Towards Next Generation Power Grid Transformer for Renewables:Technology Review

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Abstract

This paper develops a technical framework for the next-generation power grid transformer (NGPGT) for grid renewables. This framework is structured to overcome the environmen-tal challenges produced due to the explosive use of non-renewable base energy generation sources. The use of these sources cannot meet the required electricity for the world's growing community due to their availability, cost, and lack of flexibility. However, modern energy systems focus on the use of renewable energy sources where the grid transformer's interaction acts the essential role in their generation, transmission, and distribution. The lack of central-ization, local monitoring, interoperability, authenticity, and precise bi-directional flow may limit the application of current framework power grid transformers in grid renewables. In this paper, a new technical framework, called NGPGT, is developed by introducing some ex-tended features for addressing the challenges shown in the current-generation transformers. This is structured by enabling some advanced technical features with the existing frame-work which includes automatic condition monitoring, intelligent inverters, edge computing, automatic controlling, and intelligent management. This paper also illustrates the benefits and scopes of the NGPGT compared to the existing transformer by assembling essential re-quirements and obligatory components. Additionally, this paper highlights a few difficulties of implementing NGPGT in terms of operational, communication, energy management, and economic point of view which may enable further research scopes for the researchers.

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Abstract

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Keywords: Power grid, Smart transformer, Emerging technologies, Next-generation transformer, Renewable energy, Technological challenges

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1. Introduction

Renewable energy supplies are important to any civilization to satisfy the need for universal access to clean, sustainable, and affordable energy. We are aware of the fact, which may be fossil fuels will run out in a matter of decades. We just do not have enough energy stored to meet the entire demand of our industry and populations [1]. An economical and eco-friendly strategy is defined as using alternative energy sources such as biomass, wind, and solar energy. Such a strategy may be implemented as a stand-alone energy source or with little change in an existing power system [2].

According to expectations, in 2023, renewable energy sources will account for 12.4 percent of the global energy usage [3]. With the use of sustainable energy sources the most significant increase in the electrical sector, meeting 29.4 percent of the consumption for energy in 2023 compared to 23.9 percent in 2017 [4]. However, bio-energy (in the form of solid, liquid, or gaseous hydrocarbons) will be the main driver of growth in renewable consumption from 2018 through 2023, accounting for 30 percent of the increase [5]. In contrast to the previous year (2017), The production of sustainable energy reached 376 TW-hours (TWh) globally in 2018 [6]. Wind and solar energy production increased by 11 percent and 28 percent, respectively, in 2018. With an increase in the generation of 219 TWh, Asia was mostly responsible for the rise in sustainable energy production in 2018. The amount of sustainable energy generated globally also increased, reaching 40 percent in Asia. Together,40 percent of the shares are under the hands of North America and Europe, with South America and Eurasia (5 percent) leading the way (12 percent) [7]. A graphical representation of clean energy transition is shown in Figure 1.

Sustainable energy is the fine and foremost energy source for any power system community grid network. so advancing technology in grid networks in the near future will be dependent on clean and sustainable energy so far the smart grid network focuses on this renewable energy in the present world [8]. Traditional power grids are no longer capable of meeting the demand for massive power generation. Figure 2 illustrates a general overview of the traditional power grid. The phrase smart grid is used to characterize a variety of innovative data-based services in the production, distribution, and storage of sustainable energy [9]. The transmission grid has become extremely difficult to grasp and prototype in order to use new regulating or activation approaches for developments due to the inclusion of environmentally friendly energy sources. Several projects have been or are currently focused on developing transformer technology as a critical component of a future sophisticated distribution network that enables power routing and simplifies energy management, or on assisting in the integration of renewable energy resources or storage devices into the grid via their direct current (dc) or alternating current (ac) gateways [10]. Creating a smart transformer-based power grid may have a variety of benefits, such as the following: i) To control increasing demand without overloading current electrical infrastructure or increasing

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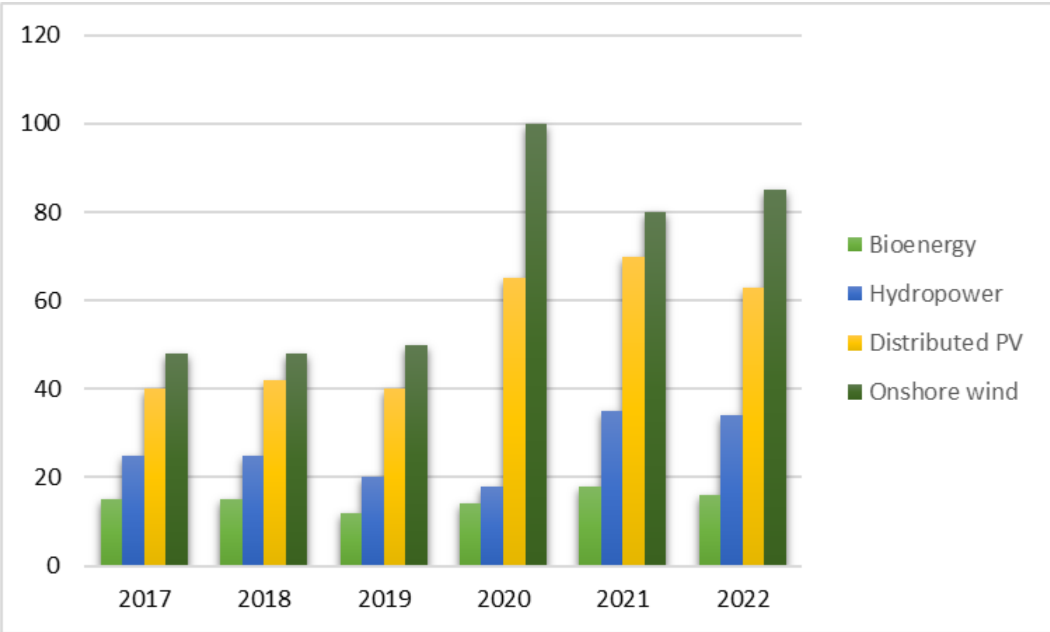

Figure 1: Transition towards renewable energy

capacity; ii) To utilize self-healing capabilities and distributed generation supply methods to reduce the frequency and length of grid disruptions; iii) To achieve self-sustainability in order to ensure the security of supply; iv)To use sustainable energy sources to act on climate change; and v) To deliver electricity to places where utility providers are incapable of providing satisfactory services [11].

A transformer is the core part of the power grid for any operation [12]. Transformer, which performs the crucial task of adjusting voltage levels, stepping up for effective long-distance high-voltage transmission, and stepping down for the distribution of power to consumers, have undergone a lot of technological advancements over the years [13]. Transformers have passive parts that transfer electrical power flowing between circuits, or between several circuits. A fluctuating magnetic flux in the transformer's core is caused by a fluctuating current in any of the transformer's coils, and this causes a fluctuating electromotive force across any further coils that are coiled around the same core. Despite the absence of a metallic (conductive) connection among the two terminals, power transmission energy can be transferred across distinct coils [14].

To develop a smart grid that integrates renewable energy these traditional transformers can't handle large amounts of electricity or operate at their highest efficiency. The next-generation power grid transformer has advanced significantly since it was first developed to include flexible generation and energy consumption has been pushed by academics, scientists, and practitioners in an effort to boost intelligence and construct the next-generation power grid transformer. It is the conversion of a traditional power transformer to an intelligent power transformer that allows the integration of ICT devices in the field of intelligent power production, distribution, and transmission [15]. These transformer promises to revolutionize

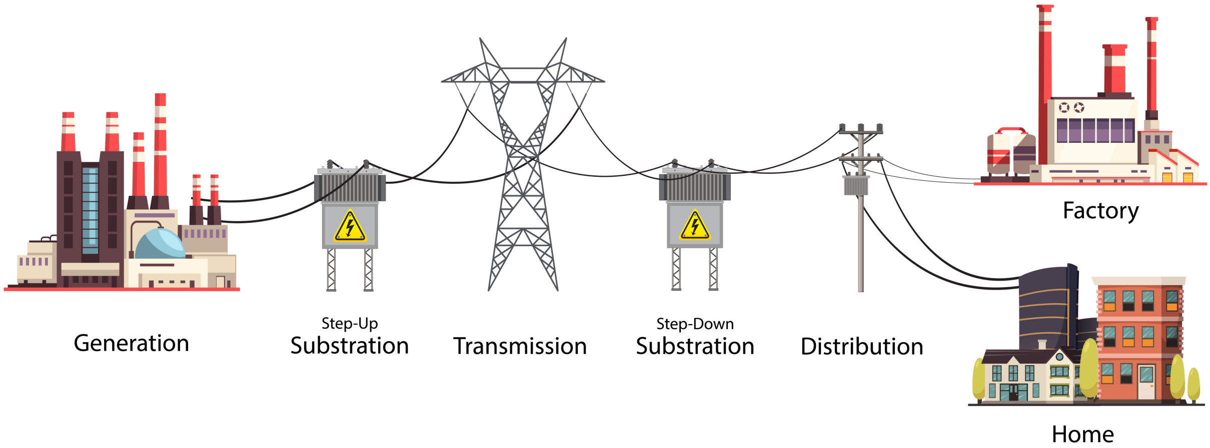

Figure 2: Traditional power grid

how electricity is generated. Linked to a centralized entity, they are collections of energy storage utilities, dispersed generation resources, and regulated loads. Cloud computing, artificial intelligence, the internet of things, and other cutting-edge protocols are all part of the next-generation power grid transformer.

1.1. Motivation and Contribution

It is evident from the critical studies included in Table 1, that NGPGT has a wide range of applications in the sector of sustainable energy. In order to ensure the efficient operation of NGPGT's sustainable energy sources over the long term, it is imperative that advanced features may be enabled. This is due to the fact, the lack of these features may hinder the adaptability, accessibility, and stability of the transformer, in addition to other issues. Many of these demonstrate extra difficulties that could occur while adding add-on components to NGPGT. The PGT system currently has a number of flaws, and it is important to investigate these problems in order to address them by developing the PGT technology. The main contributions of this study are:

i) This study merges the transformer concepts in the power grid (microgrid, smart grid, and VPP) systems and proposes the comprehensive concept of the renewables-integrated power grid transformer.

ii)This paper offers a comprehensive review of the evolution of the transformer from a conventional grid transformer to a next-generation grid transformer for renewables. In addition, it is demonstrated how each transformation of the power grid transformer results leads to an increasingly integrated renewables energies complexity.

iii) A possible framework for a next-generation power grid transformer is suggested which may have the possibilities of development accumulating over the existing power grid transformer major issues and causes of problems as well as finding out the solutions by adding some featuring components.

Table 1: Summary of important surveys

Reference	**Overview of renewables integrated power grid framework**	**Existing power grid transformer framework**	**Possible framework for next generation power grid transformer**	**Opportunities & challenges of integration**
[16]	✓	✓	✗	✗
[17]	✗	✓	✗	✗
[18]	✓	✗	✗	✗
[19]	✓	✗	✗	✗
[20]	✗	✓	✗	✗
[21]	✗	✓	✗	✓
[22]	✓	✗	✗	✓
[23]	✓	✗	✗	✗
[24]	✓	✗	✗	✓
Current study	✓	✓	✓	✓

iv) This article provides a thorough road map of power grid transformers for the next generation that has tremendous opportunities in the power system community with possible benefits that we briefly described. Lastly, having the integrating challenges with the implementation in reality, finally, however, we have suggested the direction towards the next level of research into accountability.

2. Power Grid Renewables: Technology Framework

2.1. Microgrid

The power distribution community is in charge of administering the enormous and complex power system. The connectivity has been, currently, and therefore will continue to be constituted by sharing a variety of renewable sources of energy. Future electrical systems will include a variety of generators and energy consumers distributed over large areas and linked to a central control network. Electric power could be delivered in a range of methods, but consumers like it to be of the utmost quality, minimum cost, and most reliable [25]. A microgrid is an innovative approach to ensuring a steady supply of electricity in a power grid. It is a comparatively tiny electricity grid that can work alone or in tandem with the other small power system. Figure 3 demonstrates an overview of a microgrid. Microgrid has two kinds of connected working mode, one is network connection mode which means that each of these features, such as frequencies, voltage, and power flow are directly regulated by the power network and exhibits dependable and responsive characteristics [26]. Another one is, It may also separate from the main grid during an exigency, such as a transmission line fault or uncertainty, and as an independent power unit known as a stand-alone MG, where it would be responsible for its own control of the voltage, current, or frequency profile.

Microgrids are used for power trading in two different circumstances: i) When there is an overflow of the potential energy supply from distributed energy resources (DERs). ii) When the output of the DERs exceeds the consumption of electricity on the grid [27]. The design architecture may enable both the operating and regulation modes for an MG to produce the needed power for consumption effectively and efficiently. DERs, storage devices, and traditional control and monitoring systems make up a typical MG setup.

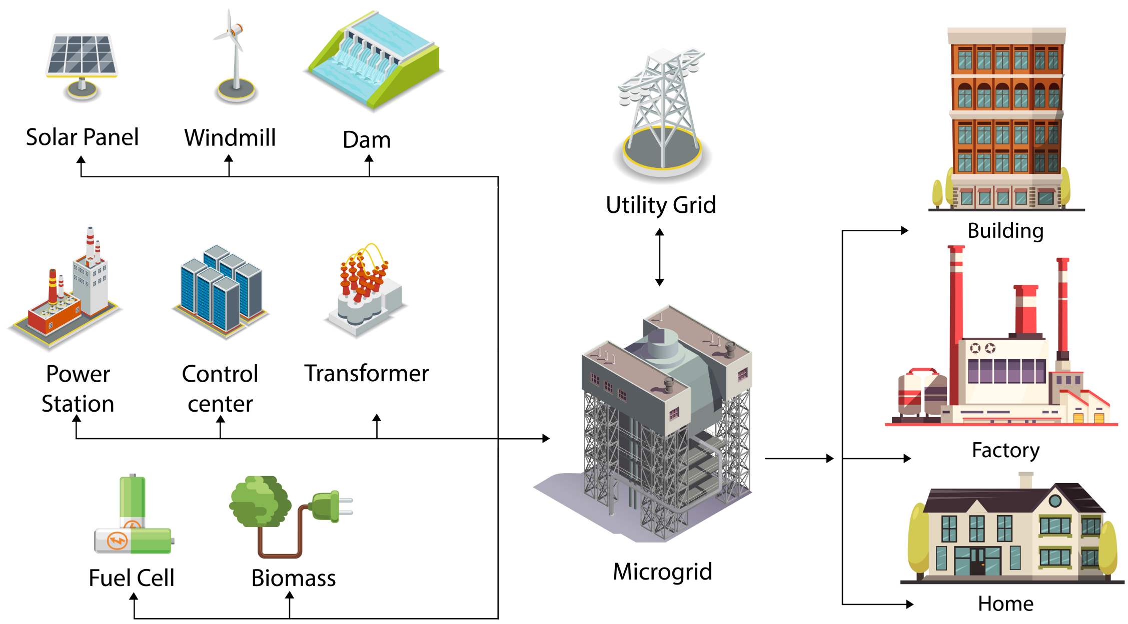

Figure 3: Overview of microgrid

2.1.1. Components of energy sources

i) *Traditional energy sources:* Power may be generated using several sources of energy like hydrocarbons, natural gas, nuclear energy, and oil. More than three-quarters of the world's energy originates from the following sources:

Natural gas may be used in a generator that runs on gas coupled to an SG since the combustion products include very few tars or particles. Open-cycle gas turbines (OCGTs), which may run on gas or oil distillate, are the most prevalent form of a gas-fired plant. Because the gasoline is fed on the turbine, such structures have a miles quicker response time. Synthetic gases such as hydrogen (H2), carbon monoxide (CO), and a small quantity of carbon dioxide may be made using solar energy. However, gases ejected from a gas turbine result in a significant dissipation of heat to the environment [28].

Heat energy is transformed from fossil fuels into high-pressure, high-temperature steam, which is then used for producing power in traditional power plants. It is common practice in coal-fired power plants to first heat the combustion chamber with distillate oil before injecting the coal. Coal-fired power stations burn bituminous coal, sub-bituminous coal, or lignite. When the temperature is exactly perfect, coal crushed to dust in ball mills is blasted into the chamber for the burning of fuel, where the pulverized fuel burns and produces heat [29]. Coal combustion heat is utilized to convert water to high-pressure steam, which is subsequently applied to power an electrical generator.

The synchronous generator is one of the most crucial components of energy distribution channels. It can generate up to 40 kV of power, which may be increased even more by using a transformer to send the signal via a high or extra high voltage transmission line [30]. Synchronous generators are frequently used in varying wind turbines due to their low rotating synchronized revolutions, which produce grid-frequency electricity. The generator can be powered by steam, hydroelectric, and gas turbines. In microgrids with strength levels that are lower, diesel engines can be utilized to power generators. Prior to the examination, modeling can predict the behavior of the SG in many eventualities, including overload and failure mechanisms [31]. The following four basic methodologies are used to model SGs in general: i) Frame dq0. ii) Approach to the winding function (WFA). iii) Model of the phase domain (PDM). iv) The technique of finite elements (FEM) is both dependable and secure.

ii) *Renewable energy sources:* Renewable energy sources (RESs) are growing in popularity as people become more conscious of the need to conserve energy for the future. Fossil fuels are currently mostly used to heat and power our homes, as well as to fuel our cars. Coal, oil, and natural gas are convenient for providing our energy demands, but there is a finite quantity of these energies on the planet [32]. In contrast to the wind, sun, and water, the earth's heat, biomass, and plants are all renewable energy sources that are constantly regenerated by nature. It not only relieves the strain on nonrenewable sources of energy but also gives consumers the opportunity to save money [33].

Solar energy is the most eco-friendly and abundant type of renewable energy. It can be used for a multitude of purposes, including producing power, lighting or creating a pleasant indoor environment, and heating water for the home, commercial, or industrial applications [35]. As a result of advances in solar technology and global developments in the structure of the electric sector, a substantial solar electric business for powering urban grid-connected homes and buildings arose over the previous decade. Due to the lack of moving parts and heat stress, solar energy systems are very easy to maintain and operate [36]. Many photovoltaic (PV) solar cells, which are generally formed of semiconductor material, make up a photovoltaic (PV) solar system. The photovoltaic (PV) system generates electricity by harnessing the sun's energy [37]. Batteries are unnecessary for PV systems that are connected to the power grid. However, some grid-connected systems use them for emergency backup power. This photovoltaic system converts 7-17 percent of light energy into electricity. Solar penetration might reach 27 percent by 2050, according to the International Energy Agency, making it the greatest global sustainable source of power [38].

The wind's renewable energy, non-polluting nature, long-term viability, and omnipresent nature make it a globally sought-after technology [39]. A wind turbine may be thought of as the polar opposite of a fan. Electricity is used to create wind in a fan. Wind turbines, on the other hand, utilize the wind to generate power. Wind farms appear to have achieved their primary goal of generating electricity with a minimal carbon footprint, while

Table 2: 10 Countries almost generate 100 percent renewable-based electricity [34]

Countries	Population (millions)	Hydropower (percent)	Wind (percent)	Geothermal (percent)	Solar (percent)	Total WWS (percent)
Albania (2019)	2.87	99.58	0	0	0.42	100
Bhutan (2020)	0.78	100	0	0	0	100
Congo, DR (2018)	92.4	99.60	0	0	0.09	99.70
Costa Rica (2019)	5.14	68.23	15.66	13.19	0.66	97.74
Ethiopia (2018)	117.9	95.93	3.93	0	0.15	100
Iceland (2019)	0.369	69.07	0.04	30.89	0	100
Namibia (2018)	2.59	97.36	0.43	0	2.21	100
Nepal (2018)	29.7	99.69	0.28	0	0.02	100
Norway (2019)	5.39	93.44	4.11	0	0.01	97.56
Paraguay (2019)	7.22	100	0	0	0	100

also contributing to Natural Capital [40]. It is regarded to operate at a constant or fixed speed. Fixed-speed wind turbines with direct grid coupled squirrel cage induction generators connected to the wind turbine rotor through gearboxes are one of the most often utilized wind farm ideas in power systems [41]. Because a squirrel cage induction generator uses reactive power, compensating capacitors are used to provide the magnetizing current of the induction generator, thereby boosting efficiency. Despite availability, Wind farms can make a one-time, possibly insignificant contribution while additional efforts are made to generate a clean energy supply and better control demand [42].

Because of technical breakthroughs in offshore engineering and the rising cost of traditional energy, offshore energy resources will become economically feasible in the next years. Tidal dams or barrages are now regarded as certain energy sources capable of generating electricity on a large scale [43]. To satisfy the Sustainable Development Scenario (SDS), this technology must be deployed swiftly, with a 23 percent yearly increase required until 2030. The predictability of the tide in the face of any weather change is a benefit of this strategy. Furthermore, the density of water is 800 times higher than that of wind. Nearly 12 knots of water and 110 knots of wind provide the same amount of power. The most often used technique is tidal barrage systems. One or two-way turbines can harness the power of ebb and flood tides, respectively, to power the facility. If the water level on either side of the barrage is the same, electricity will not be produced [44]. Tidal stream turbines (TST), which are quite similar to wind turbines, are the second common method. TSTs are more effective than on- and off-shore wind turbines due to their smaller size and less noticeable visual impact, both of which are achieved by placing the majority of the device underwater. Based on the ebb and flow of the tides, this method transforms the kinetic energy of the water into electricity [45]. The water's kinetic energy is captured by the turbine, which then generates electricity. In order to generate electricity, hybrid generators use both tidal range and steam generators. Dynamic tidal power, a mix of tidal range and current power generation, is also becoming more popular. TST is the most promising technique of them all since it ignores the detrimental environmental impacts of barrages [46].

Biomass is a type of fuel made from organic resources like scrap lumber or tree branches, straw, and animal manure. It is the sole renewable source of carbon, it may be used to create a variety of products. Moreover, biomass is the term for the organic waste produced by plants during photosynthesis, making them all green energy sources. Biomass can be utilized to produce electricity in three different ways: i) The fuel can be burned, ii) Degraded by micro-organisms, iii) Or transformed to a gas or liquid fuel [47]. It's the same as if we were using fossil fuels. The word thermal generation refers to the process of generating energy by burning materials. Methane is burned in certain biomass facilities to create power. Instead of steam, the turbine is spun by the results of burning methane [48]. A generator is driven by the spinning of the turbine, much as it is with solid biomass. An important feature is sometimes overlooked which biomass should be burned as close to its source as feasible, as fuel expenses and carbon emissions from long-distance transportation can considerably a dramatic rise in carbon emissions from fossil fuels [49]. Biomass plants, unlike other renewable energy sources, can create electricity continuously. They don't rely on sporadic factors like the wind or the sun. So, biomass-based electricity is reliable. Country-wise electricity generation through renewable energy sources like hydropower, wind, geothermal, and solar is as shown in Table 2.

2.2. Smart grid

In the modern world enhancing energy consumption and reliance on fossil fuels have become major global concerns. So, there is indeed a growing trend to employ renewable energy sources (RES) to generate electricity. The power system faces significant challenges as a result of the high penetration of renewable energy sources and energy management. For a prolonged day, a conventional and centralized system for the transmission and distribution of electrical energy is being used. The world is currently developing and in the future, the global demand for energy will increase day by day. Approaches that require energy and management are totally dependent on the power grid [50]. In this concept smart grid also known as the intelligent grid is a new solution for demand and energy management for the next-generation network compared to the conventional network. The modern electrical system has the potential to be changed by smart grids. The term smart grid refers to a communication-based approach to power system management. It's a two-way communication interface that provides the grid to the consumer and the consumer to the grid [51]. Figure 4 illustrates the overview of the smart grid. Distributed intelligence, communication technology, and digital control techniques are crucial attributes of smart grids [52]. The smart grid has distinctive features including ICT-based monitoring, self-healing methods, decentralized generations, smart meters, 5Gwireless networks power grids, virtual power plants(VPP), and the integrity of renewable energy and in particular, the IT security of grid networks [53]. The primary objectives of these smart power networks are to improve efficiency, reliability, flexibility, and improving service monitoring [54]. The purposes of smart grid infrastructure are to increase the efficiency of power grids while maintaining their security and reliability, transform existing power grids into interactive utility networks and remove technical barriers to large-scale installation and full integration of renewable energy sources [55].

2.2.1. Smart power generation

It's a one-of-a-kind, cutting-edge mix of characteristics that paves the way for a more sustainable, dependable, and cheap energy infrastructure. Future energy systems will grow smarter and more intricate, and the preparation of strategies for generating electricity for future intelligent power-generating systems more challenging to achieve using standard electricity mix optimization techniques [56]. An integrated approach is provided here to examine optimum pathways in order to take the first step toward solving the challenge. The integrated model consists of the following components: i) To design the best power, a multi-criteria optimal model is applied. ii)The reliability of the generation capacity mix to meet electricity demand within specified constraints is evaluated using an hourly simulation model that aims to achieve a real-time demand-supply balance. The optimal power-generating mix was obtained, and extensive information was provided [57].

The model's goal is to discover the best power-generating mix possible. If the optimal generating mix combination found in the first stage fails to pass the hourly demand-supply balance simulation, the simulation model will change the mix until a balance is achieved. In detail, as feedback, 1 GW of natural gas power will be raised as a peak power supply to satisfy the supply-demand balance, and then gaseous power will be enhanced by 1 GW in the optimization model based on the original optimized result. The proposed integrated model can be used to come up with solutions for organizing power production that is both cost-effective and good for the environment. This will help us move forward into smart power

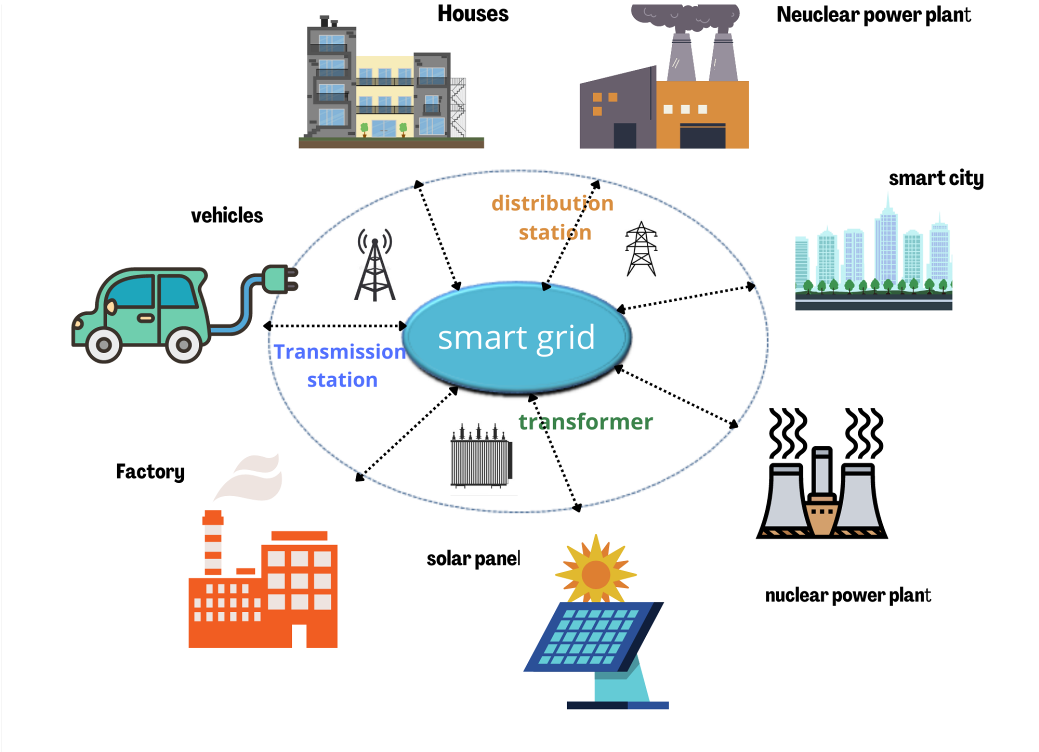

Figure 4: Overview of smart grid

electric utilities with a lot of sporadic sustainable energy and loads that can be controlled and managed by smart control strategies. Finally, this may enable the development of realistic power-generating mixes for future smart electrical systems [58].

i) *Future power generation sources:* In the future, power may generate through various renewable sources such as the following:

• Bioenergy: Bioenergy could be called smart renewable energy in the sense of renewable energy community [59]. It is derived from the crops like products and also wastages in surroundings environment [60]. It should have the potential to generate electricity in grid networks as well as integrate with the smart grid.

• Geothermal energy: Geothermal energy is defined as energy that is obtained through biological cycles from the earth's core [61]. This energy is sustainable and reliable in the energy market. It originates from heat produced during the global initial formation and the decomposition of elements. In the earth's core, stones and fluid absorb this thermal energy. This smart renewable has dealt with the energy security of grid networks.

• Speed breaker: Speed breakers could be a source of renewable energy. It drives the mechanical load to the power energy which is a part of generating electricity in the smart grid. The speed breaker is typically equipped with a spring or roller system to remove these mechanical energies as a vehicle passes over it. Rotational motions only operate the dc generator and generate electricity [62].

• Human motion: Human motion that simply walking, and jumping can be sources of smart energy. Various systems of electromechanical mechanisms can be used to recover this energy and transform it into electric energy. The application of a walking load on top of piezoelectric material is another method of using walking to generate electricity [62]. Piezoelectric materials work through the application of pressure to their surface, and typically, the polarization of these materials changes as the applied load changes. This procedure of generating electricity in grid networks has the potential to integrate with the smart grid.

• Bio batteries: Bio-battery is a type of energy storage technology that works by converting organic chemicals into electricity. Glucose from human blood, for example, is a typical sort of organic chemical which might be utilized to power electrical devices. Enzymes in the human body normally break down into glucose, which is subsequently converted into electrons and protons. With the help of enzymes which are synthesized to make glucose, which is directly used in bio-batteries to generate power [63].

2.2.2. Smart energy management

In the modernized world, the demand for power energy from the power system community is enhancing day by day. But this demand for power energy is not constant all day. The increasing demand for electrical energy produces a mismatch between the supply and demand that are accountable for power system losses which may involve. In this perspective, power energy needs to be stored for a certain time that could be supplied to generation instantly. so power energy which is from renewable energy is integrated into the smart grid and has the capability to the storing devices in batteries, supercapacitors, and flywheels. Energy management in a smart grid network, Concerned with the energy demand response to the grid to the consumer has features with the energy monitoring and environmental aspects [64]. In advancement technological aspects, smart metering structure, self-healing based grid, cyber security, IoT based monitoring of energy which could be given the realistic figured out of smart grid energy management [65].

2.2.3. Smart communication

Smart grid is a communication-based approach grid network that capabilities two ways of communication interfacing from the grid to the consumer and consumer to the grid. The power system community has to demand the quality control and monitoring of power energy in smart grid networks in comparison to existing networks. From this grid perspective, ICT-based grid infrastructure is emerging in modern power systems. It could be communicated with consumers which provides grid system flexibility and resilience in the generation and distribution of the network. To focus on modernization, IoT-based, 5G wireless communication, vpp, Zigbee, and WiMAX are the crucial medium of communication to the grid system which collects organized information, stores and sends information continuously to electrical network [66]. This communication system provides real-time grid networks to enhance grid controlling, grid resilience, operating modes of communication, and remotely controlled smart grid [67]. Some technological features of the smart grid system are as shown in Table 3.

Table 3: Smart grid technological category and examples of hardware and software systems [68].

Technological category	Examples of hardware	Example of software and systems
Transmission optimization	Superconductors, FACTS, HVDC smart transformer(SST)	Analysis of network stability, systems for automatic recovery, transformer asset management
Distribution grid management	Transformer sensors, wire and cable sensors, switches and capacitors, remote- controlled distribution generation and storage, and distribution management systems	Geographical information systems,supply chain management systems, outage management systems, and workforce management
Wide area control and survellieance	Phasor management systems and other sensors	Systems for widespread monitoring, widespread adaptive defense, supervisory control , and data gathering
Smart metering infrastructure	Smart meters, servers and relays	Data management system

2.3. Virtual power plant (VPP)

After a protracted interval of growth, the virtual power plant has accomplished milestones in the power sector [69]. This innovative network provides access to the newest intelligent power system trademark, the virtual power plant (VPP), which incorporates and autonomously organizes a variety of distributed energy resources, power storage infrastructure, and loads, represents and regulates the power generation activities, and contracts intelligently on the electricity market that monitors the flux within the aggregation [70]. Figure 5 shows a broad overview of the virtual power plant. VPPs offer significant benefits over traditional power plants in terms of effective transmission infrastructure, adaptable physical traits, and strict regulation designs. They are by nature collections of energy storage services, controlled loads, and distributed generation resources (DER) linked to a centralized body [71]. Remarkable research on VPPs from numerous angles has been stimulated by the rising demand for sustainable energy consumption and checking to a large extent. Utilities have frequently used VPPs, virtual power plant aggregators, and the ICT sectors in recent years as a result of the certainty of significant gains in power system constancy and flexibility, particularly in reducing the requirement for additional peak-period energy generation [72].

2.3.1. Components of VPP

i) Distributed energy resource unit: DERs are power production unit that uses a variety of energy sources in varying amounts to provide users with a more affordable, highly de-

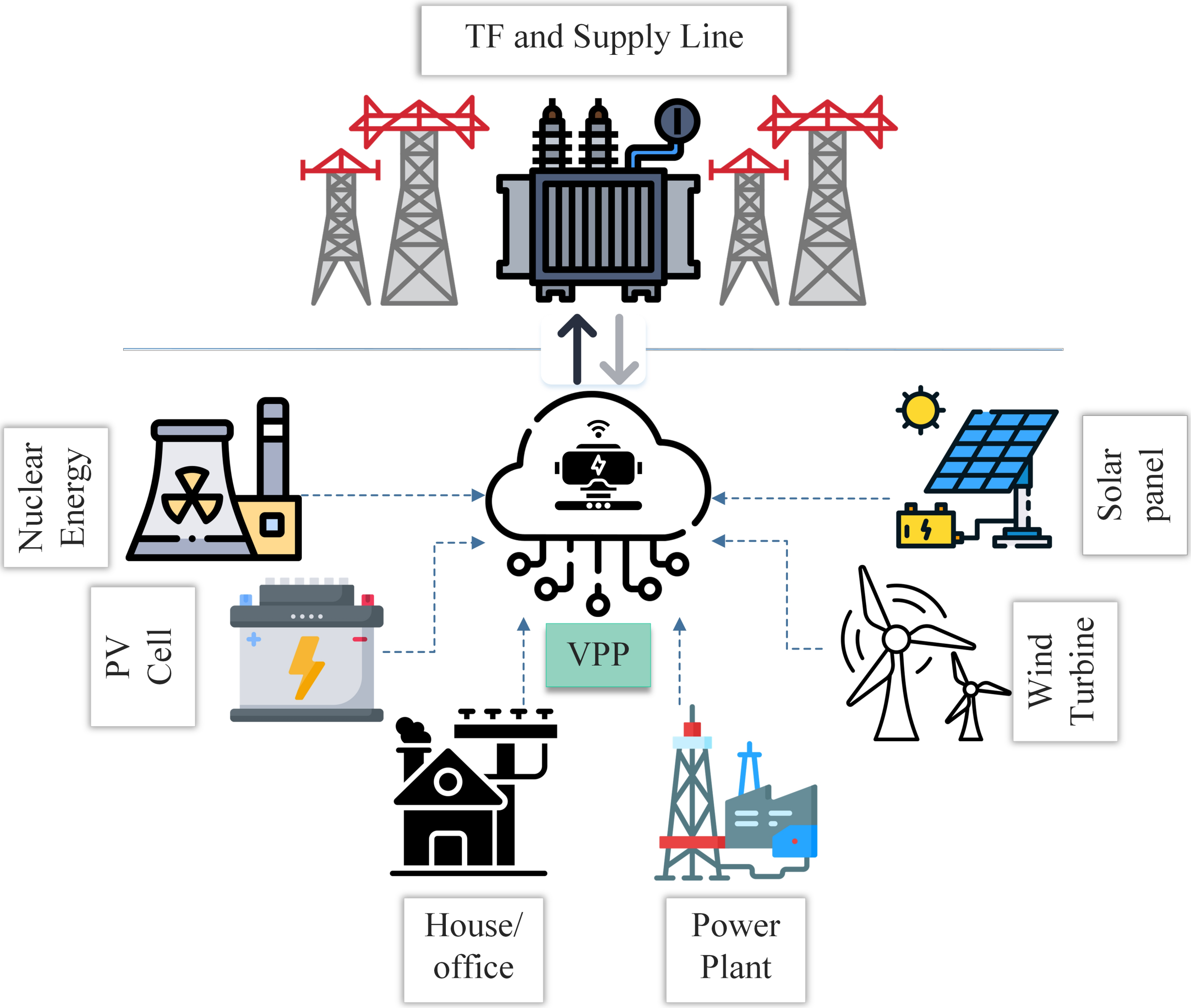

Figure 5: Overview of virtual power plant

pendable, and efficient energy supply. DERs are classified in various ways. Depending, for example, on energy sources, which are typically classified as renewable or non-renewable. Renewable energy sources such as solar thermal systems, wind turbines, hydroelectric generators, tidal and geothermal facilities, and photovoltaic arrays are reliable. Moreover, non-renewable energy sources include nuclear power plants, biomass, gas turbines, and fuel cell manufacturing facilities. But DERs also include CHP facilities, smart grids, and microgrids [73]. The crucial benefit of a DERs is, it offers load support during peak hours or consistent power delivery during a power outage. Because storage devices charge during off-peak hours and discharge during peak hours, the load assistance during peak periods aids in lowering power prices.

ii) Energy storage unit: When the demand is at its greatest, ESSs efficiently disperse the energy they have produced during off-peak periods. ESSs exist throughout a sizable fraction

Table 4: Characteristics comparison among microgrid, smart grid, and virtual power plant [75].

Microgrid	Smart grid	VPP
Grid-connected or off-grid	Only grid-connected mode	Virtually grid connected
Remote system used for MG storage is essential	Storage is required	May or may not require storage
Only use DER at retail distribution level	Distribution generation with LDC	Depends on intelligent meters and communication mechanism
Controllable loads	Variable loads	Cluster of loads
Focused on self-management	Focused on self-management	Focused on participation
PCC usable	Robust control technology	Open protocol usable
Self control & monitoring	Digital self control & monitoring	Virtual self control & monitoring

and play a crucial function as virtual power plant amalgamates a wide variety of players in a vast geographical region. For example, for both micro and macro applications, they maintain frequency and voltage levels in DERs coupled to VPPs at the root stage. They can have a centralized or decentralized infrastructure, and their goal is to provide municipalities with enough power support while aiming to increase the robustness, safety, and effectiveness of associated systems [74]. Several dispersed ESSs work well during widespread power grid disruptions, much as a central power supply. The whole structure is therefore provided with a remarkable level of power within minutes to hours if necessary.

iii) Flexible loads: Flexible loads are defined as those that are able to modify their general consumption habits regarding changes in the price of energy or incentive wages. There are two components to the so-called responsive or flexible loads. A structure that serves as a conduit for information between the load and the center portion makes up the first component. The second component is the control system necessary to govern the amount of flexible load used [76]. In a VPP, the usage level of flexible loads may be altered to satisfy specific requirements. These changes can be done using a valid control command or the dynamic pricing approaches price signal class. A comparison is deployed among microgrid, smart grid, and virtual power plant is shown in Table 4.

3. Existing Power Grid Transformer: Fundamentals and Framework

Technological advancement has been growing in electrical grid networks, now the modern power system deals with the continuity of the power energy distribution in the transmission lines. As the use of clean and sustainable energy and distributed generation (DG) has grown, the electrical power grid's complexity has gradually expanded, demanding two-way current in the distribution network, decentralized supervision, monitoring, and self-healing [77]. In this scenario, SST has made a significant contribution to upgrading the distribution's overall system performance and resiliency. To better enable the combination of decentralized resources and sustainable energy, the solid-state transformer (SST) is suggested to replace

Table 5: Transformer applications and communication in power grid [80].

Domains	Actors	Applications
Bulk generation	Generators of large amounts of electricity	Power generation, asset management
Transmission	Long-distance conductors of electricity	Transmission monitoring and control system to optimize and stabilize transmission
Distribution	Actors provide power to consumers and collect electricity from them	Asset management, substation automation
Customers	Consumers of electricity	Solar and wind generation
Service provider	Businesses that supply utility users with services	Asset installation and maintenance, client management
Operations	Managers of electricity movement in the grid	Network operations, grid monitoring, grid control, analysis of data
Markets	Participants and operators	Retailing and trading, market management

the distribution power grid's existing 100-year-old 60Hz transformers [78]. An MV stage, a dc stage, and an LV stage make up the solid-state transformer (SST). It uses medium-frequency (MF) transformers to produce galvanic isolation. SST offers a wide range of sophisticated control capabilities, including input power control/VAR injection, voltage stability, power transfer control, reduced voltage ride through, islanding operational reliability, current limiting, network impedance mismatch, and energy management systems [79]. SST also offers auxiliary services that help to enhance and simplify the contacts of direct current (dc) and alternating current (ac) equipment. So the primary concept of SST is to perform voltage transformation by separation of medium- to high-frequency signals, hence potentially reducing weight and bulk. Some application and communication-based mechanisms of transformers in a power grid system are as shown in Table 5.

3.1. Functionality of solid-state transformer

An SST's basic functioning can be described as an isolated ac-ac PEC. Various topologies are invited to be candidates for creating SST. In addition, the separated ac-ac PEC depiction of an SST allows for modular assembly, which has emerged as a crucial feature of the design of many modern PECs [81]. Despite the enormous number of topologies proposed, four SST topologies have demonstrated promising performance in a variety of applications. Here are the four SST topologies: i) Passive dc-link, unidirectional; ii) With a passive dc-link, it's bidirectional; iii) Active dc-link, unidirectional; iv) Active dc-link, bi-directional. Several SST topologies ac-dc, dc-link, and dc-ac phases all make use of PECs as fundamental building blocks [82]. PEC parts, such as high-frequency transformers, drive circuits, switching elements, and storing elements, have a finite lifespan. Switching elements, storage elements, drive circuits, and high-frequency transformers are examples of PEC components [83]. These components have limited voltage and current ratings that cannot go over SST design specifications. PEC modules connected in series or parallel might be used to solve this issue. Figure 6 represents the infrastructure of the solid-state transformer.

3.2. Design and structure

The idea of solid-state transformers has generated considerable interest as prospective transformers in smart grid applications. Solid-state transformers outperform traditional transformers in terms of performance, offering a number of additional services based on power electronics converters. The galvanic isolation between the transformer's LV and HV sides is a key feature. An SST employs high-frequency ac (HFAC) (usually 10 kHz to 20 kHz) to reduce the transformer size while maintaining isolation between primary and secondary [84]. Two main components make up solid-state transformers: a converter to create high-frequency AC from input line frequency AC, and an HFT for high-frequency isolation. On LV and HV side converters, especially on the HV side, the sustained voltage of power semiconductor devices must be very high [85]. For the construction of the converters employed in the SST framework, this might be a significant difficulty.

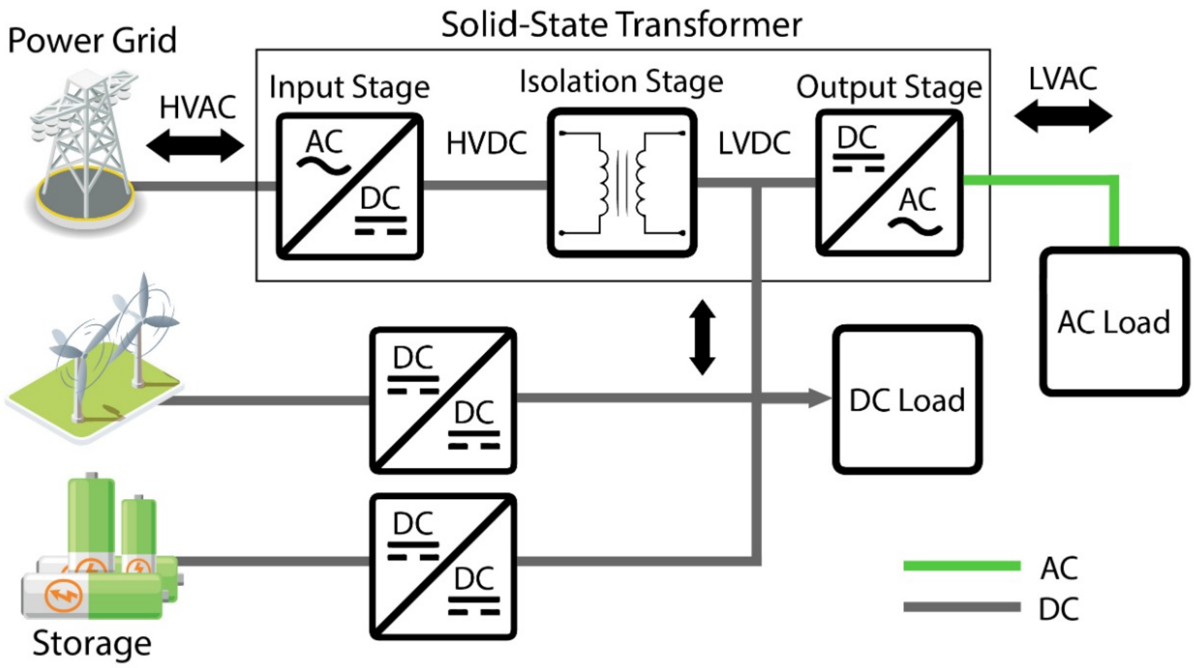

Figure 6: Solid-state transformer

3.3. Winding and core design

Regarding power density and efficiency, it is crucial to consider the winding pattern and type of core while designing a transformer. Due to its greater surface area exposed to the environment, the core-type transformer offers stronger insulation and cooling mechanisms, which is suited for HFT design. However, because the SST was created using HFT, it is important to take the high-frequency effect into account [86]. High frequency caused primarily two effects—skin effects and proximity effects—to take place. Typically, the conductor's DC

Table 6: Component-wise failure of transformers and reactors-worldwide-survey [89].

Component	CIGRE survey	IEEE survey-1986	EPRI 1991 survey	Australia-New Zealand survey 1985-95	Doble client survey-1996-98	ZTZ services 2000-05-Transmit	PGCIL: AC power transformers	PGCIL: shunt reactors
Windings	27.6%	41%	21%	30%	13.4%	17.3%	6 (23%)	10(44.45%)
Magnetic circuit	5.2%	10%	-	-	5.8%	9.5%	2 (7.69%)	-
Bushings	32.8%	13%	30%	19%	9.6%	38%	12 (46.1%)	6 (27.2%)
Tank & Dielectric fluid	17.2%	3%	17.2%	-	-	-	-	-
Tap changers	13.8%		13.8%	25%	15.4%	7.9%	4 (15.38%)	-
Other accessories	3.4%	17%	12%	-	6.9%	-	2(7.69%)	6(27.2%)

resistance is used to calculate the winding losses. The phenomenon known as the skin effect occurs when an AC circulates inside a conductor so that the current density is the greatest close to the conductor's surface and significantly decreases as depth increases [87]. As a result, the conductor's real area shrinks, eventually leading to an increase in AC resistance. On the other hand, AC resistance also rises as a result of the magnetic fields produced by neighboring conductors. The current in each conductor concentrates in a smaller region as a result. This occurrence is referred to as the proximity effect [88].

3.4. Materials

Regarding leakage current, size, thermal, and many more characteristics of the switch's material is a crucial aspects of the switch's design. It has been demonstrated, SiC is superior to Si for high-power and high-frequency applications. Additionally, SiC material offers far higher efficiency than Si, and devices with high power density can switch at higher levels of voltage, current, and frequency. These compounds have only so far been used to increase SST effectiveness. SiC-based MOSFET and IGBT devices have been proposed and investigated. IGBT, IGCT, ETO thyristor, and power MOSFETs are suited for powering high-voltage semiconductor devices [90]. Very high voltages may be tolerated by these switches. High-voltage applications may also be solved by arranging a number of low-voltage power semiconductor devices. The use of embedded systems in a series connection of power switches can significantly mitigate this shortcoming and also provide the capability to operate at high frequencies for the series configuration. The solid-state transformer's primary side semiconductor switches must be made to function at 15 kV [90]. MOSFET and IGBT are frequently utilized in electrical circuits as switching devices. The characteristics of MOSFETs include high input impedance, quick switching, outstanding thermal stability, voltage control current, and others. IGBTs have high input impedance, low power requirements for controlling voltage, a straightforward control circuit, strong voltage resistance, and high current tolerance [91].

3.5. Topologies

SSTs are divided into the following categories, types, and power levels. In terms of the number of levels, the categorization is as follows:

i) Single Step: It has been without a constant DC connection. Though it offers a cost-effective design and the renewable energy portion is supported by galvanic insulation but occurs some significant losses and massive current ripple.

ii) Double Step: It could be categorized into two parts: one includes the HVDC connection, while the other includes the low-voltage alternating current (LVAC) connection. It has possibilities for the power transmission between RES and DES However, it may have been difficult to connect with FACTS in the high-voltage environment [92].

iii) Three Step: Finally, This network has been unveiled, with both LVDC and HVDC cables being added to keep the system stable and ripple-free and also supports the RES and DERs.

Another possible categorization may involve points of types:

iv) Type A: it is simple in construction and has the power conversion capability with MFT(medium frequency transformer). It has an obstacle to monitoring the closed-loop operation and the loss of zero voltage switching.

v) Type B: It consists of an AC-DC conversion stage with a low-voltage DC output, followed by a DC-AC conversion with a low-voltage AC output.

vi) Type C: The LVDC link is a variant of Type B, in which the two stages support galvanic isolation and voltage stepping down.

vii) Type D: It is consisting of a three-stage conversion procedure with one MFT isolation and two DC connectivity links (MVDV and LVDC).

viii) Type E: This system is based on zero-voltage switching (ZVS) modulation, which has proven to be extremely efficient [93].

3.6. Controlling operation

Controlling SST could be a top priority for a grid network. One of the controlling operations could be multi-objective modulated predictive control. It fixes the issues with the traditional predictive control method in creating voltage harmonic spectra and functioning at very high frequencies while focusing on speeding up the system's response time. The phase shift control approach is additional. This technique involves applying a phase shift between the high-frequency transformer's primary and secondary voltages (HFT). It could have features to regulate the system's power flow's intensity and direction [94]. Another way to minimize voltage fluctuations and their transient duration is the feed-forward control method. To account for inductor energy variations, a feed-forward control scheme is suggested. A second feed-forward control strategy is suggested to regulate the voltage of the rectifier controller section. The dynamic voltage conditions of the system's DC voltage are improved by both control loops.

4. Critical Requisites for Next-generation Power Grid Transformer

The nation's electricity system is undergoing an upheaval. The system becomes more complex as a result of the integration of a massive amount of renewable sources and new demand loads, which has occurred alongside a tremendous increase in installed generation capacity recently. Additionally, the grid must manage power flows in many directions, round-the-clock, due to the presence of numerous generators, prosumers, and decentralized generation sources [95]. Energy utilities are addressing these issues by using digital technologies, with the goal of assisting users in obtaining information and insights that can be used to make better decisions and manage assets.

• Transformer currently serves as the hub of electrical networks and are anticipated to take on a considerably larger role in the future power grid as it expands, they are the prime candidates for the integration of digital and smart grid technology [96].

• The modern electrical grid is increasingly dependent on digital transformers, which autonomously control voltage and stay in touch with the smart grid to enable remote administration and real-time feedback on power supply characteristics [97].

• In terms of distribution and transmission, the utilization of these transformers is expanding. Intelligent electronic components, as well as sophisticated monitoring and diagnostics functions, are included in these transformers [98].

• Transformers, which perform the crucial task of adjusting voltage levels, stepping up for effective long-distance high-voltage transmission, and stepping down for the distribution of power to consumers, have undergone a lot of technological advancements over the generations. These include high-efficiency distribution transformers, biodegradable oil-filled transformers, ultra-low sound transformers, and ultra-high voltage AC and DC technology.

• The major goals for many utilities, however, continue to be enhancing monitoring and maximizing maintenance. For instance, load peaks, both expected and unanticipated, cause high temperatures that reduce transformer life.

• There are times when unexpected failures can happen, disrupting the network and resulting in fines and other consequences. Furthermore, the flow of electricity in the distribution network at the consumer end of the grid is altered by renewable power plants run by a sizable number of small, local energy producers. The next-generation transformers are gaining ground as a solution to the new and upcoming grid concerns [99]. The three main components of digital transformer solutions are hardware, software, and services that work together seamlessly to manage the flow effectively, consistently, and safely.

• To provide utilities with dependability, efficiency, and future readiness, hardware, software, and services must seamlessly integrate. To collect data for local monitoring, diagnostics, and control, built-in components such as digital sensors, dissolved gas analyzers, and digital safety devices are used. Through the usage of the cloud, the same data may also be tracked and used for station control, as well as for preventative and predictive maintenance.

4.1. Interoperability

The capacity of two or more software components to work together despite variations in language, interface and execution platform is known as interoperability. Being concerned with the reuse of server resources by clients whose accessing techniques may be plug-in compatible with the server's sockets, it is a scalable kind of reusability. When it comes to plugging compatibility, electrical equipment demand both static form compatibility and dynamic voltage and frequency compatibility [100]. Compatibility and interoperability have certain similarities. While giving them a more comprehensive perspective of all their information, helps organizations to operate more effectively and efficiently.

4.1.1. Authenticity

Transformers with digital capabilities can perform real-time data analytics and remote monitoring of their critical parameters. So, grid assets and power networks can be used more effectively, increasing reliability. Additionally, these transformers have a digital hub that can connect to a variety of smart devices on a modular platform with plug-and-play capabilities. Digital capability can increase reliability and reduce outages through proactive measures, in addition to enhancing efficiency and product life. The digital transformer serves as a voltage regulator by supplying the exact amount of power needed and reacting quickly to power grid variations. They are the best choice for power systems that are intended to integrate renewable energy sources and thanks to these capabilities. In the meantime, digital distribution transformers at the transformer level offer intelligence to maximize dependability, save operational and maintenance expenses, and manage the asset more effectively. Technologies companies are aiming to build sensor technology right into the transformer during production, which would increase accuracy. Providers of technology are also incorporating digital technologies into dry-type transformers. Transformers of the dry-type variety is designed to operate without the use of oil, instead relying on air and noncombustible solid insulating material to keep the core and coil at a safe operating temperature, as opposed to how transformers are typically cooled and insulated by oil. They become safer and more environmentally friendly as a result. These transformers are best used in high-risk situations, such as offshore, densely populated areas, and delicate ecosystems. Smart sensors collect data and combine it to produce powerful analytics in digitally enabled dry-type transformers [101].

4.1.2. Cyber security

Along with the numerous technical features listed, new digital transformers also address clients' cybersecurity concerns. This is accomplished by including extra security measures, like Wi-Fi that is equipped with RFID access cards. A decryption key is required for the user to read the encrypted data because it is stored in a secure manner [102].

4.1.3. Failure Mechanism Analysis

Failure mechanisms are the principles that may be determined from theory or experiment on the relationships between fault characteristics and transformer state measurements. A worldwide survey of component-wise failures of transformers is shown in Table 6. Transformer condition evaluation presents difficult problems, such as how to effectively extract important elements of the transformer operating state and perceive the correlation of complicated transformer failures using machine learning in combination with the current underfault method [103].

4.1.4. Data Quality

Data on power grid transformers, including operational capacity, oil tests, live-line detection, online monitoring, maintenance records, and fault issues, has been collected by academic institutions, power utilities, and manufacturers thus far. However, the transformer state data is heterogeneous, has uneven data quality, and is asynchronous since it is stored in separate, unrelated sub-systems. Because of measurement inaccuracies, duplicate data, and data absence, assessing a transformer's condition is erroneous. When data quality is low, diagnostic and predictive results for transformer problems will not accurately reflect reality. Therefore, improving transformer data quality is essential [104].

5. Road to Next-generation Power Grid Transformer

In the past ten years, numerous energy sectors, research centers, equipment-operating companies, and manufacturers have worked to develop cutting-edge technologies that are frequently used in power grids, such as big data, cloud computing, the Internet of Things, mobile internet, and artificial intelligence. These innovative technologies can facilitate the mining of rules from climate data, electric grid operational data, and transformer operating information. Power grid transformer operation and maintenance have benefited from the deployment of advanced measurement infrastructures in smart grids, as well as the gradual emergence of large-volume, multi-type, and rapidly-growing transformer state data, which has facilitated the use of big data, artificial intelligence, and other technologies [105]. IoT technology is currently achieving vital appeal in the power sector. In 2023-2025, it's anticipated that 20–50 billion items will be globally connected to the internet [106]. In addition, a significant number of highly accurate smart sensors have been researched, produced, and used, offering a more extensive data foundation for big data analysis. The progress of power grid transformers is moving in the field of high voltage, huge capacity, intelligence, dependability, and energy efficiency. A visual representation of the applications of next-generation power grid transformers is shown in Figure 7. The capabilities of the upcoming power grid transformer include the following: i) Self-protection by separating the complete maintenance crew in the event of a transformer overload. ii) No wires are required. Preventing power or data loss as a result. iii) Real-time defect detection using current, voltage, and temperature. iv) Remotely monitoring several transformers [107]. v) The usage of wifi results in improved fault monitoring accuracy and reaction times. vi) By monitoring the system, you can increase stability and dependability [108]. vii) This method prevents excessive current and temperature. A structural comparison of the existing power grid transformer and next generation power grid transformer is shown in Table 7.

5.1. Add on components

In the present transformer sector, intelligent transformers with self-diagnosis capabilities are a massive issue. The use of intelligent sensors and actuators; clear channels of communication; efficient management of operational data; accurate diagnosis and evaluation of operating conditions; close monitoring of operational data and fault alert functionality may all be features of intelligent transformers that set them apart from conventional transformers [109]. Further implementation should focus on this type of smart transformer that can withstand the widespread use of intermittent new energy sources and applications (such

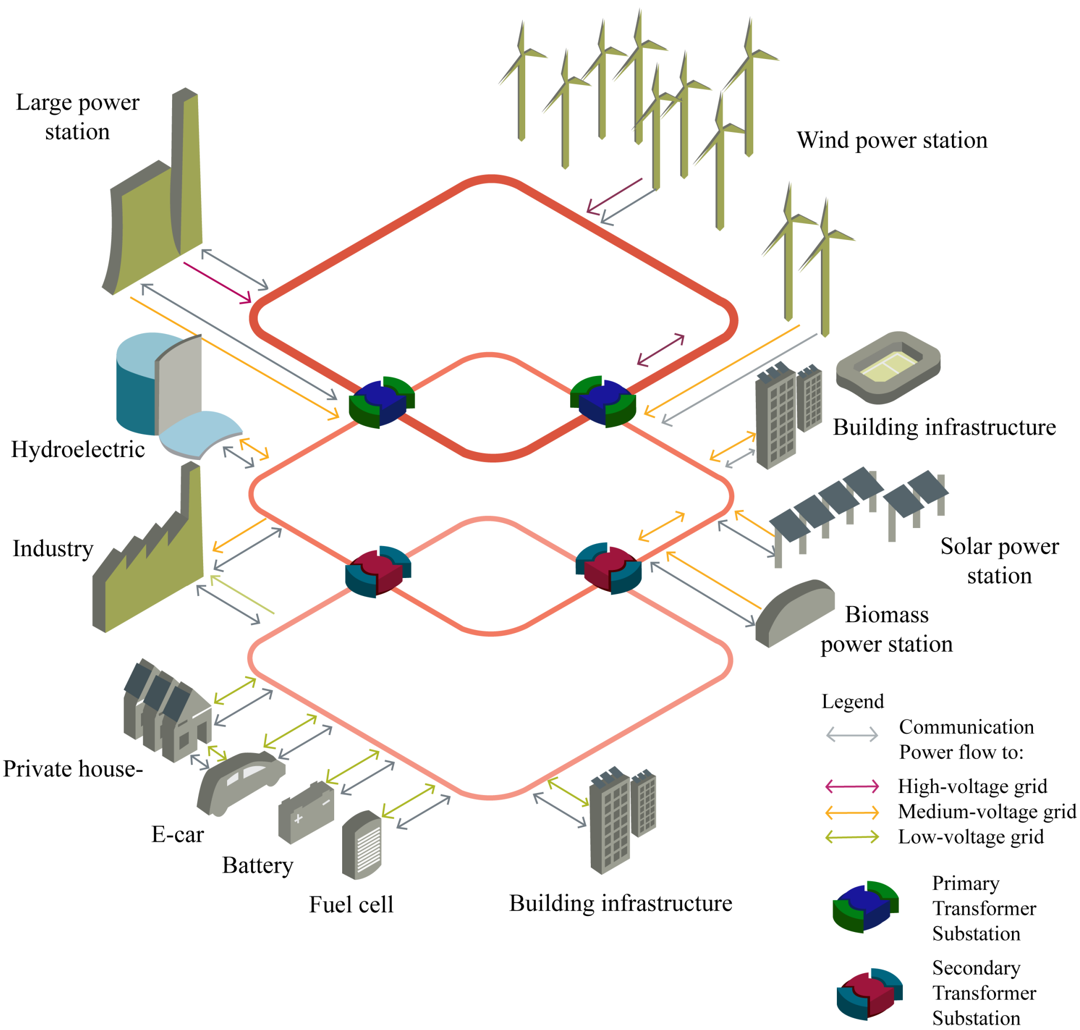

Figure 7: Application-based next-generation power grid transformer

as solar power production and electric automobiles) [110]. Figure 8 depicts the technology that may be used to digitalize the transformer. This digitalization of transformers is completely automated and allows only authorized workers to secure, monitor, and operate related equipment from anywhere in the globe.

5.1.1. Intelligent condition monitoring

Condition evaluation for power grid transformers primarily evaluates and assesses the health condition using a small number of state characteristics and uniform diagnostic criteria, which fails to fully take advantage of faults [111]. The transformer's current monitoring system is not fully automated. Currently, a technician must read data from the transformer panel, which might result in reading errors, inaccuracies, and a long wait before receiving the reading value for the winding temperature, oil level, and top oil temperature. In order to

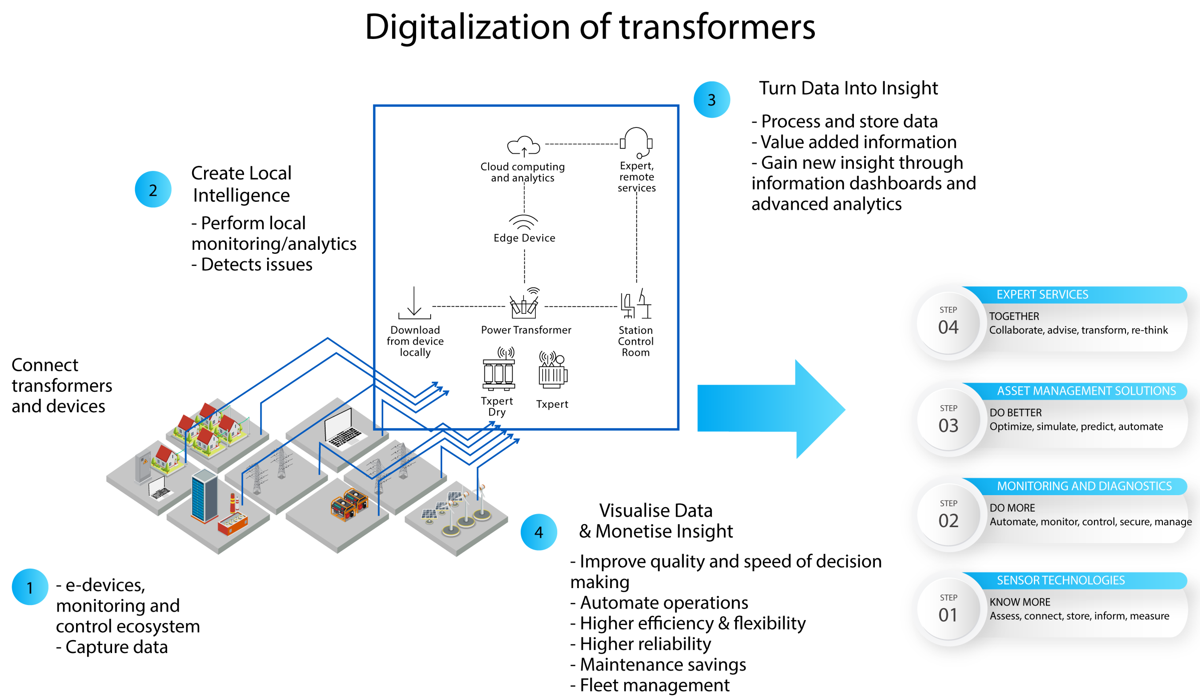

Figure 8: Digitalization of transformer

visualize and enhance the current framework for transformers state evaluation, it is crucial to use innovative methodologies [112]. The acquired transformer data has big data traits due to the advancement of online monitoring tools, cyber-physical systems, and the Internet of Things [113]. The primary goal of real-time condition monitoring for the power grid transformer is to alert users to any potential abnormal events [114]. Placing the sensors on the asset and connecting them to a microprocessor board with the appropriate programming will enable real-time monitoring. This data may then be transferred to a server or cloud for data analysis and real-time monitoring. The following are the primary benefits of adopting IoT for real-time monitoring; minimizing the usage of hardware for data transmission from the sensors to the monitoring system; the server or cloud may be accessed from several locations, not only one monitoring center [115]. Since there are many suppliers of sensors, numerous manufacturers of microprocessor boards (including Arduino, Raspberry Pi, Intel, and Beaglebone), and numerous competitors offer cloud services with various options for transformer condition management and analysis.

5.1.2. Intelligent command

Approaches to the intelligence controlling method, operating the existing transformer in future-oriented is, however, AI-based field operation which could be optimization operators, artificial neural network, digital logic, machine learning, recurrent neural networks, and evolutionary computation. That means it provides the databased analyzed operation and decentralized monitoring, network sustenance of transformer. It would be a meaningful continuity of energy distribution in transmission lines observing enhancement and reliability [116].

5.1.3. Edge computing

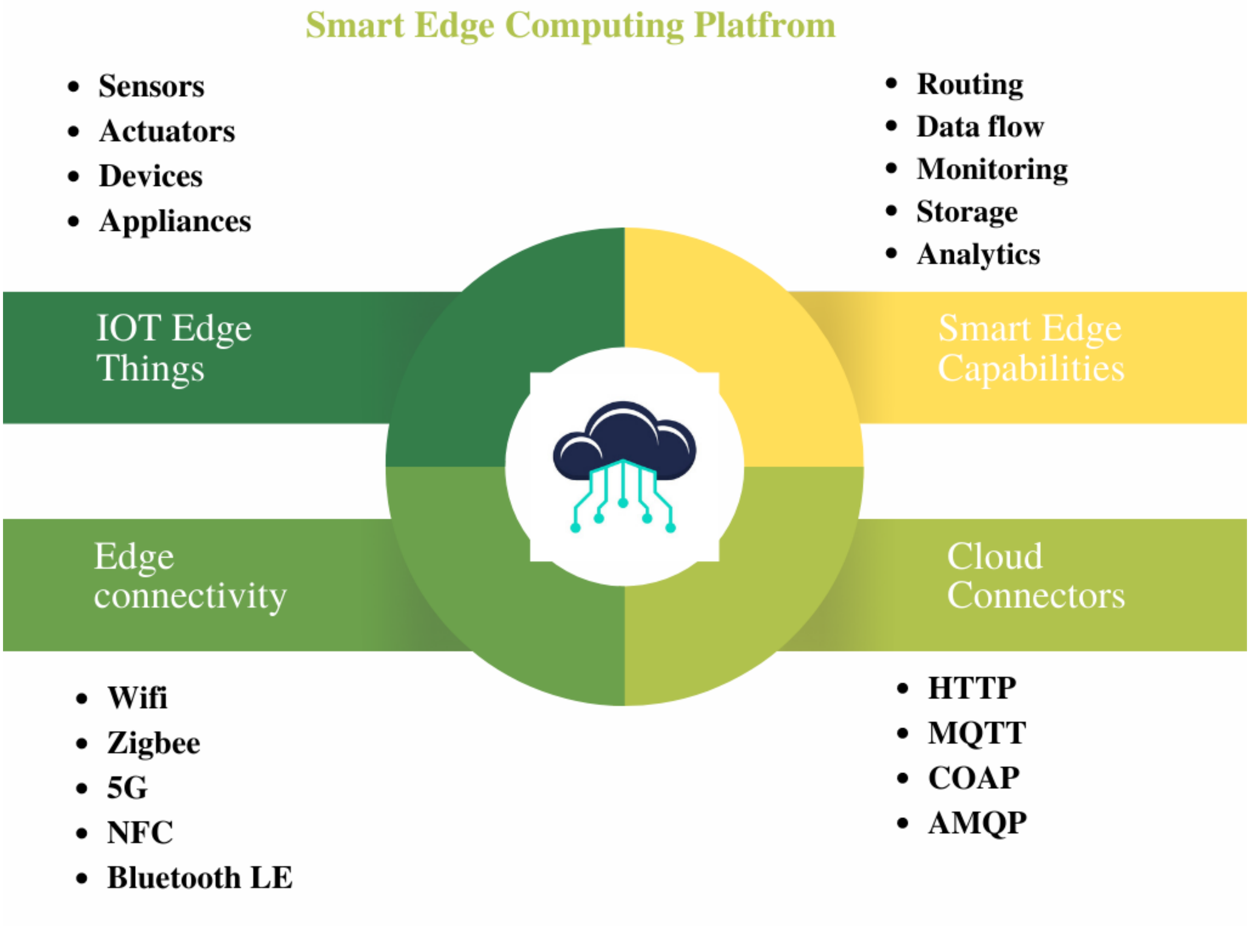

Figure 9: Generic IOT devices functionality

By 2025, the amount of data in the globe is projected to increase by 61 percent to 175 zettabytes. Data centers cannot ensure adequate transfer speeds and reaction times despite advancements in network technology, despite the fact, these factors are frequently a crucial need for many applications. A distributed computing system called edge computing puts all applications closer to data sources like IoT gadgets or regional cloud servers, where data is processed and analyzed closer to the source of creation. Since no data needs to be sent to a cloud or data center for processing, latency is drastically reduced [117]. The immediate data that edge computing uses is real-time data produced by sensors or users. With the help of edge computing, particularly mobile edge computing on 5G networks, it is possible to analyze data more quickly and thoroughly, leading to deeper insights, quicker responses, and better consumer experiences [118]. The existing transformer has a deficiency with respect to data securing and data storage in the central data center. To Optimization in this aspect edge devices in the transformer will be able to make connections, and perform transmitting data to the regional network and the data center. Figure 9 shows the smart edge computing platforms which illustrate technologies needed to make IoT devices. It resembles an intelligent gateway- interprets, classifies, and cryptographically transmits data between multiple origins [119]. They are the pioneers to monitor and analyze data to quickly recognize discrepancies in order to avoid severe failures in transformers.

5.1.4. Intelligent inverters

To be intelligent, a power electronics inverter system needs a digital design, reliable software, and two-way communication capabilities. In order to promote human comfort using Wi-Fi technology and participate in two-way communication with the user, an eco-friendly IoT-based smart controlled inverter is suggested. Through a mobile application or web URL, the user may manage the linked load and keep track of the status and current load of the connected devices. Where the user may connect or disconnect the gadgets in accordance with their preferences or needs. A current sensor measures the load current, and a Wi-Fi module transmits the data it has collected to a Web URL [120]. The implementation method was organized in order to design a transformer supporting the grid in contending with sporadic generation through the intelligent inverters. As more dispersed sources of energy go digital, intelligent inverters getting more involved in decisions to ensure the transformer's stability and dependability, integrating with the smart grid. This could have autonomous decisions in the case of 'out of tolerance' voltage or frequency, intelligent inverters will 'randomize' the time they spend disconnected from the grid [121].

5.1.5. Smart materials

Developing criteria for next-generation transformers should be focused on their electrical conductivity, thermal conductivity, passive power conversion, and thermal management system performance characterization. Diamond-Based Semiconductor materials, however, diamond is suitable and offer high breakdown voltage capabilities to switch at high frequency as well as the best thermal conductivity. Nanocomposite soft magnetic materials is another innovative material for intelligent transformer, offering disruptiveness in passive power conversion and utilizing at high frequencies it offers low loss operation [122]. Self-healing ceramics and polymers, these materials have the potential in the field of electrical insulation and provide high thermal conductivity and capabilities in quickly recovering. Super-hydrophobic Materials, it uses for conductors and insulators provide enhancement reliability. Metal hydride alloys could be used as a material to help regulate the thermal energy in transformers. Comparing metal hydride alloys to conventional transformer materials, they show improved heat dissipation. carbon nanotubes and graphene, Carbon nanotube-based conductors might have the same operating performance as materials that are superconducting at room temperature because of the material's ballistic conductivity [123].

Table 7: Structural comparison between an existing power transformer and next-generation power transformer

Characteristics	Existing power transformer	Next generation power transformer
Current flow	Bi-directional	Fully automated
Monitoring	Perform local monitoring	Real time remote monitoring
Control	Generalized	Distributed
Network	Radial network	Neural network
Energy source	Integrated traditional renewable energy sources	Integrated smart renewable energy sources
Operation type	Central control based operation	Databased analyzed operation
Data server	Central data server	Cloud computing data server
Control method	Traditional predictive and phase shift control method	Edge devices inverters controlling method

5.1.6. Intelligent management

In the process of distributing power, power transformers, one of the network's essential components, may act as strategic bottlenecks. In aspects of the electrical environment, these transformers are needed to be the managerial point of view better tools are required to allow for management based on facts rather than presumption. Constantly and effectively keeping track of the load, operating conditions, and transformer condition while having control over cooling systems and online tap changers needed to be focused. Transformer utility environment cost and competitiveness are effectively reduced and enhanced customer service and reliability [124]. The significance of dynamic rating as a transformer management feature is frequently cited. Based on real-time measured ambient and transformer temperatures, conditions, cooling state, and load, the dynamic rating of a transformer is the highest load that may be applied without exceeding predefined thermal and current rating limits. Advanced transformer management systems use upgraded thermal models, which are inherently more accurate, in addition to real-time observations and calculations for dynamic rating [125]. An advanced TMS should incorporate Smart Cooling functionality that, upon detecting a rapid rise in load, predicts what the final winding temperature will be and promptly activates cooling fans and pumps to cool the transformer without waiting for the temperature to drop to the desired level. Transformer Management System acts as a lone point of contact with the outside world, substantially streamlining communications and making it easier to access data about every aspect of the transformer's functioning and status. SCADA, LAN/WAN, a modem, and the internet gather a wide range of data, such as operating information in real-time, condition status, maintenance warnings, and asset life consumption. A conceptual frame of evolution of existing power grid transformer to the next-generation power grid transformer by adding some feauturing components is represented in Figure 10.

5.2. Future Trends Of Next-generation Power Grid Transformer

Investments in power transmission and distribution infrastructure and grid assets, including transformers, will increase as global renewable energy production continues to scale

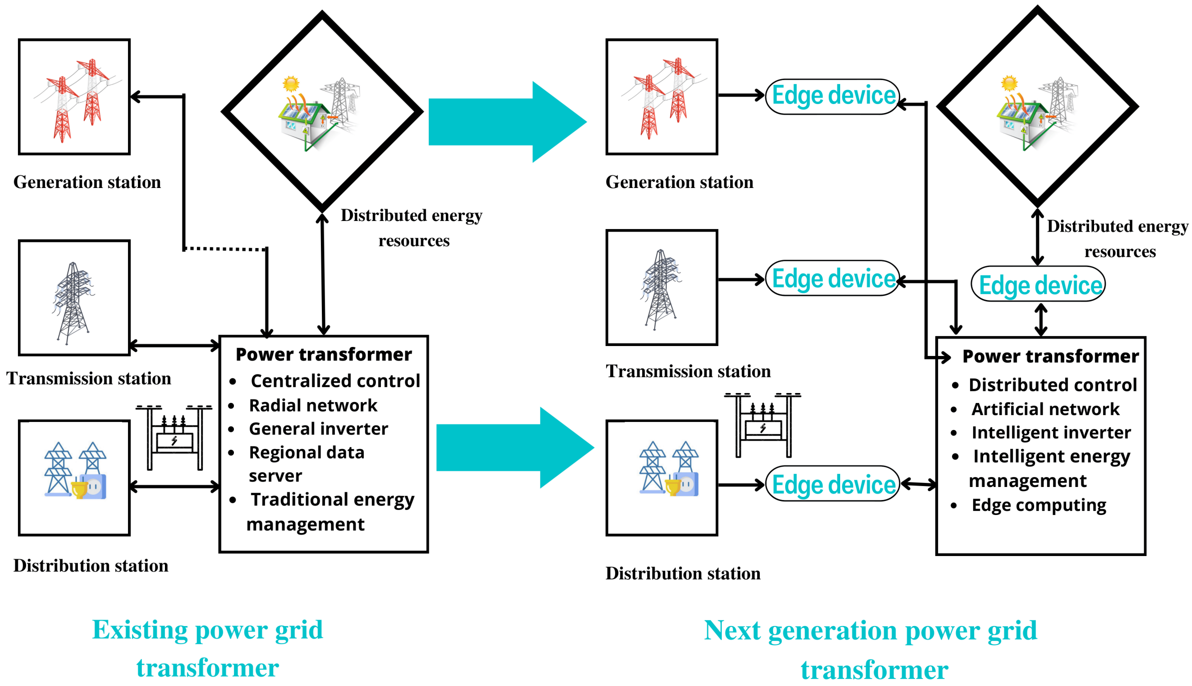

Figure 10: Evolution of existing power grid transformer to the next-generation power grid transformer

up. Despite a mature industry, a substantial increase in electrical consumption, growing electrification rates, economic expansion, and rising population throughout China, India, Asia, the Middle East, and Africa will drive up demand for both power and distribution transformers [126]. The modern energy grid, which autonomously controls the voltage and keeps in touch with the smart grid enables remote technology.

Administration and real-time feedback on power supply characteristics are increasingly reliant on digital transformers. Since smart transformers are created with contemporary uses in mind, many of them will feature brand-new materials, design strategies, and internal technology. The generation of conceptual ideas for future power grid transformer is shown in figure 11. This opens up a wide range of new possibilities, some of which won't be recognized until smart transformers are operational. Transformers now serve as the hub of electrical networks and are anticipated to take on a considerably larger role in the future power grid as it expands, they are the prime candidates for the integration of digital and smart grid [127]. At the distribution and transmission levels, the utilization of these transformers is expanding. These transformers have sophisticated monitoring and diagnostics tools as well as clever electrical gadgets [128]. Significant prospects are brought about by the use of active equipment in smart grids, such as smart transformers, which are driven by intelligent software and networking capabilities. Here are some probable future scenarios regarding intelligent transformers:

• The purpose of the future power grid transformer is to deliver dependable and high-quality electricity in an affordable and environmentally friendly way, where Distributed

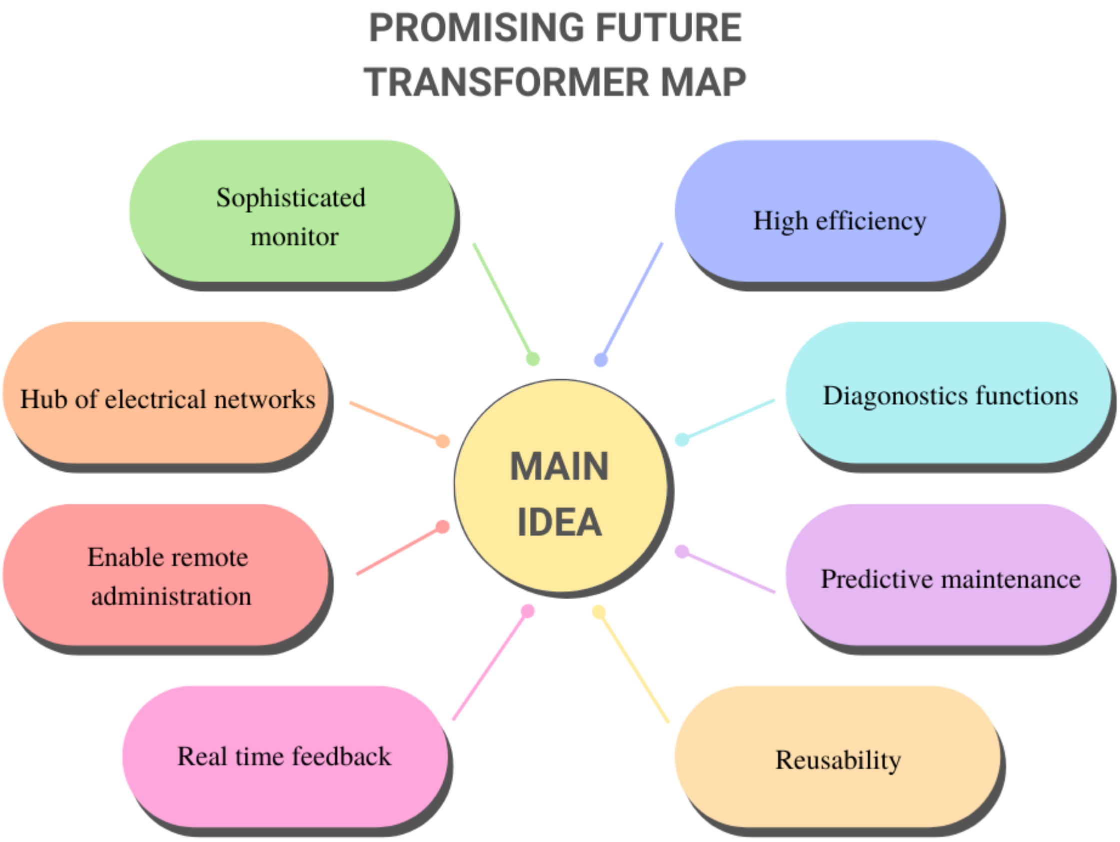

Figure 11: A conceptual idea for future power grid transformer

Generations (DGs) are strongly integrated and self-healing is necessary [129]. A novel approach to power system protection is required given this view of the power grid of the future. The future smart grid's dynamic nature will create this requirement, which is why several protection systems and procedures have been studied and tested over the years. An easily fixable by leveraging its own cyber-physical resources, like as intelligent transformers, the smart grid is able to avoid or mitigate failures, even cascading ones, in an online and automated manner. When a disruptive event, such as a line failure, happens, it combines three capabilities: i) load shedding; (ii) generation management; and (iii) optimizing flow distribution through smart transformer coordination. Smart transformers are assessed in three healing modes in which they function at various phases of a cascade failure.

• Transformers with digital capabilities will allow for real-time remote monitoring and data analyses of their critical parameters. This raises dependability and permits greater use of grid resources and power networks. Such transformers also have a digital hub with plug-and-play capabilities that can access a variety of smart devices on a modular platform. Digital capabilities may increase dependability and prevent outages in addition to extending product life and efficiency [130].

• As a voltage regulator, a digital transformer delivers the exact amount of power needed and reacts quickly to power grid variations. Digital transformers are the best choice for electrical systems intended for the accumulation of sustainable energy because of these characteristics. Digital distribution transformers, on the other hand, offer intelligence at the level of the distribution transformer, maximizing dependability, optimizing operations and maintenance costs, and managing the asset more effectively. In order to increase accuracy, technology vendors are attempting to integrate sensor technologies directly into the transformer during the production process. It will bring tremendous change in the field of digitalization of transformers. In 2023, the worldwide smart transformer market was worth

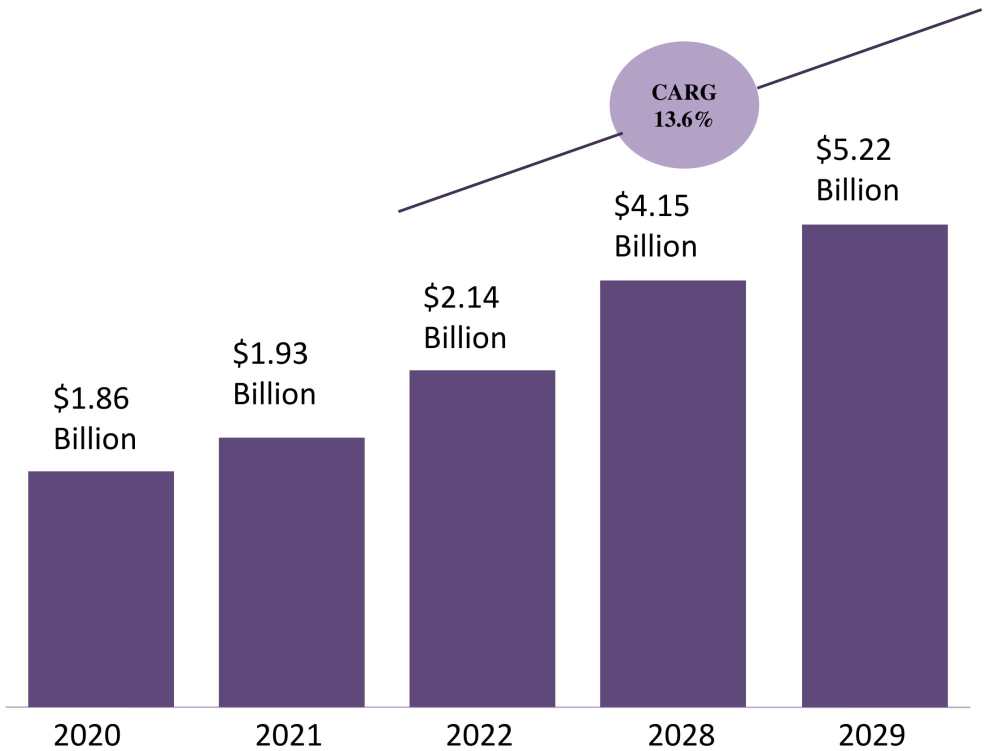

Figure 12: Global smart transformer market rises

USD 1.93 billion. The market is expected to increase at a CAGR of 13.6 percent between 2022 and 2029, from USD 2.14 billion in 2022 to USD 5.22 billion in 2029. Figure 12 sums up the global transformer market rising.

• Energy consumption will be directly decreased with smart transformers.As a result, it will also directly lower greenhouse gas emissions. They are therefore a crucial component of any energy or lighting upgrade. Smart transformers not only safeguard electrical equipment from power fluctuations, which helps electrical equipment survive longer, they also immediately cut power usage by offering a consistent, perfect power supply that feeds electrical equipment with its ideal voltage [131]. They can also be managed dynamically through their connectivity to the smart grid, enabling facilities to monitor and control the transformers directly during times of power fluctuation and assisting them in making sure that their power supply maintains voltage optimization even when new demands are placed upon it.

Table 8: Communication technologies used in smart transformer and their applications

Communication technologies	**Frequency mode**	**Characteristics**	**Applications in smart power transformer**
GPRS(general packet radio service) [132].	900 MHz & 1800 MHz	In packet transmission mode, transmit and receive data	Used in transformer monitoring system. a) It is capable of lowering the cost of replacing a damaged transformer. b) Improves reliability [133].
PLC (Programmable logic controller)	NB: 3-500 KHz BB: 2-250 KHz	Consists of 5 parts: Chassis, input & output module, supply module, CPU, communication interface module.	Used in transformer cooling control system. a)Automatically switches between the cooling banks. b) Eliminates mistakes caused by human involvement [134].
Zigbee	868 MHz, 915 MHz, 2.4 GHz	Support for many network topologies, including point-to-point.	Used in insulation online monitoring system. a)capable of overcoming the drawback of remote monitoring. b)Solves data acquisition problem [135].
WIMAX (Worldwide Interoperability for Microwave Access)	2-11 GHz and 11-66 GHz	OFDM-based Physical Layer. Communication protocol is IEEE 802.16.	Used in implementation architecture of transformer. a) Data rate up to 70 Mbps. b) Development of 4G communication chip

• When a traditional transformer starts to fail, someone has to physically travel to its location to confirm its status and fix any issues. Smart transformers, on the other hand, include solutions to verify conditions and information remotely, from either a central office or mobile command station. This support vastly improves operations and helps power companies better manage networks [136].

• These transformers are easier to inspect, safer to use, and more dependable as a result of their connection with a smart grid and improved remote monitoring.

• Smart transformers are made to use power more efficiently and distribute it throughout the grid. This results in more efficient electricity utilization and lower emissions of greenhouse gases. A more effective grid results in less fossil fuel being consumed by conventional power plants, which also results in fewer emissions and improved urban air quality.

• When a transformer breaks, electricity is lost, often for days at a time, and many homes and businesses are left without power. Intelligent transformers can take over operations, direct power more effectively to avoid this, and make up for it. Communication technology, characteristics, and application of next-generation transformer are shown in Table 8.

6. Challenges for Next-generation Power Grid Transformer

6.1. Communication point of view

6.1.1. Data handling and processing

The digitalization of the transformer consists of a wide variety of things: internet-connected, cloud-based, and edge-based computers. A system that can identify and tolerate faults in these devices is necessary for their administration. Therefore, it is crucial to have a requirement that appropriately controls the transformer's interface with these devices, their setup, and the accessibility of various user levels [137]. Next-generation transformer power systems need effective data handling and processing due to the increased data volume. Utilizing time-honored techniques and hardware is impractical when dealing with large amounts of data. The decision-making process is aided by the real-time data that is gathered and analyzed. Therefore, processing in the near future will need the use of cutting-edge technologies and equipment. Because nodes can see the status of the central server or their neighbors, they may save more data transfer. However, because of the most virtual nature of its processing, it is desirable to be able to cope with massive volumes of large data [138].

6.1.2. Data privacy, security and management

The concepts of security and privacy are inextricably linked. If the degree of security is inadequate, the grid transformer will be subject to unauthorized manipulation, compromising its privacy. It is very difficult to provide a high degree of privacy and security due to a lack of universal standards such as cyber protection. Data gathering and analysis are critical components of a grid transformer. This data is generally obtained online and maintained at regular intervals. After assessing the acquired data, judgments are made on the most effective grid distribution activities [139]. Although a sophisticated data management system may be utilized to assess transformer grid performance, the existence of a data security standard is still required. In addition, the most important security needs are information integrity, mutual trust, and authentication. Apart from security, privacy is critical for maintaining consumers' faith in PGT. To secure information, the use of smart devices with personal and sensitive information necessitates strict privacy measures. In general, three primary aspects are crucial to privacy problems. Personal privacy, privacy-preserving data mining, and underlying privacy of employed technology are examples of these. For these three features of the future-oriented digital transformer, standard requirements may be observed [140].

6.2. Energy management point of view

The proper usage of the grid power largely hanged on the accurate regulation of the energy management system of the transformer. It is directly connected with both transmission and distribution through reporting continuously about different information such as energy usage, power consumption, cost and availability of energy, market demand, and so on. It manages the production of the power based on the demand forecast of energy and follows power according to the customer need. The excess occurrence is stored in the power grid or supplied to the main grid through the mechanism of EMS. Again, it aware the end users about the proper usage of power by giving the information on present energy available and cost [141].

6.3. Economical point of view

There are many expenses connected with the energy consumption of integrated PGT for grid renewables. These costs consist of gadgets, operational expenses, fees for technical services, and maintenance expenses. Moreover, when diverse renewable energy sources are connected to the grid, there is also an integration cost. On one end, the grid transformer is directly affected by the high expenditure of an EMS. Alternatively, the performance of the transmission and distribution transformer of the power system might be compromised by the use of less expensive materials. Thus far, maintaining a balance between both perspectives has been difficult [142].

6.4. Operational point of view

The next-generation transformer has the ability to run all of its functions autonomously with little human involvement With the aid of several sensors, actuators, and controls. The important key characteristics connected with the digitalized transformer are self-healing supervision and optimization, automatic maintenance and reconfiguration based on the situation, adaptive protection and management, advanced forecasting, and demand support [143]. Self-healing and optimization are the processes to optimize the operations of the PGT in case of fault, uncertainties, and load variations. The changeable character of the generation units and the load or the affection of the fault or uncertainties in the electrical system may damage the nominal functions of the transformer which may result from large deviations of the voltage, current, or frequency. Dynamically challenging for an automated transformer to restore and optimize the operations of its components in case of emergency. Adaptive protection and management are also the challenges of PGT for the grid system based on the situation or environment shift by adjusting its settings to match the new state [144].

7. Conclusion

The modern power energy infrastructure has developed noticeably in the field of power transmission distribution and management integrating with the digitalization of transformers. The next-generation transformer probably combining of many sophisticated components resulting in reliable operation in the transmission lines. It incorporates consistent information security solutions, edge computing, cloud-based monitoring, and other technical services. An attempt is made in this study to assess the current transformer technologies in order to establish a hypothetical baseline for ensuring future developments. Some future systematic devices which are about to be adopted are also described using the existing components, including intelligence-based control and management, intelligent inverters, energy management, and enhanced communications. There is also a brief explanation of the critical requisites for renewable power grid transformer implementation. In conclusion, to establish a next-generation power grid transformer it is necessary to conduct additional developmental research employing a transformer needs to be carried out.

8. Reference

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Declarations

Availability of data and materials
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Competing interests
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