Jacobian matrix at SN bifurcation points.

**Figure 24.** Solar power generated for 14 buses connected to PV generating stations at SN bifurcation points.
For this case, all the PV farms have been suddenly disconnected from the network by simultaneously opening all circuit breakers at $t = 20s$. Instantly just after the disconnection, due to the PV generation loss, the synchronous rotor speed of swing bus G25 suddenly dropped as shown in Figure 25. The steady state rotor speed is about 0.9765 p.u corresponding to a drop in frequency and reaching down to 48.825 Hz. The secondary control has been deactivated in the simulations.

Figure 25. Response of synchronous rotor speed of the swing bus “G25” after all PV farms disconnection.

Figure 26 illustrates the active and reactive power generation at swing bus G25 during and after disconnection of all the PV farms. A transient peak of 4.35 p.u is being observed for the active power generation just after the instant of disconnection of all the PV farms and later on within short interval transient has been cleared off. A small change,
from 2.026 p.u to 2.1135 p.u. and dip up to 1.898 has been observed for the reactive power generation for small interval and later on it settled to a lesser value 1.765. The synchronous machine turbine governor action sustained for 10 s to cope up the disconnection after which the power oscillations have been damped out and the system restored to its normal operation.

There are a significant drop in the overall network voltage profile because of the sudden and simultaneous disconnected of all the PV farms from the network. In particular, for buses Mednine and Tozeur, numbered as “194” and “144,” respectively, as shown in Figure 27. The voltage dropped from 0.9988 p.u to 0.957 p.u with a dip up to 0.941 for the bus Mednine. On the other hand, for the bus Tozeur the voltage dropped from 0.985 p.u to 0.896 p.u with a dip up to 0.885.

**Network short-circuit.** Since the network bus 48 “Zarzis” exhibits weak static voltage, on the basis of bifurcation diagram analysis, it has been chosen as the three phase fault occurring bus in the power network. A three-phase short circuit has been applied at t = 20 s, and cleared in 150 ms. The resulting voltage profiles at buses TG Zarsis, Robbana, Djerba and CPV_LABB are shown in Figure 28. Due to the three-phase short circuit a significant voltage drop, reaching 0.20 p.u, has been observed at bus “48” TG Zarsis. The PV bus CPV_LABB “54” is the geologically nearest PV bus with bus “48” TG Zarsis. From Figure 29 it has been observed that the PV bus CPV_LABB “54” has experienced a dip in bus voltage reaching down to 0.92 p.u due to three phase fault occurring at bus “48” TG Zarsis. Since the PV bus has been protracted by a fast, continuously acting controller in accordance with schema of regulation in Figure 14, the voltage regulation at all PV bus is guaranteed. Figure 30 depicts reactive power production pattern of PV bus CPV LABB “54” to provide voltage backing during fault period. It is observed that the PV bus CPV_LABB “54” has been contributed the most in supporting the network voltage.
regulation, because the PV bus CPV_LABB “54” is the geographically nearest generating bus to the faulted bus “48” TG Zarsis. During the transient, the PV generator active power supply decreased because of the short circuit and has been shown in Figure 31. The results also show that the system is stable. Also, the power network has a good transient performance with rapid recovery of terminal voltage, reactive, and active power during and after the fault clearance.

Voltage dip faults at CPV_IPP “bus 56.” Since the reactive power requirements of PV farms are within a power factor of 0.95 lag to 0.95 lead, the system performance to transient three-phase voltage dips has been evaluated and analyzed in compliance to the GCs requirement. The fault is applied at the heavily connected bus among the largest PV farm CPV_IPP “bus 56.” The voltage dip occurs at 20 s and persists for 150 ms with an off-peak voltage level of 60%. Figure 32 show the bus voltage behavior of all the PV farms and especially at the
terminal of the CPV_IPP “bus 56” site during the fault-ride through. Instantly after the occurrence of fault, the voltage at all the PV bus drops according to the geographical distance of the respective PV farm from PV farm CPV_IPP “bus 56.” During the fault-ride through these voltage start rising towards their rated values with overshoot in voltage at some buses. These overshoots are because of low capacity of those PV farms. Immediately after the fault is cleared at 20.15 s, as the PV farms begin a voltage regulation mode, the voltage at the PV terminals start to reach their rated values. The active power flow through the branch 56–224 are as shown in Figure 33. The active power output from the whole PV farm, prior to the fault, was 200 MW. Afterward, the power initially decreases to 192 MW during the fault and stabilizes at 196 MW before the clearance of fault. Finally, the power resumes to 200 MW with an overshoot up to 215 MW. The mirrored characteristics of P and

Figure 30. Variation in reactive power at all 14 PV buses after three-phase short circuit at terminal of bus 48 “Zarzis.”

Figure 31. Variation in active power at all 14 PV buses after three-phase short circuit at terminal of bus 48 “Zarzis.”
Q output is a sign of the controlled converter action only limited by the nominal current rating of the converter. The reactive power decreases with increase in the active power output and vice versa. As elaborated in section “Power system model,” the output reactive power from PV farm at “bus 56” has been maintained at a steady state value of 0.1184 p.u level to achieve 0.95 power factor before the occurrence of fault and illustrated by Figure 34. Upon fault occurrence at $t = 20s$, the SPVGP has drawn 0.41 p.u reactive power from the grid for a few cycles. Finally, it has recovered the steady state value of 0.1184 p.u level after the fault clearance. During fault duration, the proposed control action has to increase the voltage at the converter terminals as shown in Figure 32. The simulation results confirm that the PV controllers have the capability for reestablishing the voltage at the PV terminal after

Figure 32. Voltage variation at all 14 PV buses in the case of a 3-phase fault at terminal of largest PV farm CPV_IPP “bus 56” site.

Figure 33. Active power variations at all 14 PV buses during 3-phase fault at terminal of largest PV farm CPV_IPP “bus 56” site.
the clearance of the short-circuit fault. The terminal voltage variation at the P-Q buses namely TG Zarsis, Robbana, and Djerba, nearby of the CPV_IPP “bus 56” site, decreased significantly as shown in Figure 35. After the fault clearance, the terminal voltage at these buses have not been recovered to the steady state value because these buses are near the fault location and are not augmented with voltage auto recovery capability. Further, these results on these above-mentioned P-Q buses have been validated by the eigenvalue analysis as shown in Figure 36.
Investigation of voltage stability demonstrates that the dynamic comportment of the voltage depends strangely on short circuit capability of the transmission network at the bus of integration with the PV station. The dynamic performance of the grid has presented compliance with voltage ride-through capabilities that can be improved by means of supplementary reactive supply. The supplementary generation of PV power has been found to considerably improve the voltage regulation, even in the case of over-voltages. Due to the additional reactive power absorption capacity offered by solar generators, a significant improvement in the system voltage regulation capability has been found. The bifurcation diagrams of voltages showed that with high PV penetration, voltage bifurcation may occur at higher voltages. Conferring to the bifurcation diagram, the maximum capacity of SPVGs that can be supported and accepted by the Tunisian grid is 2185 MW. Abrupt disconnection of PV farms results in a frequency deviation of 48.825 Hz, and voltage drop 6% of the nominal voltage. Mostly, the south-western area of the country has been affected by this disruption for which a secondary frequency regulation action is necessary. The all-encompassing view is positive for future network integration of PV in Tunisia.

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