Assessment Techniques to Ensure Reliable Electrical Insulation for More Electric Transportation

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***Abstract*—Partial discharge testing of complete, low-voltage induction machines and dry-type convertor transformers for the More Electric Transportation is discussed. The current standard (i.e. IEC 60034-18-41, 60317-0-1 and 61378-1) offers very few answers to the new challenges posed to the insulating systems reliability of these increasingly electrified electrical machines. Based on tests performed on different kind of specimens and the literature, the most promising assessment technique to ensure a reliable insulation is based on optical sensors. In addition, this work seeks to give some precise, but simple, indications on how to take into account the effect of altitude and high frequency in the qualification of an insulation system for More Electric Transportation and the limits of the different standards involved are highlighted.**

***Index Terms*—Partial Discharges, Insulation, Windings, High frequency, More Electric Aircraft, More Electric Vehicles.**

I. Introduction

Environmental protection and energy efficiency are among the most interesting topics in an increasingly energy-intensive, connected and populous planet. The replacement of traditionally non-electric systems (such as hydraulic and mechanical actuators) with electrical counterparts in aircraft is the concept pursued by the More Electric Aircraft (MEA) philosophy to achieve greater efficiency, reducing weight and fuel consumption and, consequently, emissions. For the road transportation the challenge continues towards electric mobility, with electric vehicles (EVs) that will change the structure of our network and global energy consumption patterns, towards greater use of renewable and clean sources.

In every sector where electricity is produced or used, the penetration of power electronics is growing, with converters becoming increasingly central elements in the networks and fundamental for the electrification of transport. The new technologies of wide band-gap semiconductors (WBG) such as silicon carbide (SiC) and gallium nitride (GaN) allow the realization of components with higher characteristics than those made with silicon, allowing the realization of power modules with higher and higher voltages and shorter switching times. The market for WBG modules is driven by the transport, aerospace and power generation sectors, which are the first to benefit from technological progress. Here, smaller, lighter and more efficient WBG converters promise great benefits.

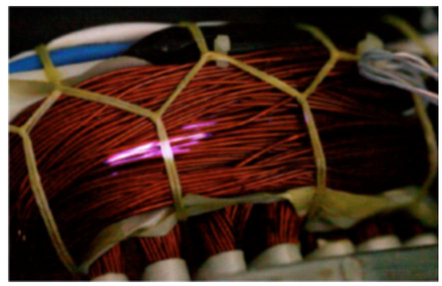

Fig. 1. A typical phase-to-phase insulation failure [4].

The benefit in terms of performance of their use has been highlighted, but the stress generated by these new devices poses critical problems to the insulation system of all connected equipment. The voltage steps with steep rise front that are generated, in the order of magnitude of nanoseconds or tens of nanoseconds, propagate like waves inside the electrical systems through connections and cables, reaching the powered components, which must be designed and characterized to withstand the stress.

In addition, thanks to the superior thermal characteristics of the WBG MOSFETs and the growing demand for power density, the installed voltages are increasing in the transportation sector [1]–[3]. This fact, combined with not always favourable weather and environmental conditions, leads to the need to pay great attention to the design of electrical insulation systems.

On the other hand, the standards on the qualification of electrical insulating systems affecting motors, actuators and high-frequency transformers used in the transport sector is struggling to meet the emerging needs described above.

This work aims, first of all, to highlight the main weaknesses of the normative references currently in use. After that, there will be a broad discussion on possible alternative methods, still under study, that could be used to qualify the insulation systems of future electrical machines used in the More Electric Vehicles and Aircraft.

II. Definitions and limits of the current standards

The rising electrification of transports is radically changing the design of the electrical systems on board, whether it is an

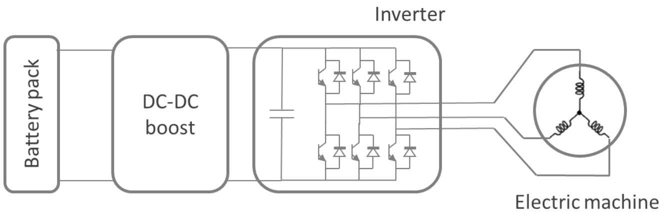

Fig. 2. BEV typical power distribution system [5].

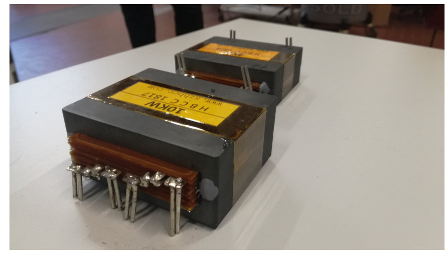

Fig. 3. An example of planar high-frequency ferrite power transformer for DC-DC converters.

aircraft, rather than a car or a ship. Although there is a certain difference in the possible architectures adopted, the presence of the following components is always guaranteed at a certain point of the power distribution line [1]:

- high frequency dry-type power transformer;
- inverter;
- ac synchronous electric machine.

Fig. 2 shows an example of the distribution line on board an full-electric plug-in vehicle. The parameters that characterize these systems are typically a DC bus voltage of about $700\,\mathrm{V}$, switching frequencies of a few hundred kHz, a thermal class that can reach up to 200 and possible operation in altitude [6] (planes easily reach more than $15\,\mathrm{km}$ high, while cars $3\,\mathrm{km}$ when they go to the mountains).

The part most affected by these operating conditions, beyond the electronics, is the insulating system of the various components. The standards that help to design, test and qualify these elements correctly, however, are not ready for the many problems that have arisen with the advent of the More electric Aircraft and the More Electric Vehicle.

In an orderly fashion, the basic parameter to which reference must be made for the qualification and design of the insulation is the Partial Discharge Inception Voltage ($PDIV$) [7]. However, when a converter is used, because of the impulsive waveform (square wave), it is difficult to identify in practice the exact moment in which the partial discharge (PD) activity begins [8], so one must be satisfied with the so-called Repetitive PD Inception Voltage ($RPDIV$). This quantity is of great interest because the PD activity is very harmful to the polymers. Once triggered, the polymer chains that make up the insulation break and carbonized pathways are created, quickly leading to a catastrophic failure of the entire electrical system [10]. In electrical machines connected to an inverter, therefore, it is essential to identify the $RPDIV$ for each of its insulating systems. The latter are generally divided into turn-to-turn (t-t), phase-to-phase (p-p) and phase-to-ground (p-g).

Applying the IEC 60034-18-41 [7], designed specifically for low-voltage rotating machines, during the $RPDIV$ tests of systems intended for electrified transport, the following problems are encountered:

- the electromagnetic noise generated by the WBG devices completely overlaps with the PD signals detected by an antenna;
- in the case of vacuum chamber tests to simulate altitude, very high waiting times between one voltage step and the next are required;
- there is not an enhancement factor that takes into account the impact of humidity, altitude and frequency;
- there is no simple strategy so far for qualification and testing of turn-to-turn insulation.

For high-frequency power transformers typically used in DC-DC converter systems (transformers with impregnated planar windings as shown in Fig. 3) the problem is even more serious, since the PD test is not even required in the reference standard, IEC 61378-1 [11]. However, it should be noted that the standard introduces a correction factor in the dielectric strength tests to take into account the effect of the pressure decrease due to the altitude.

One could try to rely on the standard that regulates the minimum characteristics required for the winding wires, the IEC 60317-0-1 [12]. Unfortunately, only the breakdown endurance is defined and not the PD resistance, even though the latter represent a dangerous source of accelerated degradation.

III. Alternative systems for PD detection

PDs can be detected in different ways [7], [10]:

- detection of secondary photons emitted by means of a photomultiplier tube;
- tan-delta measurement as a function of the voltage (the dissipation factor has a discontinuity point at the $PDIV$);
- direct measurement of the induced current along the line connecting the load to the voltage generator (possibly using a coupling capacity to amplify the signal);
- detection of the electromagnetic wave generated by the discharge by means of an antenna;
- monitoring of the ozone concentration near the place of discharge;
- identification by directional amplification of the sound waves emitted by the discharge events.

In the case of the electric machines discussed here, it is clear that not all are suitable for the purpose, because of the boundary conditions imposed: it must be an almost non-destructive test, possibly easy to perform and economical, and finally allow the identification of the weak point(s).

Therefore, only the first three approaches will be discussed below, considering that suggested by the standard (antenna detection) as impractical, in the absence of new elements.

A. Inverter-fed Rotating Machines

The design and qualification of the insulation systems of a low-voltage electric motor driven by an inverter, in general, are carried out in three steps:

1) degree of insulation estimation through preliminary tests;
2) tests to verify the chosen degree of insulation on simplified models;
3) qualification test of a stator prototype.

At first, to estimate the degree of insulation required, preliminary tests are carried out on very simplified systems that simulate the motor main characteristics: these models are made up of two pieces of interlaced wire of the stator winding, known as twisted pairs (TP).

Once the insulation has been chosen, tests are carried out on models that are a bit more complicated: the motorettes. They are a section of a slot with wire deposited inside, complete with liner and impregnating resin, which exactly reproduce the geometry and the final materials on the stator of the electric motor.

Finally, once one is sure of the design choices, from all points of view, the complete stator should be tested, putting it into operation in the most severe working conditions possible in terms of temperature, ageing and power supply voltage.

Figs. 4, 5 and 6 show the measurements made on a TP using three different systems at the same time: collection of secondary photons by means of a photomultiplier, direct measurement of the current by means of a Hall effect probe and detection of the electromagnetic signal emitted by the PDs by means of an antenna. While the red line always indicates the time course of the voltage in all three graphs, the blue line represents the detected signal intensity, useful for identifying PDs.

In the first case it is the logarithmic number of photons detected: as it can be seen, at the beginning of the last voltage step a peak of photons was recorded, to testifying to the PD inception. In the second image, instead, there is the current measured on the ground branch connected to the sample: the PD inception changes the current trend that would normally be due to the very rapid change in voltage and therefore can be detected for comparison. Finally, in the last graph there is the detection of PD by means of the electromagnetic signal emitted by them, which normally has an intensity and frequency greater than the background noise.

The obvious advantage of the first type of measurement is the fact that it is virtually immune to electromagnetic interference from any source, allowing a safe and timely detection. On the other hand, the specimen and the optical sensor must be placed inside a dark chamber, for the measurement to be carried out, and also the point where the discharge activity takes place must be exposed so that the secondary photons are not prematurely absorbed by the surrounding materials. This would theoretically exclude the possible application of the technique on the entire motor.

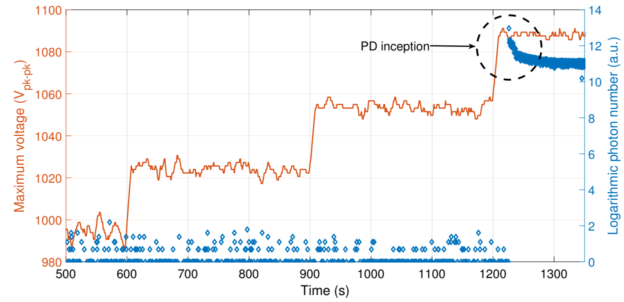

Fig. 4. Measurement of PD activity through a photomultiplier unit during a test on TP. The highlighted area refers to the detail shown in Figs. 5 and 6.

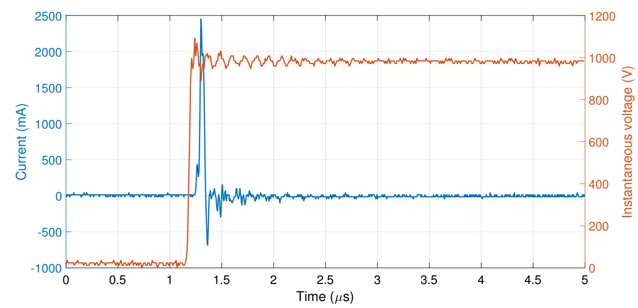

Fig. 5. PD activity measurement by means of a Hall effect current probe, simultaneously with the detection of Fig. 4. The identification is possible using a technique such as that described in the work of Borghi et al [13].

Nevertheless, Fig. 7 shows the result related to a small motor PD test of the phase-to-ground insulation system ($V_{nom} = 220\,\mathrm{V_{rms}}$, $P_{nom} = 500\,\mathrm{W}$, impregnated random-wounded). The detection method is still at a stage of development: probably the addition of one or two additional optical sensors, positioned at different points of the darkroom, would increase sensitivity to acceptable levels. As can be seen, although the number of photons detected is really low and makes the measurement very tricky, it also shows that it is possible to carry it out. Further research will demonstrate in the future whether the technique can be reliable, including for the identification of micro-cavities within VPI-impregnated insulation (Vacuum Pressure Impregnation).

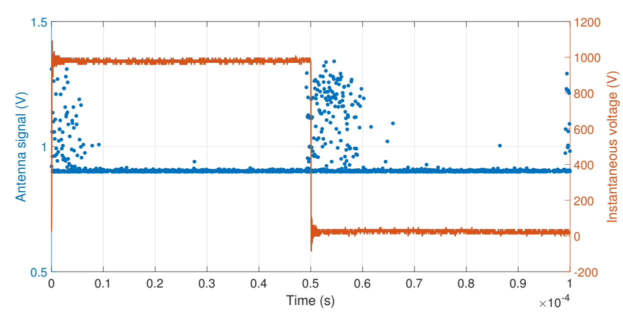

Fig. 6. PD activity detection by means of a horn antenna, simultaneously with the detection of Fig. 4.

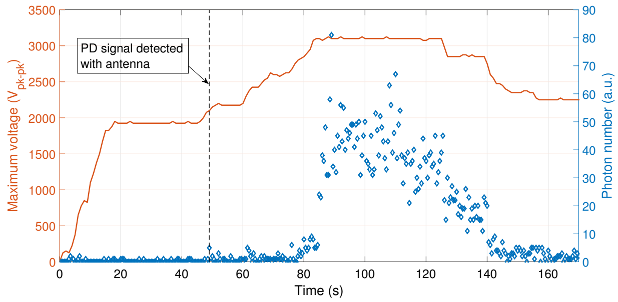

Fig. 7. PD activity detection in a motor by means of the optic sensor, using 50 Hz AC voltage. The latter is expressed in peak-to-peak.

The other two methods, in addition to having a very poor signal-to-noise ratio, in some cases impossible to make acceptable (the standard only gives indications for test voltage rise times above 300 ns), also have the problem of providing data sometimes difficult to interpret, requiring qualified professionals for the system qualification. However, they have the indisputable advantage of being able to detect the discharge anywhere within the specimen and potentially, through refined reflectometry techniques, also to be able to establish the weak point(s).

B. Inverter-fed Power Transformers

The transformers installed in DC-DC converters used in the transport sector are typically made of ferrite, to cope with the high frequencies used and to limit weight to a minimum. For the same reasons, it is common practice to have only dry insulation. Again, the three types of insulation mentioned above can be identified, as with electric motors.

In the case of these transformers, there is no pd-free design of the insulation at all. However, the growing need to contain weights and increase voltages, has led to an increasing number of failures in these devices, at the level of insulation, after a few months of operation [14]. Consequently, everything seems to indicate the need for new design and qualification criteria. In other words, we could propose, with regard to the insulation of this type of transformer, the same indications as those provided by the IEC 60034-18-41 standard for low voltage electric motors [7].

In addition, it should be noted that also in terms of PD tests, the same observations made for the inverter-fed low-voltage motors are proposed again. Laboratory measurements on the transformers shown in Fig. 3 led to results that were completely similar to those shown in Fig. 7 (therefore omitted for convenience).

IV. Discussion on some PD testing procedures

The question of how to take account of the effect of environmental and electrical parameters in the qualification tests for insulation, which the standards do not take into account, should be addressed. As far as altitude and frequency are concerned, several works seem to suggest that there is a linear relationship between these and the $PDIV$ in the range of interest [15]–[17], so it is possible to consider adding an enhancement factor to those already existing in IEC 60034-18-41 [7], in order to correctly establish the test voltages. Table I shows a possible proposal. Relative humidity remains outside, for which no precise rule has yet been identified.

For altitudes of more than 10 km, however, it is recommended to perform the tests in a vacuum chamber, without applying the enhancement coefficient.

TABLE I
Proposed table extension for enhancement factors based on experimental data reported in [15] and [17].

		Enhancement factor (EF)		
		phase-to-phase	**phase-to-ground**	**turn-to-turn**
Altitude (km)	≤ 2.5	1.35		
	≤ 5	1.85		
	≤ 10	4		
Frequency (kHz)	≥ 10	1.0	1.0	1.1
	≥ 100	1.0	1.0	1.2

V. Conclusions

This work has first identified some gaps in the standards dealing with the qualification and type testing of insulation of low-voltage electrical machines powered by converters for the transport sector, in the framework of More Electric Vehicles and Aircraft.

In view of this, a number of alternative PD testing methods have been proposed and analysed, which are essential to ensure the effective reliability of the insulation of these systems. On the basis of laboratory measurements on a wide range of different test specimens, ranging from electric motors to ferrite planar transformers (typical of DC-DC converters), it was concluded that the optical sensor (photo-multiplier tube) could be an excellent response to emerging problems. In particular, it is virtually immune to electromagnetic interference, provides data that can be easily interpreted, is easy to use and seems to be possible to use it for detection on entire machines (helped by the fact that in this area one has the smallest possible footprint).

Finally, it is proposed to introduce two new enhancement factors in IEC 60034-18-41 [7] that take into account the conditions of altitude, depending on the vehicle in which the machine will be installed, and frequency, if the PD tests are conducted at the mains voltage (i.e. 50-60 Hz).

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