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The Influence of MPPT Algorithms in the Lifespan of the Capacitor Across the PV Array

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ABSTRACT PV systems efficiency highly depends on the MPPT strategy to be implemented in the PV converter. Many MPPT methods on the literature are focused on improving the steady state and transient system performance extracting the maximum energy from the sun. In this paper, the impact of the MPPT methods in the PV converter is analyzed focusing the study on the capacitor across the PV array lifespan. The obtained results demonstrate that the low frequency PV voltage oscillations that are present in many MPPT methods have a large negative impact on this capacitor lifespan. Experimental and simulation results are presented in order to show that advanced MPPT methods, which avoid these low frequency oscillations, achieve higher capacitor lifespan values compared with the values obtained by applying well-known MPPT methods such as the perturb and observe or incremental conductance strategies.

INDEX TERMS Harmonic analysis, pulse width modulation, motor drives.

I. INTRODUCTION

In the last decades, power demand is constantly increasing in most modern societies. In this electrification process, the power conversion systems, and particularly power electronics, are playing a key role [1]–[3]. Among the energy sources, renewable energy sources such as hydroelectric, wind energy conversion systems or photo-voltaic systems (PV), are the most attractive in terms of taking care of the environment [4], [5]. In particular, PV energy has become one of the most promising alternatives due to its massive availability as well as its easy installation, fast deployment and cost reduction in the last decades [5]–[7]. It can be affirmed that the grid-connected PV systems will play a main role to solve the future energy requirements.

Depending on the power level of the PV installation, the optimal implementation of the PV power system is different [5]. For instance, in high-power PV facilities the most common solution is to use three-phase two-level inverters to connect the solar arrays directly to the grid through a low frequency transformer. In other cases such as industrial, residential, or low-power applications (power level lower than 200 kW), the mainstream solution is to use a two-stage power conversion system. Usually, it is composed of a dc-dc power converter to step-up the PV voltage plus an inverter to perform the grid connection [8]–[10]. A generalized PV power system based on two power converter stages (dc-dc and dc-ac) is shown in Fig. 1, where the most conventional control methods for each stage are also represented.

The technical literature presents multiple control strategies to connect an inverter to the grid [11]–[14]. Among them, the PI-based on the synchronous *dq* frame shown in Fig. 1 is widely adopted by the industry. This control scheme performs the power converter grid-connection allowing unity power factor with minimum grid currents harmonic distortion. On the other hand, the optimal operation of the PV string is achieved by the maximum power point tracking (MPPT) algorithm which targets to obtain the maximum power from the instantaneous ambient conditions (solar radiation and temperature). In a PV system with two power stages (as shown in Fig. 1), the MPPT algorithm is executed by the dc-dc power converter. However, in high-power PV systems,

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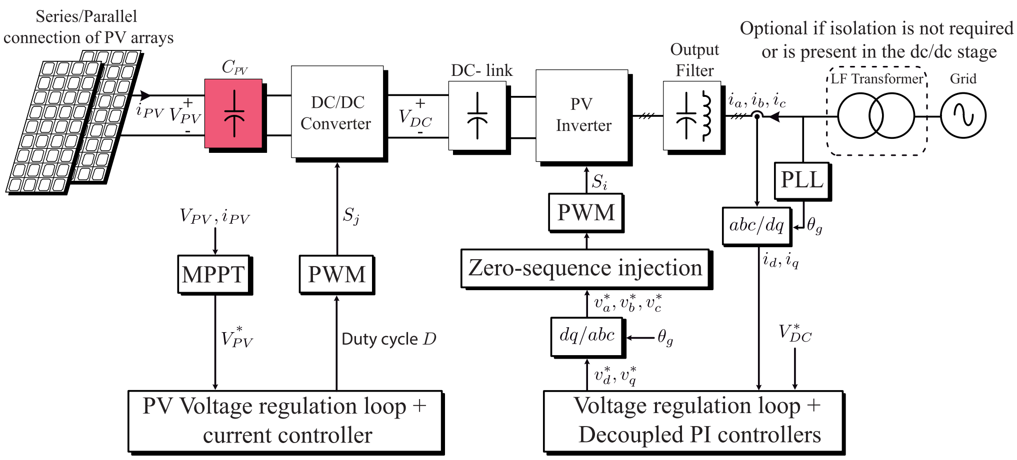

FIGURE 1. Generalized PV system with two power converter stages (dc-dc and dc-ac).

the dc-dc stage is usually avoided and the MPPT is implemented in the central PV inverter (leading to the development of global MPPT methods).

The catalog of MPPT algorithms is very wide. Among the MPPT strategies that are available in the technical literature, the perturb and observe (P&O) and the incremental conductance (INC) techniques are the most successful solutions implemented in the industry [15], [16]. However, many other options can be found such as those based on neural networks, fuzzy logic, or other more complex strategies in order to optimize the MPPT performance [17], [18]. The objective of this paper is to analyze the impact of the MPPT execution on the expected lifespan of the most critical power component of the PV power electronic converter, that is, the power capacitor that is connected in parallel with the PV arrays (called C_{PV} and highlighted in red in Fig. 1).

It is important to note that the calculations to estimate this impact have been done just considering the steady state performance of the MPPT methods, but this does not represent a limitation of the obtained conclusions. It can be affirmed that PV systems are normally operating in steady state because of the extremely slow dynamic behavior of the weather conditions compared with the execution period of the MPPT method.

It is also important to highlight that the PV capacitor lifetime depends on two different factors. In one hand, it depends on the capacitor equivalent series resistance (ESR) value, and the low frequency capacitor current oscillations provoked by the MPPT method being executed each T_{mppt}. On the other hand, the capacitor lifetime degradation also depends on the high frequency current ripple provoked by the operation of the power converter at f_{sw} that is directly related by the PV converter topology. In any case, the PV converter topology, including the capacitor bank technology, is mainly defined by the nominal power of the system, regulations to be fulfilled, efficiency, weight, size and cost. Once the converter topology is defined, a useful method to improve the capacitor C_{PV} lifetime is to look for the most suitable MPPT method, which is the focus of this work.

In section II, a brief summary of the P&O and INC methods is addressed considering also, for comparison purposes, an advanced MPPT technique based on a binary search (called BNS [19]). Section III highlights the impact of the MPPT algorithms in the capacitor C_{PV} lifespan of the PV system. Finally, in sections IV and V, the experimental validation and the conclusions are shown.

II. IMPLEMENTATION OF SOME MPPT TECHNIQUES

Among the existing MPPT techniques, P&O and INC are the most popular ones being vastly adopted by the industry [15], [16]. This is because of their simplicity, relatively good performance, low computational requirements as well as their easy implementation using an off-the-shelf mid-range micro-controller control platforms. However, in recent years, new MPPT techniques have emerged in order to achieve faster convergence, also avoiding low frequency PV voltage oscillations around the optimal MPPT voltage value. Among these advanced MPPT techniques, for performance comparison purposes, the binary-search MPPT algorithm (BNS) has been included in this section [19].

The P&O technique is the most common method used in the PV industry because of its simplicity. It is important to highlight that the P&O algorithm is constantly perturbing the system, which means that the PV voltage always oscillates around its optimal value [20]–[22].

A good alternative to the P&O strategy is the well-known INC algorithm, since it studies the P-V curve trend in a more sophisticated way, estimating the derivative of the P-V curve in order to find its maximum point. However, as it happens when the P&O method is applied, in practical applications the INC MPPT strategy also presents PV voltage oscillations around its optimal value.

Finally, the application of BNS method in PV systems consists in the modification of the operational region limits to efficiently look for the optimal PV voltage value [19]. In addition to fastly achieve the final value of the PV voltage, the BNS algorithm is prepared to develop a flexible MPPT where the power to be generated can be the maximum available or an specific power value imposed by the PV system operator. It is important to highlight that, at the contrary of the conventional P&O and INC strategies, the BNS method considers a threshold band leads to a steady state performance that avoids the oscillations around the optimal PV voltage in order to look for the required power.

III. IMPACT OF THE MPPT TECHNIQUE OVER THE RELIABILITY OF THE CAPACITOR ACROSS THE PV SYSTEM

Capacitors are key components in power conversion systems [23]. Their capacitance and voltage rating are selected to be minimized in order to reduce the system costs. Additionally, regarding reliability in power converters, capacitors are identified among the most frequent failure case [24]. Among capacitor technologies in manufacturer portfolio for power electronics applications, multi-layer ceramic capacitors, metallized polypropylene film capacitors and aluminum electrolytic capacitors are the most common [23]. In particular, aluminum electrolytic are the cheapest technology, but with reduced reliability. On the contrary, film capacitors are considered the most reliable at the expense of a higher cost [9], [23], [25]. It is important to highlight that in solar PV applications, depending on the nominal power of the facility, the PV array maximum voltage is in the range 50-1500 volts considering applications from domestic to utility-scale systems respectively. Taking into account typical capacitance values of PV systems, that is usually in the mF range, capacitors to be connected in parallel to the PV arrays are aluminum electrolytic capacitors (connected in series and/or parallel to achieve the expected capacitance and voltage ratings) because of their vast capacitance values, high maximum voltage ratings and low cost at the expense of high ESR values.

In any case, the capacitor lifespan intrinsically depends on the rated voltage, the current as well as the temperature of the device T_h. In order to estimate the power capacitor lifetime (L_c), it is usual to model the capacitor as:

$$L_c = L_0 \left(\frac{V}{V_0} \right)^{-n} e^{\left(\frac{E_a}{k_B} \left(T_h^{-1} - T_0^{-1} \right) \right)} \tag{1}$$

where L_0 is the rated lifetime at voltage V_0 and temperature T_0. E_a is the activation energy and k_B is the Boltzmann constant. Additionally, considering electrolytic capacitors, the model can be simplified to:

$$L_c = L_0 \left(\frac{V}{V_0} \right)^{-n} 2^{\frac{T_0 - T_h}{10K}} \tag{2}$$

From (2), it is possible to conclude that increasing the capacitor temperature in $10\,K$, its remaining lifetime is reduced in 50%, which highlights the importance of the hotspot temperature. The hotspot temperature can be modeled as the ambient temperature T_a plus the convolution of the capacitor losses P_d with the thermal impedance Z_{th}. In this sense, in steady state operation, it is necessary to consider the thermal resistance R_{th} as:

$$T_h = R_{th} P_d + T_a = \Delta T_h + T_a \tag{3}$$

In (3), P_d depends on the current through the capacitor as well as the ESR. It has to be noticed that the ESR has higher importance at low frequencies, while the equivalent series inductance (ESL) value affects to the capacitor impedance at higher frequencies (generating EMI and malfunctions in high-frequency applications). In this way, as the MPPT methods are executed at very low frequency (because of the very slow dynamic behavior of the ambient conditions, i.e. temperature and solar radiation), it can be derived that the ESL value does not significantly affect to the influence of the MPPT method on the lifespan of the capacitor C_{PV} that is connected in parallel to the PV array.

Considering the frequency dependence of the ESR, it is possible to use the Fourier representation as:

$$P_d = \sum_{h=0}^{\infty} I_{c,h}^2 R_{ESR,h} \tag{4}$$

where $I_{c,h}$ is the $h-$harmonic of the capacitor current and $R_{ESR,h}$ is the ESR value for the corresponding frequency component. The ESR value depends on the capacitor technology as well as the frequency. For instance, the ESR of electrolytic capacitors is higher for low frequency harmonic content than for high frequency components [26]. The ESR of a capacitor can be separated in three different terms:

$$R_{ESR} = R_{ESR,0} + R_{ESR,f} + R_T^{\frac{T_0 - T_h}{E}} = R_0 + R_T^{\frac{T_0 - T_h}{E}} \tag{5}$$

The first term $R_{ESR,0}$ is constant, the second term $R_{ESR,f}$ depends on the frequency content of the capacitor current and the third term R_T exponentially depends on the hotspot temperature [27]. In this work, the first two terms are represented by R_0.

Taking all these facts into account, it is clear that L_c clearly depends on the power capacitor technology (because of the ESR value) and the way the capacitor is operating (because of its voltage, and mainly the harmonic components of the capacitor current). As the power capacitor voltage and its ESR inherently depend on the power capacitor technology and the specific power application, the capacitor lifetime is closely related to its operation in terms of its current quality. In this way, in a PV system the evaluation of the capacitor C_{PV} current, that directly depends on the MPPT method, will show the direct impact in the capacitor C_{PV} lifetime. This is the focus of the experimental results included in this work.

IV. EXPERIMENTAL RESULTS

The impact of the MPPT algorithms on the capacitor C_{PV} lifespan has been evaluated in the laboratory using a traditional dc-dc scheme based on a boost converter topology, which is shown in Fig. 2a. The PV string has been emulated using the E4360 PV Emulator from Keysight [28]. The E4360 PV emulator has been configured considering the waveforms

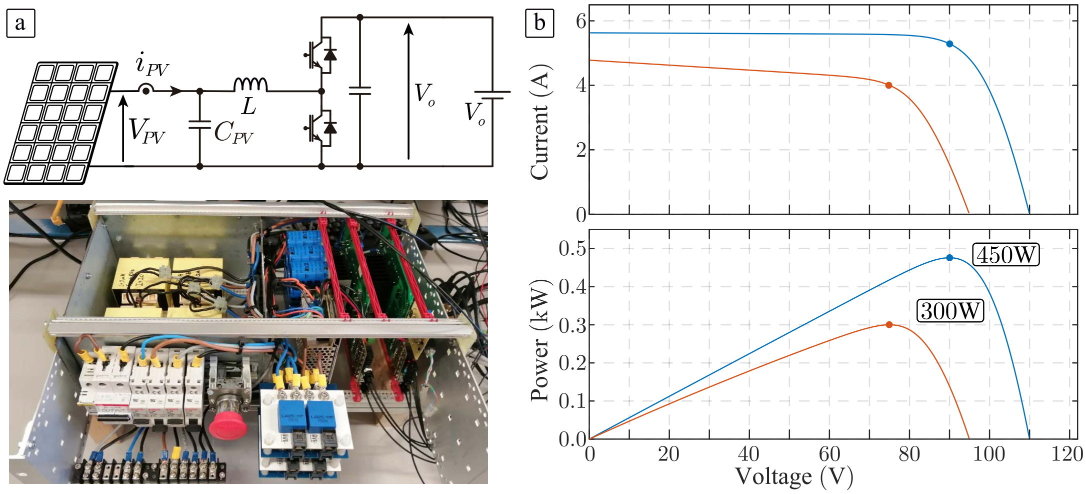

FIGURE 2. **Experimental setup used in the experiments. a) Electrical diagram with the experimental rig used. b) Configuration of the PV emulator.**

TABLE 1. **Parameters of the experimental setup and the MPPT algorithms.**

Description	Value
PV capacitor (C_{PV})	1.2 mF
DC-link capacitor (C)	5.64 mF
Smoothing inductor (L)	3 mH
DC-link voltage (V_o)	160 V
Switching frequency (f_{sw})	4 kHz
Sampling frequency (f_s)	4 kHz

MPPT Configuration			
MPPT period (T_{mppt})		0.5 s	
P&O / INC		BNS	
Parameter	Value	Parameter	Value
voltage step	2 V	th	5 W
-	-	th_{reset}	15 W
-	-	μ	0.1

shown in 2b. The most relevant parameters of the dc-dc prototype are summarized in Table 1.

In order to evaluate the impact of these MPPT methods on the capacitor C_{PV} lifespan taking into account the capacitor current harmonic components, the PV emulator has been configured to operate with two different solar radiation conditions. This fact enables the possibility to evaluate the techniques considering an abrupt change in the weather conditions as well as in the steady state operation. The most relevant parameters for all techniques are listed in Table 1, where it can be observed that the P&O and INC MPPT strategies share the same operation parameters.

The experimental results are represented in Fig. 3. As it can be observed, the experiment consists in an abrupt variation in the solar radiation. In the beginning of the experiment, the PV system is working normally and the MPPT methods are being executed successfully achieving PV voltages around its optimal value (that depends on the solar radiation and the temperature). From this steady state operational point, in $t = 10s$ the solar radiation, and therefore the available PV power, drops abruptly forcing to the MPPT algorithms to look for the new optimal PV voltage value. After some time, in $t = 30s$ the solar radiation is restored to its previous value. As it can be observed in Fig. 3, it is clear that the MPPT strategies performance is good because the final optimal PV voltage value is achieved. It is clear that the BNS method has superior dynamic performance because the optimal PV voltage value is fastly achieved. On the other hand, it can be seen that the application of the BNS strategy leads to have a constant PV voltage while the other methods present PV voltages with low-frequency oscillations. The frequency of these voltage oscillations depends on the frequency of the execution of the MPPT methods (T_{mppt}) that is fixed to 0.5 seconds.

The performance of the MPPT techniques can be evaluated considering the following expression:

$$\eta = \frac{\int_{t_0}^{t_1} p_{pv}(t)dt}{\int_{t_0}^{t_1} p_{av}(t)dt} \cdot 100 \quad (6)$$

where p_{pv} is the power generated by the PV and p_{av} is the available power from the PV string. Thus, as higher is η, the performance of the MPPT method is better.

This figure of merit has been firstly evaluated taking into account the complete experimental results considering the three MPPT methods. It can be seen that η values are similar considering the P&O and INC MPPT techniques. However, the BNS strategy obtains a higher η value equal to 97.52%. If the η factor is evaluated only taking into account the instants where the solar radiation changes, the performance difference among the MPPT methods becomes more evident. The terms η_f and η_r are the values of the η factor but only evaluated in some specific time intervals. η_f is evaluated taking into account the time interval from $t = 10s$ to $t = 15s$, while η_r is evaluated taking into account the time interval

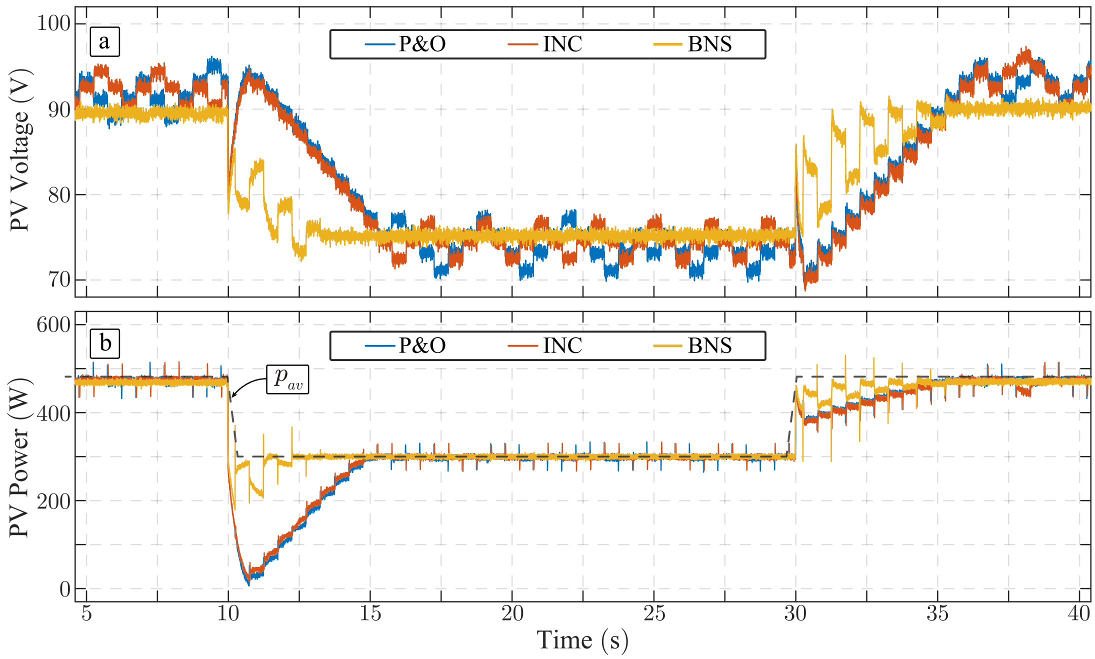

FIGURE 3. Comparison of the MPPT techniques considering an abrupt solar radiation variation a) PV array voltage b) Power extracted from the PV array.

TABLE 2. Performance of the MPPT algorithms considering the η factor as figure of merit.

MPPT technique	η (%)	η_f(%)	η_r(%)
P&O	91.56	51.70	63.31
INC	91.82	54.83	63.02
BNS	97.52	93.54	67.35

from $t = 30\ s$ to $t = 35s$. The obtained values are summarized in Table 2 where it can be observed that the BNS method is superior compared with the other methods. It is very important to highlight that this result is not surprising and it is not the focus of this paper.

The focus of the paper is to evaluate the impact of the MPPT methods in the capacitor C_{PV} lifespan. In this sense, the current that is flowing through this capacitor has been captured and analyzed in the frequency domain. The corresponding current spectra have been represented in Fig. 4 considering the same color palette that was used in Fig. 3. As shown in Fig. 4a and Fig. 4c, both P&O and INC methods present undesirable harmonic components at very low frequency whereas the BNS strategy presents a better quality harmonic spectrum. From the measured capacitor currents and considering the hotspot temperature estimation presented in (3)-(4), the resulting corresponding capacitor temperatures have been estimated considering different R_{th} values.

The most important parameters to carry out this estimation and the obtained results are presented in Table 3. In the table, the resulting C_{PV} hotspot temperatures depending on the MPPT methods are determined by using (3)-(5). With these calculations, and applying (2) it is possible to determine the corresponding capacitor C_{PV} lifetime L_c applying each MPPT method. In order to develop the MPPT method comparison, the result obtained by the P&O algorithm is used to normalize the results obtained by the other MPPT strategies in order to calculate the corresponding capacitor C_{PV} lifespan increment ΔL_c present in MPPT method x (where x can be INC or BNS) as

$$\Delta L_c = \frac{L_{c_x}}{L_{c_{\text{P\&O}}}} \cdot 100 \tag{7}$$

It can be observed that, in all cases depending on R_{th}, P&O and INC present very similar results in terms of the capacitor C_{PV} lifetime L_c. However, because of the superior quality of the capacitor C_{PV} current, the application of the BNS method leads to improve the capacitor lifespan L_c with values from 2% up to 20%.

In order to extend the results for higher power PV installations, not available in our laboratory facilities, multiple scenarios have been simulated. The nominal power in multi-string PV systems is in the range up to $[100-150]k$W whereas the required capacitance C_{PV} to be connected in parallel to the PV array (for an optimal system controllability) is in the range of $[6-15]\ m$F. These data have been taken from the industrial solution PV100 by GPTech [29].

First of all, the impact of the MPPT methods in C_{PV} lifespan has been evaluated considering a 100kW PV array with a capacitance value equal to $C = 10m$F. Several frequencies of MPPT execution have been evaluated in order to check the influence of the T_{mppt} factor in the capacitor C_{PV} lifespan. T_{mppt} equal to 0.5, 1 and 2 and 5 seconds have been evaluated. The obtained results have been summarized in Table 4, where the results of the INC method are not included because, as presented in Table 3, it presents very

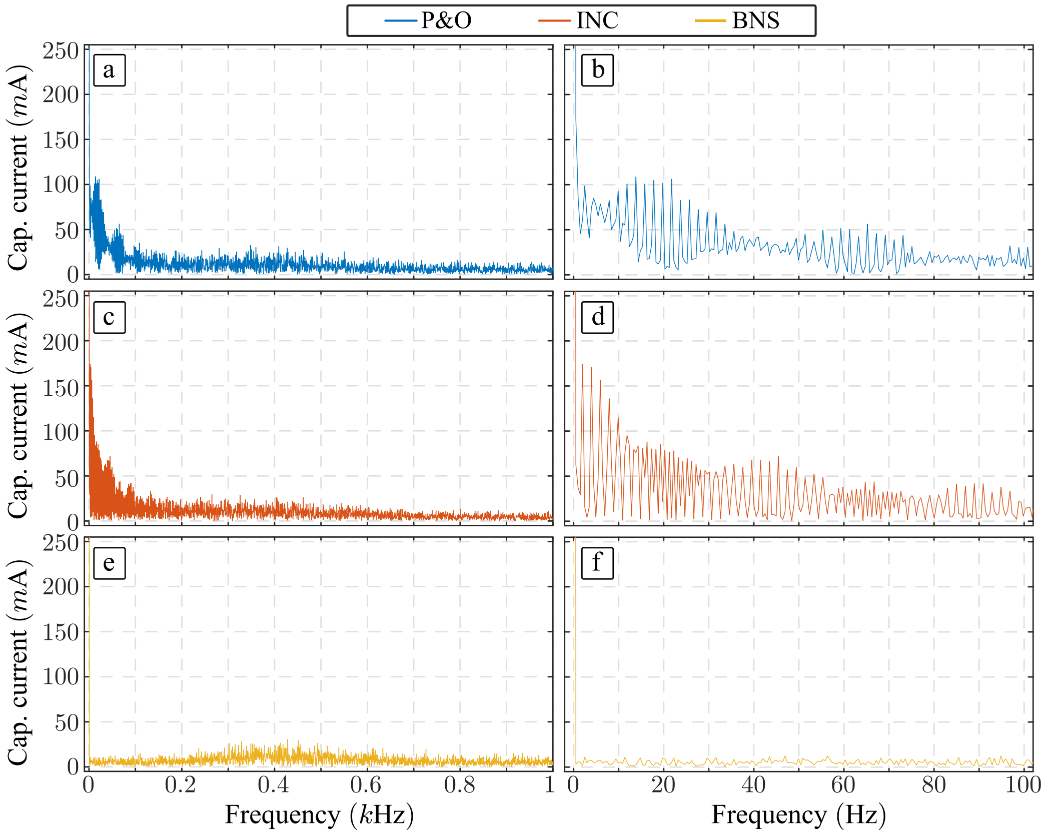

FIGURE 4. a) Capacitor C_{PV} current harmonic spectrum for P&O MPPT b) A low-order harmonic spectrum detail c) Capacitor C_{PV} current harmonic spectrum for INC MPPT d) A low-order harmonic spectrum detail e) Capacitor C_{PV} current harmonic spectrum for BNS MPPT f) A low-order harmonic spectrum detail.

TABLE 3. Evaluation of the impact of the MPPT technique on the capacitor hotspot temperature and the corresponding impact on the capacitor lifetime.

Variable	Value	Variable	Value
$T_0(°C)$	50	$T_a(°C)$	25
$R_{ESR}(50°C)$ (Ω)	0.1	E_a (eV)	20
R_0 (Ω)	$0.7 \cdot R_{ESR}$	R_T (Ω)	$0.3 \cdot R_{ESR}$

R_{th} [K/W]	P&O T_h °C	INC T_h °C	BNS T_h °C	INC ΔL_c [%]	BNS ΔL_c [%]
0.5	25.50	25.51	25.18	-0.01	2.24
1.0	25.99	26.01	25.26	-0.01	4.43
1.5	26.47	26.50	25.54	-0.01	6.61
2.0	26.93	26.98	25.72	-0.01	8.37
2.5	27.38	27.44	25.90	-0.01	10.82
5.0	29.49	29.59	26.75	-0.01	20.91

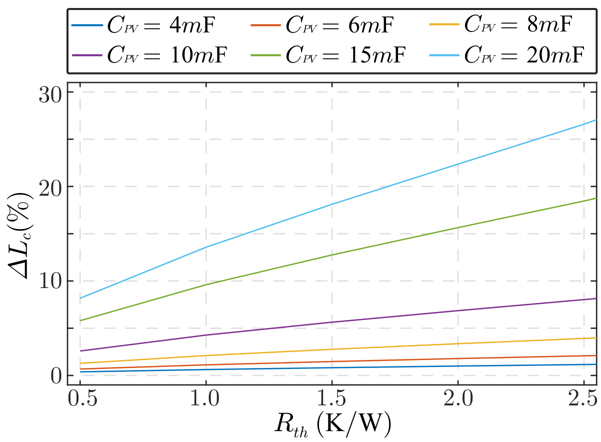

FIGURE 5. Impact of application the BNS method over the capacitor C_{PV} lifetime with different thermal impedance characteristic and capacitance values.

similar results compared with the P&O strategy. From the obtained results, it can be observed that the BNS method again presents a superior performance in terms of extended capacitor C_{PV} lifespan. Also, it can be also observed that the T_{mppt} value does not affect at all the capacitor C_{PV} lifespan because the corresponding very-low order harmonic content in the C_{PV} capacitor C_{PV} current is always present (but at different frequencies) leading to degrade the C_{PV} lifespan in the P&O and INC methods.

The obtained improvement in the capacitor C_{PV} lifespan ΔL_c applying the BNS method compared with the P&O performance considering a 100kW PV array has been evaluated also considering different capacitance values. The results are summarized in Fig. 5, where it can be observed that the benefits obtained by the application of the BNS method in

TABLE 4. Evaluation of the impact of the MPPT technique on the hotspot temperature reduction for different thermal impedances, PV power = 100 kW, C_{PV} = 10mF and T_{mppt} = [0.5, 1, 2, 5]s

R_{th} [K/W]	P&O T_h °C	BNS T_h °C	BNS ΔL_c [%]
0.5	31.84	31.48	2.59
1.0	37.08	36.47	4.27
1.5	41.49	40.70	5.63
2.0	45.43	44.48	6.85
2.5	49.07	47.95	8.03
5.0	64.95	63.06	13.99

terms of increasing the ΔL_c value are more evident with higher values of C.

V. CONCLUSION

MPPT strategies are a key part of PV systems seeking to obtain the maximum power taking into account the current weather conditions (solar radiation and temperature). These MPPT methods are normally evaluated considering the transient and steady state responses of the PV system but their influence on the PV system reliability is not usually explored. In this work, the influence of the MPPT methods on the capacitor C_{PV} that is connected in parallel to the PV array, that is one of the most critical components of the PV system in terms of reliability, is addressed. In this paper simulation and experimental results show that the low frequency voltage oscillations present in this capacitor, typical in MPPT methods such as the P&O and INC, provoke the presence of low-order harmonic components in the current that flows through the capacitor C_{PV}. This fact leads to a non negligible capacitor degradation reducing the overall PV system reliability. In this way, from the obtained results, the application of an advanced MPPT method where the oscillations around the optimal maximum power PV voltage becomes fundamental.

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