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# System-level Reliability Enhancement of DC/DC Stage in a Single-Phase PV Inverter

Saeed Peyghami, Pooya Davari, Huai Wang, and Frede Blaabjerg  
sap@et.aau.dk, pda@et.aau.dk, hwa@et.aau.dk, fbl@et.aau.dk

Department of Energy Technology, Aalborg University, Aalborg 9220 East, Denmark

## Abstract

This paper studies the impact of modulation scheme, mission profile and PV array configuration on the reliability of a double-stage single-phase PV inverter. A single-phase double-stage inverter with two boost-based Maximum Power Point Tracker (MPPT) is considered and the reliability of dc/dc stage is estimated under different mission profiles. Furthermore, two types of PV panels with different output characteristics are considered to demonstrate the impact of PV array design on the PV converter reliability. Moreover, a phase shifted-switching scheme for the dc/dc converters and inverter is proposed to improve the overall reliability. The outcome is the PV converter reliability enhancement through suitable PV panel selection and proposed phase-shifted modulation scheme, which can be a system-level design for reliability guideline for PV converter and PV system designers.

## 1. Introduction

Power electronics plays a main role in energy conversion process of modern electronic power systems integrating renewable resources, electronic loads with the conventional power systems. Integrating power electronics in power systems is associated with many advantages including better controllability, flexibility, and efficiency. However, it is also pose to new challenges in terms of reliability and availability. Thermal cycling and power cycling are the main factors affecting the aging of active and passive components in a converter. These factors can trigger failure mechanisms of components, which should be managed during manufacturing, design, control and operation procedures.

Power module and capacitor manufacturers aim at improving the lifetime of power converters by strengthening individual components. Furthermore, improving the converter reliability can be feasible employing Design for Reliability (DfR) approaches during converter design procedure [1]–[3]. So far, mission profile based DfR methods have been presented to evaluate the converter reliability in order to maintain a desired lifetime.

Besides enhancing reliability at component and converter levels, the entire system reliability can be improved through active thermal management at control stage either by thermal stress reduction or thermal stress redistribution [4]. For instance, different modulation methods have been presented in

order to reduce the thermal loss of converters in [5], [6]. Furthermore, reactive power injection under grid code requirements is presented in [7] in order to improve the temperature cycling of a wind turbine. Thermal stress reduction employing active power is further presented in [8], [9] by utilizing a storage system in the dc link of a back-to-back based wind converter. Lifetime extension by temperature swing reduction employing adjustable switching frequency is introduced in [4]. A power sharing approach is also presented in [10] in order to improve the reliability of parallel operated dc converters.

This paper proposes reliability enhancement approaches in a single-phase double-stage PV inverter in both system and control level. The main contribution of this paper is to illustrate the system-level impact of PV array characteristics on the converter reliability. Moreover, in the control level, a phase-shifted modulation scheme among different power stages is proposed, which can decrease the thermal losses and enhance the overall reliability.

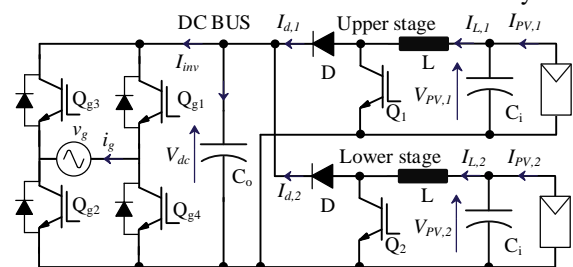


Fig. 1. Structure of the single-phase double-stage multiple MPPT PV inverter.



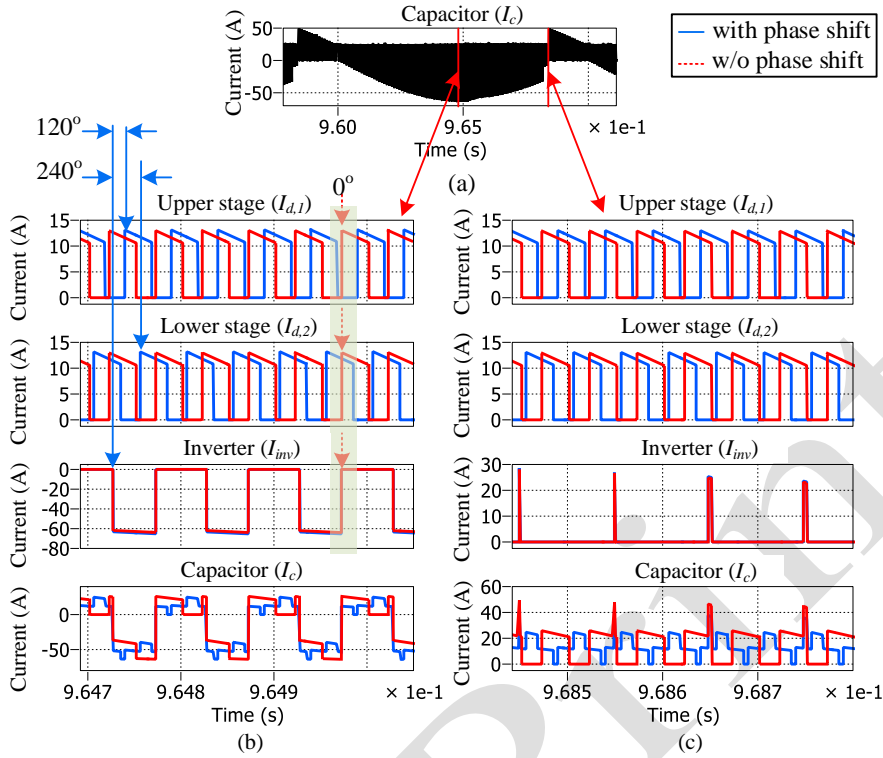


Fig. 4. Impact of high-frequency ripple elimination by phase shift: (a) capacitor bank current (b) converters current at peak current of capacitor, (c) converters current at zero crossing point of capacitor current.

can be found by  $AD_c = \sum I_i/L_i$ , where  $I_i$  is the time interval the capacitor stays under voltage  $V_i$  and hot-spot temperature  $T_i$ , and  $L_i$  is the lifetime of the capacitor under specific operating conditions following (1). The hot-spot temperature can be obtained by electro-thermal model of the capacitor as  $T_i = T_{amb} + R_{th} \times P_{loss}$ , where  $T_{amb}$  is the ambient temperature,  $R_{th}$  is the thermal resistance and  $P_{loss}$  is the power loss of the capacitor:

$$P_{loss} = ESR(100\text{Hz}) \cdot \left( I_{100\text{Hz}}^2 + \sum_f k_{ESR}(f) \cdot I_f^2 \right) \quad (2)$$

$$k_{ESR}(f) = \frac{ESR(f)}{ESR(100\text{Hz})}$$

$k_{ESR}(f)$  is given by the manufacturer. The capacitor lifetime hence can be obtained by the reliability data given in [11] for radial lead electrolytic capacitors with an upper category temperature of  $105^\circ\text{C}$  and 5,000 h rated lifetime. Due to the higher ripple currents in dc link, a capacitor bank with five parallel connected capacitors is designed as reported in Table 1. Therefore, the reliability of the capacitor bank including five capacitors connected in parallel can be found based on the series reliability network model.

Number of cycles to failure in Insulated Gate Bipolar Transistor (IGBT) switches and diodes depends on the junction temperature minimum value  $T_{jm}$ , temperature swing  $\Delta T_j$  and heating time of

power cycle  $t_{on}$  as given in (3), where the constants  $A$ ,  $\alpha$  and  $\beta$  are given in [2], [13].

$$N_f = A \cdot \Delta T_j^\alpha \cdot \exp\left(\frac{\beta}{T_{jm}}\right) \cdot \left(\frac{t_{on}}{1.5}\right)^{-0.3}, \quad 0.1s \leq t_{on} \leq 60s \quad (3)$$

The accumulated damage of the IGBT switches is estimated by  $AD_s = \sum n_f/N_f$ , where  $n_f$  is the number of cycles with heating time  $t_{on}$ ,  $T_{jm}$  and  $\Delta T_j$  are minimum junction temperature and junction temperature swing induced by the mission profile respectively, and  $N_f$  is the number of cycles to failure under these loading condition which can be obtained by (3). Furthermore, Monte-Carlo simulation is employed to calculate the reliability function of IGBTs following [2]. Moreover, the reliability of the two IGBTs and two diodes of the two parallel-connected boost converters are found based on the series reliability network model.

#### 4. Control System

The PV converter includes two boost units and a single-phase inverter as shown in Fig. 1. The control block diagram of the converters is shown in Fig. 5, where conventionally, the boost converters are working in MPPT mode and independent from the inverter control system, which is responsible for injecting the PV power into the grid and regulating the dc bus voltage. The high frequency ripple

currents of the converters are absorbed by the dc link capacitor bank, where boost converters introduce a 20 kHz ripple current and its harmonics. Furthermore, the inverter injects a 10 kHz ripple current and its harmonics as well as 100 Hz ripple current. According to the KCL at dc bus, the high frequency ripple currents can be reduced by making

a phase shift among PWM carrier signals of the three converters. For instance, a  $120^\circ$  phase shift can reduce the 20 kHz ripple current of capacitor bank by 43% as shown in Fig. 4. Thereby, following (2), the power loss and consequently the hot-spot temperature of the capacitor bank is reduced and consequently the reliability is improved.

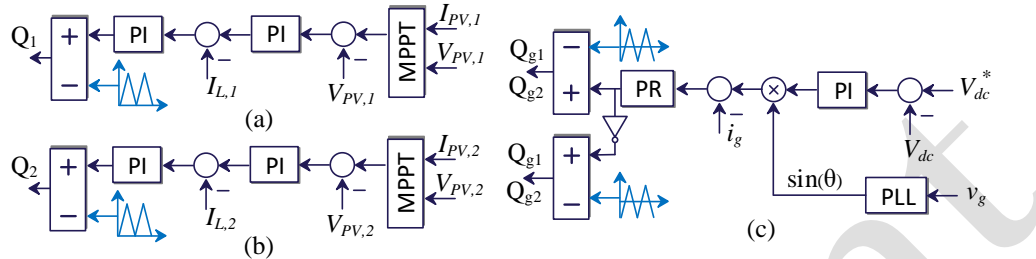


Fig. 5. Control block diagram of (a) upper DC/DC stage, (b) lower DC/DC stage, and (c) inverter.

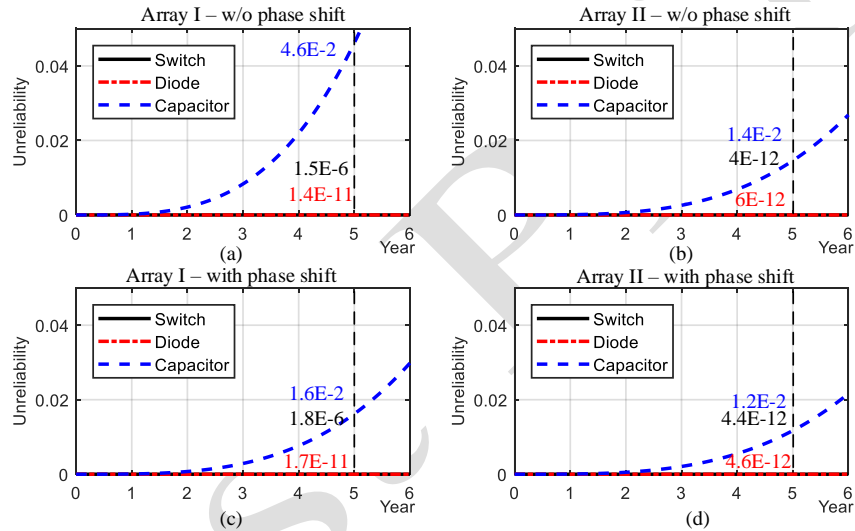


Fig. 6. Unreliability function of different components under mission profile A; (a) Array I w/o phase shift, (b) Array II w/o phase shift, (c) Array I with phase shift and (d) Array II with phase shift.

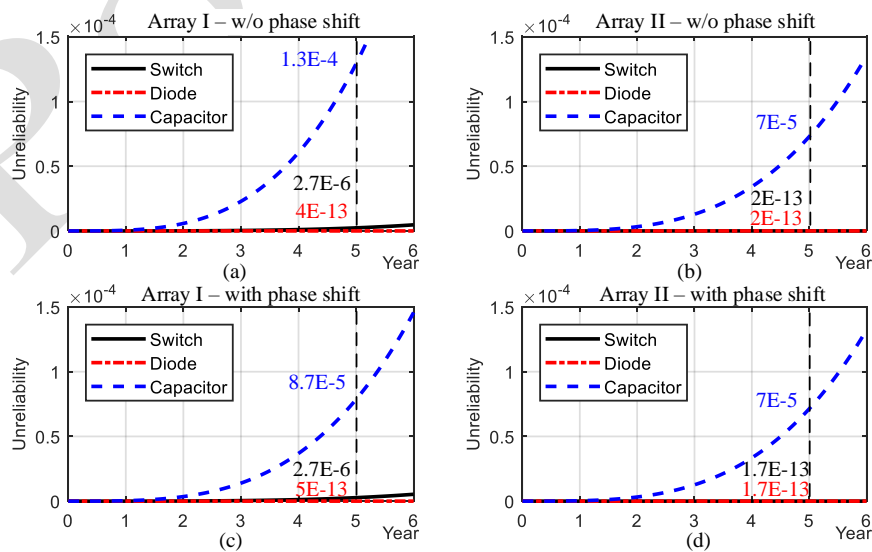


Fig. 7. Unreliability function of different components under mission profile B; (a) Array I w/o phase shift, (b) Array II w/o phase shift, (c) Array I with phase shift and (d) Array II with phase shift.

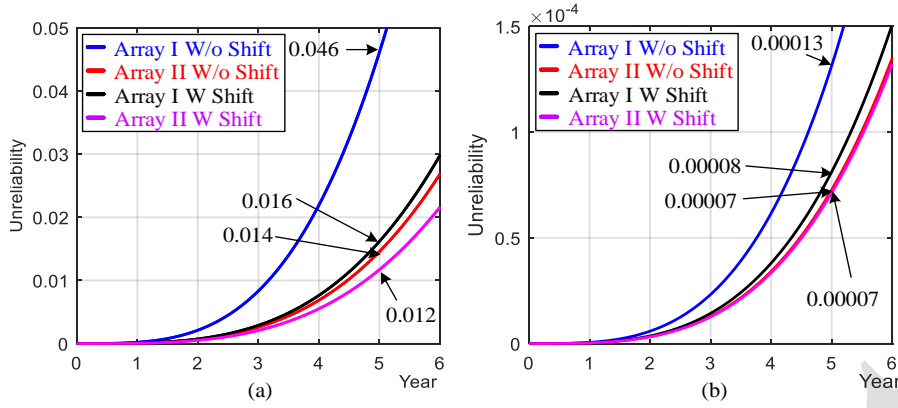


Fig. 8. Total Unreliability of converter under different case studies considering (a) mission profile A and (b) mission profile B.

## 5. Results and discussion

The cumulative distribution function of the failure probability, i.e., the unreliability function of dc/dc conversion stage of the PV converter is investigated under different PV array configurations, mission profiles and modulation schemes, and the obtained results are reported in Fig. 6 to Fig. 8. Fig. 6 and Fig. 7 show the unreliability of the converter components under mission profile A and B, respectively. Furthermore, the total unreliability of converter under mission profile A and B is illustrated in Fig. 8(a) and (b). The obtained results are summarized as follows:

- (1) The dc link capacitor bank is the most fragile component of the converter as shown in Fig. 6 and Fig. 7. The dc link capacitor is affected by the low-frequency ripple currents induced by the single-phase inverter and high-frequency switching ripple currents, while very low frequency solar irradiance fluctuations are passing through the active switches (IGBTs and Diodes). Therefore, the unreliability of capacitor bank is higher than active switches.
- (2) According to Fig. 6 and Fig. 7, the PV Array II has better reliability compared to the Array I under both mission profiles. According to Fig. 2, the MPPT voltage range for Array II is between 280 V and 380 V, while the MPPT voltage range of Array I is from 180 V to 250 V. Therefore, the duty cycle of boost converters in case of Array II is lower than Array I. The output ripple current of a boost converter  $I_{ripple}$  is

$$\frac{I_{ripple}}{I_o} \approx \sqrt{\frac{D}{1-D}} \quad (4)$$

where  $I_o$  is the output dc current and  $D$  is the switching duty cycle. By increasing the duty cycle as shown in Fig. 9, the output ripple current will be increased. This ripple current is absorbed by the dc link capacitors. Hence, lower duty cycle introduces lower power loss and

higher lifetime. Moreover, according to (5) [15] (the parameters' definition is given in page 276-277 in [15] –  $k_{T1}$ ,  $k_{T2}$ ,  $k_{T3}$ , and  $k_{T4}$  are the temperature coefficients, for IGBT  $k_i = 1$ ,  $k_v = 1.3 \sim 1.4$ , and for diode  $k_i = k_v = 0.6$ ), the IGBT and Diode switching and conduction power losses ( $P_{sw}$  and  $P_{cond}$ ) will be reduced under lower duty cycle and lower input current  $I_{in}$  operation, consequently implying better reliability. Notably, for the both PV Arrays the output power and voltage of the converter is the same and increasing the input voltage will decrease the input current and switching duty cycle.

$$\begin{aligned} P_{cond}(IGBT) &= (I_{in} \cdot (V_{ce0} + k_{T1} \cdot (T_j - 25))) \\ &\quad + I_{in}^2 \cdot (r_{ce} + k_{T2} \cdot (T_j - 25)) \cdot D \\ P_{cond}(Diode) &= (I_{in} \cdot (V_F + k_{T1} \cdot (T_j - 25))) \\ &\quad + \frac{I_{in}^2}{1-D} \cdot (r_F + k_{T2} \cdot (T_j - 25)) \\ P_{sw}(IGBT) &= f_{sw} \cdot E_{on+off} \cdot \left(\frac{I_{in}}{I_{ref}}\right)^{k_i} \cdot \left(\frac{V_o}{V_{ref}}\right)^{k_v} \\ &\quad \cdot (1 + k_{T3} \cdot (T_j - T_{ref})) \\ P_{sw}(Diode) &= f_{sw} \cdot E_{rr} \cdot \left(\frac{I_{in}}{I_{ref}}\right)^{k_i} \cdot \left(\frac{V_o}{V_{ref}}\right)^{k_v} \\ &\quad \cdot (1 + k_{T4} \cdot (T_j - T_{ref})) \end{aligned} \quad (5)$$

Therefore, employing Array II decreases the power loss on the converter components and improves the reliability. As it is shown in Fig. 8(a), the unreliability of the converter is reduced from 4.6E-2 for the PV Array I to 1.4E-2 for the PV Array II during 5-year of converter lifetime, which means the failure probability is decreased by factor of 3 employing the PV Array I under mission profile A. Moreover, as shown in Fig. 8(b), employing Array II decreases the unreliability from 1.3E-4 to 7E-5 under mission profile B, and hence, the failure probability is decreased by factor of 2. Therefore, a proper design for PV Array collection can improve the

overall lifetime of the converter.

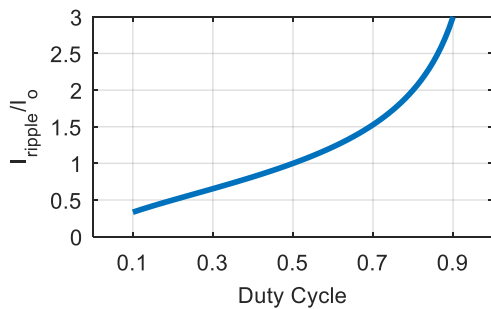


Fig. 9. Ripple current of a boost converter ( $I_{\text{ripple}}$ ) in terms of switching duty cycle –  $I_o$  = output dc current.

- (3) The dc link capacitor bank reliability is affected by the low- and high-frequency ripple currents. The high-frequency ripples are induced by the dc converters and inverter. Applying a suitable phase shift among switching carrier signal of converters, the high-frequency ripples can be eliminated. For instance, a  $120^\circ$  phase shift among the switching signals of converters can reduce the 20 kHz ripple current by 43% as shown in Fig. 4. Hence, the power loss and hot-spot temperature of capacitors can be decreased consequently improving the capacitor bank lifetime and reliability. The effect of phase shifted switching scheme on the reliability of components can be seen from Fig. 6(c, d) and Fig. 7(c, d). For instance, applying phase shifted scheme for the PV system with Array I under mission profile A, the unreliability of capacitor bank during its 5-year lifetime is decreased from  $4.6E-2$  to  $1.6E-2$  as shown in Fig. 6(a) and (c).
- (4) The impact of location on the reliability of converter is illustrated in Fig. 8 for mission profile A and B. The unreliability of the converter under mission profile A is higher than the mission profile B during 5-year lifetime of the converter. According to Fig. 3, the annual solar irradiance in location A is higher than location B, and hence, the converted energy and annual converter loading in case of mission profile A is greater ( $\approx 20\%$ ) than mission profile B. Furthermore, the annual ambient temperature in location A is higher than location B, consequently, the thermal stress induced by mission profile A is greater than mission profile B.

## 6. Conclusion

This paper studies the influence of mission profile, PV panel configuration and phase-shifted modulation scheme on the reliability of a single-phase double-stage PV inverter system. According to the obtained results, the mission profile has dominant impact on the reliability of PV converters due to the thermal stresses on the converter components

induced by the mission profile. Furthermore, an appropriate PV array collection design can considerably improve the PV converter reliability, since the output characteristics of the PV array determines the operating point of converter. A suitable coordination between control systems of converters can also reduce the dc link capacitor bank power loss and its hot-spot temperature, consequently improving the reliability of the converter. The mission profile-based numerical analysis validates the effectiveness of the PV array configuration design and proposed phase shifted switching scheme on the reliability of the single-phase double-stage PV inverter.

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