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RESEARCH ARTICLE

Additive Manufacturing as an Insulator for Medium Voltage Power Electronics Applications

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ABSTRACT The use of additive manufacturing (AM), more especially 3D printing, to medium voltage power electronics is examined in this research. It focuses on how this technology may transform insulating techniques and component manufacture. The study indicates how 3D printing may be used to create intricate component geometries that are not possible with conventional production methods. Additionally, it compares the insulating qualities of traditional and 3D printed materials. Taking into account aspects like heat resistance, electrical insulation strength, mechanical durability, and adaptability to complex designs, the study illustrates the advantages of 3D printed insulators in improving device performance and manufacturing efficiency. This paper presents a case study on the development of a 20 kV inductor for medium voltage applications utilizing ABS (acrylonitrile butadiene styrene) 3D printed parts. The study validates ABS's efficacy as an insulator compared to traditional materials. The study emphasizes additive manufacturing (AM) as a potential method to produce power electronics components, and 3D printed insulators present a strong substitute for traditional materials. This development signifies a new era in power electronics, characterized by improved performance, design flexibility, and advancements in material science.

INDEX TERMS Additive manufacturing, power electronics, insulation breakdown, medium voltage (MV), inductor, dielectric strength, ABS.

I. INTRODUCTION

Over the past decade, Additive Manufacturing (AM), also known as 3D printing, has significantly advanced, expanding its applications beyond simple prototyping to the production of complex components for a variety of energy industries, including electronics [1], [2], electrical machines [3], [4], Batteries [5] and power electronics [6], [7], [8]. AM techniques offer the unique advantage of creating three-dimensional passive components such as resistors, inductors, and capacitors, circuit boards, and packages for power electronic devices with unparalleled design flexibility and efficiency. This paper explores the utilization of AM in the fabrication of components and converters for medium voltage power electronics, emphasizing the transformative potential of this manufacturing approach in enhancing device performance, reducing size and weight, and improving manufacturing speed and flexibility compared to traditional manufacturing methods.

The landscape of electronics 3D printing includes a variety of technologies, each with its own specialties. Aerosol jet printing is appropriate for flexible and three-dimensional devices because it provides excellent resolution and the capacity to print on non-planar surfaces. Scalability issues and restricted material compatibility, however, might be challenging [1], [10], [40], [41]. Inkjet printing provides versatility, high resolution, and compatibility with a wide range of materials, but conductivity limitations and printhead clogging can arise [1], [10], [40], [41]. There are benefits and drawbacks to other methods such as stereolithography

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and selective laser sintering. Mechanically robust components may be made by selective laser sintering, however good conductivity can be challenging to achieve. Although it can fabricate complex structures, stereolithography may not be able to use all conductive resins [1], [10], [40], [41]. Fused Deposition Modeling (FDM) is an affordable 3D printing process that may be applied to the manufacture of simple electrical components. Using conductive filaments, FDM enables the creation of unique electrical enclosures and components. However, when using FDM for electrical 3D printing applications, consideration should be given to restrictions in resolution, conductivity, and material compatibility [1], [10], [40], [41]. Understanding these strengths and limitations is crucial for selecting the most suitable technology based on specific requirements in electronic component fabrication.

Compact, light-weight, and efficient devices are needed for the development of power electronic converters for uses in renewable energy, smart/micro-grids, and electric transportation [9]. In order to accomplish these goals, advances in manufacturing techniques as well as semiconductor chip design and selection are required. AM has emerged as a potential answer to these problems because of its capacity to quickly prototype and implement complicated ideas [10], [11]. The use of additive manufacturing (AM) in the creation of power converters and componentry has been made easier by recent developments in printable materials, improved printing precision, and lower prices. These breakthroughs have produced innovations that greatly boost performance and efficiency.

Early use of additive manufacturing (AM) in power electronics, for example, has shown that it is possible to create power inverters with 3D-printed heat sinks [12], [13], [14], which improve thermal management and lead to more effective and compact designs. Moreover, AM's capacity to achieve sophisticated bobbin designs for high-frequency power inductors [16] and optimize winding geometric shapes for inductors [15] emphasizes its potential to reduce power losses and precisely control component parameters, highlighting the major advantages of AM in the design and fabrication of power electronics.

Despite these benefits, the use of AM in medium voltage power electronics could lead to insulation breakdown issues, owing to material characteristics that may not yet equal those produced through traditional production procedures. This work discusses the benefits, drawbacks, and future possibilities of several AM methods with an emphasis on using AM for insulation in medium voltage power electronic components and converters. The goal of this investigation is to shed light on the potential applications of AM insulating materials in medium voltage power electronics, opening the door for the development of more compact and highly efficient power devices in the future.

To achieve the goal of this article, first, a survey of the involvement of AM in various application in power application is conducted in section II. Then, a comparison of available insulation materials whether using traditional or additive manufacturing is performed in section III. Section IV focusses on the use of the 3D printed Acrylonitrile Butadiene Styrene (ABS) where it's electrical capabilities are tested and used to develop an inductor bobbin as a case study. Finally, the conclusion presents the findings of this work and the recommendations.

II. STATUS OF ADDITIVE MANUFACTURING MATERIALS

To understand the current state and future prospects of additive manufacturing in medium voltage power electronics applications, a review of the existing literature is conducted. This literature review encompasses studies focused on material development, process optimization, and case studies of successful applications.

The choice of appropriate materials is a crucial component in additive manufacturing. The development of 3D printing materials with improved mechanical, thermal, and electrical characteristics has advanced significantly [17], [18]. Thermoplastics with good dielectric qualities, low cost, and ease of printing, such polylactic acid (PLA) and polyamide (Nylon), have been studied [19], [20]. Applications for these materials include the construction of connections, enclosures, and structural parts for power electronic systems.

Power electronics has also shown interest in photopolymers, such as digital light processing (DLP) resins and stereolithography (SLA) resins. These materials may be used to produce microscale power electronics components such as printed circuit boards (PCBs) and sensor housings because of their superior surface smoothness and high-resolution printing capabilities [21], [22], [39].

For power electronics applications, ceramic materials with remarkable electrical insulating qualities and durability at high temperatures have also been investigated. Ceramics with exceptional mechanical strength and dielectric characteristics include silicon nitride and aluminum oxide (Alumina) [23], [24]. These ceramics have been used in the production of high-power devices, insulating components, and substrates for power electronics.

Metals have also been identified as suitable materials for additive manufacturing in power electronics. Because of its great electrical conductivity, copper has been researched for use in power electronic systems to provide heat sinks, busbars, and conductive routes [8]. Aluminum alloys have demonstrated potential in situations where weight reduction is crucial because of their lightweight design and strong thermal conductivity [25].

To enhance the efficiency and dependability of 3D-printed power electronics components, researchers have also concentrated on process optimization strategies. To achieve the required mechanical stability, thermal control, and electrical insulation, variables including printing settings, post-processing strategies, and surface finishing processes are critical [6], [26].

The effective integration of additive manufacturing in medium voltage power electronics is illustrated by a number of case studies. These studies demonstrate the creation of working prototypes, showcasing the cost-effectiveness, performance optimization, and design flexibility made possible by 3D printing. Notable uses include the manufacturing of custom-shaped medium voltage medium frequency transformers [27] and high voltage transformer pulsers [28].

Even with these advancements, there are still obstacles facing additive manufacturing in medium voltage power electronics. Additional research and development is needed in the areas of material compatibility, heat control, and process scalability. Furthermore, to guarantee the dependability and security of 3D-printed power electronics components, guidelines and standards for their qualification and certification are crucial. The next part contrasts conventionally manufactured insulation with additively manufactured insulation because the main goal of this article is to explore the potential of employing 3D printed insulation for medium voltage applications.

III. INSULATING MATERIALS: TRADITIONAL VS ADDITIVE MANUFACTURING

A new class of materials for insulation in medium voltage transformers has been introduced by the development of Additive Manufacturing (AM) or 3D printing technology. These materials offer an alternative to conventional insulation materials including mineral oil, paper, and resin-based insulators. The differences between conventional and 3D printed insulating materials are emphasized in this comparison, with particular attention paid to their characteristics, uses, and possible drawbacks.

Traditional Insulation Materials:

1. **Mineral Oil**: provides superior cooling and electrical insulation. It is prone to contamination, needs frequent maintenance, and presents fire and environmental risks [31].
2. **Paper Insulation**: economical and has a solid track record of providing strong insulation when paired with oil. Due of its moisture sensitivity and biodegradability, it may have a shorter lifespan and require more care [32].
3. **Resin-Based Insulation**: has good dielectric strength and moisture resistance and requires little upkeep. The drawbacks include increased expenses, challenging maintenance, and disposal issues with the environment [33].

3D Printed Insulation Materials:

Some of the common used 3D printing materials nowadays are Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate (PET) [29], [30]. In addition to many other materials, the AM have the following advantages:

1. **Customizability and Precision**: The efficiency and efficacy of the insulation system may be improved by using 3D printing to create components with complex geometries and customized features. Using conventional materials, this accuracy is more difficult to achieve.
2. **Material Variety**: With the development of AM technologies, a wider variety of insulating materials are now accessible, such as sophisticated polymers and composites with tailored mechanical strength, dielectric characteristics, and thermal stability.
3. **Environmental Impact and Safety**: Compared to mineral oil, many 3D printed materials have a lower environmental effect, and some of them are recyclable or biodegradable. Moreover, the lack of flammability or poisonous elements in some 3D printed materials could contribute to a safer operation.
4. **Rapid Prototyping and Production**: Faster design iterations and insulation component production are made possible by additive manufacturing (AM), which speeds up deployment and customisation for certain applications. This agility is in contrast to the labor- and time-intensive procedures that are frequently involved in using traditional insulating materials.

Although there are many benefits to 3D printed materials, there are also drawbacks to take into account. Compared to traditional materials, these materials' long-term performance and dependability under high voltage and fluctuating temperature settings are not as well-documented. Extensive testing and standardization are necessary since the dielectric characteristics of 3D printed materials, such as permittivity and dissipation factor, might change depending on the printing method, material composition, and post-processing [29], [30].

Initial expenditures in 3D printing technology and material research might be costly, however this may be compensated by reduced waste and increased efficiency over time. To fulfill the needs of medium voltage transformer applications, the scalability of generating large numbers of 3D printed insulating components continues to be a difficulty. In conclusion, Table 1 presents a comparison between the common AM materials and the previously listed traditional materials in terms of cost, thermal, mechanical, and electrical aspects.

- **Dielectric Constant and Strength**: Because of its exceptional dielectric strength, polyimide is a good choice for high-voltage applications. Although PET, PLA, and ABS have lower dielectric strengths, they are nonetheless suitable for a wide range of uses and have cost and flexibility benefits [29], [30].
- **Temperature Sensitivity**: Low temperature sensitivity allows polyimide and resin-based insulations to retain their characteristics across a wide temperature range. Because of their mild temperature sensitivity, PLA, ABS, and PET cannot be used in high-temperature situations [29].
- **Mechanical Durability**: PLA and paper insulation are less robust than polyimide and resin-based insulations, which offer exceptional mechanical endurance. PET and

TABLE 1. Comparison between traditional and AM materials.

Insulation Material	Dielectric Constant	Dielectric Strength (kV/mm)	Temperature Sensitivity	Mechanical Durability	Adaptability to Complex Designs	Cost
PLA (Polylactic Acid) [29,30]	3.0 - 3.5	25.8	High (degrades above 60°C)	Moderate	High	Low to Moderate
ABS (Acrylonitrile Butadiene Styrene) [29,30]	2.4 - 4.1	38.3	Moderate (degrades above 80°C)	High	High	Low to Moderate
PET (Polyethylene Terephthalate) [29,30]	3.0 - 3.3	21.6	Moderate (degrades above 70°C)	High	High	Moderate
Mineral Oil [31]	2.2 - 2.5	15 - 35	Low (stable across a wide range)	Low	Low (fluid)	Low
Paper Insulation [32]	3.5 - 5.5	16	High (sensitive to moisture)	Low	Low	Low
Resin-Based Insulation [33]	3.8 - 5.0	20	Low (stable across a wide range)	High	Moderate to High	Moderate to High
Polyimide [34]	3.4 - 3.9	300	Low (stable up to 250°C)	Very High	Moderate	High

ABS combine high flexibility and durability in a balanced way [30].

- **Adaptability to Complex Designs**: The versatility provided by 3D printing technology, which enables the development of complex shapes and customized components, helps PLA, ABS, and PET stand out in this category. Traditional materials with less adaptability are paper insulation and mineral oil [30].
- **Cost**: The most economical choices are often mineral oil and paper insulation. Despite having superior qualities, polyimide is more expensive. Resin-based insulations and 3D printed materials (PLA, ABS, PET) are inbetween, with prices depending on volume and application [29], [30].

IV. CASE STUDY: 3D PRINTED ABS AS AN INSULATOR

The ABS is chosen for this work due to its superior electrical characteristics compared to the other investigated 3D printing materials in Table-1. Thorough analysis of the ABS electrical characteristics is conducted in [30], however, having lower cost helps with the additional investigation and all the trial and error process in this research. The main drawback of the ABS is the thermal sensitivity, hence, a careful design using this material is a must to avoid temperature rise above 80°C. For application where there is continuous high current in the transformer or the inductor, for instance, additional cooling might be needed.

A. PRINTING RESOLUTION

The first step is to see how thin the printed part can be when the (Ultramaker S5) 3D printer used. To ensure the best result, a very simple shape is used which is a rectangular plate. Plate dimensions chosen are (200 mm x 150 mm) which is designed purposefully so it will over fit between the electrodes in figure- to prevent unwanted flashover from occurring. with the following thicknesses -using the minimum feasible printing layer resolution of 20 μm, we printed 4 plates with different thicknesses:

- 40 μm thickness plate; failed.
- 60 μm thickness plate; flaws can be seen in Fig-1
- 80 μm thickness plate; succeeded.
- 600 μm thickness plate; succeeded.

Based on the result, some 3D printing designs can't be achieved if the minimum layer thickness cannot be met. Since the goal here is to examine the dielectric strength capability of the correctly printed sample, the 80 μm and 600 μm thickness plates will be used next.

B. DIELECTRIC STRENGTH

Dielectric strength is one of the most important electrical characteristics of an insulating material which will determine if the material is sufficient or not in a specific application with a predetermined voltage. To examine the dielectric strength, the breakdown point is the threshold that will determine the dielectric strength of a material. There are two phenomenon that are used in high voltage to address the insulation capability: flash over and puncture [36]. Where the flashover is a temporary breakdown in the air along the surface of the insulating material while puncture is a permanent damaged that occurs through the insulator. Flash over occurs at lower voltage compared to puncture. The electrical circuit used to achieve this test is shown in Fig-2 while the physical setup of the device under test (DUT) is shown in Fig-3 where the printed plate is inserted between the two electrodes. DC voltage source that can go up to 60 kV is used since the final application used in this work will be utilized in a dc system. After testing the successfully printed samples, the results are shown Table-2. One thing to pay attention to is the fact that this test assumes uniform voltage distribution, while in some application the voltage stress would not be uniform or worse situations can occur if there are unintended sharp edges which can lead a sooner breakdown. Fig-4 shows the 80 μm sample after being tested and the puncture can be easily observed. The choice of 600 μm (0.6 mm) for the other sample was based on the simulation results where it's sufficient to operate the intended inductor in 20 kV application as will be explained next.

FIGURE 1. 60 μm thickness plate with obvious flaws.

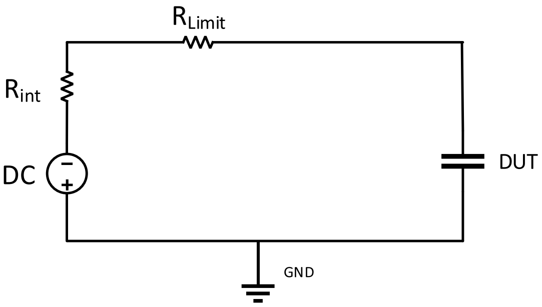

FIGURE 2. Electrical circuit used for flashover and puncture test.

FIGURE 3. Test setup showing the DUT (ABS plate).

C. 3D PRINTED INDUCTOR BOBBIN FOR MEDIUM VOLTAGE APPLICATION

Recently, research have successfully demonstrated many innovative ways to incorporate 3D printing with the design of inductors and transformers [6], [27], [28]. While the environment in low voltages applications might not be electrically stressful on the insulation of the 3D printed parts of a design, medium voltage application can be. As a result, the 3D printing of inductor bobbin is targeted here to achieve a 20 kV inductor that will be utilized in a medium voltage application. In a DC network, this inductor acts as a current-limiting element. Inductor exposure to current occurs during system transitions, such as fault conditions or system startup. The inductor must attain an inductance of 60 μH and permit a maximum current of 300 A. Thin 2 mil (50.1 μm) copper foil is utilized for the windings since the large magnitude current is only visible during brief transients. Lower copper foil thickness makes winding easier and permits rounder corners, both of which might lessen the likelihood of a lower breakdown voltage. The number of turns needed to achieve that inductance is 6 turns and the AMCC-1000 Magnetic core which has dimensions (85, 106, 171) in mm is used due to its high saturation flux density 1.56 T to allow high current without saturating. Based on the analysis conducted on the inductor designed in [36], the maximum voltage stress between two turns will be 7.1 kV under fast rise time of 100 ns. Hence, this 7.1 kV stress is used in ANSYS's FEA to examine the maximum electric field stress between turn-1 and turn-2. Fig-5 shows that E_{max} of roughly 10 kV/mm is found. Knowing that ABS has dielectric strength of 38.3 kV/mm (23 kV per 0.6 mm), the E_{max} observed is less than half the maximum stress the ABS can withstand. Thus, it is safe to use ABS with thickness of 0.6 mm or more as an insulator in this inductor.

FIGURE 4. The 80 μm sample after the puncture occurred.

TABLE 2. 3D printed ABS plates under voltage stress.

Sample Thickness	Flashover Voltage	Puncture Voltage
80 µm	-12 kV	-18 kV
600 µm	-50 kV	No Puncture (up to 60 kV)

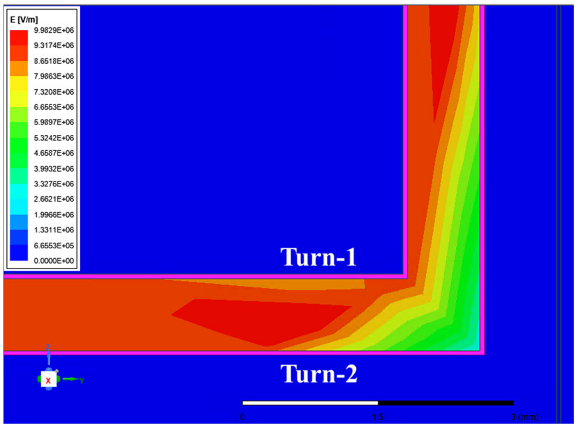

FIGURE 5. Electric field stress on the 3D printed ABS plate as an insulation between inductor's 1^{st} and 2^{nd} turn.

The insulation between turns is designed as plates that are connected together using Kapton (polyimide) tape at the corners to ease the wrapping around the corners as shown in Fig-6. The plates are printed and connected together as shown in Fig-7. The bobbin is printed as one piece as shown in the same figure. After the assembly, the final inductor is shown in Fig-8.

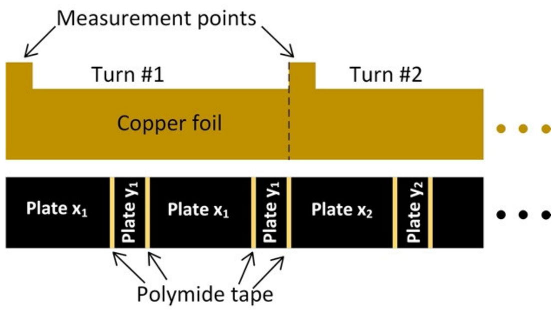

FIGURE 6. Design of the 3D printed plates as an insulation between inductor's turns.

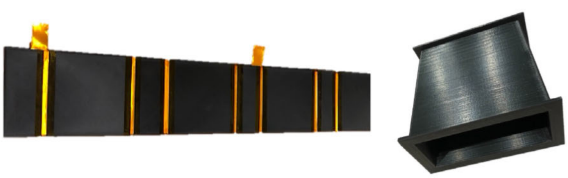

FIGURE 7. 3D printed ABS bobbin and insulation between inductor's turns.

To examine the performance of the inductor in a down-scaled environment, the double pulse test (DPT) approach is used as shown in Fig-9. This test is conducted with a short pulse width to keep the current level low, while the voltage between a turn to ground is measured using the extended measurement points from each turn as shown in Fig-6. Since only 1.5 kV voltage probes are available, 1 kV input voltage is applied and the inductor withstood such voltage and the voltage stress across the turns is depicted in Fig-10. by controlling the gate resistance, two different rise times are used to observe if there will be a change in the voltage stress. Rise time effect is briefly explored here to emulate how the improvement in power electronics nowadays due to using wide band gap devices can affect the insulation capability. reducing the rise time from 75 ns to 25 ns led to increased voltage stress by almost 20%. Research have investigated this phenomenon in machine windings [37], [38], inductors [36], and for MV and

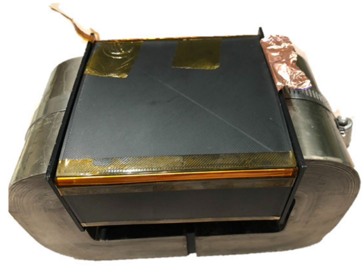

FIGURE 8. 20 kV inductor after assembly.

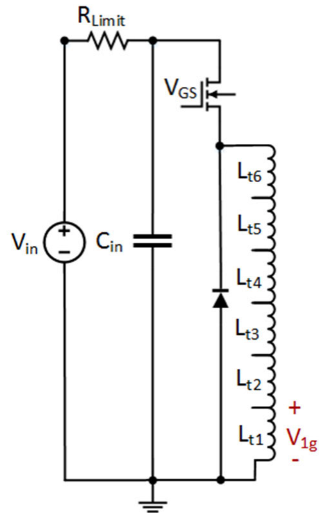

FIGURE 9. DPT circuit using the designed 6-turn inductor.

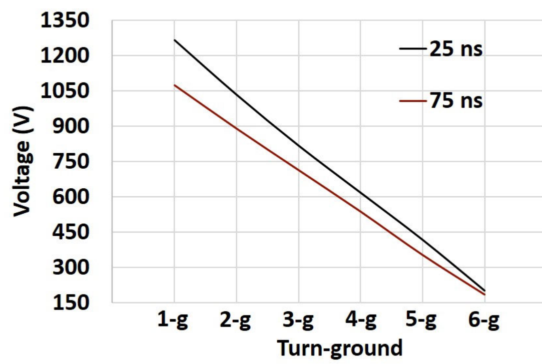

FIGURE 10. Voltage stress across the inductor turns.

MF transformers in [27]. From these studies it is concluded that the faster the rise time, less uniform voltage distribution across the winding/inductor turns will be observed where first and last turns would have higher voltage stress. Such phenomenon is critical to understand and analyze carefully to ensure that the design of the insulation can indeed withstand faster rise times in today's power electronics especially in medium or high voltage applications.

V. CONCLUSION

Additive manufacturing has seen more developments and utilization nowadays in power electronics. While it has been of interest in many applications, the focus here is to explore the feasibility of using it for insulation purposes. The comparison of traditional and 3D printed insulating materials highlights the trade-off between proven performance and innovative possibilities. While traditional materials continue to provide reliable solutions, 3D printed materials offer promising advances in customization, environmental safety, and material properties. As the field of additive manufacturing matures, further research and development are essential to overcome the current limitations of 3D printed insulators, paving the way for their broader adoption in medium voltage power electronics applications. The work here demonstrated the feasibility of using 3D printed ABS material for a medium voltage (20 kV) inductor. To emulate the influence of using wide bandgap devices, which results in faster rise times, two rise times are tested experimentally to observe the voltage stress on the insulation of the inductor turns. At the faster rise time, 20% higher voltage stress is seen. Hence, the insulation capability of 3D printed materials in medium voltage power electronics should consider such impact and further research is needed to investigate innovative ways to overcome it. While this work has achieved its goal, there are some limitations. The work here utilized 3D printing to achieve simple shapes just to recognize the insulation capability while the main advantage of using 3D printing is to realize complex shapes that cannot be made using traditional manufacturing approaches. Future work will utilize 3D printing to achieve and examine complex designs under medium voltage.

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