Electrical Insulation at 800 V Electric Vehicles

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Abstract – **Currently, electric vehicles use drive-fed traction motors that rely on 400 V power supplies. But factors such as motor size, operating temperature, power, efficiency, batteries, and charging time are leading a push toward higher voltages. Accordingly, motor and power electronic designers and producers are targeting 800 V. However, this voltage could be a source of electrical stresses on electrical insulation systems. Because the insulation used in low-voltage motors is too thin, the insulation system risks being subjected to the same electrical field strength as with high-voltage motors. This article describes the potential stresses on insulation systems associated with pulse width modulated drives. Solutions for detecting insulation issues and methods of increasing insulation system function will also be presented.**

Keywords: partial discharge, lifetime, electric vehicle, drive-fed motors

I. INTRODUCTION

Global warming due to production of CO_2 risks imperiling human life. Vehicles based on fossil fuels are considered as a main source of CO_2 emissions. Compared with conventional internal combustion engine cars, electric vehicles (EVs) are being introduced to reduce greenhouse gases and, consequently, help control global warming. Despite the enthusiasm for EVs, it takes much longer to charge an EV battery than to refuel a vehicle at a gas station. Increasing customer confidence in EVs will require bringing battery charge time closer to the refueling time of conventional gas vehicles.

Current EVs employ power network voltage in the range of 150 to 450 V. A typical 400 V charging system uses around 50 kW of power. In other words, charging an EV for 400 km of driving takes almost 80 minutes. Increasing the capacity of the conductive pins in the charging plug to 100 kW reduces the charging time to 40 minutes. Cooling the charging plug further increases the capacity of the pins, reducing charging time to 30 minutes. But no matter how charging time is enhanced, battery charging still takes longer compared with refueling conventional gas vehicles. Achieving acceptable charging times thus requires employing higher voltages.

Employing 800 V of supply voltage for 400 km of driving reduces the minimum charging time of a 400 V EV from 29 minutes to less than 15 minutes. However, this change results in additional cost, time, and effort. Going from 400 to 800 V offers multiple benefits for EVs. These generally fall into two categories: charging time and vehicle structure.

In this article, we describe the effects on the charging system, charging time, and the other parts of an EV of increasing the voltage to 800 V. More particularly, we focus on the effects of the new generation of SiC- and GaN-based switching devices, which offer 50 to 100 kV/µs slew rates (compared with the 20kV/µs slew rate of current switching devices), on the insulation system of drive-fed motors in EVs [1], [2].

II. CHARGING SYSTEM

Increasing the voltage affects the charging time and size of batteries. The transfer of electrical energy is described by the following formula:

$$E = U \times I \times t \tag{1}$$

where U is the voltage, I is the current, and t is time. Accordingly, charging time is expressed as:

$$t = E / (U \times I) \tag{2}$$

Because doubling the voltage from 400 to 800 V simultaneously doubles the transfer power, applying a constant current (I) and increased voltage (U) reduces the charging time with the same electrical power. This in turn decreases the required EV battery size (normally between 200 and 400 liters).

Generally, the battery consists of modules with 10 to 15 cells. The thermal losses in the cell and module connections are important contributors to the thermal load and heating of the cells. When the current reduces by half, the copper losses will be about a quarter if the cross section of the bus bars does not change. If the wiring, module connector, and bus bar designs are chosen carefully, large weight savings are possible.

Thus, increasing the voltage can reduce the charging time and battery size, leading to lower vehicle weight and, consequently, higher efficiency [2].

III. VEHICLE STRUCTURE

To minimize losses, the charging voltage must be the same for the battery voltage and the propulsion system voltage. Accordingly, voltage modification should take into account parts other than the charging system. Redesigning components for the transition to an 800 V system causes their size and weight to vary. For example, components such as power converters may increase by up to 10%, and elevated voltage levels will result in larger internal components such as fuses. However, these volume increases could well be compensated by reductions in the high-voltage (HV) battery volume and copper cross sections.

Going to 800 V does not just result in faster battery charging. It also increases EV efficiency due to reduced electric current. Doubling the voltage reduces the current and copper cross sections by half. Moreover, losses will be about a quarter of the losses – and heat – incurred with 400 V. Reduction of the copper cross sections affects the bending radius of HV wire, leading to a reduction in vehicle volume owing to greater geometric flexibility of the connections.

The 800 V technology is ideal for vehicles whose performance is particularly sensitive to the power-to-weight ratio, as well as vehicles for which cost optimization is a priority [2].

IV. ELECTRICAL INSULATION AND STRESSES

The factors affecting insulation systems generally divide in four main groups: thermal, electrical, mechanical, and ambient, known as TEAM factors. Drive-fed motors are influenced by nearly all these factors due to high repetition rates and fast rise-time pulses. Root cause failure analysis (RCFA) of drive-fed motors shows that the source of stresses is pulses. Stator insulation faults make up 60 to 70% of stator issues. Furthermore, the most frequently reported fault is turn-turn insulation failure due to uneven voltage distribution across the stator winding [3].

Currently, the slew rate of power electronic switching devices is in the range of 20 kV/μs. In order to reduce the losses and low-order harmonics, the new generation of power electronic switching devices provide higher slew rates, up to 50 to 100 kV/μs. Although the low-order harmonics decrease, the high-order harmonics will increase, affecting the mechanical and electrical lifetime of drive-fed motors.

The thickness of the insulation materials used in the automobile industry is low compared with HV insulation systems. Increasing the voltage level to 800 V increases the electric field strength across EV insulation systems comparable to the electric field strength of HV motors. High electric field strength is recognized as the main source of partial discharge (PD) creation, leading to premature insulation failure [1], [2].

Variations in the pulse rise time and voltage level are believed to be a major source of electrothermal stress on insulation systems. Consequently, the stresses to which the electrical insulation used in EVs is exposed need to be assessed.

A. Connecting Cable and Pulse Rise Time

Due to the "impulsive" nature of the inverter output voltage, with rise times in the range of nanoseconds, the length of the connecting cable becomes comparable with the wavelength of the electromagnetic field involved. Accordingly, the voltage at the motor terminals derives from the superposition of the forward wave traveling from the inverter to the load and of the reflected wave traveling in the opposite direction. This superposition could result in a considerable overvoltage (up to double that of the applied voltage) with high-frequency oscillation at the motor terminal (Fig. 1) [3] - [17].

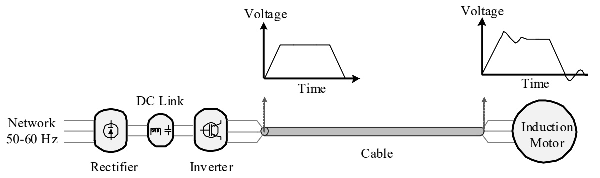

Figure 1. Schematic of a drive-fed motor system.

Increasing the cable length increases the amplitude of the overvoltage, while significantly reducing the ringing frequency. One solution might be to modify the propagation speed of the pulse in the cable and reflections. Recent developments in power electronic switching device technology allowing production of steeper pulses have prompted investigations into the effect of rise time on pulse propagation behavior in cables. It is acknowledged that for a given cable length, reducing pulse rise time results in a sharp increase in overvoltage amplitude and ringing frequency (Fig. 2). An assessment of the effects of cable length and pulse rise time on overvoltage behavior demonstrates the possibility of defining the cable critical length at each individual rise time [17] - [20]. However, the automotive industry employs integrated-drive motors. Thus, the connecting cable is eliminated.

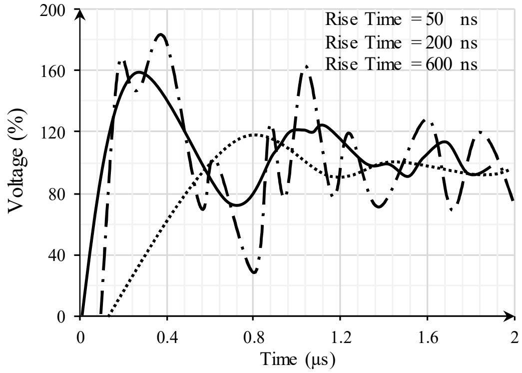

Figure 2. Effect of pulse rise time on overvoltage [3], [14].

B. PWM Topology

Power converters are implemented in various topologies. Even though multilevel modulation can produce nearly sinusoidal voltages, the voltage is always pulse modulated. In view of the more sinusoidal curvature and particularly the output voltage of PWM (pulse width modulated) drives, more levels can be employed (Fig. 3).

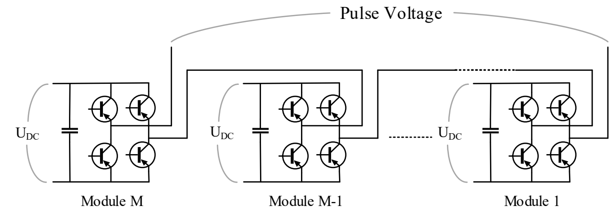

Figure 3. Topology of one phase of a series-connected H-bridge multilevel inverter [3].

The maximum overvoltage (up to two times the DC voltage link) and stress on the insulation system is generated by two-level converters. With three-level power converters, the overvoltage reduces to almost half and is in the range of 0.9 pu of the DC voltage link. With a five-level power converter topology, the overshoot is moderately decreased and in the range of 0.45 pu of the DC voltage link.

Although increased voltage levels complicate the design and implementation of power converters, the proportional overvoltage of any individual level decreases. This considerably lowers the applied stresses on the insulation system. Increasing the voltage level incrementally causes the power converter output to be quasi-sinusoidal in form, resulting in a marked reduction of the voltage drop in each turn and coil [21] - [23].

Increasing the number of power converter levels affects both the PD energy and phase resolved partial discharge (PRPD). In comparison with two-level converters, the PD amplitude in five-level power converters reduces to almost half. Furthermore, the PRPD for two-level power converters shows that PD occurs in 360°. As the number of levels increases, the PRPD pattern is similar to that of a PRPD under sinusoidal voltage.

In short, increasing the number of power converter levels reduces PD amplitude and limits PD phase occurrence, which in turn reduces electrical stresses and delays isolation aging. However, it also increases costs [24].

C. *Non-Uniform Voltage Distribution Voltage Across Stator Windings*

The use of electrical drives to control induction motors led to frequent reports of turn insulation failures. According to transmission line theory, whenever the surge impedance of an induction motor is considerably higher than the characteristic impedance of the connected cable, wave reflection occurs. The pulse amplitude could increase up to twice that of the applied voltage. As already discussed, cable length affects wave propagation properties, leading to waveform distortions such as prolonged pulse rise time and increased peak voltage at the motor terminal. Furthermore, pulses with short rise times cause non-uniform voltage distribution in the stator winding, exposing the turn insulation to destructive electrical stresses.

Considering the winding as a combination of resistance, inductance, and capacitance, it is possible to describe non-uniform voltage distribution across the winding. Reducing rise time increases the frequency, and the winding becomes completely capacitive. Thus, as the voltage is distributed across the winding, when the rise time increases, the network becomes capacitive-inductive and the measurements show oscillation in the waveform (Fig. 4).

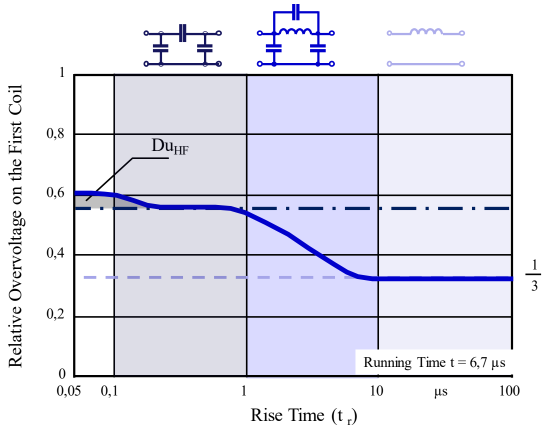

Figure 4. Variation in the winding network with changes in rise time [3].

The voltage distribution across the stator winding of low-voltage drive-fed induction motors shows that up to 90% of transient voltages drop over the first coil. Thus, the terminal coils experience considerably high dielectric stresses. Reducing the pulse rise time leads to non-uniform voltage distribution across the stator winding. This causes local overstress on the insulation system, resulting in PD activity and, consequently, premature insulation failure [3], [4].

D. *Effect of Pulse Parameters on Insulation Function*

In general, increasing the voltage raises the probability of PDs and a shortened lifetime for the insulation system [3], [4]. Moreover, reports suggest that bipolar pulses have a greater effect on insulation lifetime than do unipolar pulses with the same peak value. Among the numerous investigations on the effects of voltage waveform on electrical insulation lifetime, Kaufhold in particular has considered and evaluated the mutual dependence of voltage amplitude, PD creation, and breakdown probability (Fig. 5). He showed that creation of PDs is related to pulse amplitude and to the partial discharge inception voltage (PDIV) [25] - [28].

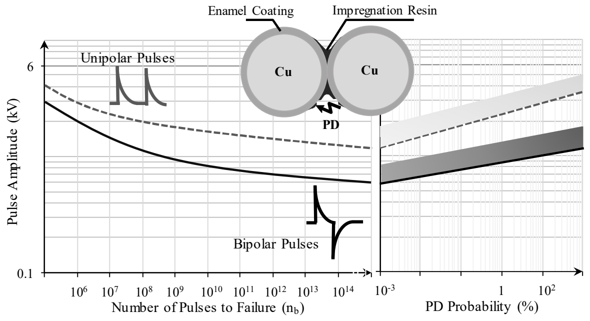

Figure 5. Insulation lifetime and PD probability vs. voltage amplitude [3].

The duty cycle (D) is typically defined by the ratio of the positive pulse time (t_p) in seconds or percentage to the whole pulse period time (T) in seconds or percentage. Increasing the duty cycle has been shown to reduce lifetime (Fig. 6). Long duty cycles expose insulation materials to more destructive stresses even without PD activities. However, work by Divljakovic et al. showed that the duty cycle has no effect on insulation lifetime [25] - [30].

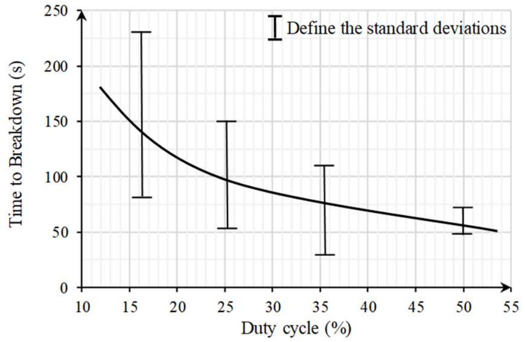

Figure 6. Interdependence of duty cycle and breakdown time [25] - [30].

Increasing rise time reduces the amplitude and energy of PDs (Fig. 7). Reducing rise time decreases PD scattering. Generally, PD rate, amplitude, and pattern change with variations in power supply frequency. Increasing the pulse repetition rate decreases the amplitude of PDs. Moreover, reducing the pulse repetition rate markedly reduces the number of PD signals (Fig. 8) [31]. The effect of the voltage waveform on PDs can be evaluated optically. We applied a 50 Hz sinusoidal voltage – in the range of PDIV – and increased it in steps of 400 V (peak-peak). We then applied an impulse voltage with 1000 Hz repetition rate, which was also increased in steps of 400 V. We analyzed the samples using a corona scope (Fig. 9) [3], [31]. The PD intensity for the impulse voltage was considerably higher than the sinusoidal input voltage at the same peak-peak voltage and at any voltage level.

Application of the impulse voltage caused the PD density to be almost uniform along the sample, while increasing the voltage level caused the PD density due to the sinusoidal voltage to increase in the curve sections. In other words, applying pulse voltage exposes nearly every part of the insulation system to electrical stresses [3], [31].

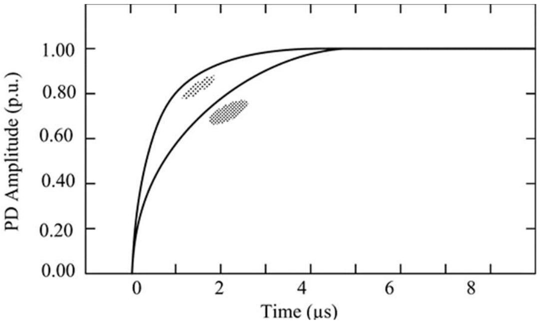

Figure 7. Pulse rise time, PD amplitude, and number of PDs [3], [31].

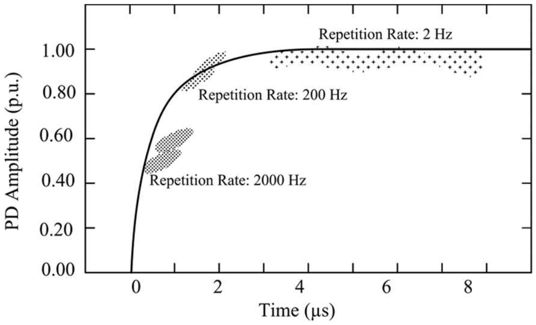

Figure 8. Pulse repetition rate, PD amplitude, and PD scattering [3], [31].

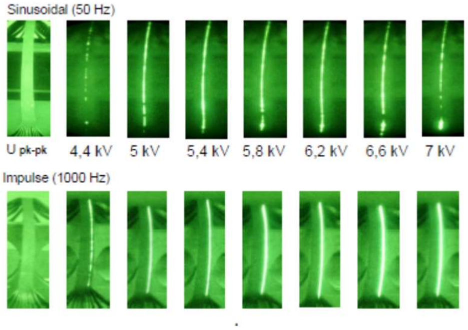

Figure 9. Effects of voltage waveform on PD [3], [31].

Thus, raising the voltage level to 800 V and faster rise times up to 50 kV/µs increases PD scattering. Furthermore, under these circumstances, the amplitude and energy of the PDs will be significantly elevated. Thus, in such circumstance the high density of PDs for pulse voltage could be logical.

V. SUITABILITY ASSESSMENT OF ELECTRICAL INSULATION

To evaluate the suitability of an insulation material for an 800 V system, the Von Roll Institute suggests a cycle consisting of diagnostic tests and aging processes to be carried out under a range of conditions (Fig. 10).

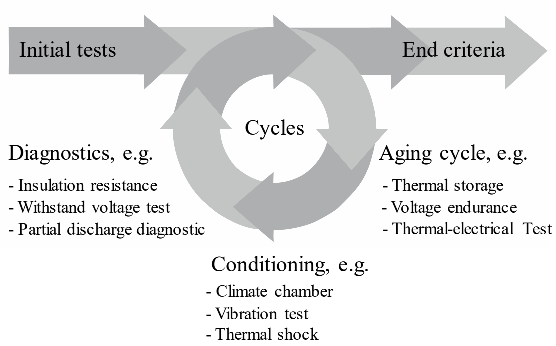

Figure 10. Suitability assessment cycle offered by the Von Roll Institute.

Insulation function should be evaluated with diagnostic tests before and after each individual aging process. Example diagnostic tests include an insulation resistance test (IR), polarization index (PI), capacitance measurements, withstand voltage test, and PD under AC and pulse conditions. The aging process may consist of thermal, electrical, or thermo-electric aging in combination with conditions such as humidity or mechanical shocks. Thermal aging in coolant could also provide meaningful results.

The Von Roll Institute has categorized insulation materials and insulation systems according to test results (Fig. 11) [2]. The categorization consists of PD-free insulation systems for 400 and 800 V, PD resistance insulation systems for 800 V and higher voltages, as well as high thermal conductivity insulation systems.

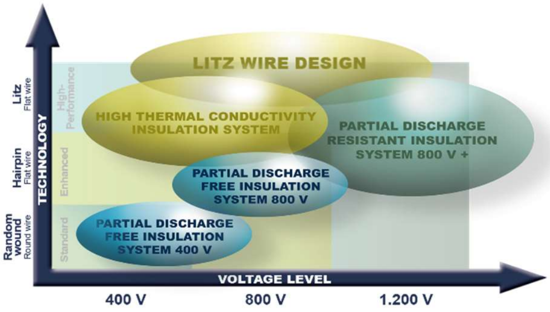

Figure 11. Insulation systems categorized by the Von Roll Institute [2].

VI. SUMMARY

Increasing voltage from 400 to 800 V reduces the battery charging time in electric vehicles from 40 to 15 minutes. It also increases the car efficiency and reduces the weight and, consequently, the price of the vehicles. Moreover, the new generation of power electronic switching devices can reduce switching losses by increasing the slew rate in the range of 50 to 100 kV/µs. However, increasing the voltage level and slew rate may in turn affect the PDIV and consequently the lifetime of the insulation system. To evaluate the suitability of insulation system design under such destructive conditions, the Von Roll Institute suggests implementing a series of tests. The experiences of cooperation with various well-known automobile companies prove the effectiveness of this quality assessment.

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