Machine Learning Technique to Predict Flashover Voltage of Nanocomposite Materials

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Abstracts: Epoxy resin is frequently employed in medium- and high- voltage transmission insulation, because of its low dielectric losses and excellent temperature resistance. At low temperatures, epoxy resin has high chemical resistance. Epoxy resin insulated types have largely superseded the conventional, paper-insulated varieties in numerous cable sectors owing to several advantages. Numerous studies have been conducted to enhance the properties of epoxy resin. With the addition of silicon dioxide (SiO2) nanofiller, the electrical and physical properties of epoxy resin are intended to be improved in this research. Epoxy resin composites with SiO2 filler were created with lengths of 5, 10, 15, and 20 mm and concentrated at 7wt%. Subsequently the key findings of this research are outlined, highlighting the significance of this study's focus on polymer utilized in the highly competitive and technologically advanced power industry, which is used globally.

Keywords: Epoxy Resin, Nanocomposites, Swelling Effect, Flashover Voltage, Machine Learning Algorithm.

1. INTRODUCTION

Over the past few decades, the use of polymeric materials in high voltage apparatus insulation systems has continuously increased. Rubbers are employed instead of regular plastics because the housing needs to be adaptable enough to follow variations in dimension brought on by changes in temperature or mechanical load. High voltage insulators use silicon rubber (SIR), ethylene propylene diene monomer (EPDM), and their alloys as housing [1].

Since their initial commercialization over 70 years ago, epoxy resins have been utilized extensively in the manufacturing of structural applications including laminates and composites, tooling, molding, casting, bonding and adhesives, and others as well as protective coatings. Epoxy resins are versatile because the epoxy ring can react with a range of substrates [2].

Epoxy resins are employed in the manufacturing sector as matrix resins and adhesives for fiber-reinforced composite materials, where they benefit from advantageous traits like high modulus, low creep, and acceptable higher temperature performance. The desirable high crosslink density of epoxy thermosets is largely responsible for these materials' high glass transition temperatures [3-5].

The usage of the new insulating materials is common in outdoor high voltage insulation. The most consideration has been given to silicone rubber. In fact, silicone rubbers are becoming more and more well-liked as a successful solution to insulator contamination issues. In order to lower costs and increase the surface hydrophobicity, electrical conductivity, relative permittivity, and thermal conductivity of polymeric materials, fillers are added to the polymer. [6-9].

Epoxy resins are a suitable high voltage insulator material due to their high dielectric strength (25–45 kV/mm). However, when utilized in environments with high temperatures, high humidity, the presence of contaminants, and UV radiation, epoxy resin is an extremely sensitive insulating substance. The key benefits of epoxy resin as an insulator material over porcelain are that it is substantially lighter, easier to handle, blends with additives easily, and has hydrophobicity [10-14].

PMNs, or polymer matrix nano composites, are a desirable class of composite materials in which nanometer-sized reinforcing fillers are evenly distributed throughout the polymer matrix.

Due to complete exfoliation and multilayer silicate platelet dispersion at the nanoscale scale in the polymer matrix, low filler contents are used [15].

One of the most significant thermosetting polymer components is epoxy resin. It is frequently used in coatings, adhesives, castings, and other products because it has many great qualities, including high thermal stability, adhesion, mechanical, and electrical capabilities. However, it is well known that the widely used epoxy resin, due to its extensively cross linked structure, tends to be fairly brittle when cured with a stoichiometric amount of typical curing agents including aliphatic or aromatic polyamides, dicarboxylic acids, anhydrides, and tertiary amines [16-18].Due to complete exfoliation and multilayer silicate platelet dispersion at the nanoscale scale in the polymer matrix, low filler contents are used [15].

In the current study, silicon dioxide (SiO_2) nanofiller was added to epoxy resins to increase their electrical and mechanical properties. Epoxy resins were used to create six samples with varying amounts of SiO_2 filler. Each sample's electrical and mechanical properties were assessed. The sample that performs the best for each tested characteristic has been chosen.

2. MATERIEL AND METHODS

2.1. Materials

By combining 15 parts by volume of epoxy resin (Bisphenol A-epichlorhydrine) with 2 parts of aromatic hardener (triethylenetetramine), epoxy polymer matrix was created. When epoxy resin reacts with the hardener to generate lengthy chains, the polymerization, it contains one or more epoxide groups that act as cross-linking sites. The epoxy matrix created by the over-aged hardener applied in this work was springy. The matrix structure, the cross-linking ratio, and consequently the molecular movements are affected by the hardener. The used powder filler is silicon dioxide in nano size less than 100 nm.

2.2. Composite Preparation

The mixture of resin and hardener is added and slowly swirled again to ensure that the filler and resin are uniformly blended under a magnetic field and that any trapped air bubbles have dissipated. When the liquid is ready for curing, which happens at 25°C after 24 hours and after 7 days for material stability, it is carefully poured into a mould and kept there. The epoxy composite mixture is formed in the mould. Therefore, samples were made using pure epoxy and epoxy coupled with nano-SiO_2 and had a 12.5 mm diameter and different lengths of 5, 10, 15 and 20 mm.

2.3. Swelling Effect Test

It is now vital to understand how well the insulation performs under such conditions because transmission line insulators are exposed to a variety of weather conditions, including rain and high humidity. In order to measure the swelling effect, samples are submerged in water for various lengths of time—1 day, 7 days, 14 days, and 21 days—and then removed, extracted, and thoroughly dried. To determine the weight difference between the sample before and after immersion in water, the sample's weight is measured. Additionally, the flashover voltage is measured to determine the impact of water absorption on the electrical characteristics of the insulators.

2.4. Flashover Voltage Test

According to IEC-1109, the flashover voltage test shows the electrical behavior of epoxy resin composites can survive the applied voltage. Figure 1 depicts the diagram for the testing circuit, which comprises of the testing transformer, wiring cable, electrodes, and a variac regulating panel.

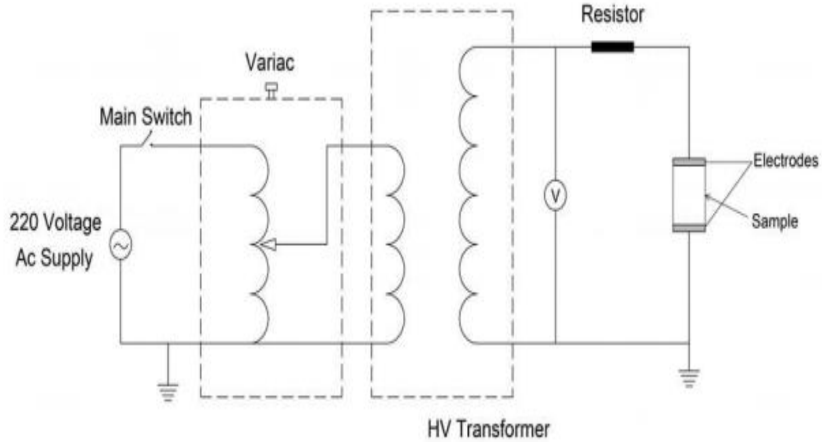

Figure 1. Schematic diagram used for flashover voltage test.

As indicated in Figure 1, a single phase high-voltage transformer (Terco type HV 9105, 100 kV-5 kVA) was used to generate the AC high voltage. A (0-250V) variac, which controls the voltage delivered to the transformer primary winding, was utilized to control the output voltage of the transformer through a control desk. The desk includes operational and signal components for the test equipment's control circuit for warning and safety. The measurement devices (Peak, Impulse, and DC voltmeters) are made to be stored on the control desk. The sample and a brass cylindrical electrode with a 25mm diameter are both attached to the transformer. The electrodes' faces were parallel and free of any blemishes or other flaws.

2.5. Machine Learning Algorithm

The area of computer science known as machine learning (ML) enables computer systems to make sense of data in a manner like that of humans. Simply put, machine learning (ML) is a sort of artificial intelligence that uses an algorithm or method to extract patterns from raw data. The basic goal of machine learning (ML) is to enable computers to learn from experience without explicit programming or human oversight.

Python is a well-known object-oriented programming language with high level programming features. These days, it is well-liked due to its portability and simple syntax. To create models for leveraging data to solve real-world problems, a variety of ML algorithms, approaches, and strategies can be applied. The most popular machine learning (ML) algorithms are those that involve supervised learning. During the training process, this technique or learning algorithm takes a data sample—the training data—and the accompanying output, such as labels or answers. After conducting numerous training data instances, the primary goal of supervised learning algorithms is to discover a relationship between input data samples and associated outputs. The primary objective of regression-based activities is to predict output labels or answers, which are continuous numeric values, for the given input data. The output will be decided using the model's training-phase learnings. Regression models use the properties of the associated input data (independent variables) and the continuous numeric output values (dependent or outcome variables) to identify specific relationships between inputs and related outputs [19, 20].

A one hot encoding can better express the representation of categorical data. Indirect operations on categorical data are not supported by many machine learning methods. The categories must be given numbers. For categorical input and output variables, this is required. The one-hot encoding or one-out-of-N encoding, commonly referred to as dummy variables, is by far the most used method for representing categorical variables. Dummy variables are designed to substitute category variables with one or more brand-new features that can only have a value of 0 or 1. The linear binary classification method (as well as all other models in scikit-learn) makes sense with the values 0 and 1, and any number of categories cam be expressed by adding one additional feature per category, as explained here [21].

The material and sample length are the ML model's inputs, and the flashover voltage experiment's findings are its output. Epoxy must either be pure or contain SiO2 as a filler. In this work, the inputs are encoded using the One-Hot approach. Figure 2 provides an illustration of the model.

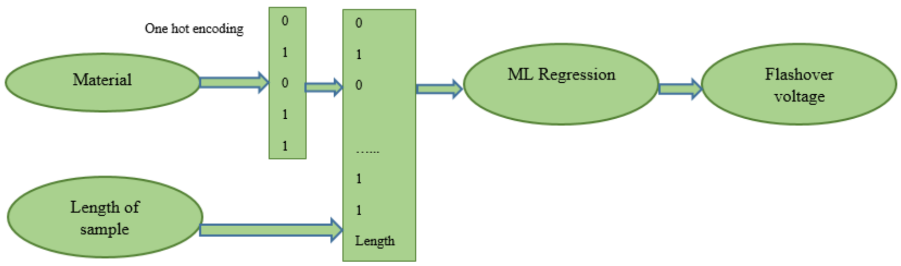

Figure 2. The model for estimating flashover voltage.

3. RESULTS AND DISCUSSIONS

3.1. Swelling Effect Test

3.1.1. Swelling Effect Test for Pure Epoxy Resin Samples with Different Length

Because insulators are subjected to a variety of environmental circumstances, such as rain and high humidity in the surrounding atmosphere, all of which operate to absorb water from the surrounding medium, the swelling rate test explains the weights of the samples before and after absorbing water. Because there is a variation in the rate of water absorption between the two materials, and because the samples contain both the basic polymer material and fillers. To ascertain how much water the samples absorb over time, they are immersed in water for a variety of lengths of time (before, 1 day, 7 days, 14 days, and 21 days). Figure 3 and Table I both display this.

Table I: Weight (gm) of pure Epoxy sample before and after immersion in water

Material	Length (mm)	Weight (gm) before and after immersion in water				
		Before	1 Day	7 Days	14 Days	21 Days
Epoxy	5	1.31	1.31	1.38	1.53	1.71
	10	2.40	2.40	2.51	2.71	2.96
	15	3.52	3.53	5.60	5.86	6.14
	20	4.88	4.90	7.67	8.00	8.41

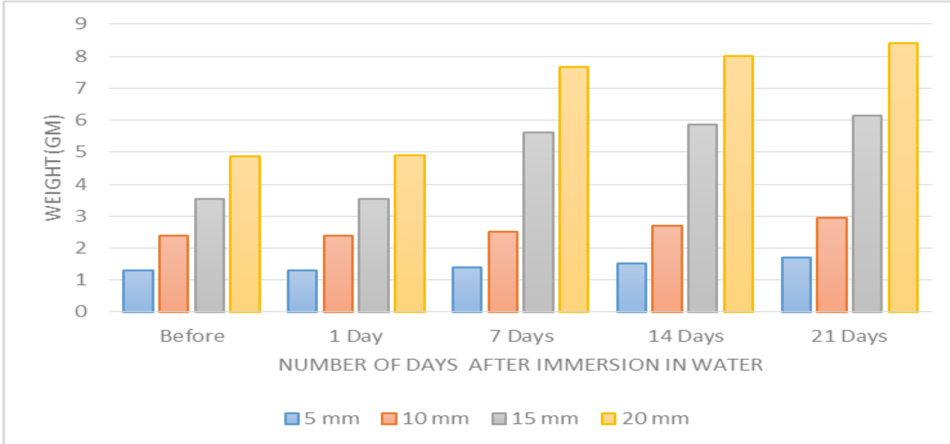

Figure 3. Weight (gm) of pure Epoxy samples before and after immersion in water.

According to Table I and Figure 3, the proportion of water absorption increases the longer the sample is in the water and the longer it is submerged. The weight of the sample, which was 5 mm in length and weighed 1.31 g before immersion, increased by 30.53% to 1.71 g after 21 days of immersion. While the sample with a length of 20 mm increased in weight by 72.34%, going from 4.88 g to 8.41 g after 21 days of immersion.

3.1.2. Swelling Effect Test for Epoxy/SiO_2 Resin Samples with Different Length

The physical structure of samples containing SiO_2 nanofiller changed as a result of swelling and disintegration. The greatest weight that samples containing SiO_2 nanofillers of various lengths gained after 21 days submerged in water is shown in Table II and Figure 4.

Table II: Weight (gm) of Epoxy / SiO2 nano filler sample before and after immersion in water

Material	Length (mm)	Weight (gm) before and after immersion in water				
		Before	1 Day	7 Days	14 Days	21 Days
Epoxy + SiO2	5	1.12	1.14	1.28	1.48	1.69
	10	2.23	2.27	2.47	2.73	2.88
	15	3.01	3.09	3.34	3.67	4.12
	20	4.13	4.22	4.54	4.97	5.53

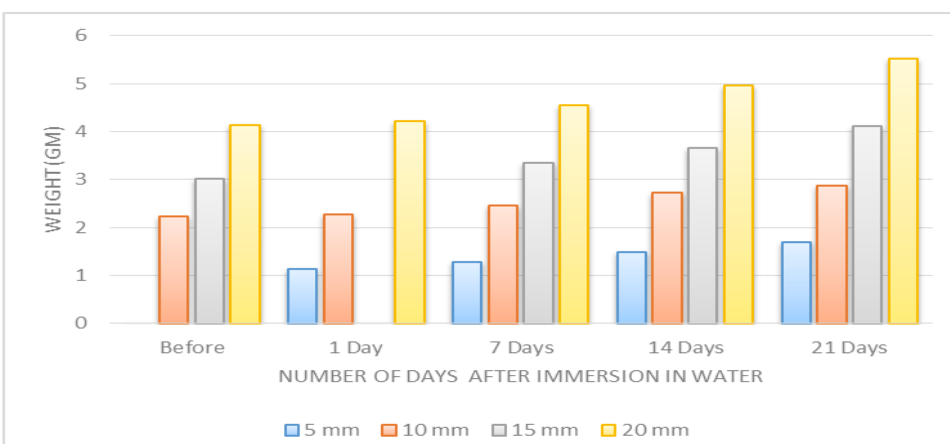

Figure 4. Weight (gm) of Epoxy / SiO2 nano filler sample before and after immersion in water.

Because the density of the polymer is significantly greater than the density of the filler, it was discovered by comparing Table I with Table II that the weight of the samples in the case of adding nano filler is lower than the weight of the sample without any filler. Fillers are added to polymers to strengthen their crystalline structure and fill any gaps. As a result, samples with nano filler as shown in Figure 4.

3.2. Flashover Voltage Test

The flashover is based on the insulator material and is caused by the breakdown of air on the insulator's surface. In the composite insulator, inorganic SiO_2 filler is used with epoxy resin. The filler is chosen to alter the physical makeup of the epoxy resin mixture and raise the epoxy resins flashover voltage. The mechanical and thermal qualities, including as the material's compressive strength and thermal stability, are impacted by the inclusion of filler. To determine the maximum flashover voltage for polymer composite insulators with various sample lengths, the flashover test is carried out for all remaining samples in dry conditions.

3.2.1. Flashover Voltage Test for Pure Epoxy Resin Samples with Different Length

Figure 5 displays the experimental flashover voltage values for samples that were submerged in water for various lengths of time. The experimental results make it evident how the flashover voltage values vary prior to and following submersion in water. It is clear from the experimental values how the flashover voltage values change before and after immersion in water.

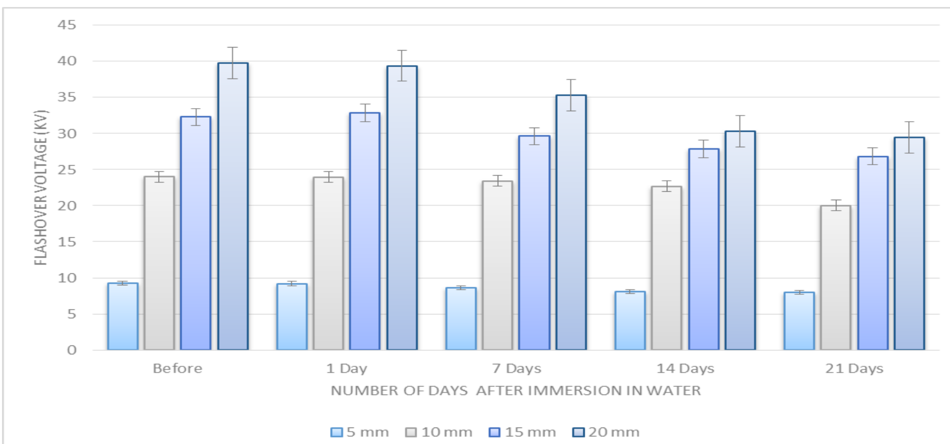

Figure 5. Flashover voltage (kV) for pure Epoxy resin samples with different length using after immersion in water.

Figure 5 shows that if the period of immersion in water changes, the flashover voltage values also change. As the time period is extended, we observe that the samples have absorbed a significant amount of water that was previously present in the polymer's voids. This has had a significant impact on the process of bonding the polymer crystal, which in turn influences the values of the flashover voltage.

3.2.2. Flashover Voltage Test for Epoxy Resin / SiO_2 Nano Filler Samples with Different Length

Figure 6 shows the average values of experimental Flashover voltage (kV) of Epoxy resin/ SiO_2 nano filler samples with different length after immersion in water.

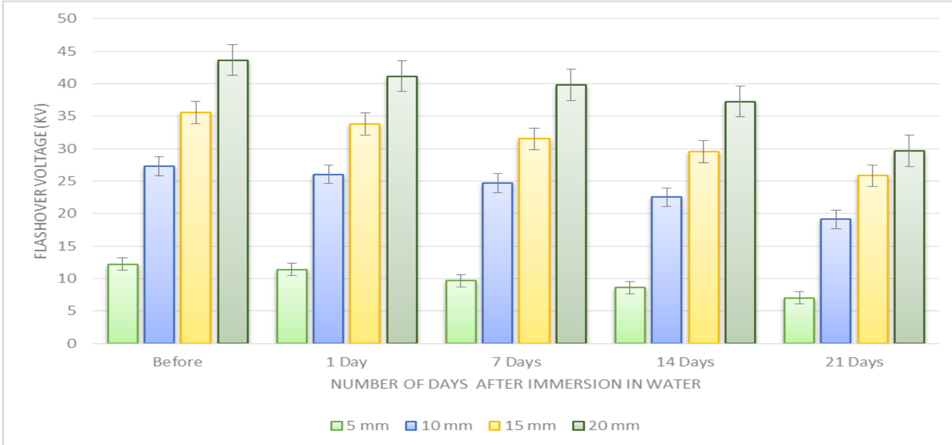

Figure 6. Flashover voltage (kV) for Epoxy resin with SiO2 nano filler samples with different length using after immersion in water.

The voltage increased gradually by voltage regulator up to the flashover occurrence. When the flashover happens, the protection scheme disconnects the main supply and holds the reading of voltage at the instant of flashover. Nano SiO2 filler improves the electrical performance of epoxy because the nano SiO2 composite insulators withstand repeated flashover test.

When epoxy insulator is submerged in water for longer periods of time (from 1 day to 21 days), the flashover voltage is only marginally altered, but the dielectric strength continues to decline when compared to epoxy insulator that is clean as shown in Figure 6. In order to create a polymer composite insulator with superior electrical performance, the epoxy insulator must be enhanced by adding an inorganic filler to mix with epoxy resin.

Contaminated weather has an impact on the surface resistance of polymer composite insulators. Free ion particles from contaminated weather are deposited on the surface and are the primary source of surface leakage current. When the electric field stress increases, the leakage current increases quickly until the occurrence of the flashover phenomenon. If all other factors remain constant, the flashover voltage will be greater the more uniform the potential drop and the more uniform the field's surface intensity. A corona discharge forms when there is a strong local surface electric field, which causes an even more uneven distribution of potential over the surface and, ultimately, a flashover. An important factor is the state of a solid dielectric's surface. The voltage is prone to distortion when there is dirt and moisture present on the surface. Even when the geometry of the surfaces has been chosen to enable it, the potential on polluted surfaces cannot be spread uniformly.

3.3. Machine Learning for Estimation Flashover Voltage

ML output test results represented the flashover voltage measurements of pure Epoxy resin with different sample length. Table III shows the test results of the ML model and the practical experiment. It can be observed that, the ML model has been trained, which can successfully estimate the flashover voltage of pure Epoxy resin composites. The flashover voltage has been investigated in four samples. Three of them have been used to train the ML model. After training the ML model, the 4th sample has been used to test the ML model and compare it with the experimental value to check the validity of the ML technique and evaluate the percentage of error (see Table III).

Table III: ML results and experimental results for flashover voltage of epoxy resin samples

Material	Length (mm)	No. of Days	Flashover Voltage (kV)	ML Results	Error Percentage (%)
Epoxy	5	Before	9.249	9.108	1.524
	10		24.031	24.000	0.129
	15		32.296	32.115	0.560
	20		39.747	39.712	0.088
	5	1 Day	9.200	9.180	0.217
	10		23.980	23.990	0.041
	15		32.860	32.810	0.152
	20		39.400	39.210	0.482
	5	7 Days	8.660	8.590	0.808
	10		23.410	23.460	0.213
	15		29.640	29.680	0.134
	20		35.330	35.300	0.084
	5	14 Days	8.080	8.060	0.247
	10		22.700	22.650	0.220
	15		27.860	27.810	0.179
	20		30.330	30.360	0.098
	5	21 Days	7.940	7.910	0.377
	10		20.020	20.060	0.199
	15		26.830	26.790	0.149
	20		29.460	29.410	0.169
Epoxy + SiO2	5	Before	12.211	12.101	0.901
	10		27.324	27.306	0.066
	15		35.611	35.578	0.093
	20		43.656	43.583	0.167
	5	1 Day	11.380	11.410	0.263
	10		26.040	26.010	0.115
	15		33.760	33.720	0.118
	20		41.160	41.120	0.097
	5	7 Days	9.650	9.620	0.311
	10		24.710	24.671	0.161
	15		31.500	31.460	0.126
	20		39.810	39.780	0.075
	5	14 Days	8.590	8.570	0.232
	10		22.520	22.520	0
	15		29.550	29.540	0.033
	20		37.260	37.280	0.053
	5	21 Days	7.000	7.020	0.285
	10		19.090	19.060	0.157
	15		25.840	25.800	0.154
	20		29.690	29.660	0.101

It can be concluded from Table III that:

- Accurate results have been obtained by ML under various polluted situations.
- ML enables to estimate all values of flashover voltage for various Epoxy resin composites.
- In many working environments, the ML can be utilized as a trustworthy estimate to assess flashover voltage.
- The findings showed that ML can be used to assess the flashover voltage of nano composite insulators and

predict the ideal sample length that resists the voltage under various polluted situations.

CONCLUSION

When compared to conventional ceramic insulators, composite polymeric insulators perform significantly better in contaminated settings throughout the initial period of operation. The objective of this technical work is to examine the flashover voltage and swelling effect tests of an epoxy resin composite that contains SiO_2 as an inorganic nano filler at a 7wt% concentration along with various sample lengths. From this research, it can be inferred that

1. The minimum value of flashover voltage is found in pure epoxy resin.
2. The flashover voltage rises with sample length, and SiO_2-loaded epoxy resin exhibits better electrical properties than pure epoxy.
3. The SiO_2/epoxy composite, which was sampled over a 20 mm length, has a maximum breakdown voltage of 43.656 kV.
4. The swelling of the samples is directly related to their length and the amount of filler material they contain.
5. The amount of water absorbed increases with the length of time samples are submerged in water.
6. ML algorithms help to cut down on the expensive expense of numerous trials and supplies.

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