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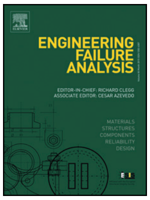

Failure analysis and reliability evaluation of modulation techniques for neutral point clamped inverters—A usage model approach

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ABSTRACT

Up to now, many modulation techniques have been proposed for neutral point clamped (NPC) inverters. In this paper, for the first time, a general methodology is applied to calculate and compare the failure analysis and reliability of NPC inverter with most commonly used control strategies. Also, the mean time to failure (MTTF) of NPC inverter is derived for different control strategies. It is demonstrated that the key feature of control strategies in determining the reliability of inverter is their loss distribution among the switches. The failure rate of components that is relevant to this study and junction temperature calculation is developed, then conduction losses and switching losses of switches for different control strategies are calculated. Finally, the most reliable control strategy is identified. Experimental results obtained have promptly justified the theoretical analysis and outlined procedure.

1. Introduction

Nowadays, continuous development of semiconductor switches has led to widespread application of power electronic systems. Usually, these systems have a large number of power semiconductor switches. In addition, most of power electronic converters are equipped with electrolytic capacitors. But the semiconductor switches and electrolytic capacitors are the most fragile components [1–3]. Also, cost reduction pressure from global competition dictates minimum reliability-oriented design margin. For these reasons, reliability is the number one challenge for power electronic systems. So, quantitative evaluation of reliability for power electronic systems being a significant concern, can be used as a criterion to compare different topologies and control strategies.

The past decade has witnessed an increasingly growing research interest in various aspects of reliability for power electronic systems, with focused specifically on inverters [4–7]. In [8], Chiodo et al. presented some crucial properties to evaluate reliability of the power electronic systems. During the last few decades, many recommendations are proposed to improve reliability, such as “fault-tolerant design”, “condition monitoring”, and “active thermal management”, to meet current and future industry needs. Mirafzal presented an instructive survey of existing fault-tolerance techniques for three-phase, two-level, and multilevel inverters in [9]. More comprehensive fault-tolerant techniques regarding power electronic converters in case of power semiconductor device failures, are reviewed by [10]. For condition monitoring (CM), a review paper was presented by [11], which described the current state of the art in CM research for power electronics. In [12], it is proposed to use the active thermal management to reduce the switching losses or to move them to less stressed devices. That can increase the reliability of power electronic modules. In [13], the authors present a global reliability comparison between two-level and three-level/five-level inverter topologies in single and three-phase operations. Harb et al. has proposed a new methodology for calculating the reliability of the photovoltaic module-integrated inverter (PV-MII) based on a stress factor approach [14]. Various fault-tolerant configurations have been

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Nomenclature

λ_{FET}	Failure rate of MOSFET (FIT $= 10^{-9}$ failure/h)
λ_D	Failure rate of diode (FIT)
λ_C	Failure rate of capacitor (FIT)
λ_b	Base failure rate (FIT)
π_T	Temperature factor
π_A	Application factor
π_Q	Quality factor
π_E	Environment factor
π_S	Electrical stress factor
π_C	Contact construction factor
π_{CP}	Capacitance factor
π_V	Voltage stress factor
π_{SR}	Series resistance factor
λ_{NPC}	Failure rate of inverter (FIT)
L	Lifetime under use condition
L_0	Lifetime under testing condition
V	Voltage under use condition (V)
V_0	Voltage under testing condition (V)
E_a	Activation energy (J)
K_B	Boltzmann's constant (8.62×10^{-5} eV/K)
a	Constant describing the voltage and temperature dependency of E_a
ξ	Stress variable under operation
ξ_0	Stress variable under test
P_r	Rated power of MOSFETs (W)
V_S	Voltage Stress Ratio
T_j	Junction temperature (°C)
T_a	Ambient temperature (°C)
T_C	Case temperature (°C)
T_H	Heat sink temperature (°C)
$R_{th,ca}$	Thermal resistance between the case and ambient (°C/W)
R_{jC}	Thermal resistance between the junction and case (°C/W)
$R_{th,cH}$	Thermal resistance between the case and heat sink (°C/W)
$R_{th,Ha}$	Thermal resistance between the heat sink and ambient (°C/W)
Z_{jC}	Thermal impedances between the junction and case (°C/W)
$P_{SW,MOSFET}$	Switching losses of MOSFET (W)
$P_{SW,D}$	Switching losses of diode (W)
T_S	Sampling period (Sec)
E_{on}	Turn on energy losses (J)
E_{off}	Turn off energy losses (J).
E_{REC}	Reverse recovery process energy (J)
$E(M,\theta)$	Commutation energy losses (J)
$I_l(M,\theta)$	Load current (A)
I_{max}	Maximum collector current (A)
M	Modulation index
φ	Current lagging angle to voltage (Deg)
V_{CE}	Collector to emitter voltage (V)
V_{CEN}	Rated collector to emitter voltage (V)
V_{CEO}	Threshold collector to emitter voltage (V)
I_C	Collector current (A)
I_{CN}	Rated collector current (A)
R_S	Collector to emitter resistance (Ω)
V_F	Diode forward voltage (V)
V_{FN}	Rated diode forward voltage (V)
V_{FO}	Diode threshold voltage (J)
R_D	Diode resistance (Ω)
P_{cond}	Conduction losses (W)
E_{cond}	Conduction energy (J)
α	Command voltage vector angle (Deg)
$\lambda_{D,F}$	Failure rate of freewheeling diode (FIT)
$\lambda_{D,C}$	Failure rate of clamping diode (FIT)

proposed in the literature for power electronics converters [15–20]. But, no reliability evaluation or comparisons of different control strategies have been presented in previous articles. For the first time to our knowledge, a general methodology is applied that permits us to compare different control strategies from the reliability point of view. Though the methodology presented here is general, results associated with a three-phase three-level neutral point clamped (NPC) inverter are presented and discussed here.

NPC inverters are the most widely used topology of multilevel inverters in MV high-power applications on the market [21] and play an increasingly important role in electric motor speed control, utility interfaces with renewable energy resources, induction

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