ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 9, September 2014

Power Switch Faults, Diagnosis and Tolerant Schemes in Converters of Photovoltaic Systems- A Review

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ABSTRACT: Converters and inverters are central power processing circuits in solar photovoltaic power generation systems. Recent surveys reported that power switches and electrolytic capacitors in converters and inverters are prone to failure due to thermal effects and electrical stress. Damage of any single component either reduces the efficiency or malfunction the entire system. Since PV power stations are remotely located ,fault diagnosis and repairing of power processing stages takes few hours to months depending upon service provided by the manufacturer. If it takes more time for fault diagnosis and fault removal, it results in zero or less amount of power generation thereby decreasing the efficiency. Since the power switchesare the central part of converters , this article presents an overview of known power switch faults, switch fault monitoring, diagnosis and fault tolerant schemes in the converters of photovoltaic application. Authors of this article have a confidence that providing fault diagnosis and tolerance competence to PV power station will contribute to improve the system efficiency and reliability.

KEY WORDS: PV converter efficiency ,converter reliability , power switch faults , switch fault diagnosis,fault tolerance competence.

I. INTRODUCTION

It has been observed that power switches in converters are prone to failure due to several reasons like varying atmospheric conditions, improper gate driver circuits, heavy loads, transients, manufacturing defects, avalanche failures, short circuit and open circuit failures , track braking etc.moreover some of the failure reasons are unknown. Failure of single switch results in overloading of other switches, resulting in efficiency and reliability reduction, system malfunction. The time taken for fault diagnosis and repairing results in lowered system efficiency or temporary halted power generation system. This signifies need of mechanism for detection of failures at early stagesand development of fault tolerance competence in converters. Design of photovoltaic electrical power processing circuit possesses challenges in front of researchers like improvement in efficiency and reliability, development of fault diagnosing and tolerant topology, component low failure rates, integrated , costefficient designsetc. There is significant need to address these issues arising in PV based power generation systems. This article deals with known failure mechanisms in power switches, briefs the role of converter in PV systems and outlines fault diagnosis and tolerant methods in PV systems.

II.KNOWN FAILURE REASONS IN POWER SWITCHES

Common failure reasons of power switches are described in this section.In low voltage power MOSFETs, failure mechanism is detected due to second breakdown phenomena [1,2] affecting the SOA , very little attention has been paid on this issue by the researchers. The MOSFETs in power converter should notbe allowed to operate in second breakdown area as they need robustness against current focusing phenomena to avoid converter failures.Due to scaling downof power switches,compactness is obtained ,but these devices are less robust than the older ones and are thermally instable. The heat

ISSN (Print) : 2320 – 3765
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Vol. 3, Issue 9, September 2014

generation and heat flow mechanism in CJ MOSFET is presented in [3], the thermal distribution, maximum temperature and contact temperatureare the causes of MOSFET degradation.The power switch reliability can be improved by using appropriate thermal management techniques[4]. Thermal stress is caused due to two main reasons first is power cycling because of load variations which induces variations in losses and second is thermal cycling due to variations of surrounding thermal environment [5]. Power cycling life time is affected by three factors thermal [6,7], mechanical and material factors[8]. Thermal factors arecreated due to junction temperature variation, mechanical factors are due to wire dimension , bonding area, layered structure of power switches etc. material factors are due to solder components and combination of several heterogeneous materials hence reliability of the MOSFETs is important as compactness and efficiency. The MOSFET $R_{DS\ on}$ is subjected to temperature variations and progressively increases with periodical temperature variations. If temperature variations are longer than the thermal time constant of the device, $R_{DS\ on}$ drift may degrade wire bond, bonding pads and the die hence a reliability model is developed to compute $R_{DS\ on}$ drift and device life time [9]. MOSFET failure due to soft breakdown have been studied [10] and it is reported that drain current and transconductancedecreases with small W, affecting the reliability.It is also seen that temperature loadings affects the reliability of soldered joints in IGBT by developing cracks and fatigue processes which results in failure [11]. Semiconductor power modules experience cyclic temperature variations, two types of thermal cycles are identified [12], power cycles coming from application of electric current in active parts of modules during operation phase and passive cycles from ambient phase.

The SC capability is one of the most important factor in determining the robustness of IGBTs in very high power applications [13] .Under SC condition IGBT has to sustain high voltage and high current which increases local device temperature[14]. At high temperatures SC withstand time is also reduced. A method to detect device destruction under SC condition using simulation has been presented [15], the results show that V_{TH} and I_{sat}degrades when IGBT is kept under stress.IGBT fails after few hundred microseconds of SC turn off.According to [16], IGBT SC failure mechanisms are divided into three modes a) Power Limited Failure – Device destructs near the current peak and failure occurs near SC turn on [17] ,b) Energy Limit Failure- In this device fails during steady state, the high energy dissipation causes local temperature to increase beyond critical value thereby preventing the ability to sustain maximum allowable collector to emitter voltage , and c) Inhomogenous operation failure or ‘turn off failure’[18].SC failure mechanism of 1200 V trench IGBT is presented in [16] , results showed that most of the devices failure occurred during blocking state after few hundred microseconds of SC turn off conditions. Due to large leakage currents , thermal runaway occurs hence switching devicesfails after SC turn off. Higher device temperature results in larger leakage current causing local heat generation.According to [19] ,off state failure is irrelevant of electrical and thermal failure modes and it is more associated with turn off dynamics under certain current and voltage conditions.The inverter life time prediction method is carried out by using a model based on electro thermal and thermo mechanical simulation [20] . Die attach solder fatigue failure mode is considered and other failure modes can be accumulated separately for life time estimation.

The package reliability of IGBT modules depends upon thermo mechanical properties of semiconductor dies bonded to substrates with aluminum wires and solder joints, [21] which show that there is huge scope of research in power electronic device packaging technology. Aluminum wire bond lifting, substrate fracture and other factors due to thermo cycling are important issues in module failures[22] also the reliability of wire bond and substrate determines the reliability of whole module[23,24].Reliability of different wire bonding technologies for IGBT is studied [25] and it is suggested that design focused on quality, reliability and performance is very essential. Wire bonding lift off failure is another dominant factor which limits the reliability of the IGBT module .It is reported that wire bonding affects gate- emitter capacitance (Cge) , gate-collector capacitance (Cgc) and parasitic inductance between collector and emitter. Gate to emitter voltage during turn on and collector to emitter voltage during turn off can be monitored for as an indication of wire bonding lift [26].Thermal fatigue results in solder cracks between copper base plate and direct copper bonding substrate , this shows the need of specific simulation tools for research on IGBT reliability [27] also the solder life time depends upon temperature variation, maximum and minimum dwell temperatures [28].Finite element techniques can be used to model thermal fatigue effects in IGBT modules, chip temperature , temperature distribution and thermal resistance etc. [29] presents three dimensional model which considers die size, layout and substrate geometry to check device performance by changing material properties and geometries.Good thermal management of IGBT module is a challenge, and new type of packaging material need to be introduced , cooling technologies should also be improved [30].In [31] performance of PT and NPT IGBT is carried out under unclamped inductive switching and SC conditions ,huge power loss wasobservedwith change in device characteristics hence to study the switch behavior author depicts the need of good physics based simulator. There are many challenges in IGBT module technology in the areas of improved cooling techniques, development of heat sink, power density/volume, thinner wafer, loss reduction, good conversion efficiency, cost reductionsetc [32]. The IGBT failure conditions vary with case temperature, turn off current level and load inductance [33]. In inductive load due to thermally assisted carrier multiplication at reverse biased p-base and n-drift region IGBT failure takes place [34]. The clamped inductive turn off failure of IGBT is studied under over current and over temperature and it was observed that IGBT periphery call at the gate runner edge was responsible for failure, it is stated that layout design has to play important role in ruggedness improvement under overloading conditions [35]. The influence of metallization thickness of ceramic substrates on reliability of power electronic switches under high temperature cycling is studied [36]. The reliability testing method of IGBT power modules is discussed to detect failure modes and structures, finite element modeling method is used to analyze the stress and strain distribution [37].The SC behavior of IGBT and COOLMOS devices is tested under repetitive SC conditions [18,56]. An active protection circuit for fast clamping and safe shutdown of fault currents in IGBT's is proposed in [57], which allows IGBT to work on high gate voltage with short circuit protection ability. The circuit is tested against various parameters like temperature variations, rising rate of fault currents, gate voltage etc. The results shows that the over current condition can be precisely detected without current sensor, initial peak current can be limited due to the fast detection scheme , peak power and energy of fault current can be reduced.

The review of switch faults signifies the need to develop models, simulation tools, packaging technology,good thermal management schemes for better reliability of power switches thereby improving the efficiency and reliability of converters and inverters.

III.ROLL OF CONVERTERS IN PHOTOVOLTAIC APPLICATIONS

Converters are important part in PV systems. DC-DC converters change DC power from one voltage level to another. Inverters on the other hand, convert DC power to AC power.PV panels are considered to be stable and main role of power conversion is performed by converters, hence researchers have focused attention on converters for efficiency and reliability improvements.Plenty of converter topologies and MPPT algorithms are suggested for PV applications by researchers. Most of the topologies focuson increasing the efficiency of the system ,as renewable energy sources are very uncertain in nature.Buck, boost, buck and boost converters are currently being used in power generation systems. Different PV interface architectures are proposed for Photovoltaic power generation systems in which converters are connected in series, parallel or combination of both.Some of the familiar interfaces are single DC string single inverter, module integrated converters and inverters, module integrated DC-DC converters fed to central inverter, multi-converter strings [38] etc., according to authors panel integrated converters and inverters provide more efficiency and reliability. The controllers of converters have MPPT algorithms which tracks maximum power point in varying atmospheric conditions. Variety of MPPT techniques have been proposed by researchers with their merits and demerits. Nowadays trend is to use PV panels to feed the power directly to grid or end application by replacing the batteries.According to authors [39] in non-ideal conditions the performance of MPPT degrades if photovoltaic modules are connected in series hence it is recommended to use separate power interfaces for each photovoltaic module. In series connection the defect in one converter propagates in next thereby influencing the entire system.The capacity of photovoltaic system can be increased by increasing number of power processing stages [40].

IV.CONVERTER FAILURES, FAULT DIAGNOSIS AND TOLERANT SCHEMES

This section discusses fault diagnosis and tolerant schemes for power switches applied in converters. Since power switches are prone to failure, converter design based on fault diagnosis and tolerance competence is modern way to improveefficiency and reliability and is attracting interest of researchers [64].An industrial surveywas carried out to determine reliability of power electronic converters and it was found that power semiconductor switches are the most breakable components due factors like environmental varying conditions, system transient, heavy load, thermal/power cycles, manufacturing defects etc [41]. The major need is admitted in the survey for better fault monitoring methods of converters which recommendneed of major research work to carry out in the area of power switch fault diagnosis and tolerant schemes for converters. List of fragile components according to failure rates in DC-DC converters by the survey report in descending order is power switching devices, capacitors, gate driver circuits, connectors, inductors, resistors and other devices .It is reported that 66 % failures occur in power processing stages of Photovoltaic Systems [42], the life span of the power processing stages is very shortas compared to the life span of solar PV array hence more attention should be provided on increasing the reliability of power stages with 10 years MTBF. Authors presented design of an interleaved boost converter and showed that at higher PV powers,95 % efficiency and 100000 hours MTBF can be obtained by using overrated devices.International Energy Agency reported 98 % failures related to power stages and average time to failure is about 5 years. Similar results were obtained in '1000 roofs' program in Germany and Japanese 'residential Japan' program[43].A fault diagnosis and tolerant method for DC-DC converter is presented which is applicable for open circuit faults [44]only ,here the converter operates in four modes viz. 1) normal 2) abnormal 3) Active phase shifted and 4) rebuilt modes. Faults occurring in MOSFETs are detected by phase changes at primary side and at output side. Various voltage nodes are monitored to detect the faults in MOSFETs of full bridge DC-DC converter. Defective MOSFET can be identified by comparing the node voltages in normal and abnormal modes. In rebuilt state alternate paths are used to provide the power to the load.Reliability assessment of three phase interleaved boost dc to dc converter used for Photovoltaic systems is analyzed [45], according to author output capacitor is a major factor affecting the reliability for constant impedance load. Challenges in front of photovoltaic power processing systems (P3S) are discussed in [46]. According to author research community should focus on P3S design in respect of low failure rates, high efficiency , modularity, good reliability, reduction in losses and lower costs.Authors have discussed environmental stresses on components due to variation in temperature and humidity. It is suggested to develop more efficient batteries , charge monitoring and battery management systems for PV applications. To obtain better reliability based design, authorsfurther advise to know past environmental statistics, to study various component behavior in detail for all climaticconditions , and to carry trade off designsfor all. In case of inverters , reliability can be improved by considering thermal management techniques at the time of design[78]. Fault tolerant design and reliability assessment of multiphase DC-DC converters in PV systems, has been presented [47] . It is said that component failure rates are functions of conditions like temperature, insolation , device ratings etc. The Markov system reliability model is developed and failure rate of components is obtained from steady state analysis.A fuzzy based frequency control approach is presented [48] without smoothing the PV output voltage, further it is reported that PV life span exceeds 20 years, hence the PV systems including power processing systems installed at remote locations must possess abilities like long service life time, high reliability, low maintenance costs etc. Use of snubber circuit for MOSFET in a 25W photovoltaic system with MPPT algorithm [49] is presented for reliability and efficiency improvement. Authors [50] depicts the need of PV generator emulator for analysis of reliability in PV power processing systems, PV power generation analysis, electricity performance analysis etc. A highly reliable power system with PV array for lunar application is presented in [51]. For aerospace lunar based applications, high reliability and superior performance must be given prime importance than economy. Design and implementation of photovoltaic system for power generation in remote village is presented in [52,53],additionally focus is paid on MODEM based online fault diagnosis method for a remote PV system for reliability improvement [54].A power generation system based on fusion of PV system and AC power generation has been described [55] for efficiency and reliability improvement.It is used for building integrated PV systems where DC-DC converters works under fluctuating ambient temperatures ,challenging the efficiency and system reliability. Design and selection criteria for DC-DC converters is given and it is reported that the life span of PV array is around 25 years while for converters it is too short, it is suggested to avoiduse of electrolytic capacitors thereby increasing the reliability of converters.Due to extremely varying atmospheric conditions, operation of power semiconductor devices suffers. At high voltage and current the performance of DC-DC converter degrades due to hot carrier stress [58], hence hot carrier effect need attention of researchers.Power switch and power converter performance depends upon temperature [59]. Repetitive thermal transients affect the reliability of switching devices in presence of heat sink and atbelow rated temperature. A method is presented which reduces device temperature variation by generating very high frequency switching pulses at times when the device would in off state. During low current segments of cycle , the device temperature is maintained and temperature variations are minimized.The current imbalance is due to inductive

ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 9, September 2014

coupling from power to gate traces and gate wire bonds[60]. For high di/dt applications international layout of IGBTs must be focused. Usually MOSFETs and IGBTs find their applications in middle and high power converters respectively. For di/dt control, inductance estimation of IGBT module is necessary[61]. di/dt and dv/dt of power switches causes transients where current and voltage get vary as turn on and turn off signals are sent by gate control. Voltage and current transients causes EM emissions which disturbs the neighboring components. Voltage transients generate current through parasitic capacitances. Also the generated EM field creates parasitic current and voltage in surrounding electronics components. It is difficult to measure radiated EM fields and the coupling in converters. Hence the drivers should be designed in such a way that transients must be decreased. The power MOSFET failure mechanism used in half bridge DC-DC converter is analyzed in [62] which showed that reverse recovery carrier current activates parasitic BJT resulting in failure of MOSFET. Parasitic elements like gate oxide, poly silicon gate resistance play crucial role in determining reliability.

The system reliability can be improved by using standard topologies, early or post diagnosis of power switches and developing fault tolerant topologies[63].Sung Young Kim et al [65] presented a low cost fault diagnosis method for ZVS DC-DC converter in which DC link current pulse shapes are assessed. Current is sensed by the pulse transformer connected in DC link and samples are taken at every 3 ms intervals. In case of fault the current shape changes , for gating fault reverse current through fly wheel diode flows. It is observed that in faulty case higher current will flow than normal current. For SC faults current pulses are higher and wider. The disadvantage of this scheme is that, the faults in only one leg of H-bridge can be detected. A new circuit topology is proposed for fault tolerant H bridge DC-DC converter [66] which consists of alternate paths. The faults are diagnosed, prevented and output voltage is also maintained at a constant voltage. The complexityof circuit increases due to requirement of additional components.Another new topology with fault tolerant ability has been proposed for reliability improvement[67] in which redundant switches and capacitors are connected in such a way that output voltage is balanced without help of external circuitry. Upon failure of main switching devices , the clamping switching devices works. The method works well for both short and open switch faults, working of converter is guaranteed even if any switch fails. A failure detection routine for grid connected PV systems is presented [68], which automatically analyses the performance of PV system and in case of malfunction it determines the cause. Reference values of energy yield and hourly energy yield are compared and energy losses are detected. It also decides current failures and predicts possible failures.Different soft start schemes are discussed in [69-72] for DC-DC converters. During start up in converters large current and voltage overshoot is observed causing instability which can be reduced by voltage mode and current mode methods. Current mode soft start technique is found better as current can be controlled directly [73]. Current mode control includes linear feedback, integral action of output voltage and coil saturation to obtain stability and good output voltage regulation. Different controller design strategies for DC-DC converters are presented in [74-76].A generalized model for PV inverter system reliability analysis based on environmental analysis and inverter subsystems methodology have been presented[77] which uses inverter component reliability and Monte Carlo simulation for assessment. It is stated that the failure rates depend upon type of inverter ,number and size of components, power handling capacity of the devices. The need of detailed component failure data is depicted and it is suggested to form international failure database of inverter for accurate failure forecasting further it is advisedto use film capacitors and power switch modulesfor better reliability of inverter instead of electrolytic capacitor and discrete power switches in photovoltaic application.A technique to determine output currents in voltage fed PWM inverters by using current sensor in DC link is presented [79].In reliability based comparison of four photovoltaic systems, aimed at identification of most failure prone components it was found that MOSFETs are more prone to failure and temperature is the dominant stress factor. According to authors ,in the analyzed circuits capacitors were not found to be prone to failure. Weak reliability was observed in circuits having large number of MOSFETs [80]. Reliability performance evaluation of grid connected photovoltaic power systems by considering the variation in input power and ambient conditions has been presented [81]. Reliability indices are defined for sensitivity analysis and to check effect of different factors on photovoltaic power systems.A fault detecting and localizing scheme based on protection relays and circuit breakers is applied to multi terminal DC distribution system [82], which monitors local quantities to detect the faults, it uses IGBT based circuit breakers. The protection devices working on over current principle are placed in system in such a way that the faults can be detected , fault currents can be interrupted and faulty part can be isolated. The protection devices are placed at DC bus zones, rectifier side, inverter load side , DC converter load side zone and capacitor side. Results shows that the faults can be detected in milli- seconds.A differential power processing scheme in which ,power is exchanged in case of MPP mismatch is presented [83], the converters do not operate in case of powermatch.The local converters have ability of faultmonitoring , diagnosis and protection strategiesand can communicate with each other if the inverter or the central hub is faulty .A rule based expert system for fault diagnosis in voltage source inverter is proposed [84]. The communication between user and the expert system is provided here.A FPGA based real time power converter failure diagnosis technique for fault tolerantconverter detects fault within 10 µS [85]. This technique uses redundant power switches which are triggered on failure of main switches. For renewable energy IGBT module based on Sinter technology is presented [86] which uses silver powder between IGBT chip and DCB. Silver have melting point of 900^{o}c, hence more reliability is obtained, some other advantages obtained over solder technology are positional accuracy of 50 µm, the layers are 4.5 times thinner than solder technology. Furthermore thermal conductivity is four times higher than solder technology. Homogenous temperature distribution is also guaranteed , thereby reducing the thermal effects. An AI based technique for fault diagnosis of multilevel inverter is presented [87]. In AI based approach no mathematical modeling is needed hence development time is reduced. A modified converter topology is proposed in [88], in which flying capacitor based fourth leg is added to converter for fault tolerance competence. Reliability of converter in case of switch paralleling is studied in [89] and it has been found that paralleling approach decreases the system reliability , experiments show that for good reliability less number of switches should be used. In switch paralleling difference of di/dt in all switches results different switching energies and in off state over voltages destroys the devices.Fault tolerance is applied to multilevel inverter with H-bridge by using multi coil transformer and bidirectional valve [90]. The inverter operates efficiently in case of fault due to its reconfigurable topology , though the redundant components are required, the presented converter can be applied at the places where repairing, removal of the inverter is costly. Four types of power topologies viz. 1) single cell, single power stage 2) single cell, multiple power stage, 3) multiple cell single power stage, 4) multiple cell, multiple power stage are surveyed [91] for reliability testing , in these switching power transistors were found to be prone to failureand temperature was the main stress factor . According to Flicker et al [92] most of the IGBT failures are results of temperature effects, hence measurement of junction temperature using IR imaging will be proved to be meritorious. Authors have listed standards for IGBT design and testing developed by JEDEC for PV inverter application.

V.CONCLUSION

An overview of power switch faults , various fault diagnosis and fault tolerant schemes used in converters are discussed. Major research work is needed to carry out for power switches in areas of layeredconstruction, use of thermally insensitive material , improvement in device packaging technology, development in converter topology, investigation of fault diagnosis and tolerant schemes etc. Presentlymanufactured power switches are compact and efficient but are less robust and thermally instable . Since power devices have to work under thermal stress,proper thermal management is an important issue and should be considered at the time of design. There is a major need of research on converters having capability of fault monitoring, fault localization and fault tolerance competence. Improvement in efficiency, reliability, low failure rates, reduction in losses and costs are some of the issues which need attention. Focus should be paid on development of fault modeling , fault simulation methods and development of fault tolerant standard converter topologies.

ACKNOWLEDGEMENT

Authors are thankful to Shivaji University, Department of Technology, Kolhapur, India (Maharashtra), for providing necessary facilities for completion of this review.

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ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

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Vol. 3, Issue 9, September 2014

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ISSN (Print) : 2320 – 3765
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International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

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