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Original Research Article

Reliability Assessment of Conventional Three-Level Inverters for Use in Hybrid Unmanned Aerial Vehicles

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Abstract

This research has investigated the reliability of conventional three-level inverters. In recent years, many multi-level inverters have been introduced and developed. The most well-known of them are Neural Point Clamped (NPC), Floating Capacitor (FC), and Cascade H-Bridge (CHB). Through these structures, various types of multi-level inverters have been created, which are used to achieve higher efficiency, reduce the number of diodes, switches, and most importantly, increase reliability. Increasing reliability in aerospace systems is very important. In this paper, we will determine the reliability of conventional three-level inverters that used in the Hybrid Drone motor drive system. The result shows that the CHB inverter structure is more reliable than the other two types. On the other hand, in applications like hybrid Drone motor drives that use multiple energy sources, the use of the CHB structure provides greater flexibility in design and increases reliability.

Keywords: Reliability; MLI Inverters; Hybrid Drone; Conventional Three-Level Inverters.

1. Introduction

The long-term and continuous use of unmanned aerial vehicles in agriculture, industry, aviation, and defense is very important. In recent years, hybrid unmanned aerial vehicles have been considered from the perspective of using different energy sources to increase flight continuity. The hybrid propulsion system uses an electric motor to generate the required power for the drone's flight. In unmanned aerial vehicles that use only electric motors as an electric propulsion system, low carbon emission, low pollution, low cost, and high efficiency can be counted among their special characteristics. In addition, drones that use only electric propulsion have a wider range of energy sources and can use new energy sources such as lithium batteries, fuel cells, supercapacitors, solar energy, and other sources [2]. Figure 1 shows the components of an unmanned aerial vehicle with hybrid power supply sources.

The structure of an unmanned aerial vehicle is an important part of its mission execution process. Each unmanned aerial vehicle usually consists of parts such as an energy supply system, flight control systems, propulsion systems, communication modules, and energy management systems [3].

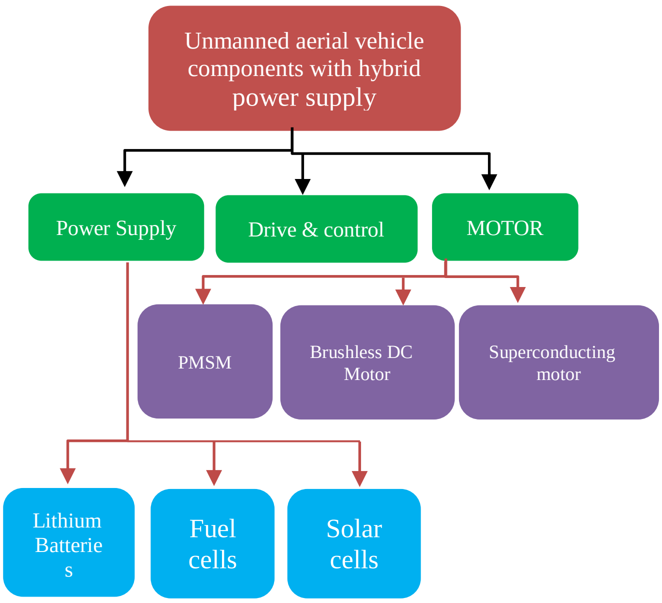

Figure 1. Unmanned aerial vehicle components with hybrid power supply

The structure of an unmanned aerial vehicle with a hybrid power supply system and an electric motor is shown in Figure 2. The battery, solar cell, and fuel cell

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provide the energy mainly used to maintain all the systems and payloads of the drone. The energy management system also controls energy distribution and consumption optimization. In addition, the energy management system is designed to maximize the endurance and range of the UAV and uses intelligent algorithms and artificial intelligence. In systems with electric propulsion, to achieve optimized system energy management and motor control, we need high energy density and low-loss inverters [4]. Some small UAVs often use brushless DC motors or PMSM permanent magnet synchronous motors as propellants because of their high efficiency, energy density, reliability, speed, and ease of control [5].

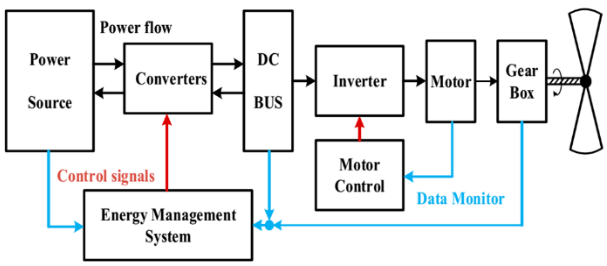

Figure 2. Components of an electric propulsion system for UAVs

Drives with high efficiency and high reliability are used to control these motors. One of the important parts of electric motor drive is the inverter. The precise design of this part plays a very important role in motor performance and increasing efficiency and flight time. In recent years, the use and applications of multi-level inverters in electronic systems have grown increasingly. Most of the research [3] in this field deals with increasing fault tolerance in multi-level inverters. However, no favorable results have been obtained regarding the reliability of multi-level inverters. Considering the increasing expansion of these inverters in the aerospace industry, we need to develop methods to determine and increase the reliability of these inverters. In this research, the structure of conventional multi-level inverters has been used.

The reason for using these structures is the ability to generate high voltage, reduce the common point voltage, output waveform with a better harmonic spectrum, reduce THD and additional harmonics, lower dv/dt for high power applications, reduce electromagnetic interference and reduce the stress of electronic power switches [1]. In this research, the reliability of multi-level inverters for use in hybrid drones has been evaluated.

2. Configuration of conventional multi-level inverters

There are different topologies and control methods for multilevel inverters. Multi-level inverters are divided into two general categories: basic and modern. There are three basic topologies for multilevel inverters.

- Neural Point Clamped or NPC
- Clamp capacitor or FC
- Cascade H Bridge or CHB

The NPC inverter was introduced in the 1990s and has been widely used in flexible AC transmission systems and industrial drives. The FC inverter with three-phase topology was first introduced in the early 1980s. Clamp capacitors smooth the voltage ripple at the switching frequency, but their capacity is small. However, increasing the number of voltage levels leads to some problematic issues: problems in thermal design, low inductance, and insulation. CHB multilevel inverters have been used in various applications, such as telecommunication amplifiers, solar cell inverters, industrial drives, and static synchronous compensators. The main disadvantage of this inverter is a separate power supply for each H-bridge cell [6]. In this article, these three basic inverters with a three-level structure were used. The circuit of each inverter is shown in Figure 3.

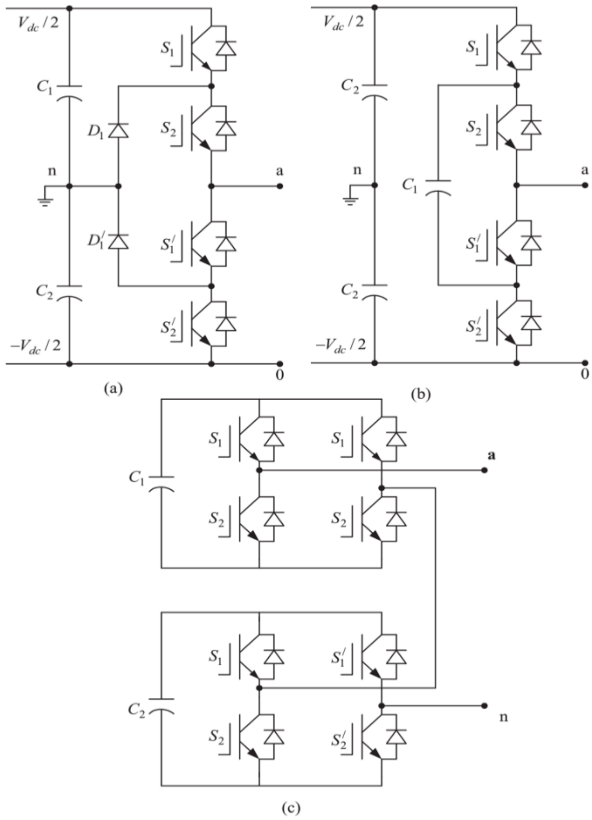

Figure 1. Circuit diagram of three-level inverter **(a)** Neural Point Clamped **(b)** Floating Capacitor **(c)** Cascaded H-Bridge

According to the structure of conventional basic inverters, we will need a boost converter in NPC and FC structures to supply the motor nominal power. On the other hand, the CHB structure does not need elements related to the boost converter circuit. In this case, we simplified the boost converter circuit for reliability assessment and assumed no separate power distribution system existed. Figure 4 shows the structure of NPC and FC inverters with a step-up converter, and Figure 5 shows the structure of the CHB inverter without the need for a step-up converter.

In this research, we used the simplest boost circuit, according to Figure 4, with a switch, diode, and two capacitors and investigated the reliability of three basic structures.

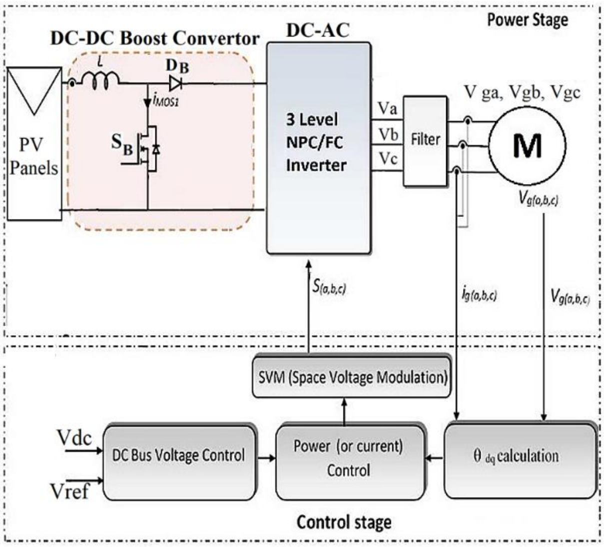

Figure 2. Implementation of inverter with NFC/FC method and voltage boosting converter

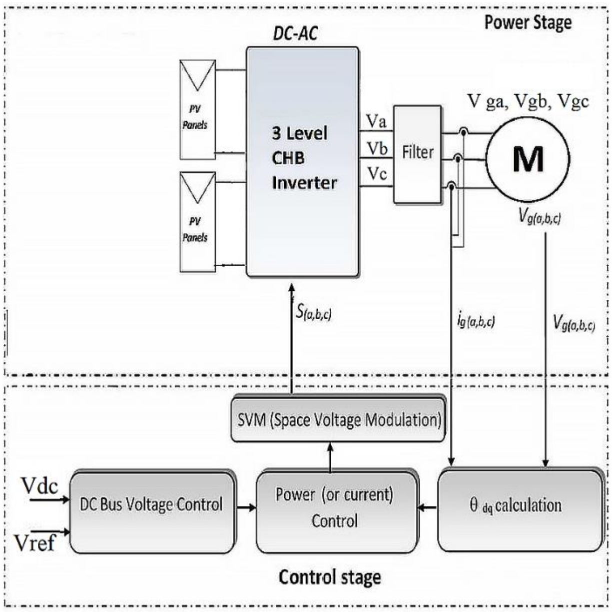

Figure 3. Implementation of CHB inverter without the need for a voltage boosting converter

3. Basic principles of reliability

Electronic equipment manufacturers aim to achieve the highest possible efficiency for each component. Optimum use, including high output quality, long life, and low power loss, is very important in power inverters. Reliability analysis is simply an area of calculating the probability of failure [7]. The reliability of a system depends on various factors. Therefore, to evaluate that system, it is necessary to break it into smaller parts and check the reliability of each part. Different aspects usually evaluate reliability. To determine the reliability of a system, researchers often use indicators such as failure rate, mean time to failure (MTTF), mean time to repair (MTTR), and availability [8]. Therefore, to determine the reliability of a system, it is necessary first to define the basic concepts. Reliability is "the ability of a component to perform the requested function under defined conditions in a specified period" [9].

Most systems include three categories of reliability. These three categories are [10]:

- Software reliability
- Hardware reliability
- Human Reliability

In studies that cover the concept of reliability, a system's reliability is usually considered independent of time, and industrial products should be in the warranty period [8]. Failure over time can be shown in three different periods. The first period is the learning phase. In this phase, the failure rate decreases with time. The length of this period can vary from a few minutes to a few hours. The second period is the failure stabilization phase. This phase shows that the failure does not change with time after the learning phase. The length of this period is random. The third period is the wear stage, which increases the failure rate with time. The combined failure graph can be obtained by combining these three periods into a single time period [10]. This combined diagram can be shown as a risk function called a bathtub curve diagram (Figure 6)[11].

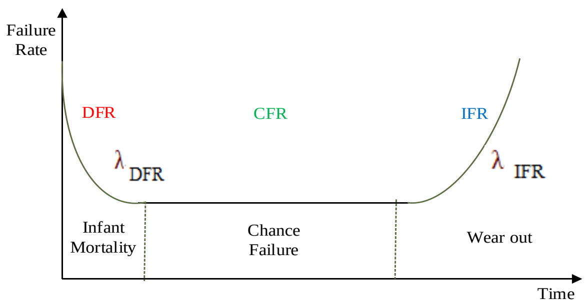

Figure 4. The classical bathtub curve [11]

This diagram consists of three parts [12]:

1. Initial failure or burn-in period, where the risk function decreases with time.
2. Random failure or useful life period, where the risk function is constant.
3. The wear-out period, where the risk function increases.

In the references [8-15], a general reliability assessment of the power electronic system is done. In reference [16], the authors have used condition monitoring to estimate reliability. In reference [17], a reliability evaluation of the DC-DC boost converter with a reliability improvement approach is done. Reliability evaluation of modular multilevel converters (MMCs) as a very important topology should be considered. In reference [18], Rashidi Rad et al. presented the reliability evaluation of modular multilevel inverters with half and full bridge cells based on two methods. Their research showed that modular inverters using half-bridge cells perform better in terms of reliability than full-bridge modular inverters.

However, evaluating reliability and finding ways to improve it is important. For this reason, there are various experimental and practical examples of the reliability of electronic power systems. Anurag et al. analyzed the effect of reactive power injection by inverters in photovoltaic systems on components' thermal performance and reliability [19]. The authors suggested that rules should be established to limit the reactive power injection by photovoltaic inverters.

Isidori et al. investigated the reliability of a three-level back-to-back converter for a 10 MW wind turbine based on the thermal behavior of semiconductors [20]. It was concluded that 60-degree discontinuous pulse width modulation obtains more appropriate thermal performance. In addition, some experimental research has been carried out for the reliability assessment of components widely used in powering electronic devices. For example, a detailed study of the reliability assessment of DC link capacitors is given [21]. Due to the widespread use of semiconductor devices in power electronics systems, evaluating their reliability is necessary and mandatory [22, 23]. For example, the reliability of IGBTs has been evaluated, and their soldering conditions have been identified as an important factor in IGBT module reliability.

4. Failure and failure rate

A failure occurs when the system stops performing the requested function for any reason. Therefore, the no-failure operation is usually a random variable that can be long or short. Failure can be divided into two categories: sudden and gradual. Sudden failure is considered a cataleptic failure, and gradual failure is a degradation failure [24].

Failure rate plays an important role in determining system reliability. The failure rate function can determine the probability of failure at a certain period of time. It can be defined as the failure probability per unit of time in the period$[t, t+Dt]$, when there was no failure before t. The failure rate can be obtained as follows [25]:

$$Failure\ rate = \frac{P(t \le T \le t+\Delta t | T>1)}{\Delta t} = \frac{P(t \le T \le t+\Delta t)}{\Delta t . P(T>t)} \qquad (1)$$

Where $P(t \le T \le t+\Delta t)$ is the probability of failure of T in the time period$[t, t+Dt]$. This probability can be related to the $CDF(f(t))$ and $PDF(f(t))$ of the failure density function [25]:

$$P(t \le T \le t+\Delta t) = f(t)\,\Delta t = F(t+\Delta t) - F(t) \qquad (2)$$

If we show the probability of failure by the failure distribution, the probability of failure occurring in a certain time interval is obtained by the confidence probability distribution, which is the difference between the sum of all probabilities (equal to 1) and the probability of failure. Therefore, we can obtain the reliability function of the constant risk part with the following equation [26]:

$$R(t) = 1 - F(t) \qquad (3)$$

Actually, this function is P(T > t). Therefore, the system's reliability can be obtained directly from the failure density function. Reliability assessment is possible only by knowing the reliability of the components. Component reliability is generally obtained by two failure distribution functions: exponential and Weibull [25, 26].

The value of Δt is usually very small and close to zero. Therefore, by assigning a small value to Δt in the previous failure rate equation, we obtain the failure rate function equation [27]:

$$z(t) = \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{\Delta t . R(t)} = \frac{f(t)}{R(t)} \qquad (4)$$

The failure rate is also denoted by λ. Using the exponential distribution, the probability distribution function with a combination of failure rates is obtained as follows:

$$f(t, \lambda) = \lambda e^{-\lambda t} \qquad (5)$$

Therefore, the reliability function is as follows:

$$R(t, \lambda) = e^{-\lambda t} \qquad (6)$$

It should be noted that the equation [7] is true for the period of constant risk. The failure rate estimated by the average number of failures per time unit is expressed as failure in time (FIT) [8]:

$$1\ FIT = 10^{-9}\ failure/hour \qquad (7)$$

5. Mean time to failure

Mean time to failure (MTTF) is the average time before the first failure of a component or device after it has been put into operation. This failure is such that the device can no longer continue its normal operation. MTTF is usually estimated in hours or thousands of hours and is often used among parts specifications. When a device's MTTF is reported as one hundred thousand hours, it means that the first failure that impairs the device's performance is expected to occur after that time. Two important points should be noted here.

1. The guarantee is only one time. There is no guarantee that the device will fail after a few hours of operation or a hundred thousand hours.

2. This time is the actual operation time of the device. For example, one hundred thousand hours equals about 11 years and 5 months. However, if the machine is used 8 hours a day, this period is actually 3 times longer, about 34 years. The reliability function expresses MTTF and is as follows:

$$MTTF = \int_0^{+\infty} R(t)dt \qquad (8)$$

Where the reliability function should be obtained by $e^{-\lambda t}$. Therefore, the simplest form of MTTF is as follows:

$$MTTF = \frac{1}{\lambda} \qquad (9)$$

6. Mean Time to Repair

Mean time to repair, MTTR is the average time taken to repair a failed device, and its value depends on maintenance conditions [7]. If we assume the time required to repair the system x has a gamma distribution with parameters m and b, then MTTR can be obtained according to reference [28] as follows:

$$MTTF = \int_0^{+\infty} xN(x)dx = \frac{\beta}{\mu} \qquad (10)$$

Where N(x) is the gamma distribution function. By making β equal to 1, the gamma distribution becomes equivalent to the exponential distribution, so the value of MTTR can be represented by $1/_{\mu}$. MTTR is very difficult to calculate and is usually determined empirically by studying previous repairs [29].

7. The average time between failures

Mean Time Between Failures (MTBF) is one of the most important quantitative parameters to help us achieve better maintenance and reliability. MTBF is the mean time between two consecutive failures. In some cases, none of the MTBF definitions can accurately describe the system's reliability. For example, when the distribution function is not exponential, it is practically impossible to predict the time to failure by MTBF [30]. But MTBF can be a good measure to predict emergency failures in systems with random failures and emergencies that may include various failures and components. In references [31, 32], the authors have proven MTBF as a good measure and stated that it provides a suitable combination of MTTR and MTTF measures. MTBF can be obtained from the following equation [33]:

$$MTTF = \frac{1}{\lambda} \qquad (11)$$

In reference [34], the condition-based fault tree analysis (CBFTA) method is used to improve the accuracy of MTBF measurement. In fact, CBFTA is a tool for updating system reliability values and accurately calculating these values. Also, CBFTA is used for system status monitoring. The results show that using CBFTA improves the system's reliability level.

8. Availability and Average Availability

Availability is one of the most important reliability measures and shows the probability of system operation at a given time. The Average Availability or Availability indicates the probability of the desired element functioning under certain conditions in the time period t. The Average Accessibility can be obtained from the following equation [8]:

$$A_{ave} = \frac{MTTF}{MTTF+MTTR} \qquad (12)$$

Therefore, the availability is improved by increasing MTTF and decreasing MTTR. Expressing A_{avg} as $\mathrm{MTBF}/(\mathrm{MTBF}-\mathrm{MTTR})$ is usually avoided [24]. According to the authors of the article [35], increasing the MTTF does not necessarily increase the value of availability and average availability. Also, availability and average availability can be increased without changing MTTF.

9. Method

In this research, two approximate and Markov methods have been used to calculate reliability. In an approximate method, we compare the reliability of different systems by reducing calculations. This method is very important in the initial estimation of the reliability of a system.

10. Approximate method

There are two general approaches to assessing reliability and calculating failure rates. The first method is component counting, which is a simple way to estimate the reliability of a system. This method is preferred when detailed system information is not available. This method uses normal operation conditions as reference conditions to predict the failure rate. However, it may be assumed that the device is not operating at reference conditions, and the actual operating conditions will affect the failure rate calculated from the parts count method. Therefore, this method can be considered an approximate method. In this method, only the number of components is important, and its structure is not discussed. Therefore, this method is typically based on quantitative analysis.

The approximate method used in this article is similar to the method used in reference [36], where the reliability of the three-level NPC and CHB inverter is investigated based on FIT. The voltage difference between the circuit elements is correctly compared in that paper. In this comparison, NPC has used IGBT with medium voltage and CHB with low voltage. In this comparison, the quantity of elements has been the center of attention. The results of that paper showed that in terms of reliability, the NPC inverter is 4.5 times better than the CHB inverter. It is clear that one of the factors required for analysis using this method is the voltage level of the investigated inverters. In fact, this comparison method is like the method of counting parts, where the failure rate is estimated based on the voltage values.

In addition, the comparison has been made when the inverters are connected to the drive. Therefore, it is necessary to make a separate comparison without a drive. As mentioned above, in the first step, we need to find the voltage level of the inverters. According to the authors [36, 37], NPC, FC, and CHB inverters can be classified as high, high, and low voltage IGBT switches. Based on this method, the diode failure rate is always 100FIT, and the high- and low-voltage IGBT failure rates are determined as 400FIT and 100FIT, respectively. Also, the failure rate of the high voltage capacitor is 300FIT, and this parameter is determined for the low voltage capacitor by 400FIT. The failure rate of the whole system can be determined by multiplying the failure rate of the diode, IGBT, and capacitor by their quantity and adding all obtained values. In general, the failure rate of a device in reference conditions can be expressed as follows:

$$\lambda_{SYSTEM} = \sum_{i=1}^{N} \lambda_{ref(i)} \times k \quad (13)$$

Where k is the number of components regarding the failure rate $\lambda_{ref(i)}$ and N is the number of parts.

11. Operating States of inverters

This section presents the main principles of a fault tolerant conventional inverter under OC (Open Circuit) faults of its components. The basic topologies of conventional inverters are presented in Fig 3. According to the fault-tolerant capability of conventional inverters, three main operational conditions can be realized as follows:

- Full Power Operating State (Healthy State)
- Partial Power Operating Sate (De-rated States)
- Total Failure Operating State (Absorbing State)

All converter components are in their healthy operating condition in a full-power operating state, and the inverter operates at its full power capacity. The semiconductor's voltage stresses are low as prescribed by their design specifications; both positive and negative voltage levels drive the load, and therefore, the motor operates in a nominal condition.

In Partial Power operating states, one or several components within the inverter face OC faults, and the inverter can continue functioning at a de-rated operation capacity, i.e., the output power decreases, and the stresses on the inverter components increase. In such circumstances, the inverter does not encounter a full output power cut, making it still possible to serve the motor.

The OC faults under which the conventional inverters operate in a de-rated (partial power) operating state are listed as follows:

- OC faults on one of the switches or simultaneous incidents on corresponding diodes, e.g., OC faults on S1 and S2 switches or D1 and $D1'$ Diodes.
- OC faults on one of the input capacitors,

The Total Failure operating state reflects a total failure of the inverter with no power transfer ability to the motor. The following is a list of conditions where an inverter total failure is realized:

- SC fault in each component,
- Simultaneous OC faults on complementary switches or diodes, e.g., OC faults on S1 and $S1'$, or D1 and $D1'$,
- Simultaneous faults in both input capacitors.

12. The exact method and Markov model

The continuous Markov process is commonly used for probabilistic modeling and solving large-scale problems in various disciplines. In this paper, for exact calculation, the Markov process is used to model and formulate multi-level inverters' reliability and performance characteristics. Proposed Markov models for multi-level inverters are based on OC and SC fault scenarios and corresponding operating states. This process is shown in Figure 7. In this figure, NPC, FC, and CHB inverters are modeled respectively. NPC, FC, and CHB inverters have five, four, and four functional states in their Markov models. The first and last states are designated as the healthy and faulty states, respectively, and the intermediate states reflect the other power reduction operating states (states 2 and 3 for FC and CHB inverters and states 2, 3, and 4 for NPC inverters) [38].

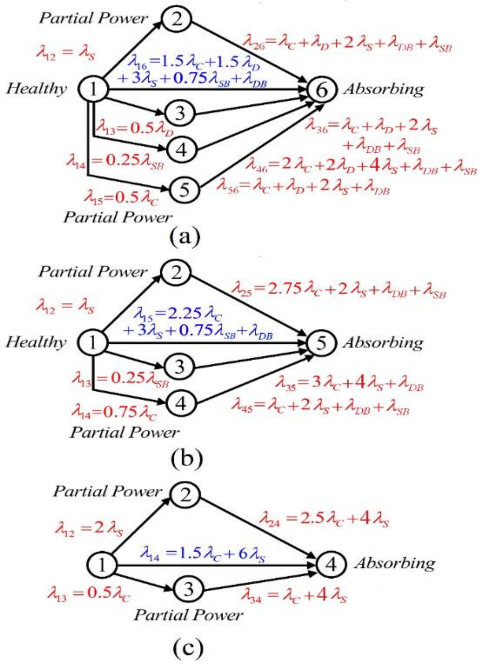

Figure 5. Markov model of the three-level inverters: **(a)** Neural Point Clamped **(b)** Floating Capacitor **(c)** Cascaded H-Bridge

According to the proposed Markov models in Figure7, the reliability of a three-level inverter is evaluated as follows:

$$R(t) = \sum_{i=1}^{S} P_i(t) \quad (14)$$

where $P_i(t)$ is the probability of the i-th operation mode, and S is the total number of healthy operations and operations with reduced power. For example, S for NPC, FC, and CHB inverters are equal to five, four, and three, respectively. Note that R(t) is equal $P_1(t)$ for sensitive loads that cannot tolerate the operating modes of the inverters. To evaluate $P_i(t)$, a state space matrix equation is specified as follows:

$$^{d}/_{dt}\,[P_1(t) \quad \dots \quad P_{s+1}(t)] = [P_1(t) \quad \dots \quad P_{s+1}(t)] \times [A] \quad (15)$$

Where A is calculated from the following equation.

$$[A] = \begin{cases} \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} & \lambda_{16} \\ 0 & \lambda_{22} & 0 & 0 & 0 & \lambda_{26} \\ 0 & 0 & \lambda_{33} & 0 & 0 & \lambda_{36} \\ 0 & 0 & 0 & \lambda_{44} & 0 & \lambda_{46} \\ 0 & 0 & 0 & 0 & \lambda_{55} & \lambda_{56} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} for\ NPC \\ \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} \\ 0 & \lambda_{22} & 0 & 0 & \lambda_{25} \\ 0 & 0 & \lambda_{33} & 0 & \lambda_{35} \\ 0 & 0 & 0 & \lambda_{44} & \lambda_{45} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} for\ FC \\ \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} \\ 0 & \lambda_{22} & 0 & \lambda_{24} \\ 0 & 0 & \lambda_{33} & \lambda_{34} \\ 0 & 0 & 0 & 0 \end{bmatrix} for\ CHB \end{cases} \quad (16)$$

and λ_{ij} $(i \neq j)$ is the failure rate of the inverter from operation mode i to j, which indicates a fault occurrence in that transition. λ_{ii} is defined as the negative sum of other failure rates in row i of matrix A because all elements in each row of this matrix must sum to zero [39]. λ_{ii} is just a mathematical concept that does not relate to any actual fault occurrence. Practical observations show the fact that SC faults are more likely to occur than OC faults in power electronic semiconductor devices [40]. Accordingly, probabilities of 3/4 and 1/4 are assumed in a switch or diode or capacitor experiencing SC and OC faults, respectively, which is reflected λ_{ij} in Figure 7. For example, λ_{26} the NPC inverter in Figure 7(a) is evaluated as follows:

$$\lambda_{26} = (2 \times 0.25\lambda_S) + (2 \times 0.75\lambda_S) + (1 \times 0.25\lambda_D) + (1 \times 0.75\lambda_D) + (1 \times 0.25\lambda_C) + (1 \times 0.75\lambda_C) + (1 \times 0.25\lambda_{DB}) + (1 \times 0.75\lambda_{DB}) + (1 \times 0.25\lambda_{SB}) + (1 \times 0.75\lambda_{SB}) \quad (17)$$

In which, λ_S, λ_D, λ_C, λ_{DB} and λ_{SB} are the switch's failure rate, inverter diode, input blocker and output capacitor, boost diode and boost switch. The failure rate primarily depends on several factors such as quality, material, voltage stress, environmental conditions, temperature, power losses, etc., which are introduced and formulated in MIL-HDBK-217 [41, 42].

It is assumed that the part is located on the failure rate curve of the part during its useful life, which is called the bathtub curve (Figure 6)[11]. As shown in Figure 6, each component has three operating intervals during its lifetime, namely debugging, useful life, and wear [33]. Assuming the initial state of the element as a healthy operating state, the initial conditions in equation (15) are expressed as:

$$[P_1(0) \quad \dots \quad P_{s+1}(0)] = [1 \quad 0 \quad \dots \quad 0] \quad (18)$$

Based on this, $P_i(t)$ is calculated as follows:

$$P_i(t) = \begin{cases} e^{\lambda_{ii}t} & ; i = 1 \\ \frac{\lambda_{1i}}{\lambda_{11}-\lambda_{ii}}\left(e^{\lambda_{11}t} - e^{\lambda_{ii}t}\right); & i \neq 1 \end{cases} \quad (19)$$

For example, P_1 toP_4 for CHB inverter in Figure 7(c) is evaluated as follows:

$$P_1(t) = e^{\lambda_{11}t} \quad (20)$$

$$P_2(t) = \frac{\lambda_{12}}{\lambda_{11}-\lambda_{22}}\left(e^{\lambda_{11}t} - e^{\lambda_{22}t}\right) \quad (21)$$

$$P_3(t) = \frac{\lambda_{13}}{\lambda_{11}-\lambda_{33}}\left(e^{\lambda_{11}t} - e^{\lambda_{33}t}\right) \quad (22)$$

By replacing λ_{1i} $(i = 2, \dots, s)$ and λ_{ii} $(i = 1, \dots, s)$ in figure7:

$$[A] = \begin{bmatrix} -(2\lambda_C + 8\lambda_S) & 2\lambda_S & 0.5\lambda_C & 1.5\lambda_C + 6\lambda_S \\ 0 & -(2.5\lambda_C + 4\lambda_S) & 0 & 2.5\lambda_C + 4\lambda_S \\ 0 & 0 & -(\lambda_C + 4\lambda_S) & \lambda_C + 4\lambda_S \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (23)$$

The reliability of a CHB inverter is evaluated as follows:

$$R(t) = e^{\lambda_{11}t} + \frac{\lambda_{12}}{\lambda_{11}-\lambda_{22}}\left(e^{\lambda_{11}t} - e^{\lambda_{22}t}\right) + \frac{\lambda_{13}}{\lambda_{11}-\lambda_{33}}\left(e^{\lambda_{11}t} - e^{\lambda_{33}t}\right) \quad (24)$$

According to Markov models in Figure7, the reliability of a CHB three-level inverter is evaluated as follows:

$$R(t) = e^{-(2\lambda_C+8\lambda_S)t} - \frac{2\lambda_S}{(2\lambda_C+8\lambda_S)+(2.5\lambda_C+4\lambda_S)}\left(e^{-(2\lambda_C+8\lambda_S)t} - e^{-(2.5\lambda_C+4\lambda_S)t}\right) - \frac{0.5\lambda_C}{(2\lambda_C+8\lambda_S)+(\lambda_C+4\lambda_S)}\left(e^{-(2\lambda_C+8\lambda_S)t} - e^{-(\lambda_C+4\lambda_S)t}\right) \quad (25)$$

Finally, the MTTF reliability criterion is defined as follows:

$$MTTF = \int_{t=0}^{+\infty} R(t)dt = \frac{1}{\lambda_{11}} + \sum_{i=2}^{S} \frac{\lambda_{1i}}{\lambda_{11}-\lambda_{ii}}\left(\frac{1}{\lambda_{ii}} - \frac{1}{\lambda_{11}}\right) \quad (26)$$

where λ_{1i} $(i = 2, \dots, s)$ and λ_{ii} $(i = 1, \dots, s)$ have positive and negative values, respectively. MTTF reliability criterion of the CHB three-level inverter is evaluated as follows:

$$MTTF = \int_{t=0}^{+\infty} R(t)dt = \frac{-1}{2\lambda_C+8\lambda_S} + \frac{-\lambda_S}{2.5\lambda_C+6\lambda_S}\left(\frac{1}{2\lambda_C+8\lambda_S} - \frac{1}{2.5\lambda_C+4\lambda_S}\right) - \frac{0.5\lambda_S}{3\lambda_C+12\lambda_S}\left(\frac{1}{\lambda_C+4\lambda_S} + \frac{1}{2\lambda_C+8\lambda_S}\right) \quad (27)$$

We present the assessment of the reliability evaluation results of three conventional inverters by considering the changes in different dominant parameters D, Vi, Po, n, G, fs, t, and the operational characteristics of the elements. The inverter components are designed with C=100uF. The minimum and maximum acceptable duty cycles are Dmin=0.1 and Dmax =0.5 because the complementary switches must be turned on with non-overlapping voltage pulses to avoid cross-connection of the switches in the same base [43]. Semiconductor elements, which are considered as switches and diodes, have an on-state voltage drop equal to 1V and drain-source resistance of the switch equal to $R_{ds} = 0.049\Omega$, and the diode, voltage drop of 1.5V, and resistance of $R_d = 23m\Omega$. In addition, passive elements are considered non-ideal. With the above design assumptions and element characteristics, the reliability assessment of the mentioned three-level inverters is calculated.

13. Results

Due to the difference in the electronic power circuits' structure and voltage levels, the base failure rate should be calculated separately for each element and topology. The main components of a multilevel inverter generally include the following:

- Diode rectifiers
- DC link capacitors
- IGBT switching devices

Using FIT is one of the standard reliability analysis methods. As mentioned, each FIT is obtained by dividing the number of failures by a billion hours, and inverting the FIT gives us the MTTF. However, a more correct relationship for the failure rate should be:

$$MTTF = \frac{1}{\lambda} \tag{28}$$

According to the mentioned approximate method, and based on the specified FIT values for the circuit components, the MTTF parameters for three conventional three-level/phase (3L-3P) inverters with almost the same performance can be calculated according to Table 1.

Table 1. The approximate MTTF for three inverters

Inverter Type / Component	FC	NPC	CHB
IGBT	12 × 400	12 × 400	12 × 100
Capacitors	2 × 300	5 × 300	3 × 400
Diodes	18 × 100	12 × 100	12 × 100
Total FITs	7200	7500	3600
Failure Rate (*failure/106 hours*)	7.2	7.5	3.6
MTTF	138888	133333	277777

By multiplying the number of elements by their FIT and summing the obtained values, we can calculate the total FITs for each inverter (for example, the number of IGBTs, capacitors, and diodes used in the NPC inverter is 12, 2, and 15 respectively). Summing up all the failure rates to predict reliability means that a failure in any element of the system will cause the system to fail. The MTTF value of each inverter can be calculated using equation (9). The results of this method show that the 3L-3P CHB inverter performs better in terms of reliability. Another parameter affecting its reliability is the number of elements used in the electronic power circuit. The relationship between inverter levels and the number of circuit components is shown in Figure 8:

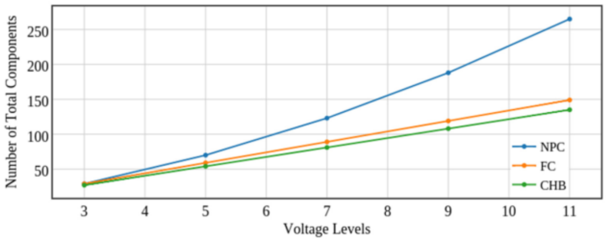

Figure 6. Number of total used components of multilevel inverters with different voltage levels

Using the previous method and reliability estimation, it can be shown that the increase in the number of levels and the number of power electronic circuit components leads to a decrease in MTTF. According to Figure 9, it is evident that the increase in voltage levels in all three inverters causes a severe decrease in the system's reliability. Therefore, it is necessary to provide another method to determine the failure rate to achieve a better analysis.

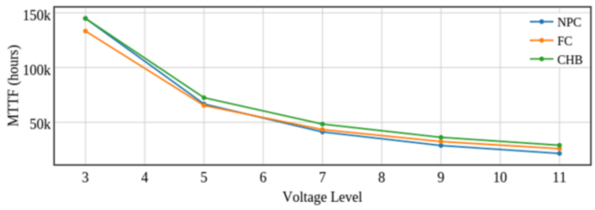

Figure 7. MTTF for different voltage levels

Adopting the exact method involves using equations (16)-(19) and first calculating λ_P for each element and then multiplying these failure rates by the number of each element to obtain the total failure rate. The failure rate of the entire system can be calculated using the following equation (26):

$$\lambda_{SYSTEM} = \sum_{i=1}^{N} \lambda_{Pi} \tag{29}$$

In this method, it is very important to calculate the most influential factor, which is the temperature coefficient π_T. Matlab Simulink software is used to calculate losses in diodes and switches accurately. A 1ohm resistor is used to measure the current.

Equations (16)-(27) are used to calculate π coefficients. Failure rates of each element for NPC, FC, and CHB main three-phase inverters with the same conditions and their values are shown in Tables 4-2. The main specifications of the three considered inverters are similar, and the input voltage, output frequency, and switching frequency are 200 V, 50 Hz, and 20 kHz, respectively. The output power of NPC, FC, and CHB is 2075, 3750, and 2150 watts, respectively. The number of capacitors used in considering inverters is also shown in Table 4.

Table 2. The calculated base failure rates for switches

Type	$P_{Loss}(S)$	$T_C(°C)$	$T_j(°C)$	π_T	π_A	π_E	π_Q	λ_P
NPC	95.27 W	45	68.817	2.288	10	1	5.5	1.511
FC	130.5 W	45	77.625	2.636	10	1	5.5	1.740
CHB	18.46 W	45	49.615	1.637	10	1	5.5	1.080

Table 3. The calculated base failure rates for diodes

Type	$P_{Loss}(D)$	$T_C(°C)$	$T_j(°C)$	π_T	π_C	π_S	π_E	π_Q	λ_P
NPC	11.144W	35	52.830	1.938	1	0.0518	1	5.5	0.0353
FC	0.088W	35	35.140	1.381	1	0.0016	1	5.5	0.0007
CHB	1.118W	35	36.789	1.427	1	0.0128	1	5.5	0.0064

Table 4. The calculated base failure rate of capacitors

Type	Capacitor	$T_A(°C)$	λ_b	π_{CV}	π_E	π_Q	λ_P
NPC	200uF	22.7	0.045	1.471	1	10	0.6619
FC	2200uF	22.7	0.065	0.856	1	10	0.5565
CHB	660uF	22.7	0.102	0.733	1	10	0.7472

The failure rate of the control circuit for all three inverters is assumed to be 0.88, similar to the reference [31]. According to equation (28), the failure rate of the whole system can be calculated by multiplying the number of each unique component by its failure rate and then summing all the values. The final results related to approximate and exact method calculation are shown in Table 5:

Table 5. The calculated MTTF for different multilevel inverters using the Markov method

Parameter/Type	NPC	FC	CHB
Failure Rate (Markov) $(\text{hours}\frac{\text{Failure}}{10^6})$	19.9853	23.6709	15.2784
MTTF (approximate)	50036	42245	65451
Failure Rate (Markov) $(\text{hours}\frac{\text{Failure}}{10^6})$	31.2436	26.1425	17.4567
MTTF (Markov)	32006	38251	57284

The results show that the CHB inverter has better reliability. The results calculated from the approximate method are very different from the exact method. It can be considered that the approximate method is not suitable for reliability evaluation, and the calculated MTTFs are larger than the exact method results. But in this case, the suitability of inverters in terms of reliability is similar for approximate and exact methods. Of course, other factors, such as cost and performance, should also be considered for choosing an inverter. Different methods have been proposed to improve the reliability of electronic power circuits, which is beyond the scope of this article. But in the following, we will try to increase the reliability of the inverter using the series redundancy method.

14. Series Redundancy

In this method, adding series components increases reliability. Therefore, the failure of one component will not lead to the failure of other components and, ultimately, the whole system. Cost is the only limiting factor in the number of series components. In a system with n-series components, the reliability function will be as follows [44]:

$$R(t) = 1 - (1 - e^{-\lambda t})^n \tag{30}$$

According to equation (29), the larger number of series components leads the reliability function to approach 1. Figures 10-12 show the effect of series redundancy on three multilevel inverters, NPC, FC, and CHB:

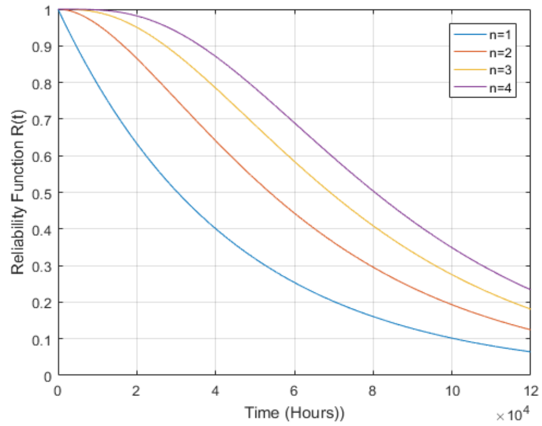

Figure 8. The effect of series redundancy on reliability of NPC.

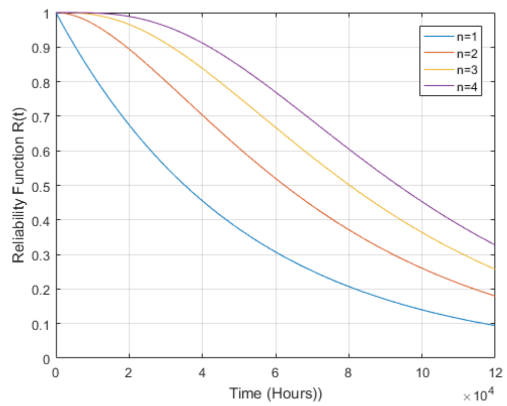

Figure 9. The effect of series redundancy on reliability of FC

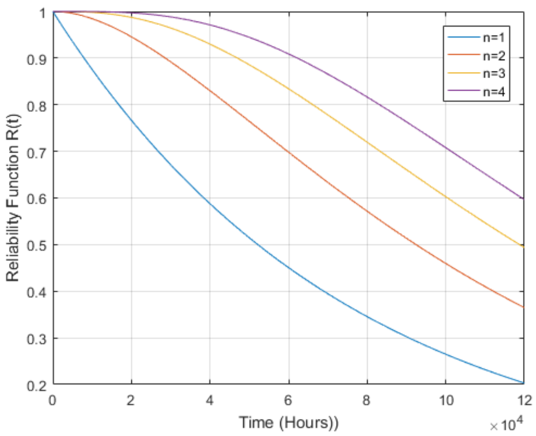

Figure 10. The effect of series redundancy on reliability of CHB

There is a lot of research on electronic power systems reliability. In references [41, 44-47], several redundancy structures and methods have been evaluated to improve the reliability of power electronic circuits. It can be said that in recent years, much attention has been paid to redundant structures in various circuits. For example, different redundancy structures have been proposed for different converters: inverters [48, 49], matrix converters [50], multilevel converters [51], DC-DC converters [52], and power factor correction rectifiers [53] are in these categories. However, a detailed and objective evaluation of many circuits, including multilevel inverters, has not yet been performed. In this paper, we first used approximate and exact methods to evaluate the reliability of three conventional multilevel inverters. However, the reliability of many modern multilevel inverters, including hybrid multilevel cells, has not yet been evaluated.

15. Summary and Conclusion

This research investigated the reliability evaluation of conventional models of multi-level inverters for use in hybrid unmanned aerial vehicles with electric propulsion. In recent years, the reliability of multilevel inverters has been raised as one of the most important research fields. However, a detailed and comprehensive assessment of their reliability and applications has not been done. In this research, the reliability assessment of multi-level inverters was investigated using two different methods (exact and approximate). The approximate method is based on the sum of all reference failure rates to predict reliability. This means that failure in any element of a system causes the failure of the entire system. The results of this method showed that the CHB inverter performs better in terms of reliability. In the detailed method, parameters such as base failure rate, temperature coefficient, stress coefficient, capacitor coefficient, environment coefficient, application coefficient, and connection construction coefficient should be determined. The exact value of the ambient factor is very important, and this factor has a direct relationship with semiconductor power loss. Therefore, Matlab Simulink has been used to determine the switch and diode losses. The results obtained from the exact method are similar to the approximate method, and the exact values for NPC, FC, and CHB are 50036, 42245, and 65451 hours, respectively. The advantage of the exact method is increasing accuracy by considering all the conditions for each inverter. According to the proposed method, it can be concluded that the CHB inverter is the best choice in terms of reliability for systems with hybrid power supply sources. The results confirmed that the predicted failure rate completely depends on the method used. In addition, the series redundancy principle of a basic multilevel inverter was also investigated. The results showed that series redundancy increases reliability. By adding a redundant section for 50,000 hours, the value of the reliability function increased by about 23.26%, 21.24%, and 24.88% for NPC, FC, and CHB, respectively.

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