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Availability analysis and quantification of electrical multiphase machines

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Abstract—This article provides a definition of the availability of electrical machines and a method to calculate it. The objective is to propose a method of classifying electrical machines according to their availability and to extract from them the most suitable for applications where the failure of the machine would be critical. The main result of this study is that open-winding machines have the highest level of availability among the studied machines. It also very clearly confirms, through rigorous quantification, that increasing the number of phases improves the availability of electrical machines.

Keywords—Availability – Failure – Synchronous machines – PMSM – Multiphase Machine – Open-winding

I. INTRODUCTION

With the development of electric mobility, the demand for specific electrical machines, their electronics and their control is growing. Historically, the world of electrical machines has developed around three-phase machines, especially those wired in star. Their ease of manufacture and control make them very popular in the industry.

In the field of electric mobility, efficiency, mass and reliability become critical characteristics for some applications. Let's take electric aviation as an example. This is a field where the previously listed features are very important and even critical for reliability. The low redundancy of three-phase machines leads to explore other solutions and mainly multiphase machines.

The world of multiphase machines opens up new perspectives, particularly for the control way. Indeed, the increase in the number of phases and the diversity of possible wiring allow a wide variety of controls and allow to take a step closer to the objective of reliability.

In the literature, there are many works which analyze the reliability of machines [1] to carry out their diagnosis.

Multiphase permanent magnet synchronous machines (PMSM) are often recognized for their degrees of freedom [2]. Those additional degrees of freedom allows lot of control strategy to increase performances or fault tolerance [3], [4], [5].

To our knowledge, there are no rigorous tools to know the ability to convert electrical energy into mechanical energy according to its number of phases and their connection in fault cases.

In order to compare the different wirings of synchronous machines, this article proposes a method for calculating their ability to convert electrical energy into mechanical energy defined as availability. As shown in [6], stator windings represent a large part of faults in electrical machines. Our study therefore focuses on the stator winding and the open-circuit faults [7].

The paper is organized as follows: Section II gives the availability definition in the context of electrical machines. Then, Section III describes the proposed quantification method. The details of the application of this method to different machines are the subject of Section IV. Finally, Section V shows the comparison of the different types of machines from the point of view of availability.

II. AVAILABILITY DEFINITION

A. General definition

The International Organization for Standardization (ISO) defines the availability of a system as its ability to perform its function. Availability integrates reliability and maintainability.

Failure is defined as "partial or total loss of functionality of the system which renders it unable to deliver the specified service".

System failure occurs when one or more faults have reduced the capabilities of the system to the point of rendering it not able to perform its function.

The notion of availability is therefore very interesting because it makes it possible to no longer see the system as being functional or not. It introduces the notion of continuity in the state of the system. The system may then be in a degraded functional state which retains the fully functional application.

B. Availability for electrical machines

In the case of an electrical machines, the availability can be defined as the conversion of electrical-mechanical energy capability. This definition is broad and not suitable for all applications. It does not take into account the level of converted power. It is therefore considered that the machine is available (functioning) when it can ensure an electromechanical conversion. This definition makes it possible to admit faults before arriving at a failure.

The fault is the loss of power converted by the machine. For example, the loss of a winding implies a reduction in

convertible energy and therefore it's a fault but not necessarily a failure. A minimum level of convertible power can be defined for each application as a failure threshold.

III. METHOD FOR QUANTIFYING THE AVAILABILITY OF ELECTRICAL MACHINES

A. Quantification of availability

The convertible power by an electric machine is the result of the magnetic interactions between the rotor and the stator. In the case of PMSM, electrical energy is supplied by the stator windings and creates a rotating magnetic field which drives the rotor. The torque provided by the machine is proportional to the amplitude of this field.

In normal operation, the magnetic field created is circular. This makes it possible to obtain a constant torque. This nominal constant torque at nominal speed is chosen as the reference for the availability quantification. The availability α of the machine is then 100% ($\alpha = 1$) in normal operation.

When a fault occurs, the torque that the machine can deliver decreases and therefore the convertible power as well. If the machine can provide a constant torque equal to half of its nominal torque, the machine then has an availability of 50% ($\alpha = 0.5$).

More generally, the availability of the electric machine can be defined as the ratio between the torque C at time t and the nominal torque C_{nom} .

$$\alpha = \frac{C}{C_{nom}} \quad (1)$$

In fault case, it is often possible to create a torque with an oscillatory component whose average is greater than the available constant torque. In this study, the value of the constant torque available is taken to calculate the availability of the machine.

The torque delivered by the machine is the image of the magnetic field generated by the stator. This rotating field is the result of the vector sum of the components created by each of the windings of the machine. These components have a magnitude which is an image of the number of turns of the winding multiplied by the current through it. Their argument in the electrical reference is mechanically fixed by the structure of the machine. The mechanical reference is a contraction of p times the electrical reference, with p the number of poles pairs of the machine.

A normalized magnitude with respect to their nominal current is used. The resultant flux $\overrightarrow{\Phi}_{Stator}$ created is then:

$$\overrightarrow{\Phi}_{Stator} = \sum_{i=1}^N L_i I_i \overrightarrow{X}_i \quad (2)$$

With N the number of phases of the machine, I_i the instantaneous current in the winding i , L_i its inductance and \overrightarrow{X}_i whose argument is the angle of the winding in the electrical reference and of modulus 1. In the case of a balanced three-phase machine, for example, the arguments of the components of \overrightarrow{X}_i are 0 , $\frac{-2\pi}{3}$ and $\frac{2\pi}{3}$. Then the electric machine availability can be defined as the ratio between the magnitude of the reachable circular field and the magnitude of the field in healthy mode.

$$\alpha = \frac{\|\overrightarrow{\Phi}_{circular\ reach}\|}{\|\overrightarrow{\Phi}_{circular\ healthy}\|} \quad (3)$$

B. Electrical constraints

In order to study the availability of a machine, the connections (e.g. the electrical dependencies) between its windings must be considered. For example, the relationship between the currents in a three-phase machine wired in star without neutral output is:

$$\sum_{i=1}^3 I_i = 0 \quad (4)$$

Or

$$I_1 = -(I_2 + I_3) \quad (5)$$

So, there are two independent currents and a constrained current in a three-phase machine wired in star without neutral output.

In this case, the circular field is achievable only if all three windings are healthy. Indeed, in case of fault of an open-circuit in a winding, the electrical dependence requires that the current be identical in the two remaining windings. Therefore, the resulting field created is unidirectional. The circular rotating field reachable by the machine is then zero. The machine is no longer available ($\alpha = 0$).

These electrical constraints are important in the availability of electrical machines, because they set the conditions of application of the currents and therefore of the resulting magnetic field.

They are also the source of great diversity within electrical machines and their controls. Depending on the different wiring, the electrical constraints change and therefore the availability in case of fault.

C. Magnetic constraints

The magnetomotive forces induced by the various windings of the machine create magnetic fluxes through the magnetic circuit of the machine. This circuit also imposes its constraints due to its geometry and the chosen materials.

It is thus necessary to take into account the phenomena of magnetic saturation in the availability of the machine. For this, the currents magnitude can be limited to the nominal current magnitude of the machine.

The geometry of the stator and the rotor fixes the angle of each winding in the electrical reference. This gives a family of magnetic flux vector holomorphic to the family of current vectors. The link between the resulting magnetic field and the electric currents is carry out. It is then possible to obtain a circular rotating magnetic field by applying the appropriate currents.

D. Other constraints and limitations

The differences in wiring vary other parameters such as the number of wires coming out of the machine, the number of joints (welding or other), the proximity of the windings between them or even the number of inverter legs of the power electronics necessary to control the machine. These parameters affect the reliability of the machine but they are not taken into account in this study.

The electric machine has other limits, including a thermal limit. It is defined by the maximum total losses that the machine can dissipate in continuous operation. The losses are mainly composed of the Joule losses in the windings and the iron losses in the magnetic circuit. Joule losses mainly depend on the magnitude of the current in the windings and the real part of their impedance which

increases with temperature and frequency (by skin effect). Iron losses increase with frequency and level of induction.

Thus, the electric machine has a nominal current for each operating point. Indeed, if the nominal torque is requested at zero speed, the currents in the windings are continuous. The effective current in certain windings (depending on the position of the rotor) is then greater than their effective current at the nominal operating point of the machine.

The currents in the windings can be considered as periodic when their period is less than the thermal time constant of the machine.

The machine can accept temporary overloads, especially in torque. This is an interesting option, useful in certain applications (starting an electric car for example). It can also be used in case of fault to partially compensate for the loss of power or to attenuate torque oscillations. In this case, the thermal limit becomes secondary. Machine capacities are then limited by applicable voltages to the windings and magnetic saturations.

IV. CALCULATION OF AVAILABILITY FOR DIFFERENT PMSM

In this section, the availability will be quantified for different PMSM with different wirings when one or more open-circuit faults occur. The objective is to provide a generic tool for classifying the different types of wiring according to their availability after a fault.

A. Availability for three-phase and five-phase machines

1) Case of three-phase machines wired in star without neutral point access

In the case of a three-phase machine wired in star without neutral point access, it can first study the electrical constraints imposed by this wiring. In this case, the sum of the currents is zero to respect Kirchhoffs current law.

In normal operation, three currents can be applied to obtain a circular rotating field:

$$\begin{cases} I_1(\theta) = I_{nom} \cos(\theta) \\ I_2(\theta) = I_{nom} \cos\left(\theta - \frac{2\pi}{3}\right) \\ I_3(\theta) = I_{nom} \cos\left(\theta + \frac{2\pi}{3}\right) \end{cases} \quad (6)$$

With I_{nom} the nominal magnitude of the currents in the machine and θ the electrical rotor angle.

These currents respect the electrical constraint (4) in healthy mode. The corresponding circular rotating field can be calculated:

$$\|\overrightarrow{\Phi_{circular\ healthy}}\| = L_1 I_1(0) + L_2 I_2(0) \cos\left(\frac{-2\pi}{3}\right) + L_3 I_3(0) \cos\left(\frac{2\pi}{3}\right) \quad (7)$$

Now, assume that an open-circuit fault appears in winding 1. In this case the availability of the machine drops to zero due to the electrical constraints as explained in III-B.

The three-phase machine wired in star without neutral point access therefore has zero availability ($\alpha = 0$) after a single fault.

2) Case of three-phase machines wired in star with neutral point access

Now let's look at the same machine but with neutral point access where a current can be applied to it thanks to a bridge arm available for the neutral wire.

a) Fault with one open-circuit

In the case of an open-circuit fault in winding 1, I_1 is zero. However, access to the neutral point makes it possible to absolve the previous electrical constraint. It is possible to apply two different currents in windings 2 and 3. As mentioned previously, these two windings generate flux which are not collinear in the electrical reference. This allows, by combining them, to obtain a circular resulting rotating field weaker than the machine's healthy mode field.

To calculate the magnitude of the resulting rotating field, the vectors corresponding to the healthy windings are projected onto the direction of the faulty winding. In fact, the direction of the faulty winding is also that of the direction of contraction of the reachable field.

The magnitude of the reachable circular field in this defective direction is obtained:

$$\|\overrightarrow{\Phi_{circular\ reach}}\| = \left| L_2 I_{nom} \cos\left(\frac{-2\pi}{3} - \frac{\pi}{6}\right) \right| + \left| L_3 I_{nom} \cos\left(\frac{2\pi}{3} - \frac{\pi}{6}\right) \right| \quad (8)$$

So, the availability after a fault is:

$$\alpha = \frac{\left| L_2 I_{nom} \cos\left(\frac{-2\pi}{3} - \frac{\pi}{6}\right) \right| + \left| L_3 I_{nom} \cos\left(\frac{2\pi}{3} - \frac{\pi}{6}\right) \right|}{\left| L_1 I_{nom} \cos\left(\frac{-\pi}{6}\right) \right| + \left| L_2 I_{nom} \cos\left(\frac{-2\pi}{3} - \frac{\pi}{6}\right) \right| + \left| L_3 I_{nom} \cos\left(\frac{2\pi}{3} - \frac{\pi}{6}\right) \right|} = \frac{1}{2}$$

In this case, the machine can provide half of its healthy mode torque after a fault. This is true to obtain a constant torque (whatever θ). It is possible to obtain a higher average torque by adding a variable component along θ .

b) Fault with two open-circuits

When two of the three phases of the machine are in open-circuit fault, for example on windings 1 and 2, the remaining winding 3 can generate a magnetic field in the direction of $\frac{2\pi}{3}$ in the electrical reference. This field is then the only component of the resulting magnetic field and its projection on the $\left(\frac{2\pi}{3} + \frac{\pi}{2}\right)$ direction is zero whatever its magnitude:

$$\cos\left(\frac{2\pi}{3} - \left(\frac{2\pi}{3} + \frac{\pi}{2}\right)\right) = 0 \rightarrow \|\overrightarrow{\Phi_{circular\ reach}}\| = 0 \quad (10)$$

The availability of the machine is then zero.

3) Case of five-phase machines wired in star with neutral point access

For a five-phase machine wired in star with neutral point access, the currents and the generated flux are oriented at $0, \frac{2\pi}{5}, \frac{4\pi}{5}, \frac{6\pi}{5}$ and $\frac{8\pi}{5}$ in the electrical reference. For the sake of simplicity, the nominal currents are assumed the same in all the windings of the machine and equal to I_{nom} .

First, the circular field in healthy mode is calculated. It can be noted that the reachable field is a regular polygon: a hexagon in the case of three-phase machines and a decagon in the case of five-phase machines. The magnitude of the maximum circular field is then the radius of the inscribed circle of this polygon, i.e. its apothem h :

$$\begin{cases} \|\overrightarrow{\Phi_{circular\ healthy}}\| = h = \frac{2LI_{nom}}{\tan\left(\frac{\pi}{N}\right)} \text{ if } N \text{ is even} \\ \|\overrightarrow{\Phi_{circular\ healthy}}\| = h = \frac{LI_{nom}}{\tan\left(\frac{\pi}{2N}\right)} \text{ if } N \text{ is odd} \end{cases} \quad (11)$$

With N , the number of phases of the machine and I_{nom} the amplitude of the nominal currents.

a) *Fault with one open-circuit fault*

When one phase of the machine is in open-circuit fault, the circular field contracts in the direction of the faulty winding. The magnitude of the reachable circular field is:

$$\begin{aligned} \|\overrightarrow{\Phi_{circular\ reach}}\| &= \left| LI_{nom} \cos\left(\frac{2\pi}{5} + \frac{\pi}{10}\right) \right| \\ &+ \left| LI_{nom} \cos\left(\frac{4\pi}{5} + \frac{\pi}{10}\right) \right| \\ &+ \left| LI_{nom} \cos\left(\frac{6\pi}{5} + \frac{\pi}{10}\right) \right| \\ &+ \left| LI_{nom} \cos\left(\frac{8\pi}{5} + \frac{\pi}{10}\right) \right| \end{aligned} \quad (12)$$

The availability after this fault is:

$$\begin{aligned} \alpha &= \frac{\|\overrightarrow{\Phi_{circular\ reach}}\|}{\|\overrightarrow{\Phi_{circular\ healthy}}\|} \\ &= \frac{\tan\left(\frac{\pi}{10}\right)}{LI_{nom}} \\ &\times \left[\left| LI_{nom} \cos\left(\frac{2\pi}{5} + \frac{\pi}{10}\right) \right| \right. \\ &+ \left| LI_{nom} \cos\left(\frac{4\pi}{5} + \frac{\pi}{10}\right) \right| \\ &+ \left| LI_{nom} \cos\left(\frac{6\pi}{5} + \frac{\pi}{10}\right) \right| \\ &+ \left. \left| LI_{nom} \cos\left(\frac{8\pi}{5} + \frac{\pi}{10}\right) \right| \right] \end{aligned} \quad (13)$$

α is about 69%.

b) *Fault with two open-circuit fault*

In this case, the fault can occur in two phases at different angles from the first one in the electrical reference, i.e. $\frac{2\pi}{5}$ and $\frac{4\pi}{5}$. This implies two possible levels of availability.

Intuitively, if the two defect phases are angularly close to the first one, weaker reachable circular field would be expected.

This proximity is calculated in the interval $\left] -\frac{\pi}{2}; \frac{\pi}{2} \right]$ (electric half-plan) because the vectors \vec{X}_i whose argument is not include in this interval gives a resultant in the interval when their associated current magnitude is negative. So the fault at $\frac{2\pi}{5}$ in the electric reference is at $\frac{2\pi}{5}$ of the first fault and the fault at $\frac{4\pi}{5}$ is considered at $-\frac{\pi}{5}$ from the first one.

The availability of the machine in both cases are:

$$\begin{aligned} \alpha_{\frac{2\pi}{5}} &= \frac{\tan\left(\frac{\pi}{10}\right)}{LI_{nom}} \times \left[\left| LI_{nom} \cos\left(\frac{2\pi}{5} + \frac{\pi}{10}\right) \right| \right. \\ &+ \left| LI_{nom} \cos\left(\frac{4\pi}{5} + \frac{\pi}{10}\right) \right| \\ &+ \left. \left| LI_{nom} \cos\left(\frac{8\pi}{5} + \frac{\pi}{10}\right) \right| \right] \end{aligned} \quad (14)$$

= 50%

$$\begin{aligned} \alpha_{-\frac{\pi}{5}} &= \frac{\tan\left(\frac{\pi}{10}\right)}{LI_{nom}} \times \left[\left| LI_{nom} \cos\left(\frac{2\pi}{5} - \frac{\pi}{10}\right) \right| \right. \\ &+ \left| LI_{nom} \cos\left(\frac{4\pi}{5} - \frac{\pi}{10}\right) \right| \\ &+ \left. \left| LI_{nom} \cos\left(\frac{6\pi}{5} - \frac{\pi}{10}\right) \right| \right] \end{aligned} \quad (15)$$

≈ 38%

It appears that the angular proximity of the faults in the electrical reference increases their overall impact on the reachable circular field.

4) *Case of five-phase open-winding machines*

Open-winding machines are machines where both sides of each winding are accessible. It is possible to wire them as desired outside the machine (wired in star for example), but it is also possible to supply each winding separately as in [8] with a dedicated full-bridge inverter.

From the point of view of electrical constraints, open-winding machines are similar to machines wired in star with neutral point access. It is possible to apply whatever the desired current in each winding even if one of them has fault. The calculations give an availability $\alpha = 69\%$ for a fault with an open winding and $\alpha = 50\%$ and $\alpha = 38\%$ for a fault of two open windings at respectively $\frac{2\pi}{5}$ and $\frac{\pi}{5}$ in the electrical reference.

B. *Generalization for N-phase machines*

The geometric approach for the calculation of availability after a fault can be generalized for machines with N phases for certain types of machine wiring.

1) *Case of N-phase machines wired in star*

a) *Machines wired in star without neutral point access*

This connection leads to an electrical constraint which forces the sum of the currents to be zero all the time. To determine their availability, it is necessary to know, in the electrical reference, the direction in which the reachable circular field is limited. For this, the vector projection of the different current vectors in a direction with a combination of current validating the electrical constraint of this wiring is carried out. It gives:

$$\|\overrightarrow{\Phi_{circular\ reach}}\| = \max \left[\sum_{i=1}^{i=N} LI_i \cos(\arg(\vec{X}_i) + \gamma) \right] \quad (16)$$

With

$$\gamma \in \left] -\frac{\pi}{2}; \frac{\pi}{2} \right]$$

And

$$\left[\sum_{i=1}^{i=N} LI_i \cos(\arg(\vec{X}_i) + \gamma) \right] \leq \left[\sum_{i=1}^{i=N} LI_i \cos(\arg(\vec{X}_i) + \beta) \right]$$

$$\forall \beta \in \left] -\frac{\pi}{2}; \frac{\pi}{2} \right]$$

And the constraint

$$\sum_{i=1}^{i=N} I_i = 0, \quad I_i \in [-I_{nom}; I_{nom}] \forall i \quad (17)$$

The search for γ can be reduced to the set of perpendiculars to the vectors \vec{X}_i in the electric reference, namely:

$$\gamma \in \left\{ \arg(\vec{X}_i) + \frac{\pi}{2} \right\} \text{ mod } \pi$$

Indeed, the reachable field is always a convex polygon whose sides are composed by the vectors $LI\vec{X}_i$. The largest reachable circle is therefore limited by one of the sides of the polygon. It is one of the limiting vectors \vec{X}_i which is tangent to the reachable field circle.

The corresponding availability can be deduced easily by using (3) and (16) but it's necessary to now $\|\overrightarrow{\Phi_{circular\ healthy}}\|$. In the case of machines wired in star without neutral point access, the apothem of the polygon in healthy mode can be calculated with (11) if N is even but it is lower if N is odd:

$$\begin{cases} h = \frac{2LI_{nom}}{\tan\left(\frac{\pi}{N}\right)} & \text{if } N \text{ is even} \\ h = \frac{LI_{nom}}{\tan\left(\frac{\pi}{2N}\right)} \times \cos\left(\frac{\pi}{2N}\right) & \text{if } N \text{ is odd} \end{cases} \quad (18)$$

b) Machines wired in star with neutral point access

With access to the neutral point and its possible control, there is not Kirchhoff's current constraint. From the point of view of availability, these machines can be considered as open-winding machines in the case of open-circuit faults of the windings.

In order to calculate the availability of the machine, it is necessary to know the electrical angle in which the reachable circular field is limited and its value. For this, the formula (16) can be used. However, the Kirchhoff's constraint (17) is no longer applicable.

The availability is then obtained by dividing the magnitude of the reachable circular field of (16) by its nominal magnitude h calculated with (11).

c) M-star machines

The case of machines wired in M star-subsystems [9] is similar to machines wired in star. The case where each star-subsystem is identical will be considered here. Each star-subsystem then supports $\frac{1}{M}$ of the machine's availability in healthy mode. In case of a complete failure of one star-subsystem, the machine has an availability of $\frac{M-1}{M}$. More generally, if P star-subsystems are completely failure, the overall availability of the machine is expressed as follows:

$$\alpha = \frac{M - P}{M} \quad (19)$$

It is possible that a star-subsystem is faulty but provides a lower torque than its nominal torque. In this case, the availability of this star-subsystem can be calculated by using (16) and integrated into the calculation of the overall availability of the M -star machine. This last can be calculated by summed the participations of each subsystem in each direction of the electrical reference.

A first approximation of the overall availability can be estimated by:

$$\alpha = \sum_{j=1}^{j=M} \frac{1}{M} \alpha_j(M_j) \quad (20)$$

With $\alpha_j(M_j)$ the availability of each star-subsystem.

(20) is an approximation because it does not take into account the possibility that one subsystem can compensate for a fault on another subsystem. Due to this approximation, the sum of availability of each subsystem is lower than the real availability.

This formula is applicable in one star-subsystem fault whether with or without neutral point access. It can be simplified as:

$$\alpha = \frac{M - 1}{M} + \alpha_d(\vec{X}_d) \quad (21)$$

With $\alpha_d(\vec{X}_d)$ the availability of the subsystem in fault. If the subsystem is a completely failure, $\alpha_d(\vec{X}_d) = 0$.

2) Case of open-winding machines

The formulation of the availability of open-winding machines is quite close to M -star machines. Indeed, each winding supports $\frac{1}{M}$ of the power of the machine.

A winding alone cannot create a rotating field. So, its availability is zero even without any fault. The availability of open-winding machines is an emerging notion of each winding state. When a winding is healthy, it creates a magnetomotive force contrary to a failure winding where the current in the winding can no longer be controlled.

The magnitude of the reachable circular field $\|\vec{\Phi}_{circular\ reach}\|$ is identical to that of machines wired in star with access to neutral point given by (16). So, using formulas (11) and (16), the availability can be formulated:

$$\alpha = \frac{\|\vec{\Phi}_{circular\ reach}\|}{h} \quad (22)$$

There is no electrical constraint due to the wiring like (17) for open-winding machines.

3) Generalization of the availability calculation method

More overall, it is possible to calculate the availability of any type of electrical machine, even that of unbalanced machines or those with more exotic wiring.

In the general case, the availability calculation takes the same form as described in III-B (16). The principle is to find, in the electrical reference, the direction in which the reachable circular field is limited.

To do this, it is possible to break down the machine into various subsystems (such as N -star for example) and sum the participations of each subsystem. It is necessary to sum participations for each of the directions in the electrical reference.

V. COMPARISON OF THE AVAILABILITY OF THE DIFFERENT STRUCTURES OF ELECTRIC MACHINES

This section compares the availability of different types of machine using the previous formulas. Fig. 1 shows the example of the availability of these machines after one or two faults depending on the number of winding and the type of wiring in the machine.

From this comparison, it can be noted first that increasing the number of windings increases the availability regardless of chosen wiring.

The second interesting point is the superiority of open-winding machines compared to a classical one with the same number of windings. Indeed, after a fault, their availability is greater than that of the machine wired in star without neutral point access. Moreover, open-winding machines do not require specific management of the neutral point like machines wired in star with neutral point access.

VI. DISCUSSION

The proposed method makes it possible to quickly calculate the level of availability of an electrical machine in the event of a fault. In this article, the study is limited to open-circuit faults. Short-circuit type faults [10] are more complex to deal with but can be integrated into this method as electromagnetic constraints, just like magnetic saturation phenomena and thermal constraints. The vector point of view in the electrical reference allows equation simplification of the electric machine and the use of geometric formulas.

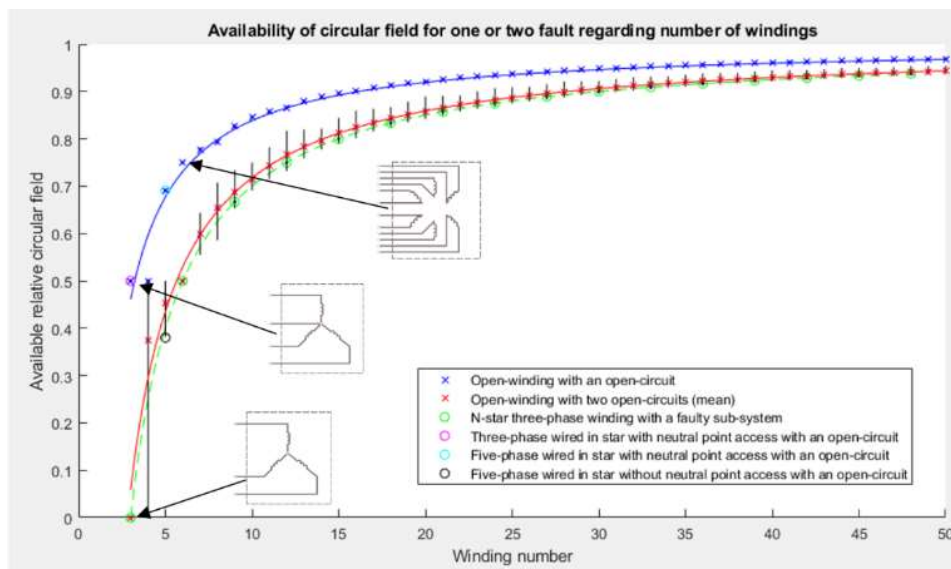


Figure 1 Availability of different structures of machine after a fault (higher is better)

This method does not consider the material and technological constraints of electric machines. Indeed, this method brings out the open-winding machines as being better from an availability point of view, but this type of machine also has some technical constraints, such as the increase of number of wires coming out of the machine and number of power electronics components.

Likewise, machines wired in star with access to the neutral point are considered equivalent to machines with open-winding. Unfortunately, the neutral wire and its power electronic are not useful in healthy mode and must support a large part of the availability in default case. Open-winding machines have the advantage of not having a neutral wire. They also guarantee more easily the electrical insulation between the various windings, in particular thanks to the toothed winding.

Machine availability can only be reached if the control strategy is able to apply the necessary currents. In fault case, required currents have different waveform and phase from healthy mode currents.

Thus, a technological vision must be provided in order to take full advantage of the proposed method and to choose the machine wiring most suited to the intended application.

VII. CONCLUSION

A definition of the availability of electrical machines and a method for quantification have been proposed. This method makes it possible to classify electrical machines according to their availability and therefore to choose a type of machine suitable for the intended application. Classification of electrical machines according to their availability leads to the conclusion that increasing the number of windings increases the availability of the machine. This study concludes that open-winding machines are widely available and therefore useful in applications such as electric aviation where a high level of reliability is required.

Experimental validation of the theoretical results will be made on a laboratory test bench. The availability quantification can be taken into account for fault tolerant

control of electrical machines. In principle, this proposed quantification method can be applied very widely to any type of electrical machine. The generalization of its formulation will be performed in further works.

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