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Study of the influence of common faults in photovoltaic pumping systems on functional characteristics

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Abstract

Forced production shutdowns following breakdowns in solar pumping systems are costly and represent a significant portion of the initial investment. In addition, the absence of a database on recurring faults and breakdowns prevents the implementation of automatic diagnostic strategies for faults which lead to irreversible breakdowns. The absence of this fault database also prevents the preventive and effective maintenance of production systems. In this article, we identify the frequent faults and breakdowns in the different modules constituting the photovoltaic pumping system operating over the sun, then we present the influence of each fault on the functional characteristics of the system. The complete system comprising a photovoltaic generator, an adaptation stage (chopper-inverter) and a submerged electric pump operates using the sun and is modeled and simulated in Matlab/Simulink.

Keywords: Photovoltaic pumping, pump operating characteristics, pumping system faults, automatic fault diagnosis.

1.Introduction

Advances in power electronics, electromechanics and control circuits are helping to boost the development of production systems. These increasingly complex systems cannot be free from disturbance and failures of various types. In order to ensure the reliability of the operation of production systems, the problem of their control in the presence of defects has been widely addressed by several authors [1, 2, 3]. Most of the research has been devoted to the problem of detecting and locating faults in order to determine the operating state of the system (normal or faulty). The literature does not present the effects of breakdowns and defects on operation.

The main objective of this article is to present the influence of frequent faults at different links in a solar-powered photovoltaic pumping system. This article in its articulations, presents in the method part, the modeling and simulation of the complete system in the “Simulink of Matlab software” interface. The complete system consists of a PV generator, the adaptation stage (boost chopper and inverter), induction motor and a submersible centrifugal pump. Subsequently, we will present the recurring defects at the level of the different elements of the system and we will end by studying the influence of the defects on the functional characteristics of the complete system thus modeled.

2.Materials and methods

2.1. Modeling of photovoltaic pumping system

2.1.1. Photovoltaic generator

In this article we use the basic structure of a single-diode photovoltaic cell. The equivalent circuit of the GPV and the different equations leading to equation (1) are those provided by Ernest and al [4].

$$I_{pv} = I_{cc} - I_c \left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{V_t \times N_{cs}} \right) - 1 \right] \tag{1}$$

The block diagram in Figure 1 shows the Simulink model of the PV module (a) and the GPV (b), based on equation (1) whose parameters involved are solved by the Newton-Raphson method in Matfile.

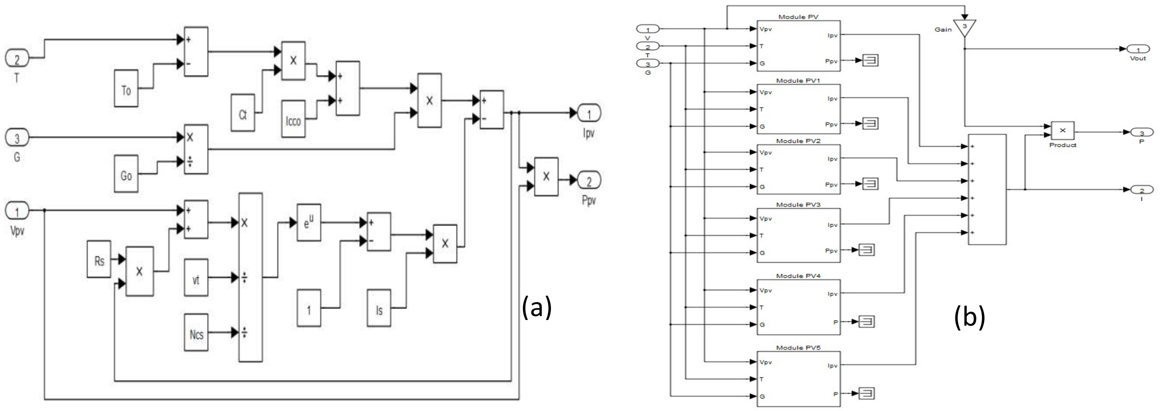

Figure 1: Simulink model of the PV module and generator

For the simulation of the GPV, we associate in series 3 rows of 6 PV modules in parallel (N_P=6, Ns=3) as presented in figure 1.b, for an available power of 1559.09 W under 24.06 A and 64.8 V and allowing the pump to provide 1.3 l/s under 6 bars.

2.1.2. Modeling of the DC-DC Converter

The Simulink model of the booster chopper presented in Figure 2 has the main role of increasing the voltage from a low value to a higher value by varying the duty cycle (d) in the following relationships (2) and (3):

$$V_{out} = \frac{V_{in}}{1-d} \tag{2}$$

$$I_{out} = (1-d)\,\mathrm{I}_{in} \tag{3}$$

V_{in} and I_{in} respectively represent the voltage and current at the input of the chopper and V_{out}, I_{out} those of the output. The values of the inductance L and the capacitance C of the converter are calculated as follows:

$$L = d\,\frac{V_{in}}{f.\Delta I} \tag{4}$$

$$C = d\,\frac{I_{out}}{f.\Delta V} \tag{5}$$

With f frequency and $\Delta I, \Delta V$ ripple size of current and voltage respectively. Using the maximum values of current and voltage, the numerical application of relations (3) and (4) gives 30 µH and 470 µF respectively.

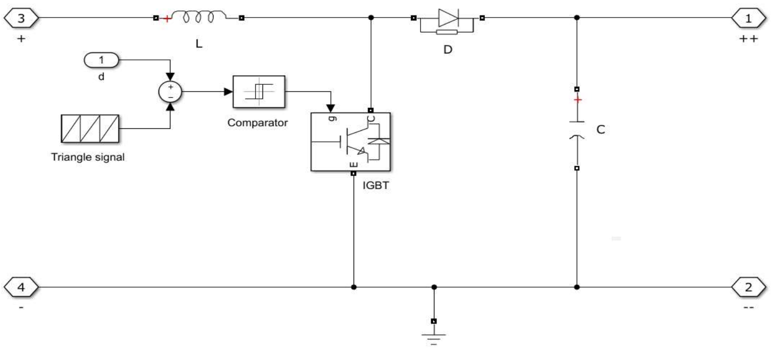

Figure 2: Simulink model of the booster chopper

At the input of the control signal, a comparator allows analysis between a triangular signal with a frequency of 100 kHz and the duty cycle provided by the MPPT-fuzzy control algorithm.

2.1.3. Modeling of the DC-AC converter

The single-phase inverter illustrated by its Simulink model (figure 3) allows the production of alternating voltage from the direct voltage coming from the chopper. The pulse width modulation (PWM) technique is used to control the switching bridge of the inverter.

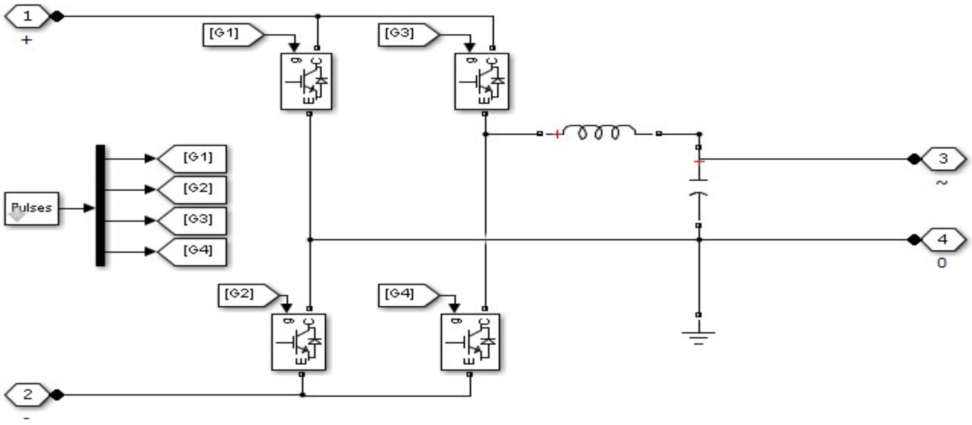

Figure 3: Simulink model of the single-phase inverter

The pulses (G_1, G_2, G_3 et G_4) of the switches (IGBT) of the same arm are complementary and generated by the PWM command implemented in the following figure 6.

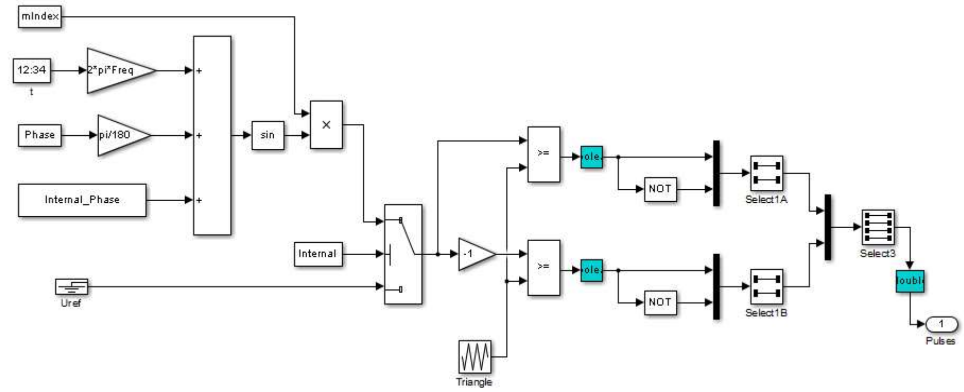

Figure 4: MLI implementation

2.1.4. Modeling of the submersible electrical pump

We represent in Figure 5 below the Simulink model of the single-phase motor coupled to the centrifugal pump. In order to allow the pump to keep an optimal speed, we applied the fuzzy adaptive control by reference model developed in [5].

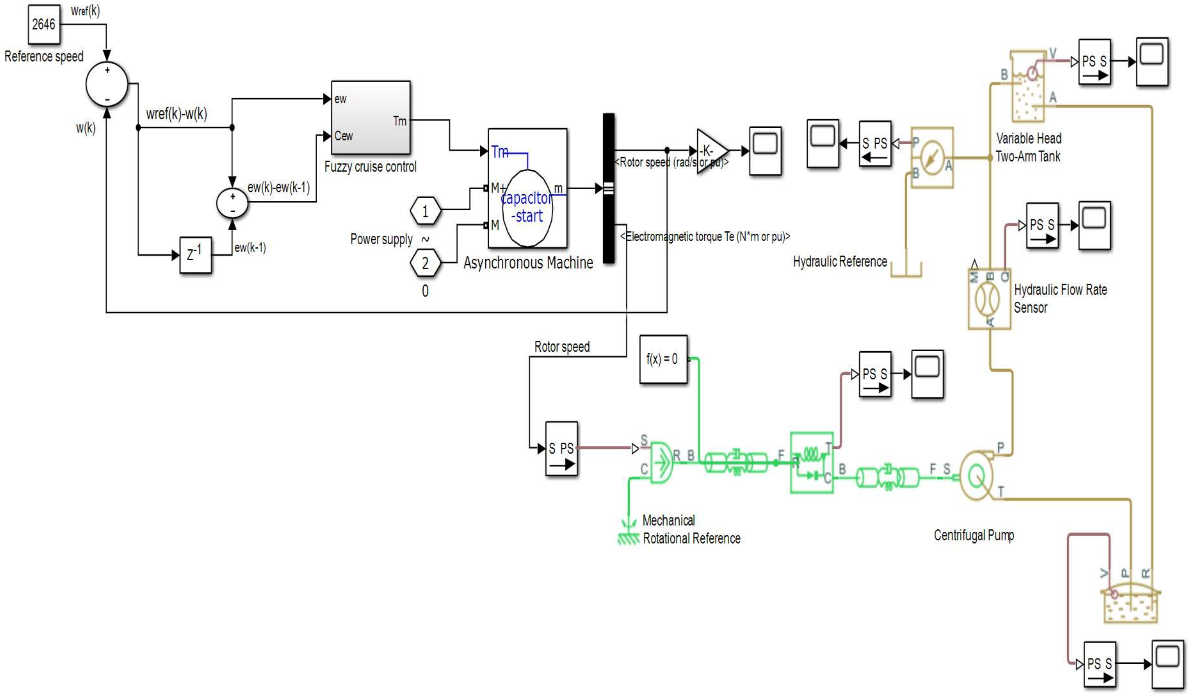

Figure 5: Simulink model of the single-phase motor coupled to the centrifugal pump

2.2. Study of common faults in photovoltaic pumping

2.2.1. Faults in the photovoltaic generator

The efficiency of photovoltaic solar energy production essentially depends on the conditions to which the photovoltaic generator is subjected. These conditions can be environmental or operational linked to the manufacturing process or defect which causes the degradation of the PV generator. These factors are the cause of a large number of faults which cause the degradation of the PV generator. In the following we list some faults that occur at the PV generator. The faults presented in Table 1 have been classified according to the location of their appearance in a PV installation (panel, connection, wiring, protection system). The first column shows the succession of the components considered. The second column gives the nature of the different faults occurring in the stages. And the last column gives the name of each category of defects for the modeling.

Table 1. Fault classification in a photovoltaic generator

PV Generator component	Nature of defects	Defect name
Cells	Torn or broken module Cell heating Degradation of interconnections Crack Corrosion of inter-cell bonds Modules with different performances Cell damage Moisture penetration	Mismatch and shading faults
Cell Grups	Diode destruction No diodes Reverse diode polarity Diode not properly connected Diode short-circuited	Diode fault Bypass
Module	Short-circuited modules Module polarity reversed Shunted modules	Module fault
Strings	Electrical circuit failure Link destruction Corrosion of connections Contact corrosion Electrical circuit short circuit Module disconnected	Connector fault
PV Generator	Diode destruction No diodes Reverse diode polarity Diode not properly connected Diode short-circuited	Non-return diode fault

2.2.2. Mismatch shading faults

The mismatch defect is the defect caused by the grouping of cells having a non-identical I-V characteristic. Any change in any of the parameters of the following equation 6 will lead to the dissimilarity of their characteristic.

$$I_{pv} = I_{ph} - I_S[\exp\left(\frac{V_{pv} + R_S I_{pv}}{nV_t}\right) - 1] - \frac{V_{pv} - R_S I_{pv}}{R_P} \tag{6}$$

The shading defect is a particular case of the mismatch defect because its presence leads to a reduction in the sunlight received by cells. The change in these parameters comes from two main factors. First, cells could have different physical properties as a result of tolerance in manufacturing. Only the module power tolerance is given by the cell or module manufacturers. It can vary between ±3% and ±5% depending on the manufacturers [6]. Secondly, PV cells may be exposed to different operating conditions caused by different faults, including the faults mentioned in Table 1. Qualitatively, the cell parameters affected by these faults can be identified (see table 2 bellow).

Table 2. Impact of various faults on cell parameters

Nature of defects	Affected parameters
Torn or broken module Shading: tree leaves, droppings, sand, pollution, etc.	Change in I_{ph}
Cell heating	Variation in T
Degradation of interconnections Crack Corrosion of inter-cell bonds	Change in R_s
Modules with different performances Cell damage Moisture penetration	Variation of all cell parameters

The impact of these defects is difficult, if not impossible to quantify. In our modeling study, we want to examine the behavior of a PV generator for any possible variation in these parameters. According to Table.2, the mismatch and shading defect can be modeled by the variation of the different parameters of the cell. Due to the disparity of cell parameters in a PV generator, the relationships in equation (6) can no longer be used. When connecting components in series, the voltage produced by each component is no longer equal for the same current. And when connecting components in parallel, the current supplied by each component is no longer identical for the same voltage. In the case of a group of cells, the sum of the voltage of all cells can be negative. This comes from the fact that one or more cells in the group produce a negative voltage when a current greater than their short-circuit current passes through them. It is in this situation that the bypass diode plays its role by becoming conducting.

2.2.3. Degradation on interconnexion

This type of defect can originate from a crack in the PV module, allowing the infiltration of humidity which promotes corrosion of the connecting ribbons between the cells. Corrosion attacks the metal connections of the PV module cells causing an increase in leakage currents and thus a loss of performance. The characteristic parameter which is mainly affected in this type of fault is the series resistance RS. In order to see the influence of the variation of the series resistance on the current-voltage characteristic of the photovoltaic module, we vary the resistance RS of equation 6. The results obtained during the four simulations are illustrated in Figure 7.

2.2.4. Heating of photovoltaic cells

Raising the temperature of PV cells is a problem because their performance decreases when they heat up [7, 8]. This problem is even more severe with the concentration of solar radiation. The conditions of use, far from standard conditions, are major factors in the final energy efficiency of the device over its entire lifespan.

2.2.5. Common faults in photovoltaic static converter

As mentioned above, the role of the converter group is to extract the maximum power from the generator and convert it into alternating power capable of starting the pump motor. The various frequent faults in the converter group (chopper-inverter) are grouped in the following table 3.

Table 3: Frequent faults in the static converter group.

Location	Nature of defect
Chopper boost	Switch short-circuit (IGBT)
	Open circuit switch (IGBT)
	Defective output capacitor
Inverter	Inverter arm switch short-circuited
	Open circuit of the switch on one of the inverter arms
	Control capacitor defective

During a given moment of system operation, a short circuit is caused across the boost converter IGBT switch. This short circuit is created by placing a branch wire across the terminals of the switch which controls the boost converter. During a short circuit of the converter control switch, its main role which is to raise and stabilize the voltage from the photovoltaic generator is eliminated.

2.2.6. Faults in the motor/submersible pump assembly

The submersible motor-pump group, generally called an electric pump, is the most important element in the photovoltaic pumping system. Although several types of solar pumps have been manufactured and put into service, and their technical viability has been proven, this technology is not immune to performance losses mainly due to intrinsic faults and breakdowns. Submerged electric pumps are generally centrifugal multistage hydraulics installed below the water level, driven in most cases by electric motors, forming in a borehole, an assembly suspended by the discharge valve from the dewatering column. Using the repair manuals for different types of electric pumps, we have grouped the breakdowns, possible causes and maintenance strategies in the following table [9, 10].

Table 3. Frequent failures in electric pumps

Failure	Possible causes	Maintenance solution
Pump won't start	-No power supply (total shade) -Open circuit or poor connection of wiring assembly -Clogged wheel	-Check the solar panel and converters (chopper and inverter) -Check cable or wiring for open circuit -Inspect pump and remove obstruction
The pump starts but stops immediately, activating the motor protection device	-Blocked wheel -Voltage drop -A 50 Hz model operates at 60 Hz -The strainer is clogged and the pump has been running dry for a long time -Abnormal motor operation -Pump removes too much sediment	-Inspect pump and remove obstruction -Adjust voltage to rated voltage or use a standard extension cord -Consult nameplate and replace pump or impeller -Remove obstruction -Repair the motor or replace it with a new one -Place a concrete block under the pump to prevent it from picking up sediment
Pump head and pumping volume decrease	The wheel is worn	Replace
Pump head and pumping volume decrease	-Pipe kinked or blocked -Clogged or buried strainer -The motor turns in the opposite direction	-Minimize the number of kinks in the pipe -Removing obstructions -Reverse the wires on the power supply terminals
Pump is noisy or vibrating	-The motor bearing may be damaged	Replace bearing

Apart from breakdowns external to the electric pump, it can also occur those which are intrinsic to the pump motor such as: single-phase and two-phase outages which affect the stator part.

3. Results and discussion

3.1. Influences of mismatch and shading faults on the current-voltage characteristic of the GPV

The figure 6 below illustrates the behavior of the current-voltage characteristic of the PV module in normal and faulty states. The four curves correspond respectively to the I-V characteristic of the PV module for:

- ✓ fault-free operation (36 PV cells);
- ✓ short-circuited bypass diode operation;
- ✓ operation at 50% shading (18 cells);
- ✓ operation at 75% shading (9 PV cells)

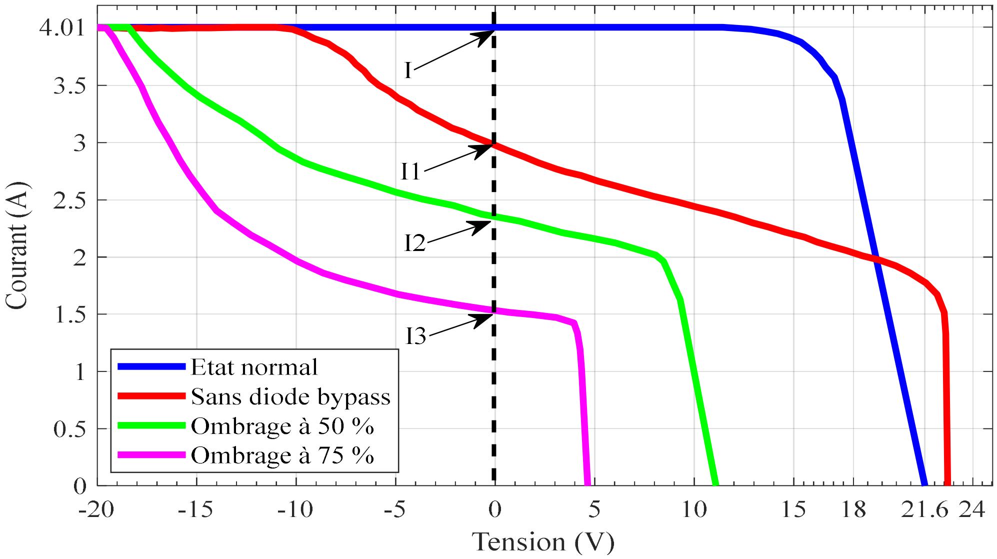

Figure 6: Characteristics under mismatch and shading faults

We can see that the different I-V characteristics of the photovoltaic module operating with faults deviate enormously from that which operates normally. The close analysis of these curves allows a comparative study of the intensities of the short-circuit currents for a zero open-circuit voltage: I > I1 > I2 > I3.

The recommended short-circuit current intensity is not reached when the module exhibits "mismatch" or shading faults. The performance of the PV module is very low when it fails. Looking at the open-circuit voltages obtained under the different types of faults, we come to the conclusion that the voltage is lower the greater the number of shaded cells. We note that during a short circuit of the bypass diode, the open circuit voltage obtained exceeds the limit value (VOC = 21.6 V) recommended by the manufacturer of the PV module. According to studies by Alonso-Garcia and Ruiz in 2006, when the voltage across the PV module is caused to exceed its open circuit voltage, a reverse current flows in the PV module. This irreparably leads to damage to all the PV cells and consequently to damage to the entire photovoltaic module [11]. Therefore, it is very dangerous for a photovoltaic generator to operate with its bypass diode short-circuited and it is also not recommended to let it operate with a shaded cell.

3.2 Influence of interconnect degradation on the GPV current-voltage characteristic

In the case of a fault which causes the dispersion of the series resistance, we see that the voltage loss for a given current is greater as the resistance increases. For a given limit, the voltage loss can be large enough to then make the group voltage negative and cause the bypass diode to switch to passing mode. Following an experimental study, [12] concluded that increasing the resistance value by around 0.90 Ω leads to a power loss of approximately 10W [12]. The results obtained support this conclusion because the coordinates of the maximum power point (PPM) of the I-V characteristic decrease when the resistance value increases.

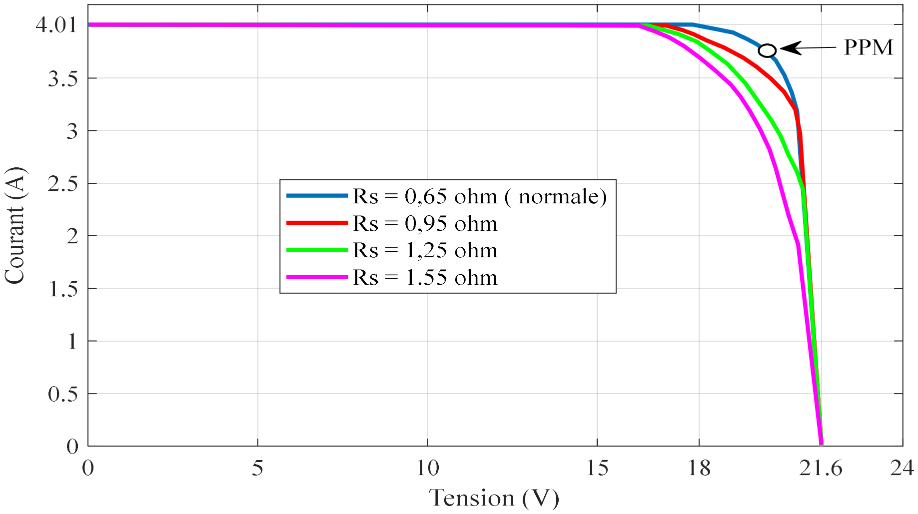

Figure 7: Characteristics in the event of a failure that causes series resistance to disperse

3.3 Influence of cell heating on the GPV current-voltage characteristic

We observe a drop in voltage as the cell temperature increases. Which proves that the increase in cell temperature hampers the performance of the PV module. It is important to note that there are dozens of forms of equations describing the temperature degradation of the performance of a PV cell, but the form generally used is that proposed by Evans [8]. The investigators agree that the abnormal rise in cell temperature promotes the aging mechanisms of solar panels, but they do not analyze the origin of the heating that they observe.

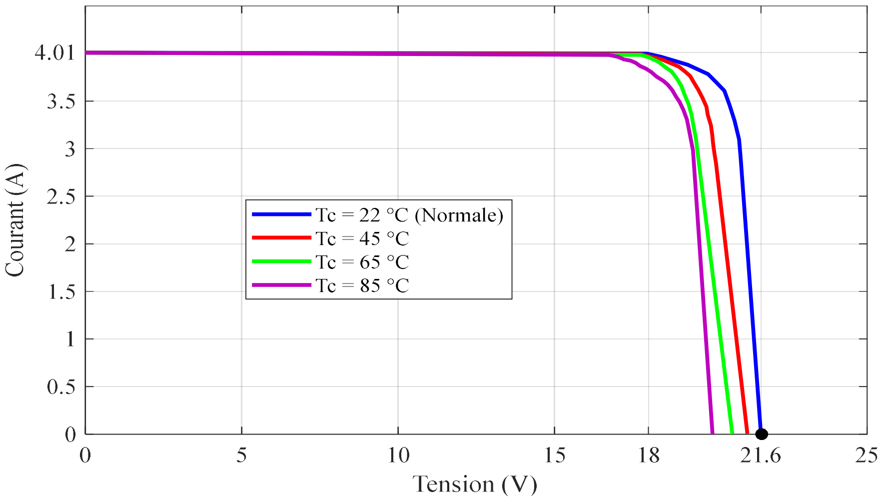

Figure 8: I-V characteristic as the internal temperature of the photovoltaic cell rises

3.4 Influence of the static converter switch short-circuit on the converted voltage

We observe that when a short circuit of the switch occurs, the voltage drops quickly, becoming unstable again. We come to the conclusion that the short circuit of the switch severely influences the voltage converted by the chopper. The problems linked to inverter failures are most of the time due to the inverter itself which is mainly composed of poorly maintained or poorly exposed electronic elements which can create failures and cause the inverter to fail [13]. Overvoltage can, for example, damage electronic components. Failures in the inverter can occur at any time during the operation of the system, so it is important to install a fault monitoring device to ensure its proper operation.

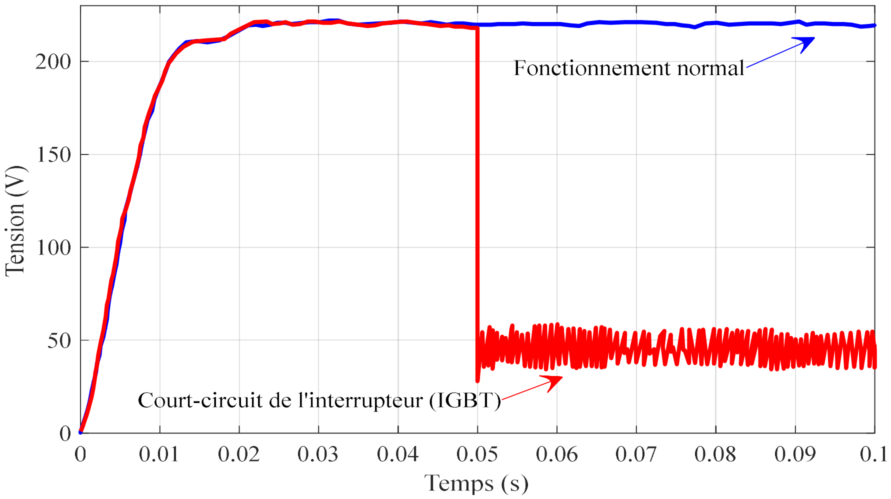

Figure 9: Behavior of the converted voltage when the switch is short-circuited

3.5. Influence of inverter control switch short-circuit on converted voltage

Figure 10 shows the behavior of the voltage at the output of the single-phase inverter in the case of normal operation (a) and during a short circuit of one of these control switches (b). We observe in Figure 10-b that the short circuit of an inverter switch results in the instantaneous loss of the wave behavior of the voltage. The inverter no longer performs its role which is to transform the direct voltage into alternating voltage. It is therefore predictable that the motor-pump unit will stop functioning in this type of fault.

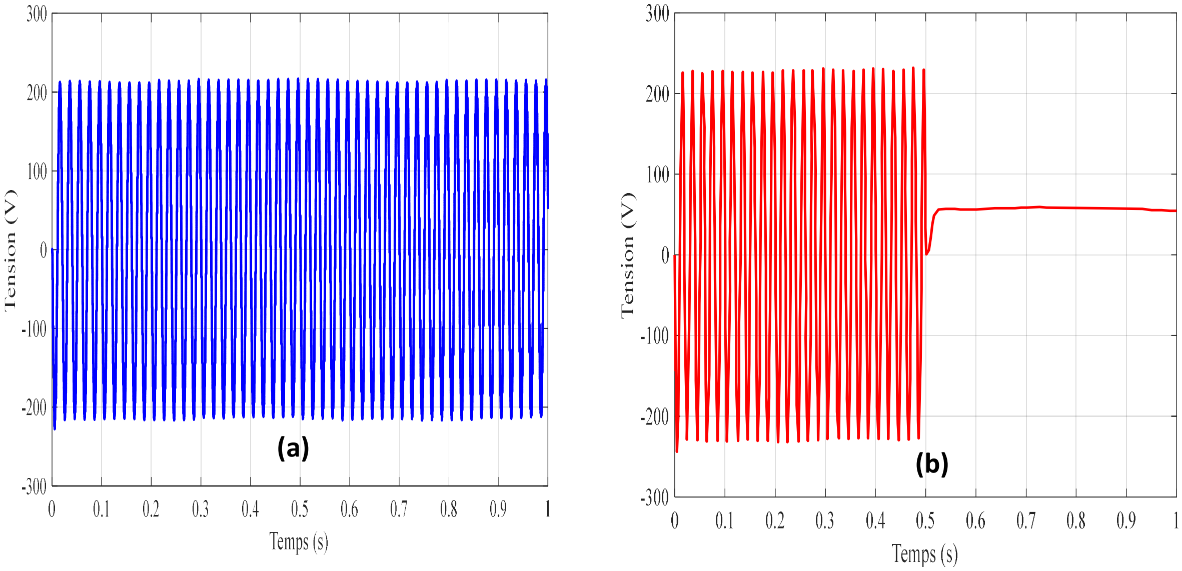

Figure 10: Inverter behavior in normal state (a) and when the control switch is short-circuited (b)

3.5. Conclusion

In this article, the aim was to show the influence of recurring faults on photovoltaic pumping systems in order to establish a database of faults that could be used for preventive maintenance. With anomalies that quickly turn into failures, we have seen that photovoltaic pumping systems, just like complex industrial systems, can suffer from multiple defects that can come from the manufacturing of its own constituent elements, its operating environment or its own terms of service. The complete photovoltaic pumping system, operating over the sun, was simulated and a comparative study between the system in normal state and the system in faulty states allowed us to analyze the impacts of each anomaly on the operating characteristics of the system. It will be interesting to propose a strategy for automatic diagnosis of anomalies in production systems.

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