Power Electronics Reliability Comparison of Grid Connected Small Wind Energy Conversion Systems

Md. Arifujjaman, M.T. Iqbal, and J.E. Quaicoe
Graduate Student, Associate Professor, Professor
Faculty of Engineering and Applied Science, Memorial University of Newfoundland
St. John's, NL Canada A1B 3X5, E-mail: mda04@mun.ca

ABSTRACT

This work presents a power electronics reliability comparison of the power conditioning system for both the Permanent Magnet Generator (PMG) and Wound Rotor Induction Generator (WRIG)-based small Wind Energy Conversion Systems (WECS). The power conditioning system for grid connection of the PMG-based system requires a rectifier, boost converter and a grid-tie inverter, while the WRIG-based system employs a rectifier, a switch and an external resistor in the rotor side with the stator directly connected to the grid. Reliability of the power conditioning system is analyzed for the worst case scenario of maximum conversion losses at a predetermined wind speed. The analysis reveals that the Mean Time Between Failures (MTBF) of the power conditioning system of a WRIG-based small wind turbine is much higher than the MTBF of the power conditioning system of a PMG-based small wind turbine. The investigation is extended to identify the least reliable component within the power conditioning system for both systems. It is shown that the inverter has the dominant effect on the system reliability for the PMG-based system, while the rectifier is the least reliable for the WRIG-based system. This research indicates that the WRIG-based small wind turbine with a simple power conditioning system is a much better option for small wind energy conversion system.

1. NOMENCLATURES

δ	Duty cycle of the boost converter
φ	Phase angle between grid voltage and current
E_{SR}	Rated off-state switching loss energy of the diode
E_{ON}, E_{OFF}	Rated on and off-state switching loss energy of the IGBT respectively
f_{WT}, f_{SW}	Frequency of the wind turbine rotor and switching frequency of the semiconductors respectively
I_{om}	Maximum amplitude of the grid current
$I_{ref,d}$, $I_{ref,IGBT}$	Reference commutation current od diode and IGBT respectively
M	Modulation index
r_d, r_{ce}	On-state resistance of the diode and IGBT respectively
T_A, T_J	Ambient and Junction temperature respectively
V_{f0}, $V_{ce0,}$	On-state voltage of the Diode and IGBT respectively
V_{dc}	Output voltage at the rectifier for the PMG-based system
$V_{ref,d}$, $V_{ref,IGBT}$	Reference commutation voltage of the diode and IGBT respectively

2. INTRODUCTION

A small scale Wind Energy Conversion System (WECS) has tremendous diversity of use and operating conditions, and consequently has evolved rapidly along with the large scale WECS for generation of electricity either on-grid or off-grid applications. Such a WECS is considered as a complex system of many subsystems ranging from mechanical (rotor, hub, gear box etc.) to electrical (converter/inverter, rectifier, control) systems and loads. Failures in any subsystems cause substantial financial loss owing to the cost of replacement and restoration. The problem becomes more severe for small systems since as small wind turbines are very subjective to installation costs and require a reliable operation over a long period of time. In view of present uses and future developments, there is significant need for reliability evaluation for the WECS in order to ensure a reliable operation and low initial cost.

Almost all commercially available small wind turbines are based on Permanent Magnet Generators (PMGs). On the other hand, a small wind turbine may be based on a Wound Rotor Induction Generators (WRIGs) for the generation of electricity. The Power conditioning systems for grid connection of both systems is different and could exhibit a variation in reliability. Not to mention that it is desirable to have a reliable power conditioning system for a wind energy conversion system. However, it is quite difficult to predict the reliability as the reliability analysis of a power conditioning system is greatly influenced by the operating conditions, i.e., covariates and therefore it is desirable to investigate the magnitude of their effects on the system reliability. Reliability calculations consider the voltage or current as a covariate for an electromechanical system [1], while the reliability of power electronic components is strongly influenced by the component temperature and variations [2]. Knowledge of the reliability of power electronic components is a key concern when differentiating between systems.

Recent research intermittently endeavors to determine the reliability and advancement of the inverter rather than the power conditioning system [2–4]. As far as the inverter is concerned which is an essential part for the power conditioning system of the PMG-based system, it is primarily designed for PV applications and reliability of such grid connected inverters is ambiguous [5] and several key aspects to increase the reliability of such inverters have been identified by previous researchers [4, 6, 7]. The dominant factor that contributes low technical reliability is the heat generation caused by the power losses when the current flows through the semiconductor switches [2, 6, 8]. A reduction in heat generation can significantly increase the reliability. In addition, fans inside the inverter have a limited lifetime and deserve special attention [4]. Nevertheless, there are other aspects (e.g. humidity, modularity, and packaging) that also require special attention beyond the technical improvement and are not a part of this present study.

Most of the reliability calculations are based on the accessible data provided by the military handbook for reliability prediction of electronic equipment which is criticized for being obsolete and pessimistic [9, 10]. A comparative reliability analysis of different converter systems has been carried out based on the military handbook by Aten, et al [10]; however, the absence of environmental and current stress factors can pose grim constraints on the calculated reliability value. Rohouma, et al [11] provided a reliability calculation for an entire PV unit which can be considered more useful, but the approach lacks valid justification as the data provided by the author is taken from the manufacturers' published data which is somewhat questionable. This is due to the fact that reliability calculations using purely statistical methods [12], manufacturers data [3, 11], or military handbook data [13] neglect the operating point of a component. Moreover, the total number of components could vary for two systems (which have the same objective) in order to meet a certain criterion of the overall system. Although higher components in the power conditioning system will exhibit less reliability and vice versa, the effects of the covariates could be different and consequently could lead to a variation in the reliability [14]. Furthermore, a reliability evaluation for the power conditioning system of a grid connected small wind turbine is essential in order to optimize the system performances as well as system cost [15]. Another important point to mention is that reliability analysis based on the covariate factor is strongly influenced by the standard reliability data book also. For example, it is shown in previous research that different values of covariate factor for a same covariate is possible by using a different reliability standard data book [16]. This variation in covariate factor also varies the reliability of an integrated system which is composed of numerous semiconductor devices. Moreover, it is well understood that an error in reliability prediction for a system could prove to be fatal for the high penetration of small wind power.

On the strength of the above discussion, it can be asserted that most of the attempts for the power conditioning system reliability analysis have been developed so far is based on either several assumptions or standard reliability data book which very often could not convey the actual reliability data of a system. This discrepancy could affect the preference of an optimum small grid connected wind turbine system power electronics that is in a great need for high penetration of the wind power. Based on the above argument, this research aims at advancing the use of grid connected small wind energy conversion system by an accurate prediction of the power conditioning system reliability. The dependence on the standards for reliability prediction is avoided by considering the Arrhenius Life Stress relation as typically used in highly accelerated lifetime testing procedure [6]. Additionally, the reliability analysis is in the component level which has the benefit that the reliability of each semiconductor device is predictable. The mean time between failures of the power conditioning system is quantified, which can be considered the most widely used parameter in reliability studies [9]. The least reliable component of the power conditioning system is also identified in order to optimize the design consideration of the power electronic interface of a grid connected small wind turbine prior to installation.

The paper is organized as follows: The power conditioning system required for the grid connection of a PMG and WRIG-based system is described in the third section. This is followed by the identification of the most frequent failure subassembly of a small wind energy conversion system from published data in the fourth section. The fifth section presents the mathematical analysis for conversion losses calculations followed by the reliability analysis of the power electronics in the sixth section. Finally, the results of the study are described in the seventh section, and the important finding of the investigation is highlighted in the conclusions.

3. GRID CONNECTION OF SMALL WIND ENERGY CONVERSION SYSTEM

Small wind turbine grid connection power electronics has changed over the years from silicon controlled rectifiers-based converters to optimized AC-DC-AC link. This change has led to less harmonic injection to the grid and has become possible due to low cost digital signal processors and new power devices such as thyristors, MOSFETs, IGBTs. It is well understood that thyristor based converters are favorable in many cases; however, use of a thyristor could require an external measure to circumvent its turn-off incapability via its control terminals. This will increase the cost of the converter system and is undesirable for small wind energy conversion system. MOSFETs are also used but could increase the conduction losses due to high values of forward resistance. In case of the IGBTs, switching times are controllable by suitably shaping the drive signal. This gives the IGBT a number of advantages: it does not require protective circuits, it can be connected in parallel without difficulty, and series connection is possible without dv/dt snubbers. In this research, IGBT based converters are considered in view of its wide ratings, switching speed and most importantly, most of the wind turbine power conditioning system in the market uses these devices. This is extremely important as this research expects to penetrate at the end user level and usually the end users collect their system what is commercially available.

The design concept of small wind turbine has progressed from induction generator based fixed speed, flapping/passive pitching-controlled drive train with gearbox to PMG-based variable speed, furling/soft stall-controlled systems with or without gearbox. There are several power conditioning system options available for a PMG-based system. For instance, PWM IGBT back-to-back converter, matrix converter, intermediate dc/dc converter or line commutated silicon controlled rectifier. However, it is found that losses in an inverter are higher than the total losses in an uncontrolled rectifier and boost converter which is typically used with an intermediate dc/dc converter [17]. This signifies that by using a PWM IGBT back-to-back converter could increase the losses than the intermediate dc/dc converter and consequently could be less effective and reliable. The matrix converter require more switches than the PWM IGBT back-to-back converter and intermediate dc/dc converter and could lead higher losses and subsequently less reliable. The use of a line commutated SCR is also could be an option, however, has some important drawbacks, such as generation of high amplitude/low frequency current harmonics and uncontrollable power factor which is lower than unity. Moreover, it has only one controllable parameter that is the phase angle and could impose more constraint on the control of the system. Furthermore, it is not capable of turning it's thyristor off incase of any failure in the line requires more protection circuitry and control complexity.

Based on the previous discussion, this research adapt an intermediate dc/dc converter based power conditioning system and Fig. 1 shows the schematic for grid connection of a

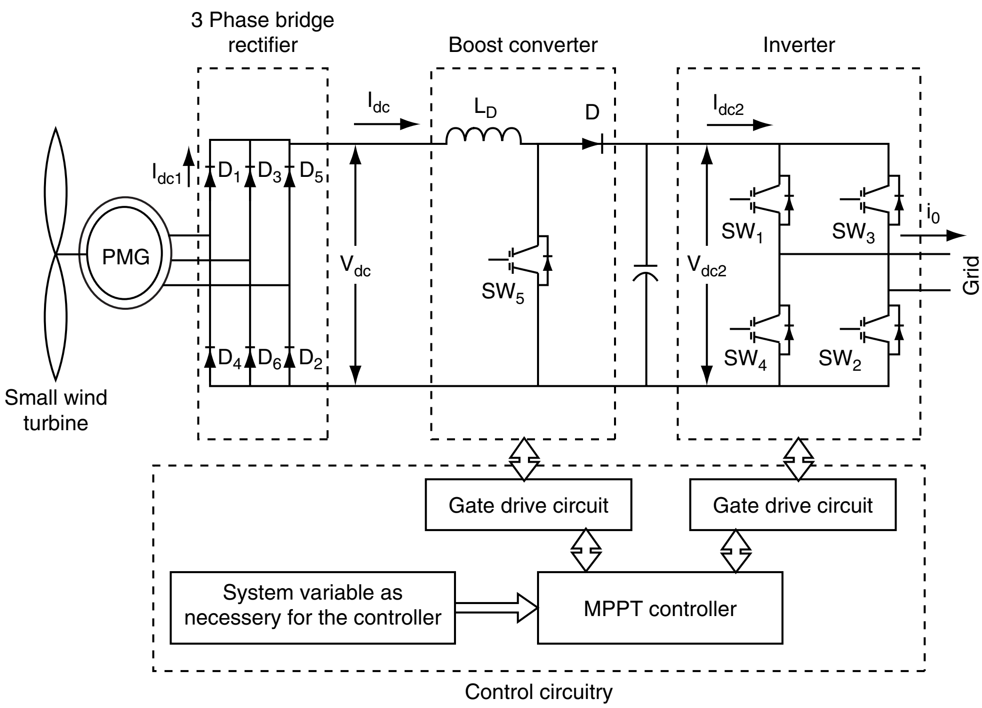

Figure 1: A PMG-based small wind turbine system.

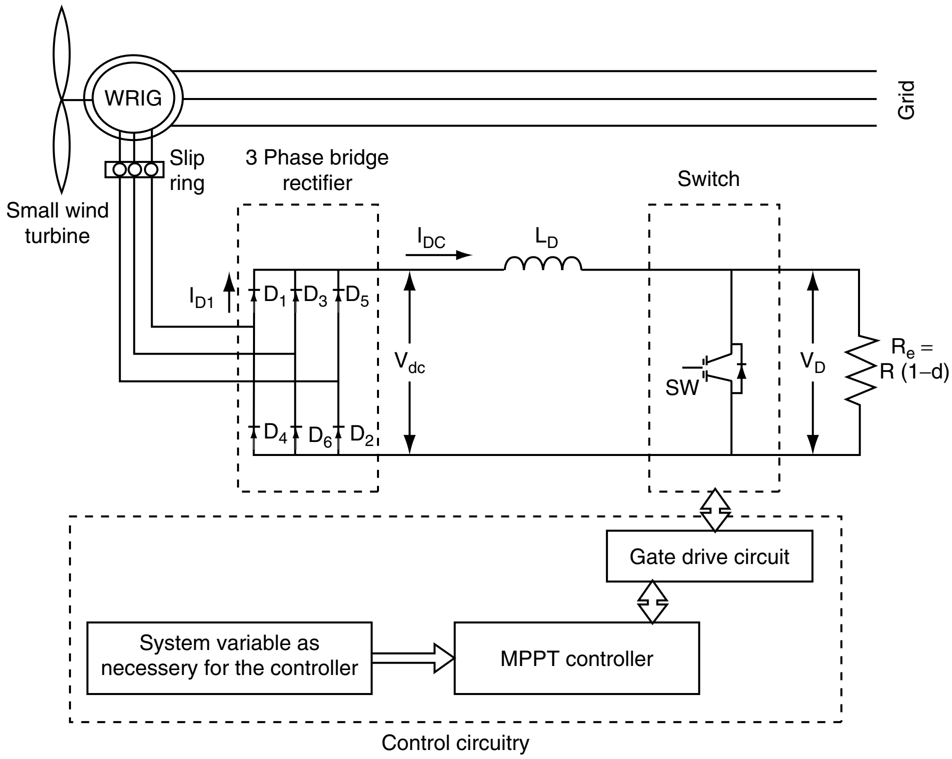

Figure 2: A WRIG-based small wind turbine systems.

PMG-based system. This arrangement employs a power conditioning system that includes a 3-phase bridge rectifier, a boost converter stage and a grid connected inverter. The boost converter boosts the voltage of the dc link as required by the grid-connected inverter. The boost converter or inverter can be controlled to achieve optimum start-up behavior and variable speed operation. Power extraction scheme is typically incorporated in the control of either the boost converter or inverter to achieve high overall conversion efficiency.

The alternative WRIG-based system is shown in Fig. 2. This arrangement is used mostly in large wind turbines. In this arrangement the power conditioning system consists of a 3-phase bridge rectifier, a switch and an external resistance. However, high cost of the induction generator is offset by the reduced cost of the power conditioning system, since only 20–30% of the rated power flow through the slip rings while most of the power flows to the grid from the stator. The switch allows the effective rotor circuit resistance to be varied hence ensuring variable speed operation. The main demerit of this system is that the energy is dissipated in rotor circuit resistance, internal and external, and this energy is wasted in the form of heat. However, the dissipated heat can be used for space heating applications in a useful manner.

4. FAILURE MODES OF SMALL WIND ENERGY CONVERSION SYSTEM

The need for long term field data is of great importance to the evaluation of technical and economical performances. Long term failure and reliability data for wind turbine subsystems are readily available because of the significant (and growing) number of wind turbines of various age, type and location in existence across the world. This information facilitates the identification of the most probable failure subsystems in WECS, and allows optimization of the design features as well as system configuration. A review has been conducted for the failure distribution of small wind turbine subsystems. Data published by

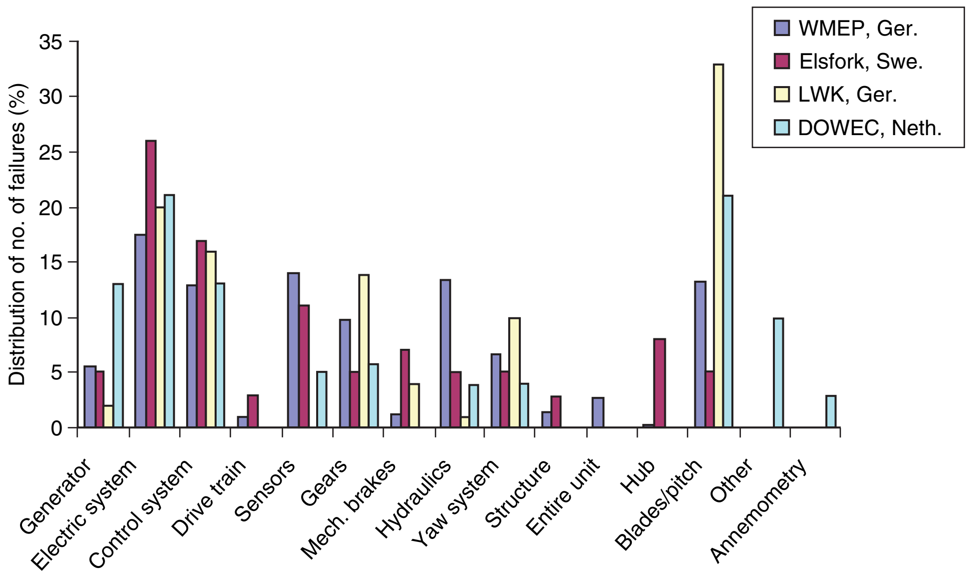

Figure 3: Distribution of number of failures of small wind turbine subsystems.

The Scientific Monitoring and Evaluation Programme (WMEP) in Germany [18], Elsfork, Sweden [19], and Landwirtschaftskammer, Schleswing-Holstein, Germany (LWK) [20] are presented in Fig. 3 along with the large wind turbine data provided by DOWEC project in Netherland [21]. In the review, mechanical subsystems consist of drive train, gears, mechanical brakes, hydraulics, yaw system hubs, and blade/pitch while, the generator, sensors, electric system, and control system comprise the electrical subsystem. The distribution of the number of failure depicted shows that the sum of the failure rates of the electrical related subsystems is higher in contrast to the mechanical subsystems. A completely reverse portrait exists for large wind turbines where the failure mode is principally dominated by the mechanical subsystems. Indeed, the electric and control system composed of power electronic components is an integral part of any power conditioning system which not only dictates the performance but also bear a major fraction of the overall cost for a small WECS. As a whole, in order to ensure high reliability, attention should be focused on small WECS with straightforward but reliable power conditioning system design that ensure easy maintenance and repair as well as less complexity in the control architecture for an optimum life.

5. MATHEMATICAL ANALYSIS

A mathematical analysis of the power losses in the power electronics components, i.e., semiconductors (diodes/IGBTs) is required in order to complete a reliability analysis of the configuration. The losses for the power conditioning systems are strongly dependent on the voltage and current waveforms. Simplified analytical derivation of voltage and current equations associated with the individual semiconductor components are derived to determine the losses. The loss calculation presented in this investigation focus on the losses generated during the conduction and switching states of the semiconductors.

5.1. Loss Analysis in a PMG-based System

For the 3-phase diode bridge rectifier, the losses are calculated for a single diode from the known voltage and current equations. It is assumed that the current and voltage in the 3-phase diode bridge rectifier are equally distributed in the diodes. Knowing the voltage and current for one diode, the losses can be obtained for all the diodes in the bridge rectifier. The conduction losses, $P_{cd,d}^{DB}$ for the diode is expressed as

$$P_{cd1,d}^{DB} = V_f I_{d1} \tag{1}$$

where V_f is the forward voltage drop of the diode and I_{d1} is the on-state current in each diode.

Under the assumption of a linear loss model for the diodes, the switching loss energy in each diode can be linearised with the rated switching loss energy for a reference commutation voltage and current given in the data sheet, and the actual commutation voltage and current and is given by [22].

$$P_{sw1,d}^{DB} = f_{WT} E_{SR} \cdot \frac{V_{dc}}{V_{ref,d}} \cdot \frac{I_{dc}}{I_{ref,d}} \tag{2}$$

where V_{dc} and I_{dc} are the output current at the rectifier output terminal.

The total losses of the 3-phase diode bridge rectifier, $P_{t,d}^{DB}$ for all 6 diodes is given by

$$P_{t,d}^{DB} = 6P_{cd1,d}^{DB} + 6P_{sw1,d}^{DB} = P_{cdt,d}^{DB} + P_{swt,DB}^{DB} \tag{3}$$

The conduction and switching loss of the boost converter is calculated by assuming an ideal inductor (L_D) at the boost converter input. For a boost configuration, the IGBT is turned on for the duration δ, while the diode (D) conducts for the duration $(1-\delta)$. The on-state or commutation current of the IGBT is the input current I_{dc}, while the inverter input current I_{dc2} is given by

$$I_{dc2} = I_{dc}(1-\delta) \tag{4}$$

The conduction loss for the diode and IGBT can be obtained by multiplying their on-state voltage and current with the respective duty cycle and is given by

$$P_{cd,d}^{BC} = I_{dc}(V_{f0} + r_d I_{dc}).(1-\delta) \tag{5}$$

$$P_{cd,IGBT}^{BC} = I_{dc}(V_{ce0} + r_{ce} I_{dc}).\delta \tag{6}$$

The actual commutation voltage and current for the boost converter are the DC link voltage, V_{dc2} and input current to the converter, I_{dc1} respectively. The switching loss for a specific switching frequency of the diode and IGBT in the boost converter are given by

$$P_{sw,d}^{BC} = f_{sw} E_{SR} \cdot \frac{V_{dc2}}{V_{ref,d}} \cdot \frac{I_{dc}}{I_{ref,d}} \tag{7}$$

$$P_{sw,IGBT}^{BC} = f_{sw}\left(E_{ON} + E_{OFF}\right) \cdot \frac{V_{dc2}}{V_{ref,IGBT}} \cdot \frac{I_{dc}}{I_{ref,IGBT}} \tag{8}$$

The sum of (5) to (8) gives the losses of the BC as

$$P_{t,(d+IGBT)}^{BC} = \left(P_{cd,d}^{BC} + P_{sw,d}^{BC}\right) + \left(P_{cd,IGBT}^{BC} + P_{sw,IGBT}^{BC}\right) \tag{9}$$

Most of the small wind turbine systems integrate a single phase inverter for industrial as well as residential application. With the exclusion of snubber circuit, the inverter consists of 4 switches and 4 anti parallel diodes. The conduction losses of a diode and IGBT for the inverter can be expressed as [23],

$$P_{cd1,d}^{INV}=\left(\frac{1}{8}-\frac{M}{3\pi}\cos\varphi\right)r_d I_{om}^2+\left(\frac{1}{2\pi}-\frac{M}{8}\cos\varphi\right)V_{f0}I_{om} \tag{10}$$

$$P_{cd1,IGBT}^{INV}=\left(\frac{1}{8}+\frac{M}{3\pi}\cos\varphi\right)r_{ce} I_{om}^2+\left(\frac{1}{2\pi}+\frac{M}{8}\cos\varphi\right)V_{ce0}I_{om} \tag{11}$$

An approximated solution for the diode and IGBT switching losses at an output current i_o is given by [24, 25]

$$P_{sw1,IGBT}^{INV}=\frac{1}{\pi}f_{sw}\left[E_{ON}+E_{OFF}\right]\frac{V_{dc2}}{V_{ref,IGBT}}\frac{I_{om}}{I_{ref,IGBT}} \tag{12}$$

$$P_{sw1,d}^{INV}=\frac{1}{\pi}f_{sw}E_{SR}\frac{V_{dc2}}{V_{ref,d}}\frac{I_{om}}{I_{ref,d}} \tag{13}$$

The loss of a single phase inverter is obtained as the sum of (10) to (13) and expressed by (14), while the total loss for the power conditioning system of the PMG-based system is expressed by (15).

$$P_{t,(d+IGBT)}^{INV}=P_{cd,d}^{INV}+P_{cd,IGBT}^{INV}+P_{sw,d}^{INV}+P_{sw,IGBT}^{INV} \tag{14}$$

where $P_{cd,d}^{INV}=4P_{cd1,d}^{INV}$ and $P_{cd,IGBT}^{INV}=4P_{cd1,IGBT}^{INV}$ and $P_{sw,d}^{INV}=4P_{sw1,IGBT}^{INV}$ and $P_{sw,IGBT}^{INV}=4P_{sw1,IGBT}^{INV}$

$$P_t^{PMG}=P_{t,d}^{DB}+P_{t,(d+IGBT)}^{BC}+P_{t,(d+IGBT)}^{INV} \tag{15}$$

5.2. Loss Analysis in a WRIG-based System

In a WRIG, a variable resistance in the rotor circuit effectively controls the rotor current as well as the speed of the wind turbine. The actual circuit of a 3-phase WRIG in conjunction with the diode rectifier and switch is shown in Fig. 4. If the rotor leakage reactance are neglected compared to inductor L_D, the equivalent circuit of Fig. 5 is obtained. In the figure, r_1 and x_1 are the stator resistance and reactance respectively; r_2 and x_2 are the rotor leakage resistance and reactance respectively; I_1, I_2 is the stator and rotor current; R_e, R and d represent the effective rotor resistance, actual rotor resistance and duty cycle respectively.

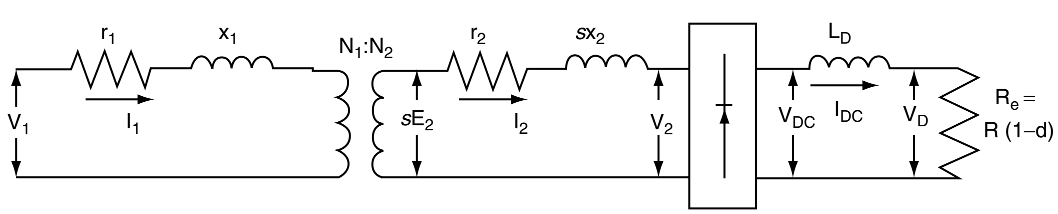

Figure 4: Equivalent circuit of a WRIG.

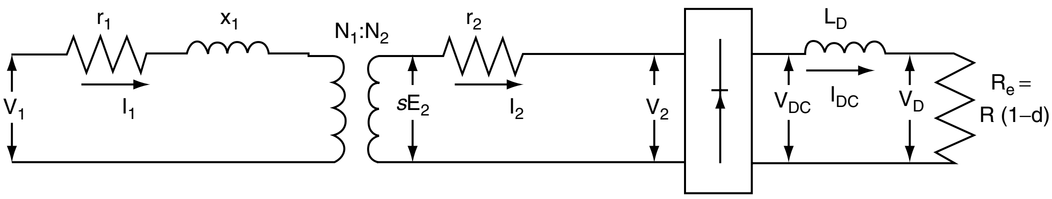

Figure 5: Approximate equivalent circuit of a WRIG.

The stator voltage V_1, referred to the rotor circuit, results in a slip frequency voltage, sE_2 given as

$$(s.V_1.N_2)/N_1 = s.a.V_1 = sE_2 \tag{16}$$

where s is the slip, N_1 and N_2 are the number of turns of the stator and rotor windings respectively and a represents the turn ratio of rotor to stator turn.

The output voltage of the rectifier can be expressed as

$$V_{DC} = \left(3\sqrt{6}s.a.V_2\right)/\pi \tag{17}$$

The voltage V_2 can be expressed as

$$V_2 = (s.a.V_1 - I_2 r_2) \tag{18}$$

The total slip power is given by

$$P_{t,slip} = sP_s \tag{19}$$

where P_s is the power delivered by the stator of the generator and represents the maximum power, P_{max} of the wind turbine.

The losses in the external rotor resistance and switch are given by

$$P_{l,ex}^{R} = V_{DC} I_{DC} \tag{20}$$

where V_{DC} and I_{DC} are the rectified output voltage and current at the rotor respectively.

The sum of the losses in the rotor resistance, rectifier, external rotor resistance and switch is equal to the slip power entering the rotor. Equating the losses to the slip power and assuming that $r_{d1} << R$, results in

$$I_{DC} = \frac{sP_S - 3I_2^2 r_2}{\left[2V_{f0} + \frac{6f_{WT} E_{SR} V_{DC}}{V_{ref,d} I_{ref,d}} + V_{DC}\right]} \tag{21}$$

The total of the losses of the 3-phase diode bridge rectifier for the WRIG-based system is the sum of conduction and switching losses and is given by

$$P_{l,rec}^{DB} = P_{cd2,d}^{DB} + P_{sw2,d}^{DB} = 2V_{f0} I_{DC} + \frac{6f_{WT} E_{SR} V_{DC} I_{DC}}{V_{ref,d} I_{ref,d}} \tag{22}$$

The losses in the slip ring consist of electrical and friction losses. The electrical losses are the sum of the resistive losses in the brushes and slip ring and the losses from the contact voltage drop between the slip ring and the brush. The friction losses are dependent on various factors, such as the area of the brush, number of brushes, friction coefficient, spring force and the speed of the slip ring. In addition, the electrical and friction losses are also dependent on the brush material. The electrical and friction losses due to the rotation of the rotor are given by (23) and (24) respectively, while the total loss of the slip ring is expressed by (25)[26]:

$$P_{l,elec}^{SR} = K_{\omega}\omega \tag{23}$$

$$P_{l,fric}^{SR} = K_{\delta}\omega \tag{24}$$

$$P_{l,sring}^{SR} = P_{l,elec}^{SR} + P_{l,fric}^{SR} \tag{25}$$

where K_{ω} and K_{δ} are constants that depend on the contact voltage drop and friction coefficient respectively. Thus the total losses of the WRIG can be expressed as

$$P_{t}^{WRIG} = P_{l,rec}^{DB} + P_{l,ex}^{R} + P_{l,sring}^{SR} \tag{26}$$

6. RELIABILITY ANALYSIS

Reliability is the probability that a component will satisfactorily perform its intended function under given operating conditions. The average time of satisfactory operation of a system is the Mean Time Between Failures (MTBF) and a higher value of MTBF refers to a higher reliable system and vice versa. As a result, engineers and designers always strive to achieve higher MTBF of the power electronic components for reliable design of the power electronic systems. The MTBF calculated in this paper is carried out at the component level and is based on the life time relationship where the failure rate is constant over time in a bathtub curve [27]. In addition, the system is considered repairable. It is assumed that the system components are connected in series from the reliability standpoint. The lifetime of a power semiconductor is calculated by considering junction temperature as a covariate for the expected reliability model. The junction temperature for a semiconductor device can be calculated as [28].

$$T_J = T_A + P_{loss}R_{JA} \tag{27}$$

P_{loss} is the power loss (switching and conduction loss) generated within a semiconductor device and can be found by replacing the P_{loss} from the loss analysis described in section 4 for each component.

The life time, $L(T_J)$ of a semiconductor is then described as

$$L(T_J) = L_0 \exp(-B\Delta T_J) \tag{28}$$

where, L_0 is the quantitative normal life measurement (hours) assumed to be 1×10^6

$B = \frac{E_A}{K}$, K is the Boltzman's constant which has a value of 8.6×10^{-5}eV/K, E_A is the activation energy, which is assumed to be 0.2 eV, a typical value for semiconductors [29],

ΔT_J is the variation of junction and ambient temperature and can be expressed as

$$\Delta Tj = T_{A1} - T_{J1} \tag{29}$$

The failure rate, λ is described by

$$\lambda = \frac{1}{L(T_J)} \tag{30}$$

The global failure rate, λ_{system} is then obtained as the summation of the local failure rates, λ_i as:

$$\lambda_{system} = \sum_{i=1}^{N} \lambda_i \tag{31}$$

The Mean Time Between Failures, $MTBF_{system}$ and reliability, R_{system} of the system are given respectively by

$$MTBF_{system} = \frac{1}{\lambda_{system}} \tag{32}$$

$$R_{system} = e^{-\lambda_{system} t} \tag{33}$$

6.1. Reliability Analysis for a PMG-based System

The reliability analysis for the power conditioning system of the PMG-based system is performed by the formulation described in section 5. A Matlab program is developed which computes the component junction temperature using the conduction and switching loss formulations as described in section 4. After the determination of the failure rate for each component using (30), the program sums up the failure rates to evaluate the total system failure rates (31). The reliability of the system is obtainable once the system MTBF (32) is known.

6.2. Reliability Analysis for a WRIG-based System

The procedure described in section 5 is used to calculate the reliability of the rectifier and switch for the WRIG-based system. A partial stress prediction method is used to calculate the reliability of the external rotor resistor. The method calculates the failure rate of any component by multiplying a base failure rate with operational and environmental stress factors (electrical, thermal etc). It is assumed that the switch carries a predetermined duty cycle variation. The power loss in the external resistor can be found by simply subtracting the power losses of the switch from the total power loss produced by the rotor rectified voltage and current. Based on this computation, a commercially available resistor is selected and the stress ratio, α is calculated as the ratio of the operating power to the rated power of the resistor.

7. RESULTS

The analytical calculations illustrated in the preceding section were carried out to determine the MTBF and consequently the reliability of the small wind energy conversion system for a pre-assumed wind speed condition. The rated power for the wind turbine is assumed to be 1.5 kW. It is well understood that typically a small wind turbine system operates at low wind speeds most of the time during a year. Thus in order to achieve economic feasibility, it is extremely important to investigate the reliability at low wind speed regime. Generally rated power of a wind turbine system is considered before deployment of a wind energy conversion system even though mostly the wind turbine operates at a fraction of the rated power. As a result, reliability at low wind speed regime are an important aspect from a system for high penetration of wind power to the community. This realistic assumption leads to determine the reliability for a wind speed of 6 m/s. It is assumed for the PMG-based system that the generator speed is proportional to the output voltage of the 3 phase bridge rectifier which provides a rated 280 volt output at the rectifier terminal at the rated rotational speed. The switching frequency for both systems is considered as 20 kHz which is usual for most of the practical applications [25]. In order to investigate the worst case scenario of the power loss in the numerical simulation study, the modulation index is assumed unity and the load current is assumed to be in phase with the output. A standard grid is considered which will reflect the optimum behavior as required by the optimum wind turbine operation. The analytical calculation is based on the data sheet on the EUPEC IGBT module FP15R12W1T4_B3 [30] and the parameters are provided in Fig. 6. The results of the analysis following the procedure outlined are presented in Fig. 7 and Fig. 8 respectively.

The calculation reveals that the power conditioning system failure rate for the PMG-based system is 1.7688×10^{-5} and the MTBF is 5.6537×10^{4} hours (6.5 years). The corresponding figures for the WRIG-based system are 7.2984×10^{-6} and 1.3702×10^{5} hours (15.8 years). It is well understood that the small wind turbine and the power conditioning systems need to be affordable, reliable and most importantly, almost maintenance free for the average person to consider installing one. As can be seen, the need to replace the power conditioning system for the PMG-based system corresponds to the MTBF value of 6.5 years. This leads to a more vulnerable system as compared to the lifespan of the wind turbine system, which is usually 15 to 20 years. Also from the financial standpoint, replacement of such a complex power conditioning system is expensive and needs a highly skilled repair professional. In contrast to the PMG-based system, the WRIG-based system exhibits longer lifetime and remains in a good agreement with the lifespan of the wind turbine, which is 15.8 years.

Housing type	Easy PIMIB
$I_{c,nom}$ (A)	15
V_{ce0} (V)	2.15
r_{ce} (Ω)	0.0833
E_{ON} (mJ)	1.75
E_{OFF} (mJ)	1.20
V_{f0} (V)	0.7
r_d (Ω)	0.07
E_{ESR} (mJ)	0.68
Diode R_{JA} (K/W)	1.05
IGBT R_{JA} (K/W)	1.75

Figure 6: Parameters of the IGBT module.

Quantity	Rectifier	Boost converter		Inverter	
	Diode	Diode	IGBT	Diode	IGBT
Power loss (W)	.5587	4.2581	22.3313	2.05459	7.9621
Junction temperature (°K)	298.8101	304.1742	321.4478	303.5238	314.7205
Life expectancy (hr)	9.895×10^5	9.24×10^5	7.5273×10^5	9.3158×10^5	8.1311×10^5
Failure rate (hr^{-1})	1.0106×10^{-6}	1.0823×10^{-6}	1.3285×10^{-6}	1.0734×10^{-6}	1.2298×10^{-6}

Figure 7: Component reliability for the PMG-based system.

Quantity	Rectifier	Switch	External resistor
	Diode	IGBT	
Power loss (W)	.9028	2.0602	31.5280
Junction temperature (°K)	299.3091	302.3264	---
Life expectancy (hr)	9.8311×10^5	9.458×10^5	7.2464×10^6
Failure rate (hr^{-1})	1.0172×10^{-6}	1.0573×10^{-6}	1.38×10^{-7}

Figure 8: Component reliability for the WRIG-based system.

Fig. 9a shows the reliability of the power conditioning system for a period of one year (8760 hours) for the PMG and WRIG-based system. The result reveals that the reliability of the power conditioning system for the PMG-based system drops to 85.28% after one year, while the reliability of the power conditioning system for the WRIG-based system drops to 93.64% after one year. The reliability of the PMG and WRIG-based system with time is presented in Fig. 9b. It is easily noted that the reliability of the power conditioning system for the PMG-based system reaches less than 50% at 40000 hours (4.5 years), this is obviously unacceptable for high penetration of any specific system. In contrast to the PMG-based system, the reliability of the power conditioning system for the WRIG-based system remains more than 70% at 40000 hours (4.5 years), which certainly could save cost of repair for the system. In both scenarios, the power conditioning system of the WRIG-based system illustrates higher reliability than the PMG-based system. The higher reliability value of the WRIG-based system is certainly advantageous in terms of maintenance and replacement costs.

Following the calculation of the reliability of the systems, an attempt is made to identify the subsystems in the power conditioning system that are the least reliable. To achieve this objective for the PMG-based system, the MTBF of the rectifier is decreased by 50% while the MTBFs of the boost converter and inverter are unchanged. In the same way, the effect of changes in the MTBFs for each of the boost converter and inverter on the system reliability has been calculated and is presented in Fig. 10a. It is observed that the inverter has the most

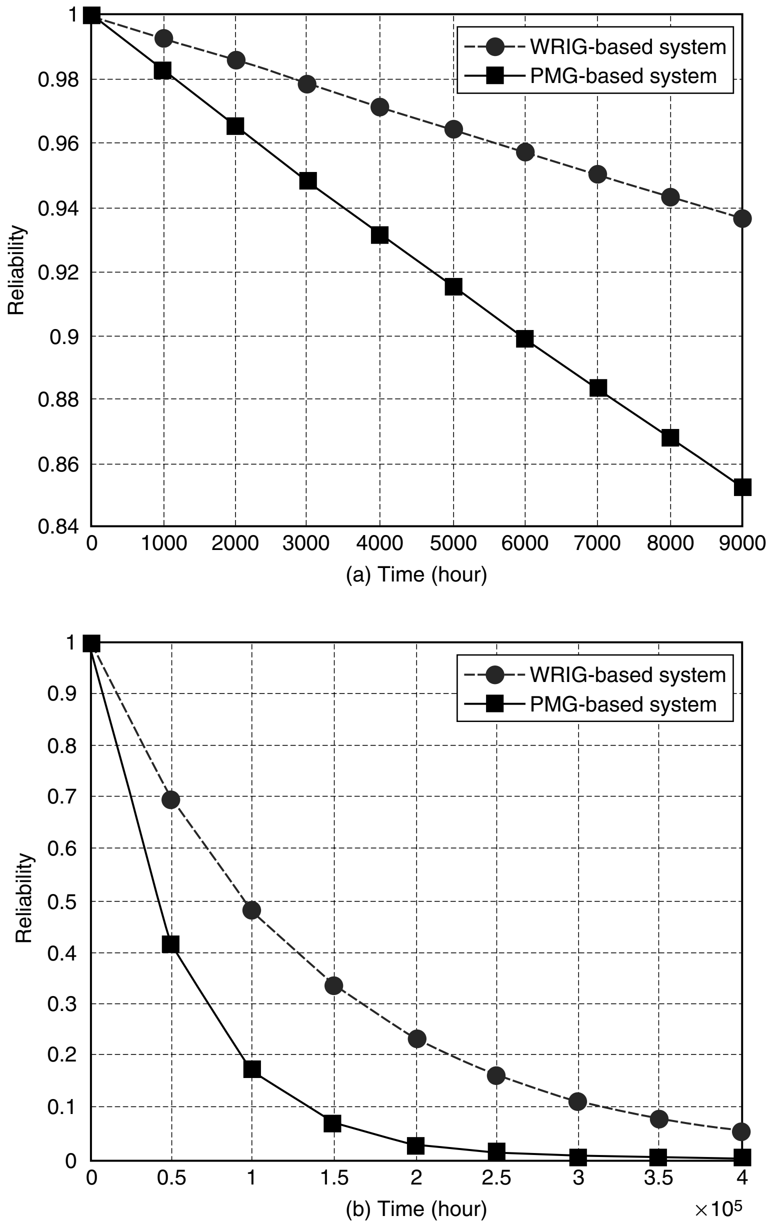

Figure 9: Reliability of the power conditioning system a) Over a year, b) Over time.

dominant influence on the system reliability, while the boost converter has less significant effect than the rectifier. It has been found in the literature that the inverter is the least reliable subsystem [3, 9, 31–33]. This study confirms the results through quantitative analysis. In a similar manner, the effect of the rectifier, switch and external resistor of the WRIG-based system is investigated with a reduction in MTBF of 50% for each, and presented in Fig. 10b. It has been found that the rectifier is the least reliable component in the power conditioning system of such a system. From the financial standpoint, a rectifier is easily replaceable while replacement of an inverter is expensive and needs a highly skilled repair professional. The power conditioning system of the WRIG-based system is composed of fewer parts as well as a lower failure rate. Maintenance and replacement costs of the WRIG-based system will be lower and thus favorable for the small wind turbine industry. As a whole, this research

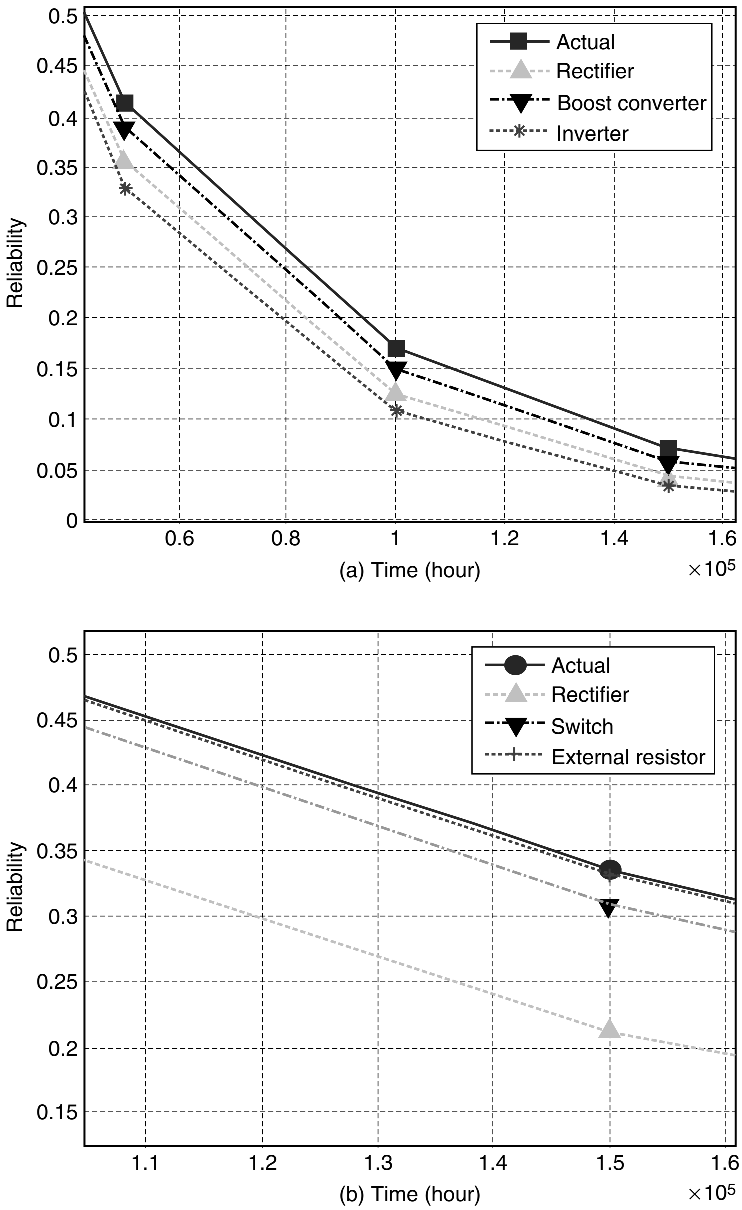

Figure 10: Effect of reliability variation of the components for a) PMG-based system, b) WRIG-based system.

suggests that one should aim for a WRIG-based system that will have a lower failure rate as well as less complex architecture and consequently will be more reliable and less costly during operation.

8. CONCLUSIONS

A brief review of the distribution of failures for small wind turbine subsystems is presented to recognize the frequent failure of subsystems of a small wind turbine system. The reliability analysis of the power conditioning system for a grid connected PMG and WRIG-based system is presented. Temperature is used as a stress factor for the reliability analysis and it is found that the power conditioning system of the PMG-based system suffers from low reliability as compared to the WRIG-based system. The least reliable component of the power conditioning system is identified as the inverter and rectifier for the PMG and WRIG-based system respectively. It is shown that the WRIG-based system with a simple power conditioning system could be an optimum alternative for future research in the small wind turbine system area.

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