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# Comparative Study of Reliability and Fault Tolerance of Multi-Phase Permanent Magnet Synchronous Motors for Safety-Critical Drive Trains

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**Abstract** – This paper is a continuation of research on the choice of the optimum type of traction electric motor for safety-critical applications (such as an electrical helicopter), based on the results of previous works. The paper describes a comparative research of the today's most promising type of electric motors for this purpose, namely multi-phase permanent magnet synchronous motor from the point of view of ensuring flight safety requirements. The results of comparative study of those motors with five, six, seven, and nine phases are allowing the selection of the most appropriate electric traction machine for the electrical helicopter regarding specified operating conditions.

**Keywords:** electrical helicopter, multi-phase electric motor, safety-critical drive, reliability, fault tolerance.

## 1. Introduction

According to the plans for the electrification of various types of vehicles on the basis of the electric energy generated by renewable sources, the task of the electrification of air traffic has now become very topical. First of all, the application of electric drives is a promising one for small helicopters designed for search and rescue operations. Besides, the choice of an optimal drive train topology, one of the main components of a traction electric motor, focusses especially on the flight safety.

Due to the constant need of electrical machines for special application cases, there are many publications describing the comparison or analysis of different multi-phase electric machines for different vehicle applications. For electrical machines of special application, such as traction motor for electric airplane or helicopter, the problem is more complicated due to the fact that these machines are only produced in small quantities and that practically no statistical operational data are available.

The main feature of the problem lies in the fact that in this case we are talking about creating a unique, not a serial motor with strict requirements on reliability and fault tolerance (FT). The correct choice of an electric motor for safety-critical drive of electric helicopter is a very important task.

## 2. Objects for Comparative Analysis

Previous studies [1] of the authors of the present paper have shown that the optimal electric machine from the point of view of system approach for the safety-critical drives is a multi-phase permanent magnet synchronous motor (PSM) with distributed stator windings and internal v-shaped arrangement of permanent magnets on the rotor. Study of characteristics and features of multi-phase electric motors is dedicated to a huge amount of research works of various scientists. The most significant results of the research of the issues reliability and fault tolerance of multi-phase electric motors are given in [2]-[10]. Based on a comprehensive analysis of research results, also taking into account own researches, PSM with 5-, 6-, 7-, and 9-phases have been accepted.

## 3. Parameter to Evaluation

For every part of safety-critical drive trains considering the project requirements and conditions of future operations, the most important parameters in term of the flight safety are: reliability and fault tolerance.

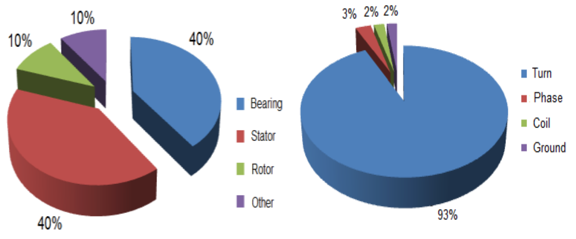
*A. Reliability*

For the safety-critical aircraft applications accurate assessment of reliability and fault tolerance indices of the main traction motor at the design stage of electric helicopter is crucial for further calculations. The main faults in PSMs can be classified as:

- stator winding faults;
- air-gap irregularities (rotor eccentricity);
- bearing failures;
- defects of the permanent magnets.

Each fault disturbs the motor's normal operation producing several symptoms, like unbalanced line currents and air-gap voltages, torque and speed pulsations, decreased efficiency and average torque, excessive heating and increased losses.

The operating experience of electric machines indicates that the most vulnerable elements of electrical machines are the stator windings and the bearings [1]. Statistical data of failure in various parts of electric machines are shown in Fig.1.




(a) (b)

Fig.1. Statistics of the failures of PSM (a) and its stator (b)

Considering the above data charts, generally reliability of electric motor $\lambda_{EM}$ can be determined by the equation:

$$\lambda_{EM}(t) = \lambda_S(t) + \lambda_R(t) + \lambda_B(t) \qquad (1)$$

where $\lambda_S$, $\lambda_R$ and $\lambda_B$ are the failure rates of parts of the electrical machine, respectively of stator (S), rotor (R) and bearing (B). In accordance with the reliability theory, the probability of failure-free operation of a system is defined as:

$$P_{EM} = \exp\{-(\lambda_{SO} + \lambda_{RO} + \lambda_{BO})\} \qquad (2)$$

where $\lambda_{SO}$, $\lambda_{RO}$, $\lambda_{BO}$ are the failure rates of the main parts of electrical machine, which is calculated in considering on defined operating conditions, with correction factors ($k_1$, … , $k_m$) for each operational mode.

On the basis of statistical data, the reliability values were estimated for 5-, 6-, 7-, and 9-phase PSM in comparison with 3-phases machine. Initial data and calculation technique for evaluating are described in [11]-[14]:

- failure rate of complete 3-phase PSM: $\lambda_M = 8.0 \cdot 10^{-7}\ h^{-1}$;

- failure rate of the one phase winding: $\lambda_W = 1.5 \cdot 10^{-7}\ h^{-1}$.

The results of reliability values calculation are presented graphically in Fig.2.

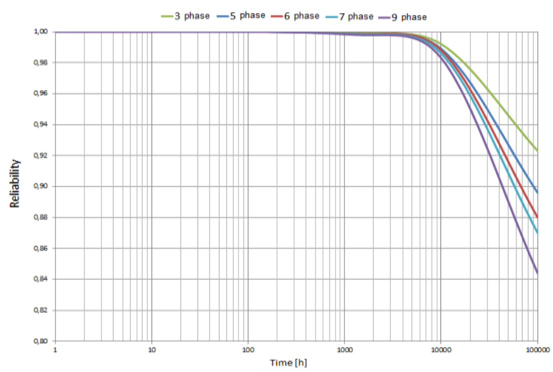



Fig.2. Reliability function R(t) of the 3,5,6,7 and 9-phases PSM

It should be noted that the data in Fig.2 indicate that the specified requirements for the designed helicopter $\lambda > 10^{-9}$/h is not achievable without a functional and/or structural redundancy, and/or other activities that improve the indicators of reliability to the required value. The main goal of presented paper is to show how it becomes possible to achieve the required values.

## B. *Fault Tolerance*

In order to evaluate the degree of fault tolerance for the traction motor of an electrical helicopter, we have analysed three characteristics of electric motor, which have a major impact on its functioning in fail operation mode, such as overload capacity (overheating stability), partial load operational mode, torque ripples for a healthy and failure cases.

Considering a normal (failure-free) operational mode, the electric motor can endure a short-term overload because the thermal capacity is sufficient large, whereas for failure cases the situation is changing dramatically. The largest number of fail operational modes caused by technological electric overloads. The consequences of overload in failure operational modes are overcurrent and overheating of the electrical machine, which lead to a reduction of reliability indices of the motor and a decrease lifetime [15]-[18], as can be seen in Fig.3 and Fig.4.

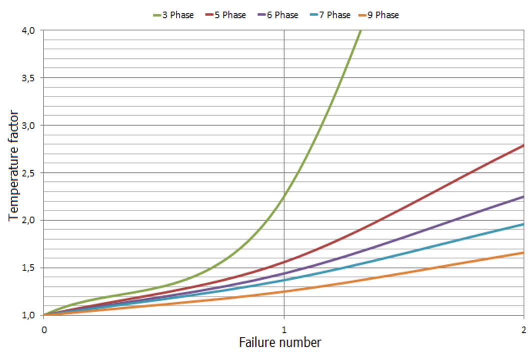



Fig.3. Overheating of stator windings in failure case (one/two phases open-circuit, 100% load)

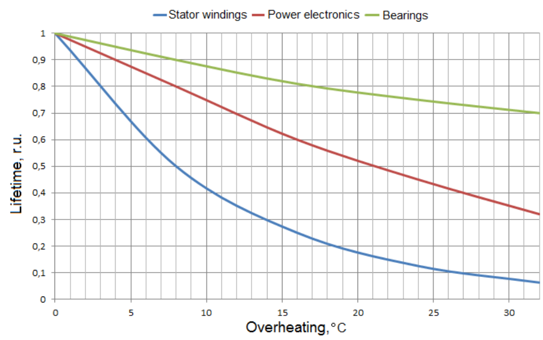



Fig.4. Overheating influence on the lifetime of the parts of electric drive

For the traction motor of the electrical helicopter considering high requirements on the drive reliability and fault tolerance, the overload capability in the fail operational modes is especially important. In such operating conditions, it is also extremely important to be able to operate stably for a specified time on modes of significantly reduced power without undue asymmetry of motor parameters. For comparative evaluation of this parameter based on MATLAB, a qualitative analysis of the potential occurrence of torque ripples in the fail operational modes was carried out.

The consequence of an open-circuit phase failure is strongly dependent on the configuration of the whole drive, e.g. there are differences between star and delta connected windings, as well as between saturated and unsaturated machines. It is not subject of this work to cover all of these possibilities but to give hints which winding configuration possesses higher potential for an acceptable fail operational behavior.

The magnetic air-gap field is a good indicator for potential torque ripples, meaning that it is directly related to most forces occurring in an electric machine. As a consequence the induction in the air-gap is chosen as a basis for the comparison of the winding schemes. For the actual comparison the air-gap field produced by different winding configurations is calculated analytically, neglecting the magnetic field in stator and rotor iron. Since the comparison shall not be restricted to a certain type of machine, the rotor is not defined resulting in the assumption that the rotor consists of an infinitely permeable iron cylinder.

Consequently only the magnetic air-gap field produced by the stator winding is considered. This implies that no definitive statements about e.g. torque ripples can be given, but the possibility of torque ripples due to stator field harmonics can be compared among the different windings.

It is assumed that for all configurations that the phases are not interconnected and each phase is connected to an individual power supply. Furthermore, to assure a certain level of comparability, winding schemes were chosen which cover about the same number of slots. All compared windings form one pole pair, for a higher number of pole pairs the numbers of slots per pole and phase possibly need to be adjusted in order to keep the number of slots constant for all windings. However this does not greatly affect the results.

For the presented study distributed windings with a number of phases that is higher than three are of interest. Four configurations were compared; Table I below contains the information about the windings including their number of phases *m*, the slots per pole and phase $q_1$, the resulting number of stator slots $N_1$ and the short-pitching *s* measured in slot pitches.

Table I. Design of compared electric motors

| *m* | $N_1$ | $q_1$ | *s* |
|---|---|---|---|
| 5 | 40 | 4 | 2 |
| 6 | 36 | 3 | 1 |
| 7 | 42 | 3 | 1 |
| 9 | 36 | 2 | 1 |

The diagrams in Fig.6 show the amplitudes of different harmonics in case of failure of one or two phase windings in relation to the amplitude of the fundamental in the failure-free mode. The values are multiplied with the order of the harmonic in order to achieve a better readability.

All results display the harmonic content of the air-gap field at points in time, when the effect of the phase drop-out is worst. That means for a one phase open-circuit failure, at the point when the phase would carry its maximum current. In case of a two phases open-circuit failure both phases are assumed to be adjacent to each other and the results show a point in time when the sum of the currents in both phases would reach its maximum value.

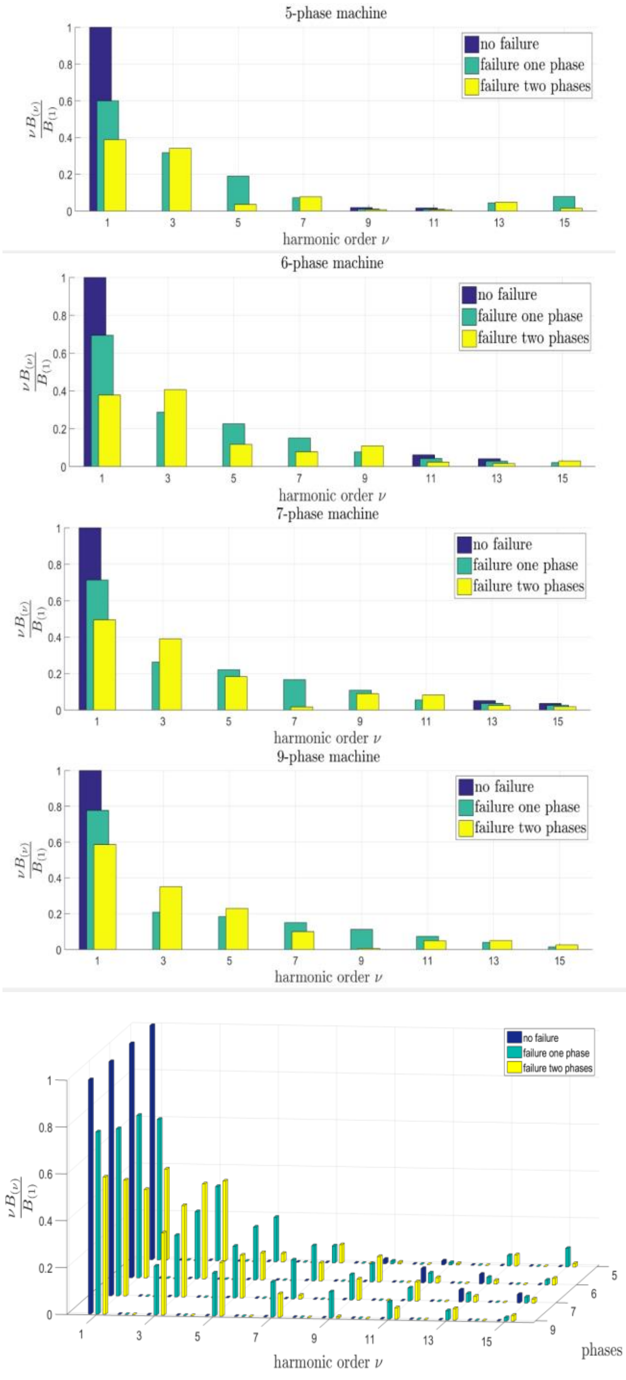



Fig.6. Harmonic content of the air-gap induction

As one could have expected the amplitude drop of the fundamental due to a failure decreases with increasing number of phases. In the opposite sense this tendency can also be applied to the harmonics, i.e. the harmonic content of the air-gap field becomes lower for an increasing number of phases.

However, if the number of phases only differs by one phase, some interesting points become visible. For example when comparing the five phase and the six phase winding it is apparent that the six phase winding (in the given configuration) will perform worse than the five phase winding in case of a two phase open-circuit failures. In turn the six phase winding can be realized using two three phase windings which depending on the application can be an advantage.

In order to choose a winding scheme over another different aspects have to be weighed. Concerning the fault tolerance the tendency is clear that a higher number of phases yields a better behavior in case of certain stator failures.

Based on quantitative analysis of transient processes, given in [19] and [20], have been plotted the graphs of the amplitude values of electromagnetic torque ripple of PSM at the time when the phase open-circuit failure occuring on the number of motor's phases, shown in Fig.7.

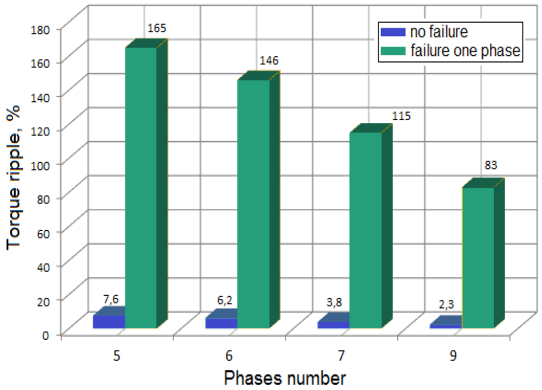



Fig.7. Electromagnetic torque ripple of PSM on the number of phases

On the basis of known quantitative data and results of the own studies were obtained the results of comparing fault tolerance indices of selected electric motors. Preliminary results of qualitative assessment are shown in Table II.

Table II. Preliminary comparison of the fault tolerance

| Phases number Parameter | 5 | 6 | 7 | 9 |
|---|---|---|---|---|
| Overload capacity | 8 | 9 | 9,5 | 10 |
| Partial load mode | 7 | 9 | 8 | 10 |
| Torque ripple | 7 | 8 | 10 | 9 |
| Total | 22 | 26 | 27,5 | 29 |

For more accurate assessment of fault tolerance of each comparable electric motor and for compliance (or non-compliance) with design requirements, based on the block diagram of the model of multi-phase PSM shown in Fig.5, a multi-state reliability Markov model was built, which theoretical base is described in [21] and [22], schematically presented in Fig.6.

The papers [23], [24], and [25] provide practical examples of the successful use of such Markov models studying issues regarding electric drive trains, such as safety, reliability and fault tolerance.

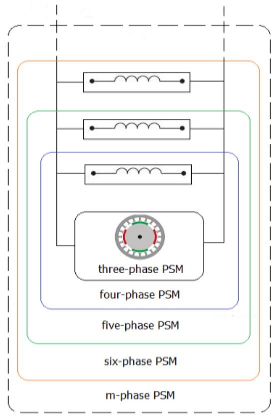



Fig.5. Structural model of multi-phase electric motor

The phase open-circuit failure has been considered as the main dangerous failure for electric motor's stator, i.e. it is the most severe kind of failure, to which less dangerous failures can be summarized. The impact of this failure on the safety operation of the power drive is very significant. In case of such a failure in a stator winding, for example, by wire breakage, the load is distributed according to the remaining intact windings; thereby the respective phase currents and consequently the thermal losses are increasing. As a result, the stator temperature increases which primarily leads to accelerated destruction of the insulation.

In this way, the phase open-circuit failure of a multi-phase PSM can be considered as the main cause for failure in electric drives, since practically all other electrical failures of the motor and the power electronics can be attributed to it [15]. That is why this is the most important and significant failure for the choice of the mostly fault tolerant electric machine's topology.

As shown in the Fig.5 the multi-phase electric motor can be considered as a system with a loaded functional redundancy and consequently, with an appropriate reserve of the fault tolerance.

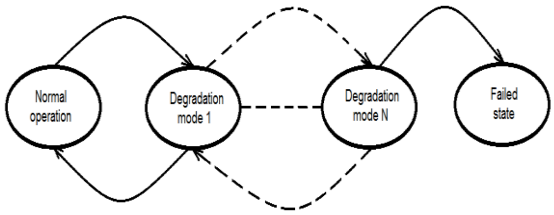



Fig.6. Multi-state Markov model of fault tolerance estimation

It should be noted that the reverse arrows characterize the technical capabilities of the functionality recovery, including the functions of control, monitoring, diagnostics and repair.

Considering the above requirements on the fault tolerance of safety-critical drives, as well as statistical data on the reliability of multi-phase electric motors, it was determined that the optimal model for the analysis of fault tolerance in such conditions is a multi-state Markov model with a minimum of four states, as shown in Fig.7. With one degradative state of traction motor is not feasible realize the required values of fault tolerance.

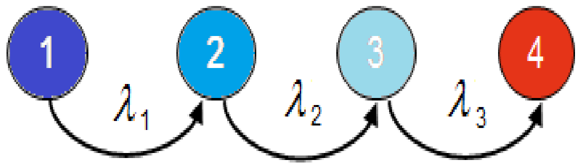



Fig.7. Markov model of traction multi-phase PSM

The first state corresponds to a completely failure-free operation of the PSM. The second and third states are states of degradation and correspond to failure cases – phase open-circuit failure, respectively, of the one and two phases. The fourth state of the model corresponds to the completely failed electric motor when the helicopter's drive completely loses the ability to operate.

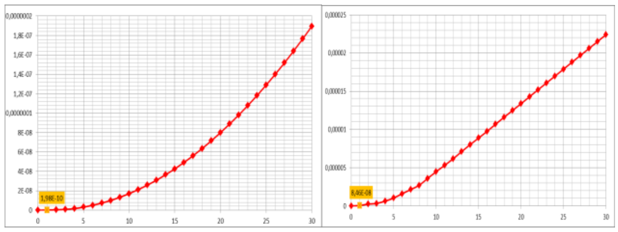
Thus, every following state of the degradation corresponds to one emergency phase loss (or one emergency phase disconnecting) with a corresponding loss of the part of functionality of the electric motor.

The values of the transition probabilities $\lambda$ are calculated based on the results of thermal calculations of the electric motor in emergency conditions, and is largely determined by the overload capacity and thermal stability of the motor, especially of its stator windings.

It should be particularly noted that in the simulation was considered the worst case, critically dangerous variant of failure. In the case of simulation of a not safety-critical failure, as well as the possibility of partial recovery of power drive's operating ability in a degraded state, the value of the fault tolerance will be significantly higher.

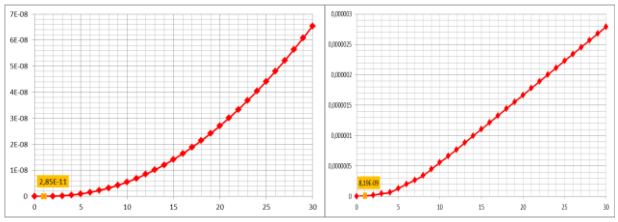
Regarding the design requirements on the fault tolerance of electric helicopter, the reliability of the traction electric motor at nominal load, reducing the power to 65% and 85%, was analyzed using the above Markov model. The corresponding graphs for a different number of phases of PSM are presented in Fig.8-11.

Fig.8-11 contain the following notations: option (a) corresponds to a power reduction of the traction drive to 65% of the nominal value and option (b) respectively to 85% of the nominal power.



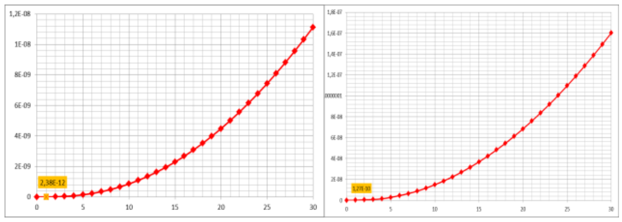
(a) (b)

Fig.8. Probability function of complete failure of 5-phase PSM



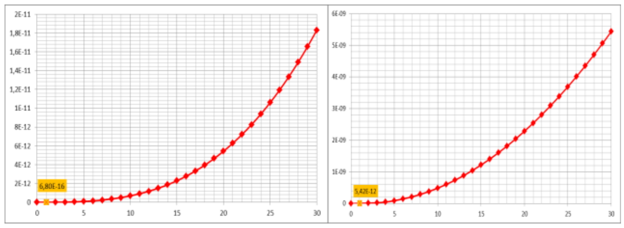
(a) (b)

Fig.9. Probability function of complete failure of 6-phase PSM



(a) (b)

Fig.10. Probability function of complete failure of 7-phase PSM



(a) (b)

Fig.11. Probability function of complete failure of 9-phase PSM

The results of simulation of two consecutive critically dangerous failures allow quantifying the degree of fault tolerance of a multi-phase electric motor, which is a one important part in the traction drive of electric helicopters. 7- and 9-phase PSM have shown the maximum compliance with the requirements relating to the safety-critical drives.

For 5- and 6-phase PSM without significantly reducing the required power and/or the use of additional methods to improve reliability, the desired level of fault tolerance is not achievable.

As further studies of reliability and fault tolerance of safety-critical electrical drives, it is advisable to evaluate the integrated performance of electric drive as a whole, considering the reliability characteristics of electric power source, power electronics and control unit.

It is also of significant interest to quantitatively assess the impact of the maintenance strategy on the reliability and fault tolerance of the motor and electrical drive as a whole.

## 4. Conclusion

The paper presents the results of complex comparative analysis of an important part of the safety-critical drive train – the multi-phase electric motor, including an analysis of the reliability and fault tolerance of electric machines in emergency operational modes.

As compared variants, 5-, 6-, 7- and 9-phase permanent magnet synchronous traction motors were examined. In the study, multiphase motors were examined as 3-phase electric motor with various level of the functional redundancy with a constantly loaded reserve.

On the basis of the developed techniques and models, taking into account the strict requirements on the safety-critical drive of an electrical helicopter, the authors carried out a comparative analysis of the fault tolerance degree of considered multi-phase PSM, which, in turn, led to the conclusion about the optimal range of applicability and feasibility of each compared variant of multi-phase motor considering the specified safety requirements.

It was shown that in case of technical capability of the safe performance reducing (at 30% or more) in emergency operational mode (the first level of degradation) given requirements for safety and fault tolerance can be provided by any of compared multi-phase motors.

If it is not possible to reduce significantly the level of performance in accordance with the requirements of the drive's safety, the electric motors with 7- and 9- phases are preferred.

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