Heightened reliability concerns in the distribution transformers market amidst the energy transition

ABSTRACT

Distribution transformers are an important part of the electricity grid as they regulate the voltage levels as required. As these transformers have to operate under extreme conditions, including extreme temperatures, overloading, voltage fluctuations and natural calamities, the original equipment manufacturers are required to implement robust design considerations. These design considerations are crucial for offshore wind applications where distribution transformers operate in a remote and harsh marine environment. Once the design considerations are adopted by the OEMs, it is expected that the performance and lifespan of distribution transformers will increase, which will improve the reliability of the overall power system in the long run.

KEYWORDS:

overloading; environmental hazards; voltage fluctuations; design considerations; offshore applications

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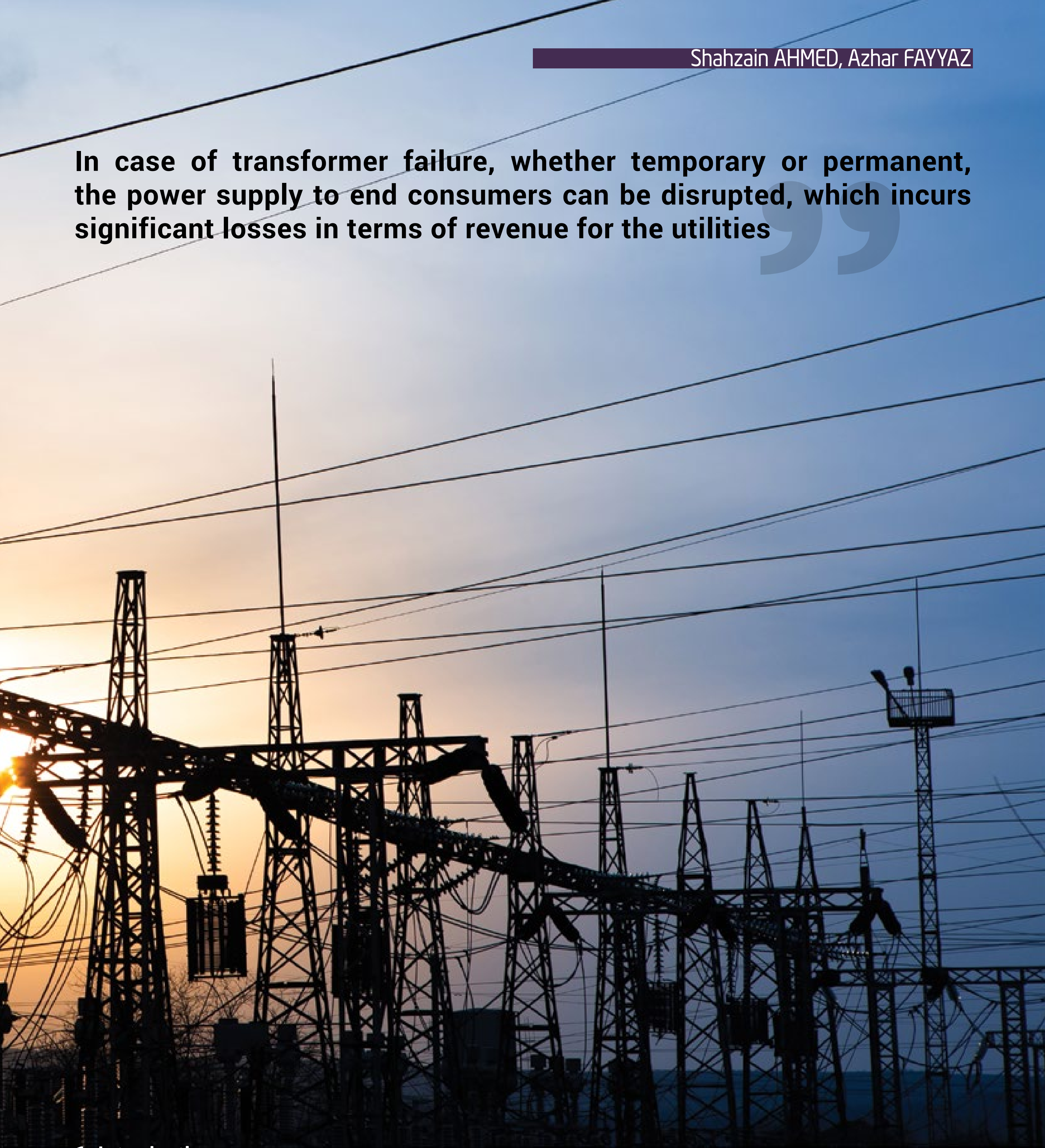

1. Introduction

Distribution transformers are a crucial part of the power system as they effectively regulate the voltage levels as required when attached to generators (like wind turbines) or deployed to serve end consumers. In case of transformer failure, whether temporary or permanent, the power supply to end consumers can be disrupted, which incurs significant losses in terms of revenue for the utilities. Furthermore, as distribution transformers are high-value equipment, their replacement cost is significantly high, which takes an additional toll on the financial well-being of utilities. The situation becomes more complicated when distribution transformers have to operate in extreme conditions, for instance, extreme temperatures, overloading, voltage fluctuations and natural calamities. Offshore wind application is a prime example of an extreme condition under which a distribution transformer has to function. This requires the adoption of robust design considerations during the manufacturing of distribution transformers with a focus on increasing the reliability, performance, and lifespan of the transformer.

As per PTR, the annual unit sales in the distribution transformer market globally will grow consistently with a CAGR of 4.4% from 2022-2027

Regardless, the distribution transformer market globally is growing on the back of an increased demand for electrification and renewable penetration. Factors like climate goals, energy efficiency, and energy transition also play a key role in driving the market. As per PTR, the annual unit sales in the distribution transformer market globally will grow consistently with a CAGR of 4.4% from 2022-2027.

Furthermore, as per PTR's estimates, the global renewable generation capacity is expected to grow from around 2000 GW in 2022 to 3400 GW in 2026. Within renewables, wind generation capacity is expected to grow radically as it is expected to meet the growing electricity needs in the future. This is particularly the case of offshore wind farms, which are in remote and harsh marine environments, which make it difficult to access and maintain the transformer. Inaccessibility makes distribution transformers at offshore sites more vulnerable to failure. This is the reason why these transformers are required to undergo stringent tests in order to comply with the standards and regulations set for the industry.

In this article, we discuss the extreme conditions under which distribution transformers have to operate. We further delve into robust design considerations for the manufacturing of distribution transformers, which are expected to improve the reliability, performance, and lifespan of the transformer. These considerations are particularly useful for offshore wind applications where distribution transformers have to operate in a harsh marine environment.

2. Operation under extreme conditions

When distribution transformers have to operate under extreme conditions such as extreme temperatures, overloading, voltage fluctuations and environmental hazards, it takes a toll on their performance and lifespan, which is undesirable from the perspective of utilities and consumers.

2.1 Temperature extremes

Transformer insulation can degrade due to long-term elevated temperatures, which eventually leads to failure. On the other hand, extremely low temperatures are also detrimental for the transformer, as they lead to issues like oil thickening and reduced mechanical flexibility. Usually, the transformers are designed to operate at their nameplate load for as long as 20 to 30 years, but in situations where they are exposed to extreme temperatures, their lifespan reduces significantly.

Last year in California, thousands of PG&E customers lost power due to the overheating of distribution transformers [1]. As per the California Independent System Operator, the transformers were designed for cooler overnight temperatures, so when the overnight temperature stayed high, the transformers did not cool down as required, which led to failures [1]. Similarly, in the UK, thousands of households lost power during a heatwave due to overheating in the equipment of the distribution grid, especially the distribution transformers.

In order to deal with unusual temperature rises, transformers are designed with windings that have lower resistance. This is helpful, especially as it allows the building of the transformers resistant to temperature rises, which are not bigger in

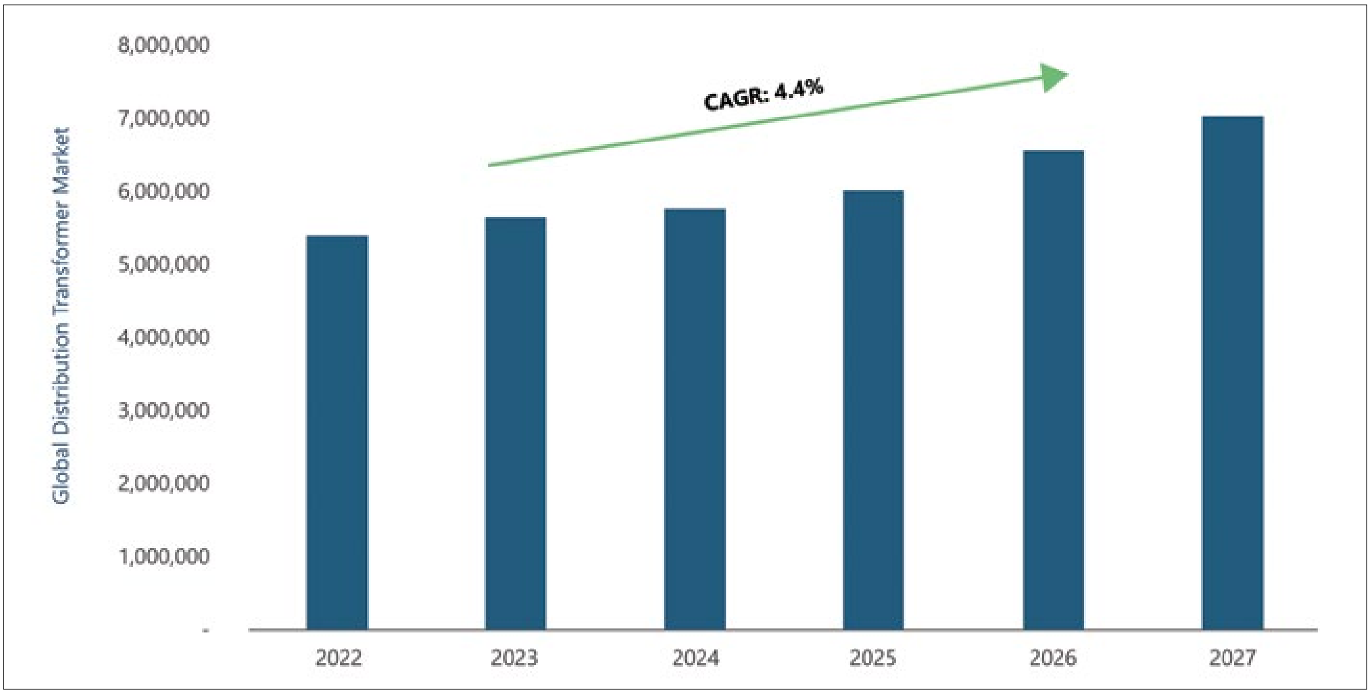

Figure 1: Annual sales in the global distribution transformer market in terms of units. Source: PTR Inc.

size. Furthermore, equipping transformers with advanced cooling systems while ensuring appropriate material is selected for transformer construction can go a long way in supporting transformers to withstand extreme temperatures.

2.2 Overloading

Traditionally, distribution transformers were only supposed to support unidirectional power flow from the distribution network to the consumers. With the widespread deployment of distributed energy resources, especially rooftop solar, transformers now have to support the bidirectional flow of power in an efficient manner. During periods of high generation from DERs, power flows back to the electricity grid through the distribution transformer, in turn increasing the load on it. The widespread deployment of distributed energy resources and bidirectional flow of power at times overwhelm the distribution infrastructure. A significant increase in the sessions of transformer overloading has been observed over the years due to the inability of distribution system operators to properly maintain, operate, upgrade, and replace transformers as required. This has caused a slowdown in the transition to clean energy and electric vehicles.

UP Power Corporation, which is a utility in India, has observed transformer burnouts due to overloading, which disrupted power supply in villages. [2] In order to resolve the issue of transformers overloading, transformers of higher capacity were installed in the service areas of the utility where overloading was observed. [2]

2.3 Voltage fluctuations

Due to grid instability, lightning strikes or faults in the distribution network, voltage fluctuations are observed in the system. These fluctuations have the capacity to stress transformer insulation, trigger voltage sag, and surge downstream. Rapid and significant variations in the voltage on the primary side of transformers can cause the winding and core of transformers to overheat. Overheating of the transformer winding and core takes place due to a rise in hysteresis and eddy current losses. Once the winding and core overheat, it degrades the insulation of the transformer, which in turn reduces its lifespan. If the surge in the voltage on the primary side is beyond the level that transformer insulation is designed to sustain, it can lead to insulation breakdown and produce electrical arcs, which has the potential to damage the winding and trigger internal faults.

When distribution transformers operate under extreme conditions such as extreme temperatures, overloading, voltage fluctuations and environmental hazards, it takes a toll on their performance and lifespan

In order to deal with the menace of voltage fluctuations, a range of solutions can be deployed. For instance, the implementation of robust insulation systems, installing surge protection devices and equipping the transformer with surge regulation mechanisms.

2.4 Environmental hazards

Natural disasters such as earthquakes, hurricanes, and floods are detrimental to distribution transformers as they can cause mechanical stress, moisture ingress, and debris accumulation, in turn leading to transformer insulation breakdown, short circuits, and eventually transformer failure. In order to make the transformers resilient against natural calamity, distribution transformers can be built with reinforced structures, sealed enclosures, and additional protection measures so that they can withstand the impact.

In 2022, a North Texas wind farm lost one wind turbine after a lightning strike, which resulted in the wind turbine catching fire [3]. As per the estimates of the fire chief, around 8000 gallons of oil were in the gearbox of the turbine, whereas approximately 1,300 gallons of mineral oil was in the transformer, which was situated at the base of the turbine tower [3].

3. Robust design considerations

As discussed earlier, distribution transformers face a range of challenges, such as extreme temperatures, overloading, voltage fluctuations, and environmental hazards, all of which are detrimental to their performance while significantly reducing their lifespan. In order to deal with these challenges, several design considerations,

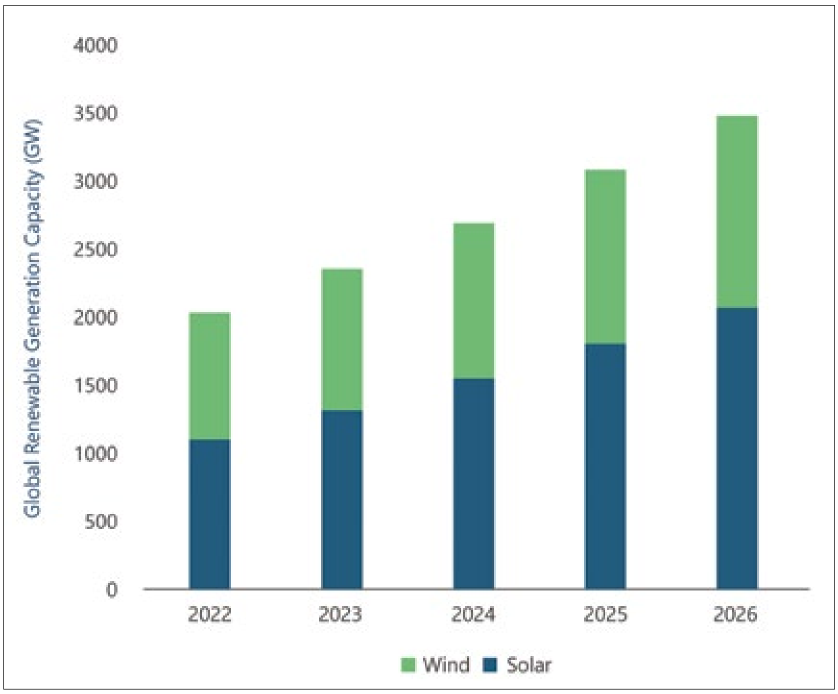

Figure 2: Global renewable generation capacity from 2022-2026. Source: PTR Inc.

Distribution transformers are also deployed on offshore wind farms, but the extreme variations in the conditions that these transformers have to endure take a toll on their performance and lifespan

which involve monitoring and diagnostics, advanced cooling systems, measures to increase mechanical strength, and improved insulation systems, have been proposed.

In order to enable early fault detection and prevent transformer failure, real-time monitoring and diagnostics through sensors, along with transformer health monitoring systems, are very crucial. Cooling systems are also very important for the optimization of performance and lifespan of distribution transformers. Their main job is to maintain the temperature within specified limits, in turn preventing thermal stress and improving transformer reliability. Similarly, the utilization of high-quality insulation materials with improved thermal and electrical properties enhances the reliability and performance of transformers. Additionally, adopting a robust design allows transformers to withstand the impact of transportation, installation and natural calamities, in turn improving reliability and increasing the lifespan of the transformer. These design considerations become increasingly important when distribution transformers are deployed with offshore wind turbines. As such, wind farms are located in remote and harsh marine environments.

4. Offshore wind application: An example of extreme conditions for distribution transformers

Distribution transformers are also deployed on offshore wind farms in order to step up the voltage, but the extreme variations in the conditions that these transformers have to endure take a toll on their performance and lifespan. Wind turbines, especially offshore ones, are designed so that they can endure high wind speeds in the ocean, but they often operate at a lower capacity. Ideally, in order to achieve 100% capacity utilization, wind speed needs to be maintained at over 30 mph. It is observed that wind turbines in Europe generate less than 20% of the rated capacity, whereas in the US, the average load factor is around 30%.

The variations in wind speed and power output of wind turbines are detrimental to the performance and lifespan of step-up transformers. As the power output fluctuates, it leads to frequent daily thermal cycling, which is not desirable. Typically, a distribution transformer observes one thermal cycle a day, but a distribution transformer at a wind farm has to endure multiple thermal cycles per day due to wind speed variations. These frequent cycles put thermal stress on the transformer winding, clamping structure and seals. It also speeds up the aging process of internal and external electrical connections. This, in turn, places the insulator in the wind turbine step-up distribution trans-

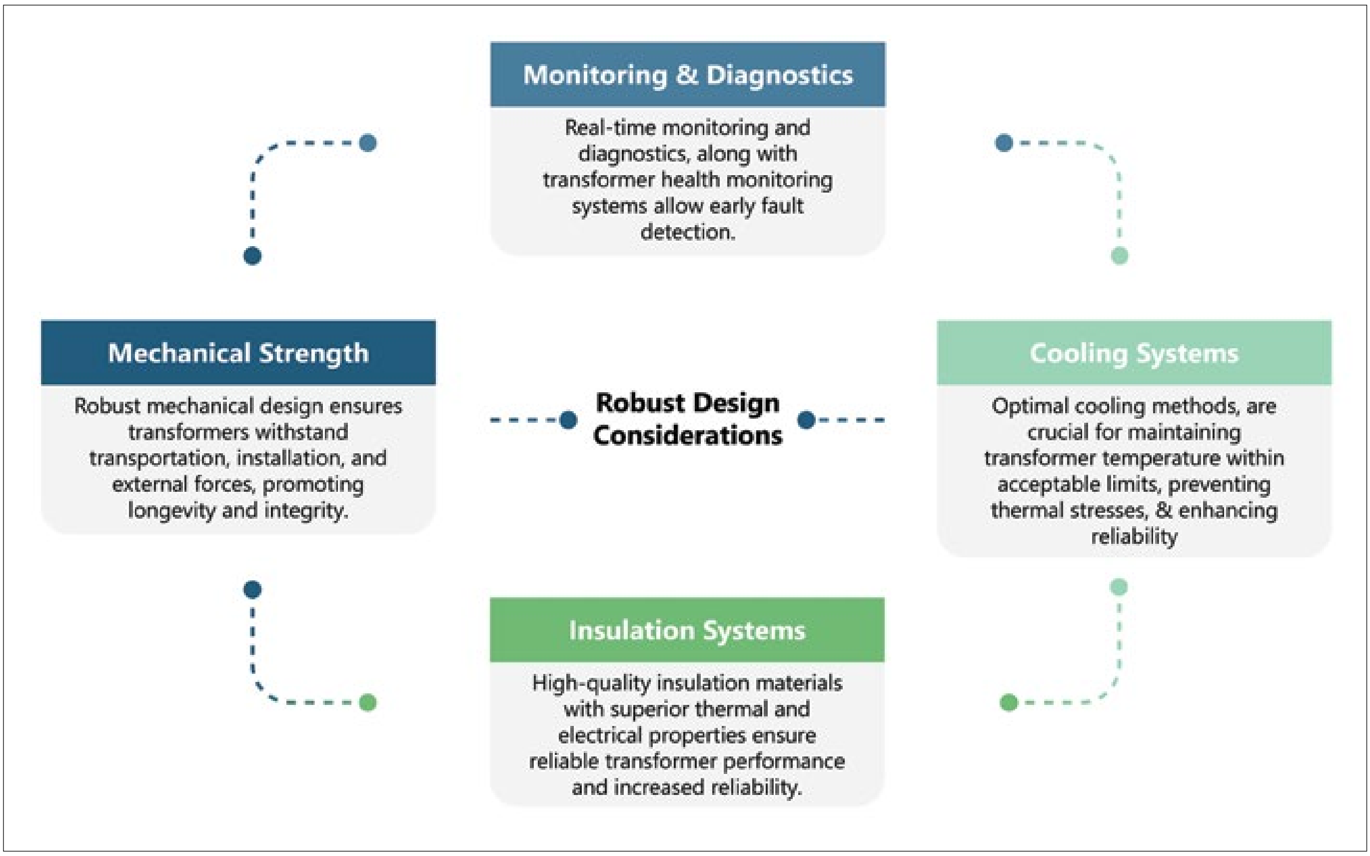

Figure 3: Robust design considerations for distribution transformers. Source: PTR Inc.

former at a greater risk of leading to failure as compared to a standard distribution transformer.

Unlike standard distribution transformers, wind turbine step-up distribution transformers must withstand frequent thermal cycling. This can be achieved by implementing robust design strategies during the manufacturing of wind turbine step-up distribution transformers, including the utilization of corrosion-resistant alloys and protective coatings. These measures enable these transformers to withstand the unfriendly marine environment, in turn increasing their lifespan. Secondly, during the manufacturing of distribution transformers that need to be deployed with the wind turbines, strict quality control measures are implemented so that the product adheres to the set industry standards. Thirdly, in order to protect the internal components of the transformers from moisture, salt water and other contaminants, sealed enclosures are used.

Additionally, state-of-the-art monitoring and diagnostic systems allow for early fault detection and prevent failure through monitoring of temperature, oil quality, vibration, and electrical performance of transformers. For optimization of transformer performance and to address potential issues, transformer maintenance, including inspections, testing and cleaning, is conducted. Critical offshore installations are supported with backup systems which allow for uninterrupted production of power in case of transformer failure.

Overall, distribution transformer manufacturers and wind power plant operators must comply with the industry standards and regulations. The regulations and standards ensure that the wind turbine step-up transformer is designed, manufactured, and operated in a safe, reliable manner that protects the environment.

5. Conclusion

As per the estimates of PTR, sales in the global distribution transformer market in terms of units will grow consistently from 2022 until 2027 with a CAGR of 4.4%. The market will be driven by increased electrification requirements and significant penetration of renewable energy in the capacity mix of countries, whereas factors like climate goals, increased energy efficiency requirements and the ongoing energy transition also play a key role in the growing market.

The distribution transformers are high-value assets and have a crucial role to play in the overall power system, so it is important to be watchful of their performance, reliability and lifespan. This is the reason why original equipment manufacturers are expected to implement robust design strategies during the manufacturing of distribution transformers. These considerations involve monitoring and diagnostics through the installation of sensors, improvements in the cooling and insulation systems and designs which increase the mechanical strength of the structure of the transformer.

It is noteworthy that offshore wind applications of the distribution transformers merit more stringent quality control measures from the OEMs as these transformers have to operate in a remote and harsh marine environment which is not easily accessible for maintenance, in turn making them more vulnerable to failure. Furthermore, wind turbine step-up transformers have to undergo frequent thermal cycling, which is detrimental to their performance and lifespan. A range of solutions, including the utilization of corrosion-resistant alloys and protective coatings, if deployed during manufacturing, can help distribution transformers withstand frequent thermal cycling.

These measures are expected to not only increase the reliability of distribution transformers but also to improve the reliability of the overall power system, in turn facilitating the transition towards a sustainable energy future.

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As an analyst at PTR Inc., **Shahzain Ahmed's** research primarily revolves around power grid subjects, focusing specifically on power and distribution transformers. He has acquired valuable experience by engaging in diverse projects within the power grid industry. His responsibilities entail conducting comprehensive research and analysis of the power grid equipment markets, in addition to monitoring global investments in the Transmission and Distribution network.

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