OPTIMIZING MOTOR DESIGN FOR REDUCED DISCHARGE ENERGY AND HIGH EFFICIENCY

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Abstract – IEEE 1349-2021 [1] for Electric Machines in Zone 2 and Class I, Division 2 Hazardous Locations, in its Annex G, provides comprehensive guidance for calculating discharge energy in VFD-driven motors due to common mode voltage (CMV). While the calculation is primarily used to assess the suitability of shaft bonding devices in hazardous locations, it also offers detailed parasitic capacitance calculations that can be used to analyze key motor design parameters affecting shaft voltage and discharge energy. This paper focuses on the critical motor parameters that affect discharge energy and explores how these parameters can be optimized to reduce discharge energy while maintaining high motor efficiency. The paper also discusses design strategies for reducing the risk of electrical discharges in hazardous locations due to common mode voltage, ensuring both safety and performance optimization.

Index Terms — Shaft bonding devices, hazardous locations, VFD-fed motors, motor efficiency, IEEE 1349-2021, discharge energy, common-mode voltage (CMV).

I. INTRODUCTION

Electric motors, particularly 3-phase squirrel cage induction motors, are commonly used in industrial applications, including hazardous locations such as Zone 2 and Class I, Division 2 environments as covered in National Electrical Code® (NEC®) (NFPA 70-2020) [2]. In these environments, the use of Variable Frequency Drive (VFD) to control motor speed and performance can induce shaft voltage, primarily caused by the common mode voltage (CMV) produced by the VFD. This shaft voltage can lead to harmful electrical discharges, potentially damaging the motor, reducing its lifespan, and posing safety risks in hazardous environments. IEEE 1349-2021 provides guidelines for calculating shaft voltage and discharge energy in such VFD-driven motors. In its Annex G, the standard details the calculation of parasitic capacitances between the stator windings, the rotor, and the motor housing. While these calculations are primarily used to ensure motor safety in hazardous locations, they also highlight critical motor design parameters that influence both discharge energy and motor efficiency. These parameters, when optimized, can help to reduce shaft voltage without sacrificing motor efficiency. However, tradeoffs often exist between minimizing shaft voltage and maintaining high efficiency, as modifying one parameter to improve safety might inadvertently affect the motor's overall performance. This paper uses Sobol sensitivity analysis, enhanced by Monte Carlo simulations, to evaluate the impact of these motor design parameters on discharge energy and motor efficiency. The goal is to identify the most influential parameters and propose design strategies that minimize shaft voltage while optimizing motor performance.

II. CALCULATION OF DISCHARGE ENERGY AS PER IEEE 1349:2021

In this section, all the equations used for the calculation of discharge energy in IEEE 1349:2021 have been reproduced. Refer the standard if any additional details on the equations are sought.

Discharge Energy is calculated using (1).

$$E=\frac{1}{2}CV_{sh}^{2} \tag{1}$$

where

E	discharge energy (joules);
C	the total capacitance, sum of all capacitances; of the rotor to the frame including the bearings across which the voltage, Vsh, appears (farads);
V_{sh}	the peak shaft voltage (volts).

Peak Shaft Voltage V_{sh} is calculated using (2).

$$V_{sh} = V_{CMVASD} / CMVR \tag{2}$$

where

V_{CMVASD}	Common mode voltage of drive (volts);
CMVR	Common mode voltage ratio given by (3);

Common mode voltage ratio CMVR is calculated using (3).

$$CMVR = (C_{SR}+C) / C_{SR} \tag{3}$$

where

C_{SR}	Stator to rotor capacitance (farads);
C	Total capacitance of motor (farads).

Stator to rotor capacitance is calculated using (4).

$$C_{SR}=F_{end}[N_S \times L_1 \times W_{SL} \times 8.85\times10^{-12}/(D_{AG} \times K+(W+D_{GW})\times K_w)] \tag{4}$$

where

N_s	Number of stator slots;
L_1	Stator iron length (meters);
W_{SL}	Stator slot width (meters);

D_{AG} Airgap distance between stator and rotor (meters);
K Dielectric constant for air;
W Stator wedge thickness (meters);
D_{GW} Coil ground wall thickness (meters);
K_W Dielectric constant of combined wedge plus ground wall;
F_{end} End effects multiplier on CSR.

Total capacitance C is calculated using (5).

$$C = C_{AG} + 2\,C_b \tag{5}$$

where

C_{AG} Airgap capacitance;
C_b Bearing capacitance.

Equation (5) is applicable for motor configuration without bearing insulation or with bonding jumpers across both bearings where both bearings are identical. Total capacitance for other typical bearing configurations is available in the standard. For this paper, only one configuration has been shown and is sufficient for the purpose of this paper.

Bearing capacitance C_b for anti-friction ball bearing is calculated using (6):

$$C_b = (N_b 4\,\varepsilon_0\ \varepsilon_r\ )/((1/R_b) + (1/(R_b + R_c))) \tag{6}$$

where

N_b Number of balls;
R_b Radius of balls (meters);
R_c Radial bearing clearance (meters);
$\boldsymbol{\varepsilon}_0$ Permittivity of vacuum (farads/meter);
$\boldsymbol{\varepsilon}_r$ Relative permittivity of the lubricant (farads/meter).

Airgap capacitance C_{AG} is calculated using (7).

$$C_{AG} = 2\pi K \times 8.85\times10^{-12} \times L_1 / \ln(\{D_1+2D_{AG}\}/D_1) \tag{7}$$

where

L_1 Stator iron length (meters);
D_1 Rotor OD (meters);
D_{AG} Stator to rotor main airgap (meters);
K Dielectric constant for air.

III. DESIGN PARAMETERS

To summarize, the key design parameters that affect discharge energy are listed below, and their pictorial representation is also provided at the end of this section:

1) Bearing: The dimensions of the bearing are an input for bearing capacitance calculation as per (6).
2) L_1: This is the stator iron/core length.
3) D_{AG}: This is the air gap. The distance between the stator and rotor.
4) Stator ID: The stator internal diameter is indirectly mentioned in (7). It is the sum of the rotor outer diameter and the air gap.
5) N_S: The number of stator slots in the motor.
6) W_{SL}: The width of the stator slots.
7) D_{GW}: This is the thickness of the coil ground wall.
8) W: The stator wedge thickness.
9) CMV: The common mode voltage of the drive.

Figure 1 illustrates the parameters stator iron length L_1, stator to rotor air gap D_{AG}, stator internal diameter and rotor outer diameter.

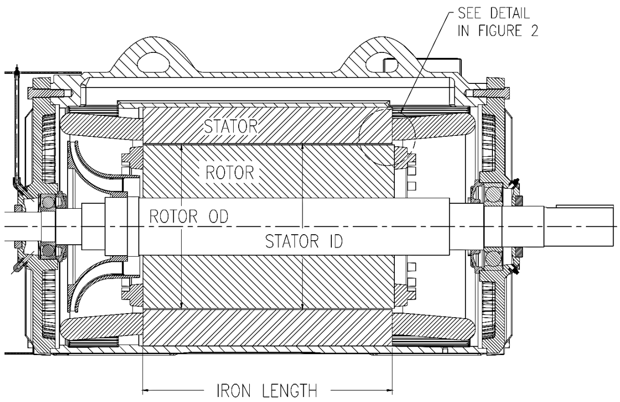

Fig. 1 Pictorial representation of stator, rotor and airgap

Figure 2 illustrates a closeup view of the stator to rotor airgap.

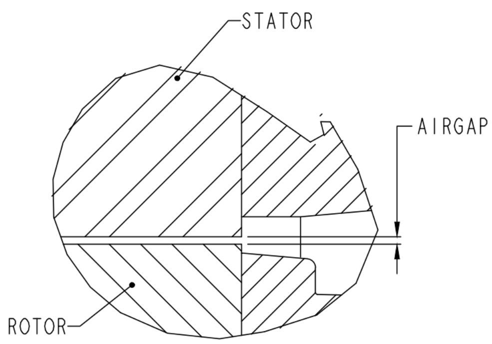

Fig. 2 Airgap close-up view

Figure 3 illustrates a section of the stator lamination with stator slots N_S and each stator slot having a width of W_{SL}.

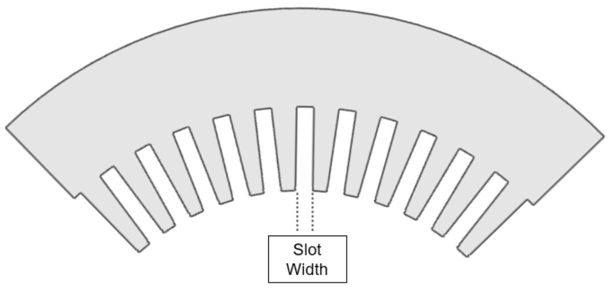

Fig. 3 Section view of stator lamination

Figure 4 illustrates a cross section of the motor winding showing the coil ground wall insulation thickness D_{GW} and stator wedge.

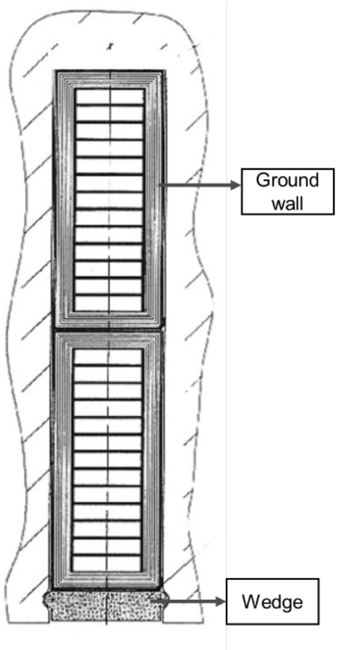

Fig. 4 Stator winding ground insulation and wedge

IV. METHODOLOGY

Sobol sensitivity analysis [3] is a global sensitivity analysis method that quantifies the contribution of each input variable to the variance of the output in a model. This method provides two main sensitivity indices: the first order index (S1) and the total effect index (ST). These indices help quantify the individual contribution of each parameter and their interaction effects on the output (in this case discharge energy). The first order index (S1) measures the direct contribution of each input variable to the output variance, ignoring interactions with other parameters. The total effect index (ST), on the other hand, captures the total influence of a parameter, including both direct and interaction effects with other parameters. The sensitivity indices are calculated using the variance-based method developed by Sobol. These indices decompose the variance of the model output into contributions from the individual parameters and their interactions. The calculations for the first order index (S1) and total effect index (ST) are as follows:

First-Order Index (S1): The first-order index (S1) quantifies the contribution of each parameter x_i to the output variance Var(Y) based on its individual effect, excluding interactions with other parameters. The formula for S1 is:

$$S_1(x_i) = \frac{Var_i(Y)}{Var(Y)} \tag{8}$$

where

Var (Y) is the total variance of the output Y (in this case, discharge energy)

$Var_i(Y)$ is the variance of the output Y when the input x_i is allowed to vary, while the other parameters are held fixed.

This index tells us how much the variation in a single parameter x_i contributes to the total output variance.

Total Effect index (ST): The total effect index (ST) measures the overall influence of a parameter x_i on the output variance, including the effects of interactions with other parameters. It is calculated as:

$$S_T(x_i) = 1 - \frac{Var_i(Y)}{Var(Y)} \tag{9}$$

where

$Var_i(Y)$ is the variance of the output Y when the input parameter x_i is fixed (i.e., its contribution is removed from the variance)

Var (Y) is the total variance of the output.

The total effect index $S_T(x_i)$ gives us a measure of how much the input parameter x_i influences the output, including both its direct effect and the effect of its interactions with other parameters.

These indices are estimated using Monte Carlo simulations, which involve sampling from predefined distributions of the input parameters and computing the corresponding output. The variance of the output is then decomposed into the contributions from each parameter using these formulas.

To estimate the first order and total effect indices, Monte Carlo simulations are used to generate a large set of random samples from the input parameter space. These samples are drawn according to uniform probability distribution. The model is then evaluated at each sample point, and the output is recorded. For this analysis, a total of 10,500 Monte Carlo samples were generated. These samples were used to simulate various combinations of motor design parameters and estimate the discharge energy. This large dataset helps ensure that the results reflect the full variability in the input space and accurately capture the impact of each parameter. The variance of the output was calculated using the VAR.P (Population Variance) function in Excel, as the Monte Carlo simulations generate a sufficiently large dataset representing the entire input space.

V. SIMULATION DETAILS

For the sensitivity analysis a NEMA 500 frame, 4000V, 500HP, 4 pole motor was selected. For the Monte Carlo simulation, a set of 10,500 random samples were generated for each of the design parameters. For stator iron length, air gap, stator ID and bearing size the upper and lower limits were set based on previously built machines and typical offerings to customer in NEMA 500 frame machines. For number of stator slots, the upper and lower limits were set based on the typical slot combinations allowed for a 4-pole motor. For stator slot width, the upper and lower limits were set based on historically built machines and other design factors like maintaining sufficient tooth width so that performance is not affected adversely. For ground insulation thickness, the lower limit was set based on the minimum thickness required to adequately insulate the windings corresponding to the supply voltage, in this case 4000V. The upper limit for ground insulation thickness was set based on the minimum insulation thickness required to meet the next typical supply voltage level. In this case, the upper limit for ground wall insulation thickness was set based on the minimum ground wall thickness required for a 6600V machine. For Wedge, the upper and lower limits were set based on previously built machines and good design practice such that the motor performance is not adversely affected. For CMV, the upper and lower limits were set between 0.6% to 135% of the VFD output. According to section G.3.7 of IEEE 1349:2021, which deals with NEMA frame size machines, the CMV can be estimated as approximately 1.35 times the drive output voltage. This has been considered as the upper limit. The lower limit has been considered based on the fact that for medium voltage drives, the CMV as a percentage of the drive output can be low owing to the multilevel topology applied in medium voltage drives.

VI. SENSITIVITY ANALYSIS RESULTS

Table I shows the results of the Sobol sensitivity analysis with Monte Carlo simulations indicating the first order and total effect indices for each motor design parameter. The parameters have been arranged in decreasing order of their first order index.

TABLE I
SENSITIVITY INDEX OF DESIGN PARAMETERS

Design Parameter	**First Order Index (S1)**	**Total Effect Index (ST)**
Stator ID	1.00	0.001
Air gap	0.96	0.045
Stator iron length	0.91	0.087
CMV	0.90	0.098
Wedge	0.85	0.154
Bearing size	0.75	0.247
Stator slot width	0.72	0.281
Number of stator slots	0.71	0.295
Ground insulation thickness	0.50	0.495

From the first order indices (S1), it is evident that some parameters have a significant influence on the output, particularly the stator ID, with a first order index of 1.00, air gap with a first order index of 0.96 and stator iron length with a first order index of 0.91. This indicates that these three parameters have the most significant direct impact on the discharge energy. The CMV with a first order index of 0.90 also has a significant impact on the discharge energy but this parameter is a characteristic of the VFD and independent of the motor's design. Ground insulation thickness has a relatively moderate first-order index of 0.50, indicating a not so significant direct impact on the discharge energy.

The total effect indices (ST) offer additional insights, showing that the ground insulation thickness has the highest total effect index of 0.495. This suggests that while it has a moderate direct influence, its interactions with other parameters significantly impact the overall discharge energy. The same can be said for the design parameter, number of stator slots, which has a total effect index of 0.295. On the other hand, the air gap, despite having a first order index of 0.96, exhibits a relatively small total effect index of 0.04, indicating that its direct impact on discharge energy is large, but interactions with other parameters are minimal.

While any one of the indices, first order index or total effect index can be considered for reducing the discharge energy it is usually the first order index which is more suitable owing to its direct impact on the output. Parameters with higher first order index should be preferred to obtain the desired discharge energy.

VII. ANALYZING THE NATURE OF RELATIONSHIP BETWEEN DESIGN PARAMETERS AND DISCHARGE ENERGY

This section explores the type of relationship, direct or inverse, which each of the design parameters have with the discharge energy. To analyze the relationship for any one design parameter, all parameters were fixed and only the respective design parameter was first increased and the corresponding discharge energy was noted. Then the design parameter was decreased and the corresponding discharge energy was noted. These discharge energy values were compared to determine whether the design parameter has a direct relationship or an inverse relationship with discharge energy. This data will help in determining whether to decrease or increase a particular design parameter value to obtain the desired discharge energy. Table II shows the relationship between each design parameter and the discharge energy.

TABLE II
RELATIONSHIP BETWEEN DISCHARGE ENERGY AND DESIGN PARAMETER

Design Parameter	**Relationship to Discharge Energy**
Stator ID	Inverse
Air gap	Inverse
Stator iron length	Direct
CMV	Direct
Wedge	Inverse
Bearing size	Inverse
Stator slot width	Direct
Number of stator slots	Direct
Ground Insulation thickness	Inverse

From Table II we observe that design parameters like stator iron length, stator slot width and number of stator slots have a direct relationship with the discharge energy, implying that increasing the value of these parameters results in an increase in the discharge energy value. For parameters like stator ID, air gap and bearing size which has an inverse relationship with discharge energy implies that increasing the values of these parameters results in a decrease of discharge energy.

VIII. TRADE-OFFS BETWEEN LOW DISCHARGE ENERGY AND MOTOR EFFICIECNY

While reducing discharge is critical for safety in hazardous locations, the motor's efficiency must also be considered. Especially with legislations around the world requiring a minimum efficiency level to be met, it becomes all the more important. Generally, the efficiency of a motor can be increased by increasing the active material used in the motor. Electrical steel for laminations and stator windings are two such materials which constitute the active material in a motor. The efficiency of a motor can also be increased by alternate methods such as using fans with lower losses, using higher grade electrical steel which has lower core loss, using copper in rotor instead of aluminium as cast/bar material to name a few. This paper does not discuss these alternate methods of increasing motor efficiency. Instead, it discusses the method of increasing active material since most of the design parameters being discussed in this paper are related to increasing the active material in a motor. For example, increasing the stator iron length or increasing the stator slot width directly increases the active material in a motor and hence increases the efficiency. This section explores some of the key trade-offs between low discharge energy and high motor efficiency and provides general guidelines which can be considered while designing a motor with the aim of keeping discharge energy as low as possible.

1) *Stator iron length and stator slot width:* Stator iron length has a high first order index value and a direct correlation to discharge energy. Increasing the stator iron length will result in more active material. Hence increased motor efficiency but it will also lead to an increase in the discharge energy. Stator slot width has a moderate first order index value and a relatively high total effect index value implying that it influences the discharge energy through both its direct effect and the effect of its interactions with other parameters. It also has a direct correlation to the discharge energy therefore increasing stator slot width will increase the discharge energy.

Table III shows how the change in these two parameters affects the overall motor efficiency and the discharge energy. For this analysis a 500HP 4P 4000V 60Hz NEMA 500 frame motor design was considered. In all the three scenarios shown in Table III, the key performance parameters of the motor like locked rotor torque, breakdown torque, locked rotor ampere were kept similar without any big change.

TABLE III
VARIATION OF DISCHARGE ENERGY AND EFFICIENCY FOR DIFFERENT STATOR IRON LENGTH AND STATOR SLOT WIDTH

	Scenario 1	**Scenario 2**	**Scenario 3**
Stator iron length	28 inches	Decrease by 14%	Increase by 14 %
Stator slot width	0.36 inches	Increase by 8%	Decrease by 15%
Motor Losses in kW	13.87	13.55	13.57
Discharge Energy in uJ	36.87	32.58	33.83
Reduction in motor losses compared to Scenario 1	-	2%	2%
Reduction in Discharge Energy compared to Scenario 1	-	12%	8%

Scenario 1 represents the base design for the rating. It has losses of 13.87kW and discharge energy of 36.87uJ. It uses stator iron length of 28 inches and has a slot width of 0.36 inches. Scenario 2 and scenario 3 are two alternate designs based on the scenario 1 design which reduces the motor losses by 2% compared to scenario 1 design. However, scenario 2 and scenario 3 take two different approaches to achieving the lower losses and higher efficiency. Clearly, scenario 2 is a better option since it achieves the same reduction in motor losses and decreases the discharge energy by 12%. The result also emphasizes the sensitivity analysis result where, as per Table I, stator iron length had a first order index of 0.90, implying that it has a high direct impact on the discharge energy. Scenario 2 reduced the stator iron length by 14% and reduced the discharge energy by 12%. Scenario 3, where stator slot width was reduced by 15%, yielded a reduction in discharge energy of 8% in line with its low first order index.

2) *Number of stator slots*: The design parameter number of stator slots has a high total effect index of 0.295 signifying that it has high influence on the discharge energy through its interaction with other design parameters even though it has a moderate first order index of 0.71. Table IV shows how the change in number of stator slots results in a change in motor losses and discharge energy. For this analysis a 700HP 10P 6600V 60Hz NEMA 580 frame motor was considered. In both the scenarios shown in Table IV, the key performance parameters of the motor like locked rotor torque, breakdown torque, locked rotor ampere were kept similar without any big change.

TABLE IV
VARIATION IN DISCHARGE ENERGY AND EFFICIENY FOR DIFFERENT NUMBER OF STATOR SLOTS

	Scenario 1	**Scenario 2**
Number of stator slots	90	Decrease by 33%
Stator slot width	0.32	Increase by 38%
Stator iron length	37	No change
Motor Losses in kW	41.12	34.35
Discharge Energy in uJ	34.48	29.03
Reduction in motor losses compared to Scenario 1	-	16%
Reduction in Discharge Energy compared to Scenario 1	-	16%

Scenario 1 is the base design with 90 stator slots, stator slot width 0.32 inches and stator iron length 37 inches. Scenario 2 reduces the stator slots to 60 and increases the slot width to 0.44 inches. The motor losses in scenario 2 is 16% lower compared to scenario 1 and at the same time the discharge energy is 16% lower compared to scenario 1. This shows that the number of stator slots can play an important part in designing a higher efficiency motor while keeping the discharge energy low owing to its high total effect index.

3) *Stator ID and air gap*: Both stator ID and air gap have high first order index values signifying that they can have a high direct impact on the discharge energy. It is usually not practical to change the stator ID from one design to another as proper tooling to punch the desired stator ID may not be available. This is due to the fact that for each unique stator ID a separate tool will have to be maintained. This is usually not a cost-effective practice. The air gap, however, can be changed to some extent from design to design. But not to the extent that a significant change in discharge energy or motor losses can be achieved. As a general guideline, considering the results from Table II, both these design parameters can be

maximized to lower the discharge energy. This guideline is particularly useful when developing a product line, as it allows for the creation of punching tools based on the finalized designs.

4) *Wedge*: This design parameter has a moderate first order index value. However, this parameter cannot be changed to an extent where it can have a significant impact on the motor losses or the discharge energy. This is again due to manufacturing constraints and impracticality of having wedges of multiple thickness. As per Table II this parameter has an inverse relationship with discharge energy therefore it should be maximized as much as possible to lower the discharge energy. This guideline is especially helpful when a product line is being developed where laminations and stator slot designs can be finalized considering the ideal wedge thickness.

5) *Bearing size.:* The bearing size has a moderate first order and total effect index value. Its inverse correlation to discharge energy suggests that increasing the bearing size can reduce the discharge energy but this will result in lower efficiency due to additional losses associated with a bigger bearing. Therefore, a balance has to be reached to select a suitable bearing size which can reduce the discharge energy, does not increase the motor losses significantly, meet the customer load requirements and bearing life.

6) *Ground insulation thickness*: The ground insulation thickness is directly dependent on the voltage rating of the motor and is usually fixed for a particular voltage rating. This is a parameter which cannot be changed from design to design considering the same supply voltage. So, even though the ground insulation has a high total effect index this parameter is better avoided for lowering of discharge energy. Also, this parameter has an inverse relationship with discharge energy. Therefore, the ground insulation thickness will have to be increased to reduce discharge energy. Increasing ground wall thickness usually will result in more losses and higher temperatures as the available area in the slot for the stator winding will decrease. This can be compensated by increasing the stator slot width so that the original wire width can be used but as per Table II, increasing the stator slot width will increase the discharge energy.

7) *CMV*: Common mode voltage is a property of the drive. This is not a motor design parameter. Owing to its relatively high first order index value signifying direct impact on the discharge energy it is best suited to keep the CMV as low as possible to keep the discharge energy low. It is the responsibility of the end user of the motor to use a drive with low CMV or take suitable measures to reduce the CMV of the drive available with the end user.

IX. CONCLUSIONS

This study demonstrates the application of Sobol sensitivity analysis combined with Monte Carlo simulations to assess the influence of various motor design parameters on discharge energy in VFD-driven motors in hazardous locations. Through this analysis, motor designers can better understand the trade-offs between minimizing discharge energy and maintaining high motor efficiency. By optimizing parameters such as stator iron length, stator slot width and the number of stator slots, it is possible to reduce the risk of electrical discharges while ensuring high motor efficiency. The paper also identifies design parameters that can be avoided to lower the discharge energy, as well as those that may not be easily modified in daily manufacturing but could be considered when developing new products. The use of Sobol sensitivity analysis provides a clear, quantitative method for identifying the most influential parameters and their interactions, offering a robust tool for motor design optimization. Moreover, the large Monte Carlo dataset ensure the accuracy and reliability of the results. This methodology could serve as a valuable tool for engineers designing motors for hazardous locations, helping to meet low discharge energy and high efficiency.

X. REFERENCES

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XI. VITA

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