

Analysis of the Modeling of the Influence of Decentralized Solar Energy PV on the Intensity of Short-Circuit Currents of the Power Electric System

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Abstract

Several advantages are linked to the integration of renewable decentralized production sources into electrical networks, including the reduction of line losses, etc. However, the integration of decentralized energies, particularly solar PV, can lead to variations in the direction or amplitude of currents in steady state, variations in short-circuit currents, changes in voltage, variations in measured impedances. These variations can have a negative influence on the proper functioning of the protection plan, including protection blinding or false tripping. This article presents a simulation model to predict the influence of the integration of decentralized solar PV energies on the intensity of short-circuit currents and the short-circuit power at a node of a power electrical system. The mathematical equations developed for modeling the energy elements of the electrical network in which the solar PV RED is integrated were based on Kirchhoff's laws and on the current-voltage characteristic of the modules. The simulation model using experimental data from a grid-connected photovoltaic system installed in DR Congo was compared with results from existing literature. Simulations 2D based on proposed models were developed as well as the verification of the consistency of the different models, by comparing the fractal dimensions of the results of our program with those of the figures obtained experimentally. The results obtained show that the integration of PV solar generators into the grid has a direct impact on the short-circuit current and the short-circuit power at the connection point. The aspects developed in this article could have direct implications in practical applications in the engineering and design of grid-connected PV systems.

Keywords

Analysis, Modeling, Simulation 2D, Fractal Dimensions, Integration,

1. Introduction

Renewable energy sources are those that come from the sun, wind, water, underground heat, biomass, etc. Some of them (hydroelectricity, geothermal and biomass), allow them to modify their output power according to the demand; while some others (solar and wind) do not allow it. Solar and wind energies can be isolated and/or connected to the electricity grid [1]. Decentralized solar PV energies have implications for the reduction of line losses because the installations are close to consumers and allow them to face the growth of demand while ensuring the security of supply and energy independence [2]. Despite their advantages, many disadvantages constitute a brake on the large-scale deployment of renewable energies, such as the higher investment cost compared to conventional fuels, the intermittency and the unpredictability due to weather conditions [3]. Power grids have been designed and sized to accommodate unidirectional power flows from high to low voltage [4]. With the integration of renewable energies, these power flows become bidirectional, and can in some cases, export power flows even at the transmission network level [5].

This has a direct impact on the protection plan. In addition, the massive integration of renewable energies on a power grid considerably reduces its reliability and causes variations in short-circuit currents, changes in voltage, variations in measured impedances, etc. [6]-[9].

The main objective of this paper is to propose a simulation model to predict the influence of the integration of decentralized solar PV energies on the intensity of short-circuit currents and short-circuit power at a node of a power electrical system. To do this, we established the mathematical equations based on Kirchhoff's laws and the current voltage characteristic of PV modules. The PV-grid system interface was provided by a voltage inverter to obtain a system of balanced sinusoidal currents in phase with the voltage. This implies that the reactive power generated must be zero. The simulation model was validated from experimental data taken from a grid-connected PV system installed in DR-Congo.

The simulations 2D based on the proposed models were developed, along with the verification of the consistency of the different models. Two-dimensional (2D) simulation is crucial for verifying a grid-connected PV electrical model in short-circuit conditions [6]-[10]. This approach allows for analysing the behaviour of the grid-connected PV installation under various conditions, assessing safety, identifying weak points, and predicting the system behaviour in the event of a fault for optimal sizing. It helps understand the consequences of a short circuit, including safety risks and potential costs, which is essential for designing a safer system. By simulating different short-circuit scenarios, components such as circuit breakers and cables can be properly sized to avoid damage and ensure performance. The

simulations 2D helps detect vulnerable areas of the installation where short circuits could occur, thus enabling preventive improvements. The simulations 2D can model the behaviour of PV cells connected to power grids and predict currents and voltages in the event of a fault, thus providing reliable insight into system operation [8]-[10]. Comparing the fractal dimensions of our program's results with those of experimentally obtained figures is crucial for the validity of 2D simulation models of a PV system connected to power grids under short-circuit conditions. This quantifies the complexity of the phenomena associated with the entire PV-power grid system, allowing us to verify whether the simulation faithfully reproduces the characteristics at all scales of the considered scenarios. Comparing the fractal dimensions of the proposed model with those of the real phenomenon allowed us to assess the model's ability to capture the fine details and fragmentation of the studied phenomenon, thus ensuring its relevance and realism. The validity of a 2D simulation model depends on its ability to reproduce the properties of a real system [9]-[11]. A close match between the fractal dimension of the model and that of the real phenomenon indicates that the simulation is capable of reproducing details at different scales.

The results obtained show that in the presence of PV solar generators, the short-circuit current and the short-circuit power at the connection point undergo modifications that may impact the protection plan and affect the dynamic stability of the electrical network.

2. Theoretical Models

2.1. General Structure of a Photovoltaic System Connected to the Electrical Grid

A grid-connected PV system will interact with the electrical grid. The main advantage of this system is that power can be drawn from the electrical grid and when power is not available from the grid, the PV system can supplement that power, these grid-connected systems are designed with or without battery storage [1] [2] [5].

The following **Figure 1** illustrates the general structure of a photovoltaic system connected to the electrical grid [1] [2] [5].

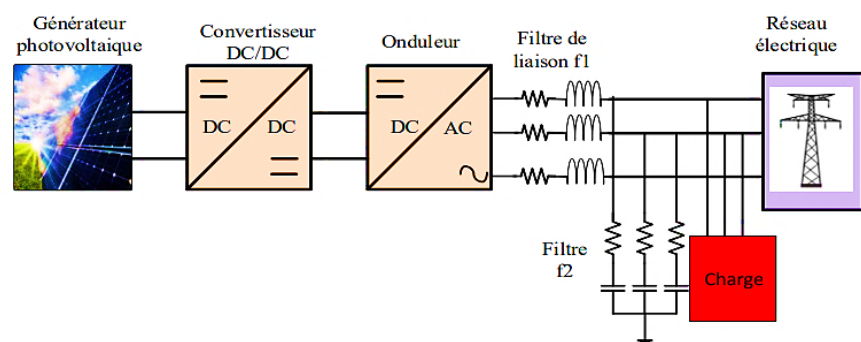


Figure 1. General structure of a photovoltaic system connected to the electrical grid [1] [2] [5].

2.2. Modeling of the Photovoltaic Generator

The PV generator consists of modules interconnected to form a unit producing high continuous power compatible with conventional electrical equipment. Thus, the I-V characteristic of the PV generator is based on that of an elementary cell modeled by the well-known equivalent circuit of **Figure 2** [1] [2] [5].

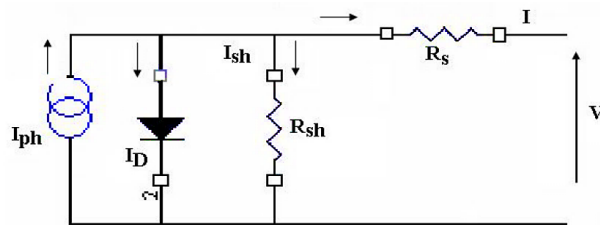


Figure 2. Equivalent circuit of a photovoltaic cell [1] [2] [5].

This circuit can be used for an elementary cell, as well as for a module or a panel made up of several modules [1] [2] [5] [6]. The Equation (1 and 2) linking the current delivered by a PV module made up of the series connection of N_s cells and the voltage at its terminals is given by [1] [2] [5] [7]:

$$I = I_{ph} - I_0 \cdot \left[\exp\left[\frac{V + I \cdot R_s}{V_T}\right] - \frac{V + I \cdot R_s}{R_{sh}} \right] \quad (1)$$

$$V_T = N_s \cdot n \cdot k \cdot T / q \quad (2)$$

where: I_{ph} , I_0 , V_T , denote respectively the photocurrent, the reverse saturation current of the diode and the thermal voltage, n the ideality factor of the diode, q the charge of the electron, k the Boltzman constant, R_s series resistors, R_{sh} parallel (shunt) and T the temperature of the cell which varies according to the illumination and the ambient temperature (see Equation (3)), according to the linear relation Shot in [1] [2] [5] [8]:

$$T - T_a = \left[\frac{(T_{fn} - 20)}{800} \right] \cdot \psi \quad (3)$$

where T_{fn} is the normal operating temperature of the PV cells ($^{\circ}\text{C}$). The value of T_{fn} is usually given by the manufacturer, T_a is the ambient temperature ($^{\circ}\text{C}$) and ψ (W/m^2) is the global solar irradiation of the location considered and received by the PV module.

From Equation (2) [1] [2] [5] [9], a simple methodology has been developed for determining the characteristics of a photovoltaic cell or panel. The two external parameters of the cell, such as the short-circuit current I_{cc} and the open-circuit voltage V_{co} , are introduced to deduce the implicit mathematical expression of the current delivered by a photovoltaic cell, as well as its I-V characteristic. At usual illumination levels, the photocurrent is proportional to the solar irradiation or luminous flux ψ (W/m^2). In the ideal case, it corresponds to the short-circuit current [1] [2] [3]. His approximate expressions taken from are given by Equation (3) [1] [5] [7] [8]:

$$I_{cc} \cong I_{ph} / \left[1 + \left(R_s / R_{sh} \right) \right] \quad (4)$$

$$I_{cc} \cong I_{c0} [\psi/800] \quad (5)$$

where I_{c0} is the short-circuit current for a standard solar irradiation of 1000 W/m². The open-circuit voltage is the voltage for which the current delivered by the cell is zero, it is the maximum voltage of the cell. In the ideal case, it is slightly lower than [1] [5] [7] [8]:

$$V_{co} = V_T \cdot \ln [I_{ph}/(I_o + 1)] \quad (6)$$

By injecting Equation (2) [9] [10] into Equation (4), Equation (1) becomes [11]:

$$I = I_{cc} \cdot [\alpha - \beta \cdot [\exp y(V - V_{co} + R_s \cdot I)]] - [(V + I \cdot R_s)/R_{sh}] \quad (7)$$

Let us pose:

$$\alpha = \psi/1000, \quad \beta = 1 + R_s/R_{sh} \quad \text{and} \quad y = 1/V_T \quad (8)$$

Temperature is a very important parameter in the behavior of photovoltaic cells. Based on the model given by [9] [10] (see expression (3)), it can be integrated into Equation (7):

$$I = I_{cc} \cdot [\alpha - \beta \cdot [\exp y(V - V_{co} + R_s \cdot I)]] - \lambda \cdot (T - T_{ref}) [(V + I \cdot R_s)/R_{sh}] \quad (9)$$

where λ is a coefficient characterizing the variation of power as a function of temperature and T_{ref} is the temperature of the module under standard conditions. The equation (10) of the characteristic relative to a field of modules formed by the series connection of M_s modules and M_p modules is extrapolated from that of a module, and it is given by [1] [5] [7] [8]:

$$I_G = I_{cc} \cdot M_p \cdot [\alpha - \beta \cdot [\exp(y/M_p) [M_s \cdot (V - V_{co}) + M_s \cdot R_s \cdot I/M_p]]] - [(M_s \cdot V + M_s \cdot R_s \cdot I/M_p)/R_{sh} M_s \cdot M_p] \quad (9a)$$

2.3. Modeling the PV-Grid System Interface

2.3.1. Modeling of the Electrical Network

Loads are consumers of electrical energy depending on their characteristics [10], see Equation (10).

$$v_a = V \cdot \sqrt{2} \cdot \sin(\omega \cdot t) \quad (10)$$

$$v_b = V \cdot \sqrt{2} \cdot \sin(\omega \cdot t - \pi/3) \quad (11)$$

$$v_c = V \cdot \sqrt{2} \cdot \sin(\omega \cdot t - 4\pi/3) \quad (12)$$

With: v_a, v_b, v_c instantaneous voltages of phases a, b and c of the electrical network in volts. Then, v maximum value of the network voltage in volts, ω is the pulsation in Rad/sec and t is the time in seconds.

In the “synchronous” operating mode, the control is used to ensure that the injected three-phase current is perfectly synchronized with the network voltages. This is often required by the network manager. To do this, simply impose a zero set point on the reactive power. The active power is controlled according to the needs of the loads.

2.3.2. Modeling of Three-Phase Inverter

A three-phase DC-AC converter with two voltage levels consists of three transistor switching arms. Each arm consists of two cells each with a diode and a transistor that work in forced commutation. All these elements are considered as ideal switches. In controlled mode, the inverter arm is a two-position switch that allows to obtain at the output two voltage levels, which gives three phase output voltages as of 120 degrees, one with respect to the other. **Figure 3** illustrates the topology for modeling the three-phase inverter with six power switches [9]-[12].

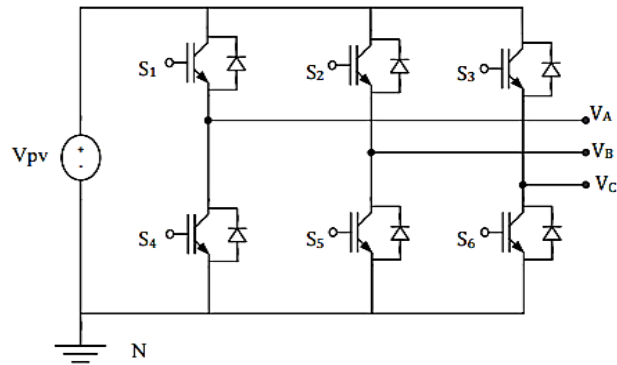


Figure 3. Equivalent diagram of a Three-phase Inverter [9]-[12].

Based on the measurement of three-phase voltages and currents after filter 1, the voltage and current on the two-phase alpha-beta plane can be calculated by the expressions [9] [10] (see Equation (13)-(16)):

$$V_{\alpha} = \sqrt{2/3} \cdot [V_{sa} - 1/2(V_{sb} + V_{sc})] \tag{13}$$

$$V_{\beta} = \sqrt{2/3} \cdot [V_{sb} - V_{sc}] \tag{14}$$

$$I_{\alpha} = \sqrt{2/3} \cdot [I_{sa} - 1/2(I_{sb} + I_{sc})] \tag{15}$$

$$I_{\beta} = \sqrt{2/3} \cdot [I_{sb} - I_{sc}] \tag{16}$$

With: I_{α} and I_{β} respectively present currents in the alpha-beta plane in A. V_{α} and V_{β} respectively translate the voltages in the alpha-beta plane into Volts. I_{sa} , I_{sb} and I_{sc} : respective currents at the terminals of the phase switches a, b and c in A. V_{sa} , V_{sb} and V_{sc} : respective voltages at the terminals of the phase switches a, b and c in volts.

2.4. Modeling of Short-Circuit Currents

The equivalent circuit of the short-circuit sequences is given in **Figure 4** below [13]-[15]:

By combining the Equations (17-22) of the real components of the asymmetrical ones and the equations of the symmetrical components we obtain [13]-[15]:

$$a^2 \cdot (I_d)^2 + I_i + I_h = 0 \tag{17}$$

$$a \cdot I_d + a \cdot I_i + I_h = 0 \tag{18}$$

$$V_d + V_i + V_h = Z \cdot I_i \tag{19}$$

$$V_d = V_{dp} - Z \cdot I_d \tag{20}$$

$$V_i = 0 - Z \cdot I_i \tag{21}$$

$$V_h = 0 - Z \cdot I_h \tag{22}$$

With V_d , V_i , V_h : Respective direct, reverse and homopolar sequence voltages in volts. V_{dp} : Nominal voltage at fault location in kV.

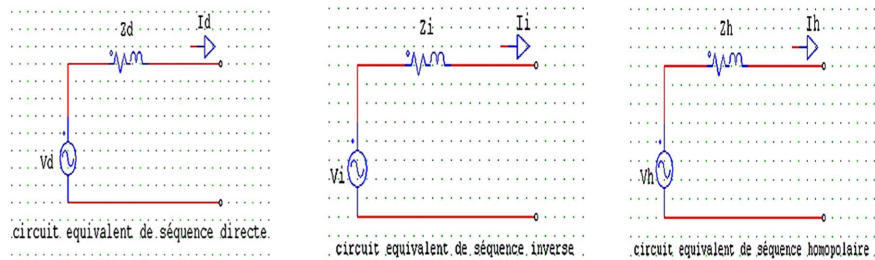


Figure 4. Equivalent circuit of the sequences [13]-[15].

The pre-existing voltage at the fault point in volts. Z_d , Z_i , Z_h : The equivalent impedances to the network in the three systems (direct, reverse and homopolar) in Ohm $[\Omega]$. V_d , V_i , V_h : The equivalent currents to the network in the three systems (direct, reverse and homopolar) in A.

In this study, we limit ourselves to the case of the homopolar fault (phase and earth) which has a frequency of occurrence. This fault is modeled according to **Figure 5** below [13]-[15]:

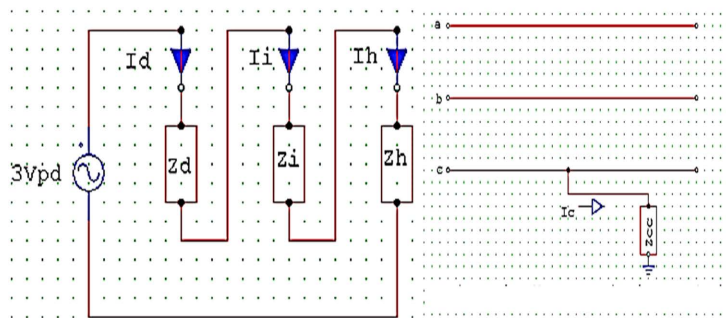


Figure 5. Representation of a homopolar short circuit (phase and earth) [13]-[15].

The short-circuit current and short-circuit apparent power corresponding to **Figure 5** above can be calculated respectively via Equations (23) and (24) below:

$$I_{cc} = -3 \cdot V_{dp} / (Z_d + Z_i + Z_h) \tag{23}$$

$$S_{cc} = -3 \cdot U_{dp} \cdot I_{cc} \tag{24}$$

Legend:

S_{cc} : Short circuit power in MVA

I_{cc} : Short circuit current in kA

U_{dp} : Nominal voltage at fault location in kV.

3. Simulation

3.1. Simulation Parameters

1) Electrical Grid

The grid in which the PV generator is integrated has the following characteristics (National electricity company SNEL/DDK/DKE/RDC/Kinshasa (2025)) [16]:

Three-phase source (20 kV/0.4kV and 50 Hz), step-down power transformer (630 kVA, 20/0.40 kV and 50 Hz), three-phase load (400 V, 50 Hz, 10 kW).

2) PV Generators

The graphical representation of the equation $I = f(V)$ for the PV generator consisting of 12 identical modules, each having a series resistance $R_s = 0.57 \Omega$ and a parallel resistance $R_{sh} = 297 \Omega$ [17]. The characteristic quantities of this module are: $V_{CO} = 45.73$ volts, $I_{CC} = 5.8$ A, $FF = 0.78$, $\eta = 10.06\%$, $P_{max} = 201.61$ W, $V_m = 37$ V and $I_m = 5.45$ A [17];

3.2. Simulation Results

See Figures 6-16 below:

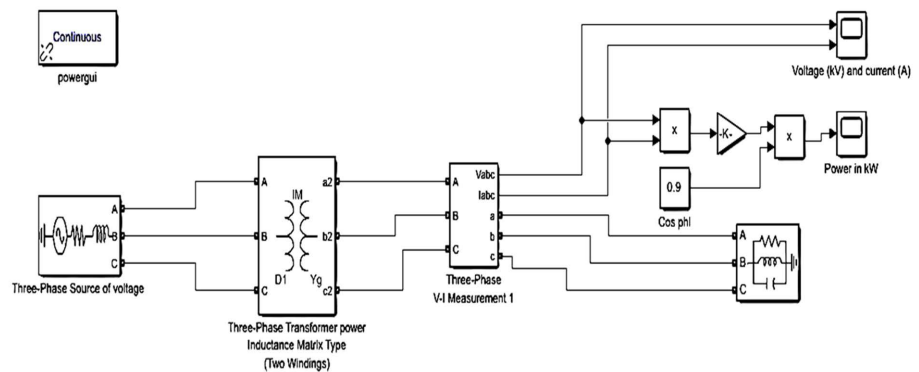


Figure 6. Healthy electricity grid model without integration of solar PV REDs.

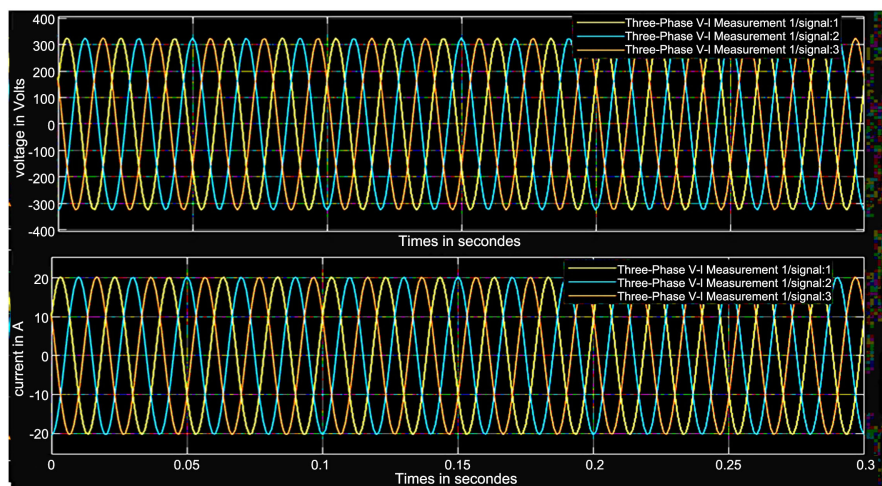


Figure 7. Voltage and nominal current curves of the healthy electrical network without integration of solar PV REDs.

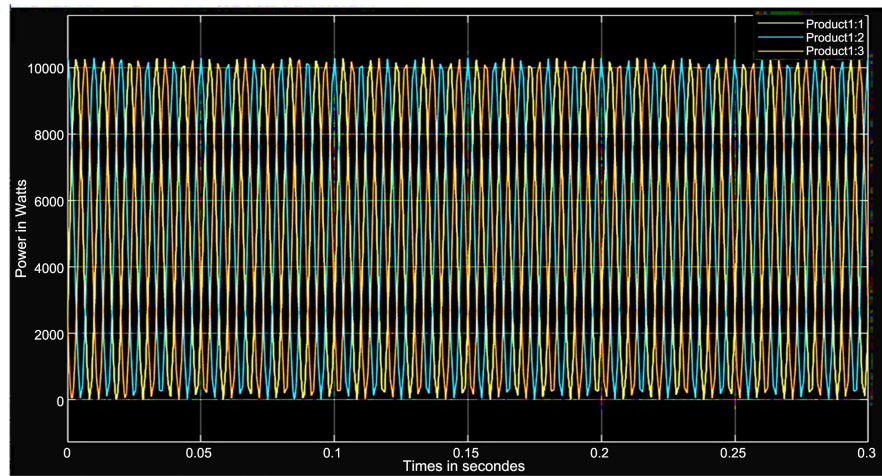


Figure 8. Active power of the healthy electrical network without integration of solar PV REDs.

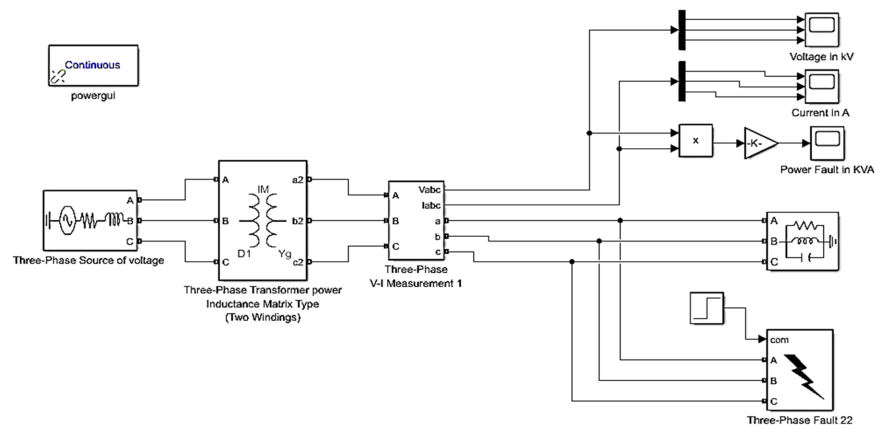
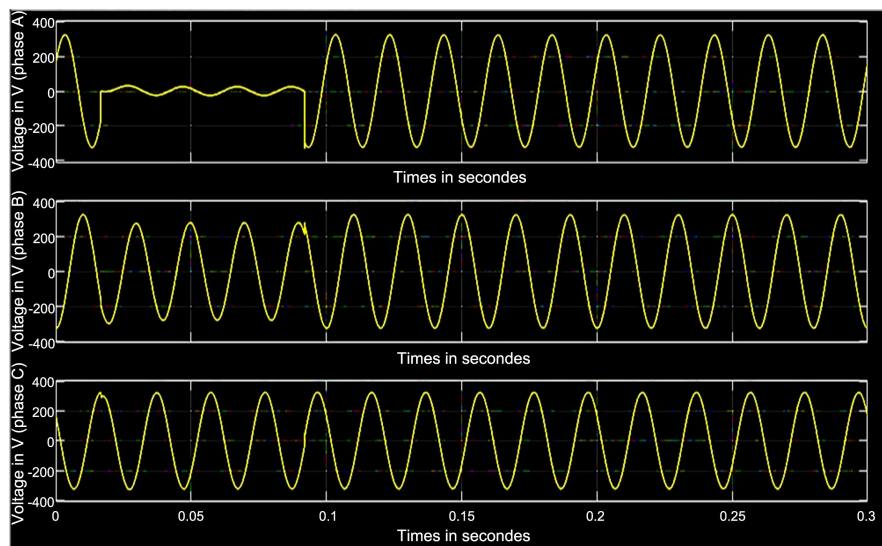
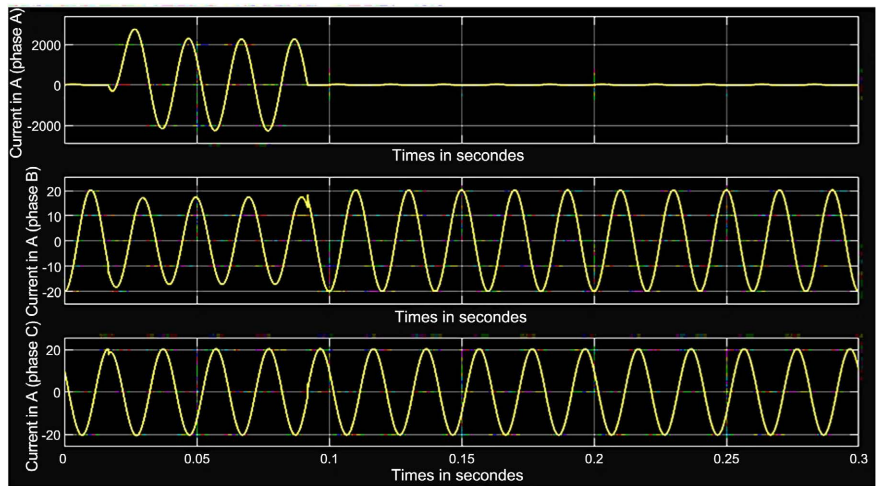


Figure 9. Model of the electrical network in short-circuit faults without integration of solar PV REDs.



(a)



(b)

Figure 10. Voltage and current profile in the network in phase-to-earth short-circuit mode without integration of solar PV REDs.

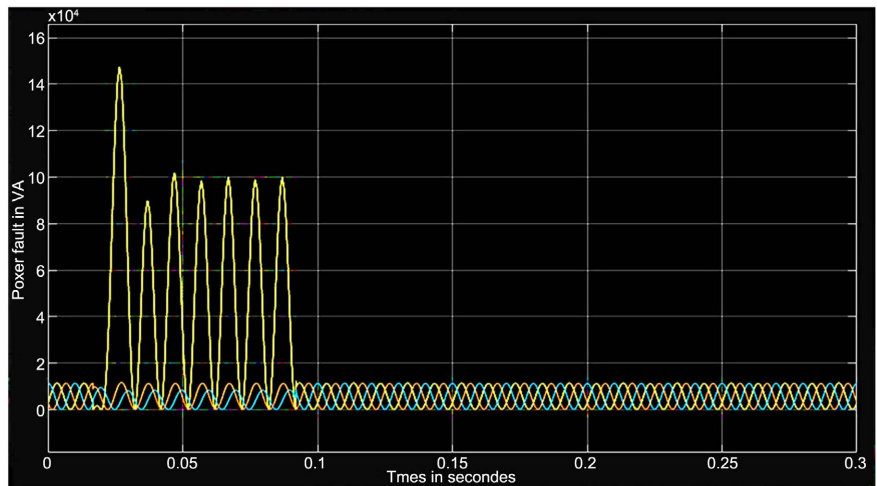


Figure 11. Short-circuit power in phase-to-earth fault regime without integration of solar PV REDs.

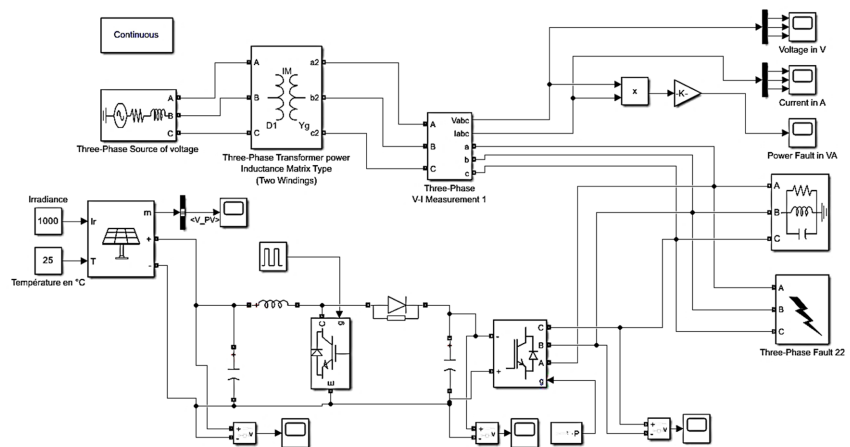
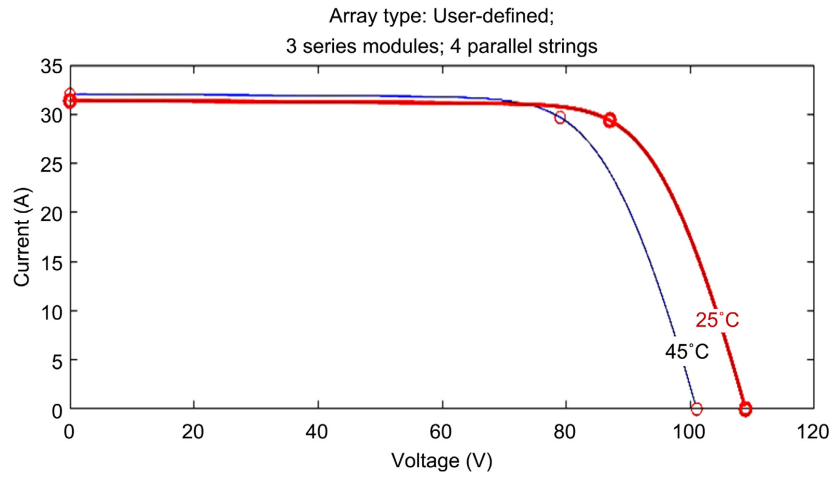
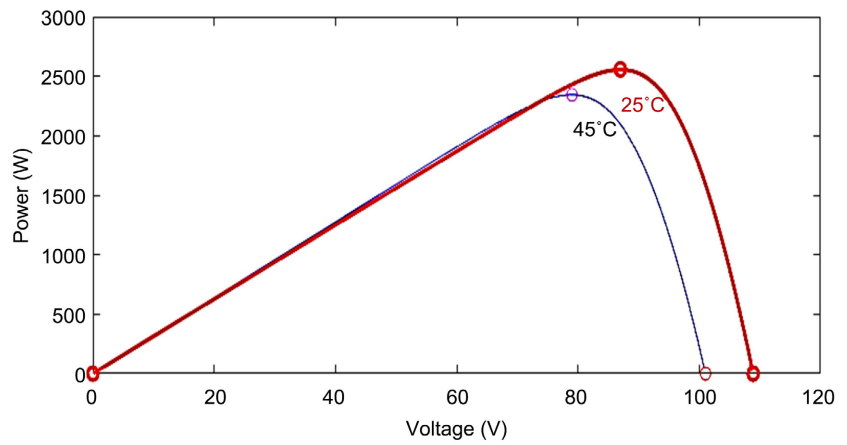


Figure 12. Network model integrating the PV solar generator.

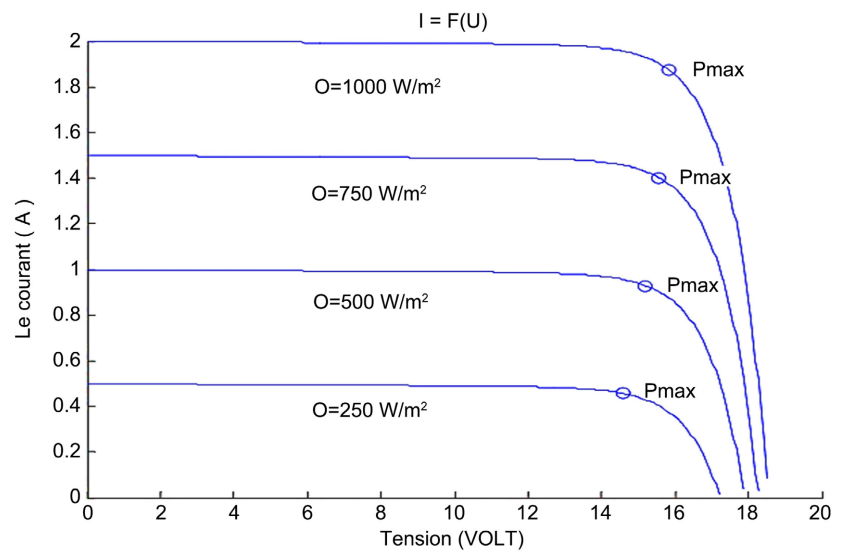


(a)



(b)

Figure 13. (a) I-V and (b) P-V characteristics of a module for different solar irradianciations at 25°C and 45°C. (Simulation results).



(a)

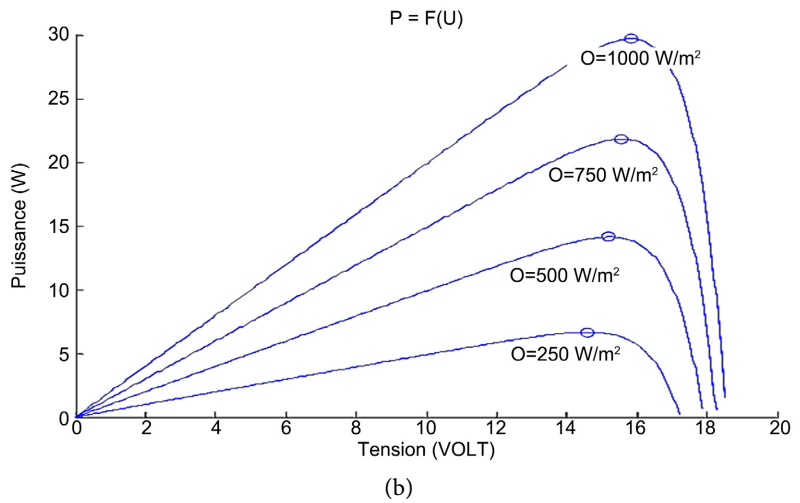
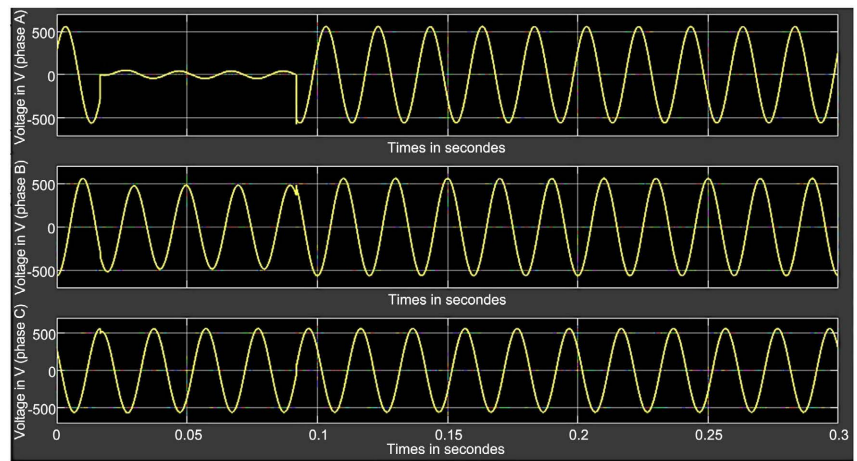
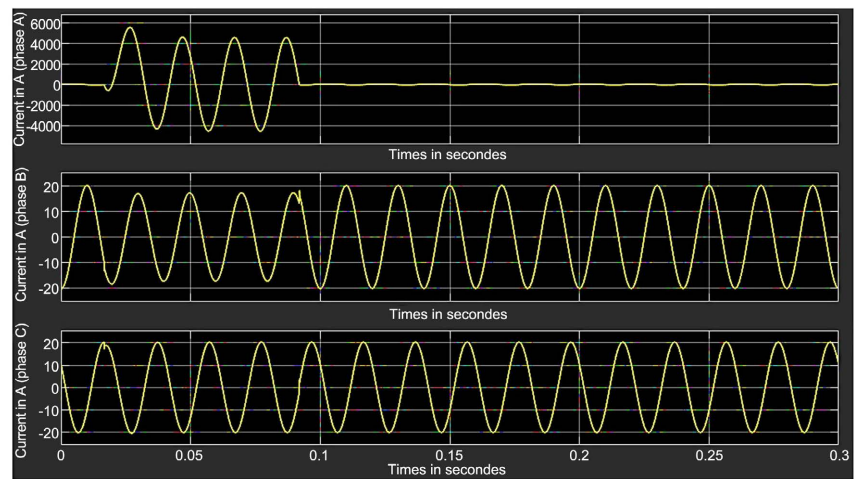


Figure 14. Influence of the flow on the characteristic $I = f(V)$ and $P = f(V)$ of a PV module. (HASSINI née BELGHITRI HOUDA, 2021) [17].



(a)



(b)

Figure 15. Voltage and current profile in the network in phase-to-earth short-circuit mode with integration of solar PV REDs.

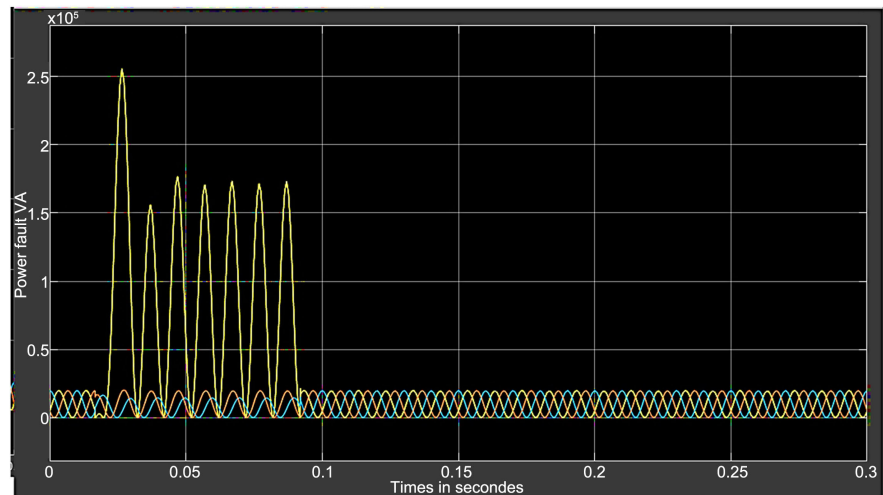


Figure 16. Short-circuit power in phase-to-earth fault mode in the presence of solar PV REDs.

4. Discussions of Results

The objective assigned by this present article is to propose a simulation model to predict the impact of the injections of decentralized solar PV energies on the intensity of short-circuit currents and the short-circuit power at a node of an electrical power system. During the different simulations, we obtained the following results:

Figure 6 gives the simulink model of the 20/0.4 kV test distribution electricity network without the integration of solar PV decentralized energy resources (RED). This configuration made it possible to obtain the results shown in **Figure 7**, which illustrates the profile of the voltage in volts and the nominal current in amperes drawn by the load in the low voltage part (400 V or 0.4 kV). From a quantitative point of view, we see that the amplitude of the voltage at the secondary of the test network on the three phases is 380 V. While that of the current is 20 A. This shows that this system is balanced. And, **Figure 8** presents the flow of active power transferred to the load. This active power is 10 kW.

Figure 9 shows the model of the power grid in a short-circuit fault regime without the integration of decentralized solar PV energies. **Figure 10(a)**, **Figure 10(b)**, **Figure 11** and **Figure 12(a)**, **Figure 12(b)** show respectively the profile of the voltage, the short-circuit current and the apparent short-circuit power in the phase-to-earth fault regime. It is noted that on the faulted phase the voltage is zero at times 0.01 to 0.1 sec (see **Figure 10(a)**), the short-circuit current reaches an amplitude of 3 kA (see **Figure 10(b)**) and the apparent short-circuit power reaches 150 kVA (see **Figure 11**).

Figure 12 gives the simulink model of the 20/0.4 kV network, including a 630 kVA transformer in the presence of the PV solar generator.

Figure 13(a), **Figure 13(b)** show respectively the current-voltage (IV) and power-voltage (PV) characteristics of a PV module for different temperatures, namely 25°C and 45°C. We note that the temperature has a direct implication on

the productivity of a PV generator. These results bring together the experimental work proposed by (HASSINI née BELGHITRI HOUDA, 2021) [17], see **Figure 14(a)**, **Figure 14(b)**.

Figure 15(a), **Figure 15(b)** and **Figure 16** show respectively the influence of the injection of decentralized PV solar energy on the voltage, the short-circuit current and the short-circuit power at the connection point. These results show that the presence of the PV solar generator in the test network causes the modification of the voltage profile. For the case in point, the voltage reaches 510 V between phases (see **Figure 15(a)**). In the event of faults, a modification of the short-circuit currents is observed (5 kA in **Figure 15(b)**) unlike the short-circuit current in **Figure 12(a)** which is 3 kA. This situation is due to the artificial modification of the impedances at the GED connection point to the network. This modification can affect the selectivity of the protective devices (mainly overcurrent relays and surge protection devices (surge arresters) by changing the characteristics of current flows and the network voltage, potentially leading to false tripping or insufficient protection, in particular by varying their tripping time. The selectivity and sensitivity of the protection devices can be seriously compromised, causing false tripping of a healthy circuit or blinding the protection of a faulty circuit. Corrective measures include recoordination of relay settings, installation of suitable surge arresters on the AC and DC sides, effective grounding of PV systems, and the use of residual current circuit breakers for overall protection. Since the short-circuit current is linked to the apparent short-circuit power, **Figure 16** shows that, in the presence of solar PV GED, the short-circuit power undergoes a modification of 250 kVA.

In the context of distributed solar photovoltaic (PV) and the impact on short-circuit current intensity, it is crucial to consider different types of short-circuit faults including single-phase short-circuit, two-phase short-circuit and three-phase short-circuit or ground short-circuit as well as the intermittent one, since each of these short-circuits can have distinct implications on the operation and safety of the system.

Therefore, it is essential to consider these different types of short-circuit faults when designing and implementing distributed photovoltaic systems. Adequate protection devices and rapid detection strategies should be integrated to ensure system safety and reliability while minimizing the impacts on the Power Grid.

The integration of PV power plants primarily affects overcurrent relays and surge protection devices (surge arresters) by altering current flow characteristics and grid voltage, potentially leading to false tripping or inadequate protection. Corrective measures include reconfiguring relay settings, installing suitable surge arresters on the AC and DC sides, effectively grounding PV systems, and using residual current circuit breakers for overall protection.

Corrective Measures

- Recoordination of Relay Settings:

Adapt the settings of the overcurrent and distance relays to recognise the spe-

cific characteristics of current flows induced by PV plants, distinguishing between fault current and overloads.

- Installation of Custom Protective Devices:

Surge Arresters: Install suitable surge arresters on the DC side (on PV modules and inverters) and the AC side (on grid equipment) based on risk studies and standards such as UTE C 15-712-1.

Residual Current Circuit Breakers (RCCB/RCBO): Install residual current circuit breakers to detect current leakage and insulation faults, thus protecting personnel.

- Improvement of the Grounding System:

Ensure equipotential bonding between all conductive parts of the PV installation and the grid.

Install effective grounding to provide a safe path for unwanted currents.

5. Conclusion and Perspectives

The work presented in this thesis mainly focuses on the analysis of the modeling of decentralized photovoltaic (PV) solar energy and its impact on the short-circuit current intensity in a power electrical system requires an imperative study ensured by what the increase in the level of penetration of decentralized PV solar energy can have significant repercussions on the short-circuit current intensity in an electrical system.

Our objective was to develop a simulation model to predict the influence of integrating decentralized PV solar energies on the intensity of short-circuit currents at a node of a power electrical system. The mathematical equations proposed for the modeling of the energy elements of the electrical network in which the RED PV solar is integrated were based on Kirchhoff's laws and those of the PV generator were focused on the current-voltage characteristic of the modules.

The simulation results obtained from the computer tools allowed us to validate the main hypothesis of our research. To this end, we can therefore confirm that the connection of a new generator (asynchronous or synchronous, PV and others) to the network can cause the modification of the voltage plan and in the event of a fault, a modification of the short-circuit currents and the short-circuit power of the connection point. This modification of the short-circuit currents is due to the artificial variation of the network impedances in the presence of GEDs which can affect the selectivity between the protection devices and the dynamic stability of the network.

It is crucial to carry out in-depth studies to anticipate these impacts and adapt the infrastructures accordingly. This is because the variation of the different voltage levels of the order of 0 to 100% can affect the PV system and contribute significantly to several types of single-phase, two-phase, and three-phase short-circuit currents as well as other types such as (transient short-circuit, short-circuit to earth and permanent short-circuit) thus requiring adjustments at the network level.

The 2D simulations based on the proposed models were consistent when comparing the fractal dimensions of the results of our program with those of the experimentally obtained figures. The aspects developed in this paper could have direct implications in practical applications in the engineering and design of PV systems connected to electrical grids.

The simulation model developed in the Matlab environment, in which different levels of programming language have been used, presents limitations encountered during the validation of this model with experimental data, such that the latter only allows identical PV solar modules, with the same I-V characteristics and receiving the same solar irradiation. This is also due to data quality issues, model simplifications, inappropriate experimental conditions, or complex interactions that are not properly modeled. To overcome these limitations, it may be necessary to improve data collection, refine the model, or adopt more robust validation approaches that take into account weather conditions.

The study and modelling of the influence of high penetration of renewable distributed generation sources in the distribution network and additional analyses comparing different scenarios (e.g. different levels of PV penetration) could be the subject of future studies.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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