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Reliability-Oriented Design and Analysis of Input Capacitors in Single-Phase Transformer-less Photovoltaic Inverters

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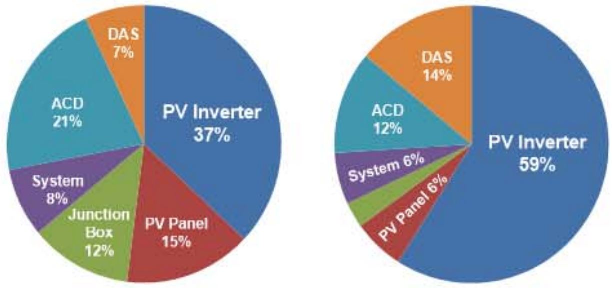
***Abstract*- While 99% efficiency has been reported, the target of 20 years of service time imposes new challenge to cost-effective solutions for grid-connected photovoltaic (PV) inverters. Aluminum electrolytic capacitors are the weak-link in terms of reliability and lifetime in single-phase PV systems. A reliability-oriented design guideline is proposed in this paper for the input capacitors in single-phase transformer-less PV inverters. The guideline ensures that the service time requirement is to be accomplished under different power levels and ambient temperature profiles. The theoretical analysis has been demonstrated by a 1 kW single-phase PV inverter.**

I. INTRODUCTION

The development of single-phase photovoltaic (PV) systems connected to the public grid has been booming progressively in recent years due to the matured PV technology and the declined price of PV panels [1]-[3]. However, the interaction between PV systems and the grid also introduces some negative impact on the public network, which makes the grid much more uncontrollable and heterogeneous. Such concerns like power quality, efficiency and emerging reliability are becoming of high interest. Associated with appropriate control methods, single-stage transformer-less inverters are adopted especially in European countries in order to obtain higher efficiency. The future PV systems are expected to have ancillary functions (e.g., low voltage ride through (LVRT) under grid faults) and to be more reliable. PV inverters are becoming one of the most critical subsystems in terms of failure rate, lifetime and maintenance cost. Leading manufacturers nowadays could provide PV modules with over 20 years of warranty. However, the number is around 5 years for PV inverters on average in 2012 [4]. Therefore, even though inverters account only for 10%-20% of the initial system cost, they may need to be replaced 3-5 times over the life of a PV system, introducing additional investment [5]. According to the 5 years of field experience in a large utility-scale PV generation plant studied in [6] and represented in Fig. 1, the PV inverters are responsible for 37% of the unscheduled maintenance and 59% of the associated cost.



(a) Unscheduled maintenance events by subsystem. (b) Unscheduled maintenance costs by subsystem.

Figure 1. 5 years of field experience of a 3.5 MW PV plant [6].

Aluminum electrolytic capacitors are widely utilized as power decoupling devices in the single-phase single-stage PV inverters because of their high volumetric efficiency and low cost. However, they are the lifetime limiting and power lossy components inside the PV inverters as discussed in [7] due to their wear out behavior and high equivalent-series-resistance (ESR). Reliability aspect design or estimation methods for PV inverters have been discussed in [8]-[12]. However, specific design guidelines for the dc-link capacitors are not given. Moreover, the reliability assessments of the PV inverters in [8]-[12] are based on mean-time-to-failure (MTTF) and mean-time-between-failures (MTBF), which represent the time when 63.2% of items would fail and are not equivalent to lifetime. The obtained MTTF or MTBF values are prone to have high degree of inaccuracy as they are based on the assumptions of constant failure rate and no wear out occurs within the time period [13]. The practical design methodology for capacitors and capacitor banks used in power converters is well presented in [14] and [15], respectively. The application limitation is that the proposed optimization does not consider the reliability performance of the capacitors and their combinations.

The scope of this paper is first to propose a reliability-oriented design guideline for the input capacitors used in single-phase transformer-less PV inverters. Then the step-by-step implementation is discussed. Finally, a 1 kW PV inverter design case is demonstrated. Optimal input capacitors are selected and 20 years of lifetime is expected to be achieved under various operation modes and ambient temperatures.

II. Proposed Reliability-Oriented Design Guideline

Fig. 2(a) presents a simplified structure of a single phase transformer-less PV inverter. The input power of the PV inverter can be assumed constant in the time scale of grid frequency period. Accordingly, Fig. 2(b) shows the instantaneous power balancing function of the input capacitor *C*. It is known that capacitors cause large portion of failures in power electronic systems (e.g., 30% as statistics shown in [16]). From this perspective, reliability performance of the input capacitors is essentially to be considered in the initial design phase rather than waiting until the test-to-pass qualification phase.

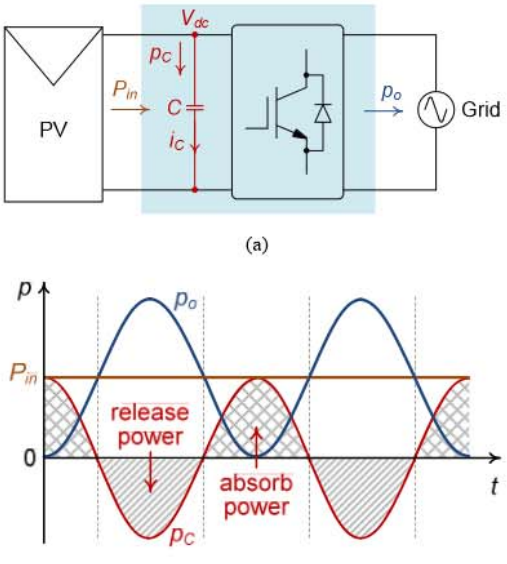


Figure 2. Single-phase grid-connected PV inverter: (a) Simplified structure and (b) Instantaneous power flow.

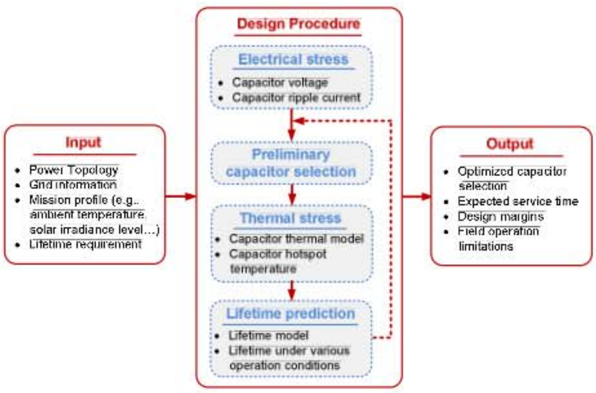


Figure 3. Proposed reliability-oriented design guideline for selection of capacitors in PV inverters.

Therefore, a reliability-oriented design guideline for the input capacitors is proposed and described in Fig. 3. The conventional design methods as discussed in [14]-[15] are treated for a preliminary selection of the capacitors. Then the thermal stresses of those capacitors are estimated based on their specific thermal models. The lifetime of the selected capacitors is therefore can be estimated based on the mission profile, operation mode and specific lifetime model. Finally, optimal selection of the capacitors can be performed by comparing different options.

III. Implementation of the Proposed Design Guideline

According to the reliability-oriented selection method shown in Fig. 3, the following steps can be followed to implement the proposed design guideline:

Step 1 - Calculation of the electrical stress of the input capacitor shown in Fig. 2(a).

$$V_{dc} = V_{PV,\max} \quad \text{and} \quad \Delta V_{dc} = \frac{P_o}{\omega C V_{dc}} \tag{1}$$

$$i_{C,\mathrm{RMS}} = \frac{P_o}{\sqrt{2} V_{dc}} \tag{2}$$

where P_o is the average power supplied to the grid, ω is the angular frequency of the grid, ΔV_{dc} is the peak-to-peak ripple of the input capacitor voltage V_{dc}, $V_{PV,\max}$ is the maximum output voltage of the PV panel and $i_{C,\mathrm{RMS}}$ is the root-mean-square (RMS) current flowing through the input capacitor.

Step 2 - Preliminary capacitor selection according to the voltage stress, minimum required capacitance derived from (1) and the ripple current value shown in (2).

Step 3 - Thermal stress calculation based on the model of aluminum capacitors shown in Fig. 4. Fig. 4 presents a simplified model of aluminum electrolytic capacitors in both electrical and thermal domains. R_{th} is the equivalent thermal resistance between ambient and hotspot. The parameters ESR and R_{th} can be obtained from simulation, measurement or datasheet from manufacturers. The hotspot temperature T_h can then be estimated, which is a kind of important stressor that induces the degradation of capacitors.

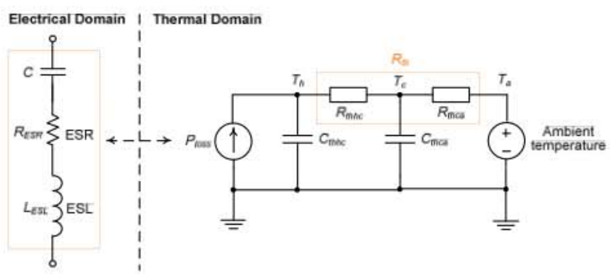


Figure 4. Models of aluminum electrolytic capacitors in electrical and thermal domains.

TABLE I. THREE KINDS OF SELECTED CAPACITORS FROM DIFFERENT MANUFACTURES.

Case No.	Capacitor Bank	Rated Lifetime (85°C)	ESR at 100 Hz (mΩ) 25 °C	45 °C	65 °C	85 °C	Natural Cooling Thermal Resistance R_{th} (°C/W)
1	Four 350 V/470 μF /1.9A	1000 hours	440	308	264	264	15.62
2	Two 315 V/1000 μF /3.63A	2000 hours	207	145	124	124	15.19
3	Two 350 V/1000 μF/ 5.5A	24000 hours	85	50.3	38	32.5	3.6

Lifetime models (Unit: k hour)

Case 1: $L_{op}=\left(4.3-3.3\frac{V_{op}}{V_{rated}}\right)\times 1\times 2^{\frac{T_{max}-T_h}{10}}$; Case 2: $L_{op}=\left(4.3-3.3\frac{V_{op}}{V_{rated}}\right)\times 2\times 2^{\frac{T_{max}-T_h}{10}}$; Case 3: $L_{op}=24\times 2^{\frac{85-T_h}{10}}$

Step 4 - Lifetime prediction for the preliminarily selected capacitors. Physics-of-failure based lifetime models are necessary to predict the lifetime of capacitors under different operation conditions. According to the derivations in [17],

$$AF=\frac{L_{op}}{L_{rated}}=\begin{cases}\left(\frac{V_{rated}}{V_{op}}\right)e^{-\left(\frac{E_a}{K_B}\right)\left(\frac{1}{T_{rated}}-\frac{1}{T_{op}}\right)} & \text{(low voltage stress)}\\ \left(\frac{V_{rated}}{V_{op}}\right)^{n}e^{-\left(\frac{E_a}{K_B}\right)\left(\frac{1}{T_{rated}}-\frac{1}{T_{op}}\right)} & \text{(medium voltage stress)}\\ e^{a_1(V_{rated}-V_{op})}e^{\left(\frac{E_{a0}-a_0V_{op}}{K_BT_{op}}-\frac{E_{a0}-a_0V_{rated}}{K_BT_{rated}}\right)} & \text{(high voltage stress)}\end{cases} \quad (3)$$

where AF is the acceleration factor between lifetime under operation temperature and lifetime under rated temperature. E_a is the activation energy, K_B is Boltzmann's constant (8.62×10^{-5} eV/K), V_{rated} and V_{op} are the rated voltage and operational voltage of the analyzed capacitor, respectively. Both the voltage stress and temperature stress dependency of E_a is presented by the two parameters a_0 and a_1. Parameters in the models can be estimated based on the testing data from manufactures.

IV. DEMONSTRATION OF THE PROPOSED DESIGN GUIDELINE

The proposed design guideline is applied on a 1 kW single-stage transformer-less PV inverter. Its nominal input voltage is 400 V with maximum voltage ripple of 5% and the maximum input voltage is 600 V. The calculated minimum required capacitance is 398 μF and ripple current stress is 1.8 A. Three preliminary options are shown in Table I. The rated lifetime values, ESR values, thermal resistances and lifetime models are obtained from datasheets of the manufacturers. It should be mentioned that the specific lifetime model is derived based on testing data by the manufacturers, which is in one of the forms shown in (3). To estimate the hotspot temperatures, the power losses of capacitors caused by ESR are obtained first. The value of ESR is updated according to the hotspot temperature under different operation conditions.

Fig. 5 compares the power loss, hotspot temperature, lifetime prediction with 1 kW output power and power de-rating curve to fulfill the lifetime requirement.

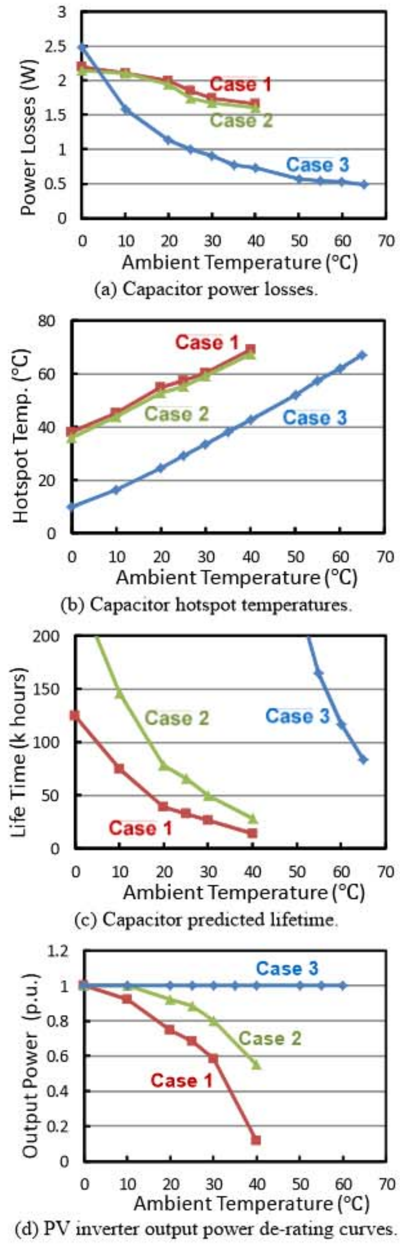


Figure 5. Simulation results of different capacitors under various ambient temperatures ((a)-(c) are with 1 kW output power and (d) is with minimum lifetime of 20 years).

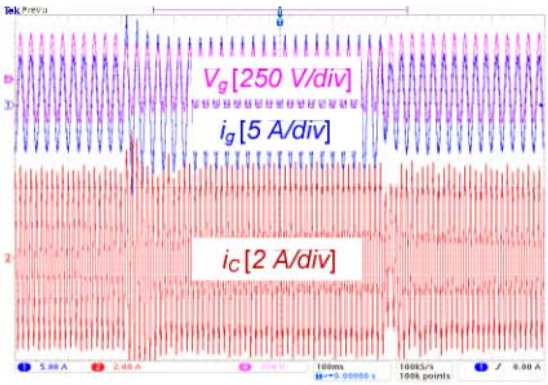


Figure 6. Experimental waveforms of capacitor current, grid voltage and grid current under grid faulty mode operation and without LVRT.

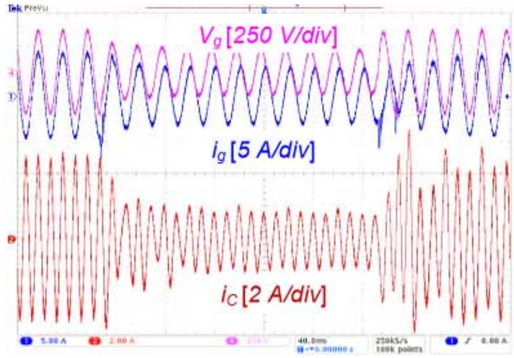


Figure 7. Experimental waveforms of capacitor current, grid voltage and grid current under grid faulty mode operation and with LVRT.

If 100k hours of lifetime (equivalent to 20 years of operation with 12 hours/day and a design margin of 12.4%) is required, it can be noted from Fig. 5 (c) and Fig. 5 (d) that only the *Case* 3 can fulfill the requirement in a wide ambient temperature range. The selection of *Case* 2 can only have 20 years of lifetime when the ambient temperature is below 20 °C. Therefore, the proposed method allows the optimal selection of the input capacitors in terms of both electrical and reliability performance.

According to Fig. 5(d), for applications when de-rating of the output power is allowed, the required 100k hours of lifetime could still be fulfilled for selection of *Case* 1 and *Case* 2 by load management according to the de-rating curves.

Since the future PV inverters are expected to have LVRT capability, the system is also tested under grid faults and the results are shown in Fig. 6 and Fig. 7. As shown in Fig. 7, by injecting reactive power and limiting the active power, LVRT allows reduction of the capacitor ripple current stress, therefore, power loss and temperature rise, compared to that without it, which prevents the capacitor from overheating and enhances its reliability.

CONCLUSIONS

A reliability-oriented design method is proposed and implemented for single-phase transformer-less PV inverters. The lifetime analysis for different options of the capacitor bank under various ambient temperatures and operation modes is performed for a 1 kW prototype. It allows the optimal selection of the input capacitors in terms of both electrical and reliability performance. 20 years of lifetime of the capacitors is expected to be achieved with reasonable robustness margin. Besides the selection of capacitors, output power de-rating and LVRT control under grid faults could reduce the current stresses of capacitors and therefore improve their reliability.

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