CHAPTER

1

Basics of Smart Grid

1.1 Introduction

The term *grid* is used for an electricity system that include all or some of the four operations such as generation, transmission, distribution, and control. A *smart grid (SG)*, also called smart electrical/power grid, intelligent grid, development of the 20th century power grid. In traditional grids power flows from a few central generators to a large number of users or customers. In contrast, the smart grid uses two-way power flow and information to achieve an automated and distributed advanced energy delivery network. Thus smart grid can be regarded as an electric system that uses two-way, information, cyber-secure communication technologies, and computational intelligence in an integrated way across generation, transmission, distribution and utilization to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable.

1.2 Conventional Grid

A conventional grid (CG)generally consists of generation, transmission, distribution and load systems. Generation system is generally a combination of large-scale centralised generation plants such as thermal, hydro and nuclear power plants. A typical modern generating unit has rated value of over one thousand MW. Transmission system is typically designed to transfer bulk of power from generating plants to distribution network at high-voltage levels over long distances. Distribution network are designed to receive electric power from transmission system to be distributed to load centres. It is therefore important to note that the nature of distribution network in CG is passive. The main features of conventional grid can be summarized as follows:

- A conventional grid has vertical structure as shown in Figure 1.1.
- The power flow is unidirectional typically distribution networks.
- The price of electricity is dictated by the utility.

- The consumers have no choice of options in terms of electricity procurements.
- Consumer is passive stakeholder in the conventional grid.

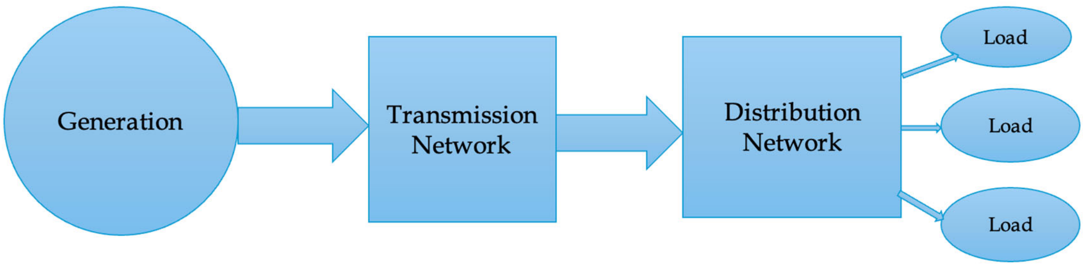

Figure 1.1 Vertical Structure of Conventional Grid.

1.3 Evolution of Smart Grid

The transformation of conventional grid in to smart grid was driven by several factors which include the technological developments in the automation industry, need to accommodate renewable energy sources due to climate change and fuel dependency, need of active customer participation in the grid operation in order to improve efficiency, reliability, stability, economy, security etc.

1.3.1 Technological Developments

Electric grids possessed some technologies since the early stage while the others have gradually been incorporated into grids over several generations as per the requirements and technological developments to improve the performance.

- Control equipment in substations driven by electro- mechanical relays replaced by digital/numerical relays.
- In 1950s the automatic telephone switchboard equipment was introduced to read and control the remote substation from the local substation which was called as supervisory control equipment(SCE)
- In the late 1960s SCE was replaced by SCADA. SCADA was extended to monitor of the majority of the transmission systems (220 kV and above) and some distribution substations in 1970s and 1980s.
- SCADA system was also used to centrally support control rooms and remote terminal units (RTUs) for data collection and control in the substations.
- Later RTUs are connected to programmable logic controllers (PLCs) originated from manufacturing industries using hardwires.
- As a course of time, hardwires are replaced by communication links.

- In the mid-1990s the RTU/PLC configuration was replaced by a different network architecture that consists of protection relays/Intelligent Electronic Devices (IEDs), PLCs and other devices communicating with each other over a network and thereby coordinating operations.
- At later stages active participation of customers was enabled by the introduction of Advanced Meter Infrastructures (AMI).

1.3.2 Changes to be Accommodated

Apart from the technological developments, CGs have found it difficult to accommodate the following changes

- Integration of distributed energy resources including renewable energy sources (RES) and Storage systems into electrical networks, specifically at distribution levels.
- Accommodation of new developments in transport industry in terms of Electric Vehicles (EV) that causes further stress on the distribution networks.
- Dynamic situation between electricity market stakeholders and electrical utilities due to liberalisation of electricity market in recent years.

These factors have adversely affected the operation, management and protection of conventional grid (CG) in number of ways. This in turn has led to initially contemplate on modernising CGs and eventually to the development of Smart Grid Concept.

1.3.3 History

The Smart Grid concept initially developed in the USA. In an article published in Wired Magazine in July 2001 a precise description of the future network, which latter on was known as a Smart Grid, states "*The best minds in electricity R&D have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming and interconnected with everything else*".

The Smart Grid concept then promoted in Europe, North America and worldwide in countries such as India, China and South Africa. The work on Smart Grids in Europe started in 2005 by the Smart Grids European Technology Platform for Electricity Networks of the Future. The aim was to formulate and promote a vision for the development of European electricity networks at 2020 and beyond. In the USA Smart Grid concept was officially promoted by the publication of the US Energy Independence and Security Act of December 2007 whereby it is stated : "*To move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options,* *and to improve the energy performance of the Federal Government, and for other purposes."* The following are some concepts of the smart grid proposed by various organization worldwide:

***The IEC smart grid** as an electric power system that utilizes information exchange and control technologies, distributed computing and associated sensors and actuators, for purposes such as the integration of the behaviour and actions of the network users and other stakeholders as well as efficiently deliver sustainable, economic and secure electricity supplies.*

***IEA Smart grids** are electricity network that use digital technologies, sensors and software to better match the supply and demand of electricity in real time while minimizing costs and maintaining the stability and reliability of the grid.*

***IEEE Smart Grid** an electrical grid that can monitor, predict, and intelligently respond to the behaviour of all electric power suppliers and consumers connected to it in order to deliver reliable and sustainable electricity services as efficiently as possible.*

***As per Swedish stand**ards it is a set of technology, regulation and market rules that are required to address, in a cost-effective way, the challenges to which the electricity network is exposed.*

1.3.4 NIST Smart Grid Conceptual Model

National Institute of Standards and Technology, Department of Commerce USA has published a Smart Grid Conceptual Model in February 2021 as shown in Figure-2. The NIST Smart Grid Conceptual Model describes the overall composition of electric grid systems and applications. It provides a high-level view of the system for better understanding of many stakeholders. Originally introduced in 2010, the Conceptual Model is updated with each Framework revision.

The visual representation of domains, interfaces, and electrical and communications flows presented in Conceptual Model provides a comprehensive understanding of various actors, roles, and responsibilities needed to ensure effective day-to-day grid operations and control. The Model allows extended concerns to be identified and understood in its context, thereby providing support for policy and planning activities from regional planning to resource adequacy assessments. Various domains and their roles/services the SG conceptual model are as follows:

Customer: The end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own sub-domain: residential, commercial, and industrial.

Markets: The facilitators and participants in electricity markets and other economic mechanisms used to drive action and optimize system outcomes.

Service Providers: The organizations providing services to electrical customers and to utilities.

Generators including DERs: The producers of electricity, may also store energy for later distribution. This domain includes traditional generation sources and distributed energy resources (DER). At a logical level, "generation" includes those traditional larger scale technologies usually attached to the transmission system, such as conventional thermal generation, large-scale hydro generation, and utility-scale renewable installations usually attached to transmission. DER is associated with generation, storage, and demand response.

Transmission: The carriers of high voltage electricity over long distances. May also store and generate electricity.

Distribution: The distributors of electricity to and from customers. May also store and generate electricity.

The roles in a particular domain often interact with roles in other domains to enable smart grid functionality as shown in Figure 1.2. Moreover, as the system complexity increases, the communications and interoperability expand operational

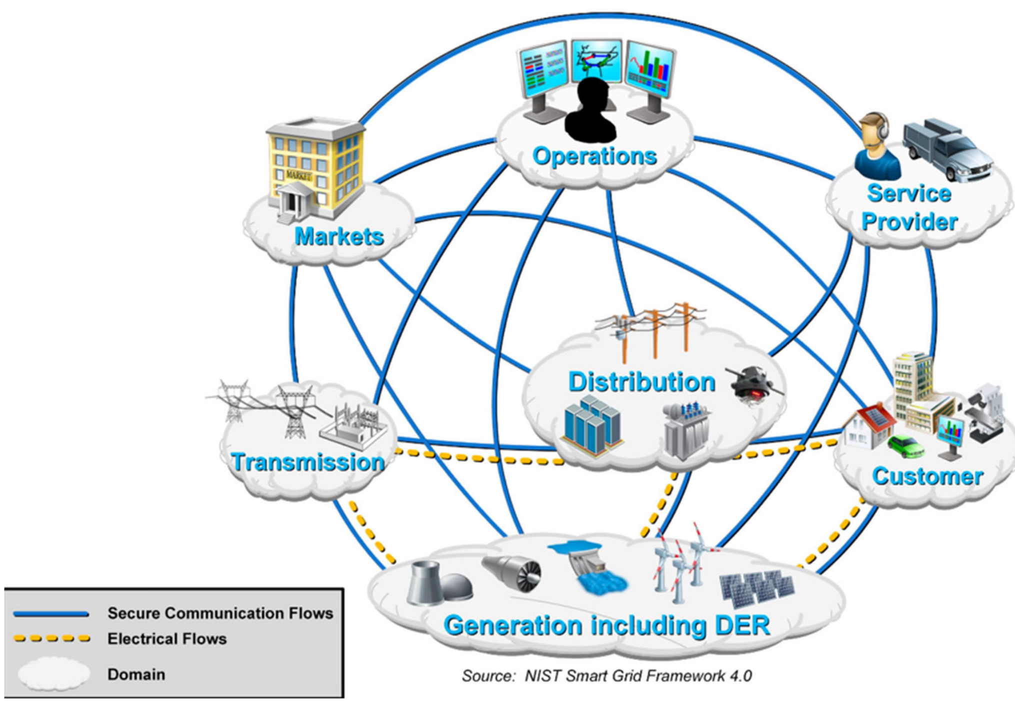

Figure 1.2 NIST Smart Grid Conceptual Model.

control beyond locational specificity of physical connections, it is likely that organizations will contain components of multiple domains. For example, the Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) in North America have roles in both the markets and operations domains. Similarly, a distribution utility is not entirely contained within the distribution domain. It is likely to contain roles in the operations domain, and perhaps also the markets domain as economic signals become more dynamic across the system.

1.4 Features and Benefit of Smart Grid

1.4.1 Features of Smart Grid

Smart Grids integrate electricity networks consisting of transmission and distribution systems and interfaces with generation, storage, and end users. The SGs employ sets of modern technologies that can be deployed globally, and guided by local commercial and legal and regulatory. The main characteristics of SGs are as follows:

- SGs have the ability to integrate different energy sources in the distributed energy system in a way that optimises power and delivered effectively to the grid
- The SG system facilitates quick electricity demand response that can ease peak load shaving, load profile shaping with high degree of effectiveness and reliability, leading to better power system stability.
- The wireless and wired communication systems and end-to-end communication management leads to integrated communication system
- Data Acquisition Systems and other technologies integrated with communication.
- New metering, system controls, and customer engagement technologies.
- The SG system uses AMI for communication between the utility company, consumers, and operators. Individual equipment and customers as well as transformers, switches, capacitor banks, voltage regulators, etc. are metered throughout the distribution system. Information from these equipment and customers is relayed to the utility in a typical two-way communication.
- The SG Applies cyber-secured communication like data supervisory control and Energy Management Systems (EMS).
- The SG enables demand profile shaping, and peak loads having to optimise power generation cost and increase consumer utility through real-time pricing technologies

- The SGs facilitate greenhouse gas emission minimisation by efficient integration of variable renewable energy sources and variable loads like electric cars unlike in conventional grid.
- The SG enables active participation of the customer who responds the requirement of the utility to reduce consumption during peak hours to relive it during times of distress.
- The SG has the infrastructure to support a two way flow of communication and of electricity from the utility to the customers which converts electricity consumers to prosumer (producer + consumer).

1.4.2 Benefits of Smart Grid

- These SG system enable seamless connection and operation of different generators in terms of size and technologies.
- Less maintenance cost due to automatic tracking and reporting compared to manual or physical tracking.
- Electricity theft is minimal due to remote monitoring of meters. Any tampering attempt raises an alert signal. Any deviations in power consumption are notified for swift action.
- They have the capability of automatic load balancing which reduces the risks of equipment failures. SGs deploy machine learning based algorithms to predict consumption patterns and manage loads dispatch which reduces stress on electrical equipment, especially during peak times.
- Electrical transmissions is regulated by intelligent technologies to mitigate electrical losses in distribution which improves the efficiency of electrical transmission.
- SGs have improved power system stability, security.
- SGs prevent transmission oscillations, overload, and resultant blackouts by facilitating automatic loading and re-routing of electricity in the event of equipment failures.
- SG consumers are timely informed about the demand and price, to plan their consumption so as to save on energy cost.
- Based on the timely data of both weather and demand SGs facilitate optimal integration of renewable energy which enables economical dispatch
- Efficient connection and operation of generators of all sizes and technologies seamlessly to a common platform.
- Consumers are allowed to participate actively in grid optimization which leads to improved overall reliability and stability of the power system

- SGs facilitate accurate and timely planning and action by availing real time data and information to create a stable, efficient, and cost-effective system.
- Reduction in the environmental impact of power systems is achieved through optimum loading of generation systems.
- Improved reliability, quality, and security of the electricity supply system.
- Improved quality and performance of energy products and services by fostering market integration and harmonious stakeholder relationship and operation.
- These grids convert electricity consumers to prosumers who do both generation and supply of grid power based on variable pricing and two-way flow of electricity and data.
- By combining or integrating weather and demand forecasts, more accurate generation planning, and dispatch can be done.
- SGs are resilient to system attacks, and disasters due to the capabilities of isolating and re-routing power flow (self-healing ability). This in turn reduces downtime and outages.

1.5 Main Features

It is very important to understand the features of Smart Grid technology so that the perfect use of Smart Grid technology can be ensured. The features of Smart Grid can be described as follows

- Smart Meters (SM)
- Distributed Generations (DG)
- Renewable Energy Integrations (REI)
- Bidirectional Communication System (BCS)
- Automatic Healing Capability (AHC)
- Data Security/Cyber Security
- Carbon Emission Reduction
- Meter Data Management (MDM)
- Field Area Networks (FAN)
- IT and Back office Computing

- Demand Response
- Electricity Storage Devices
- Distribution Automation

1.5.1 Smart Meters

Smart Meter is a unique feature in the Smart Grid which is the most dependable instrument in the field of power generations and consumption for data measurement. Smart Metering refers to usage of advanced meters in combination of communication systems to allow consumers to monitor their energy consumption and price in real time. Usually it takes the reading after a certain time and a few times a day. It also provides information of consumer loads which is utilized in Demand side Management (DMS).

Figure 1.3 Smart Meter.

1.5.2 Distributed Generation

Distributed Generation (DG) is an important part of Smart Grid Technology. Distributed Generation means generating electricity from small energy sources. Distributed Generation plays a great role in Smart Grid and is cause of some challenges in the grid operation. Some of the challenges include:

- Market oriented demand response of the Electricity. It means understanding the demand of electricity of the consumers and makes a user oriented market place for ensuring the perfect demand response.
- Ensuring the security of distributed generations and supply of electricity from generation end to the distribution end.
- Ensuring Cost Effective operations of generation and distribution so that the cost does not exceed the desired limit.
- Environmental Safety must be assured for protection of the Grid from any kind of natural disaster.

1.5.3 Renewable Energy Integration

Renewable energy integration (REI) is also an important feature of the Smart Grid. Enhancing the capability REI helps the national grid to meet the extended demand of the consumers with potential security. Environmental Impact is one of the greatest factors in case of Renewable Energy Generation and Integration. The absence of Solar Energy during the night, must be supported by storage system in the night. Voltage fluctuations due to intermittent nature of solar and wind energies are also to be countered by power electronics of the SG.

1.5.4 Bidirectional Communication Systems

Enabling the bi-directional communication system makes the Smart Grid easier to use for both consumers and suppliers. Communicating in the smart grid is like a phone conversation where users are aware of the price and usage of the electricity as well as the generation and the supplier are also aware of billing of the usage of the electricity clearly. Monitoring the whole Grid centrally is possible only through this communication system. However, the privacy must be ensured in case of communicating in the grid bidirectional or multidirectional.

1.5.5 Self-Healing Capability

Since the Smart Grid (SG) is a smart system of generating the electricity and distributing them to the consumers with a huge confirmation of data security, robustness and convenience, the smart grid technology must have one feature which is called self-healing capability (SHC). This feature includes the automatic detection of the abnormal conditions in the system like over current, surge voltage, fault current etc; sending the information to the central control room to ensure and automatic recovery/healing followed by a disturbance.

1.5.6 Data/Cyber Security

Smart Grid must be secured from considerable threats or attacks. Smart Grid can be attacked by Hackers, Cyber Terrorists, and Organized Crimes, some criminal elements, industrial competitors, careless or poorly trained employees to exploit vulnerabilities in the system. Careless operating of the system by the poorly trained employees can make the total system vulnerable to the security attacks. As SG is highly inter-connected, if one portion of the network is attacked, eventually the whole system gets exposed to serious threat and it may even led to total blackout or total system failure. Hence, cyber security must be strong enough to endure the attacks and make the system run smoothly and efficiently.

1.6 Challenges Associated with Smart Grid

SGs apply modern cutting-edge technology to address multiple challenges of the traditional grid while at the same time providing opportunities to improve their efficiency and reliability. However, several technical and socioeconomic challenges limit the development and application of the SG. SGs employ power electronics technologies like FACTS and RACDS, efficient Energy Storage Systems (ESS), etc. which have high initial cost requirements. Technical challenges in the operation of SGs include database management and cyber security. Consumers lack of understanding about the SG, hence there is a need to educate the public. For consumers to effectively participate in demand side management and other services requires training. The challenges facing the development and application of SGs are summarised Figure 1.4. The challenges also include inadequate grid infrastructure, lack of knowledge and skills by industry workforce, limited capacity of ESSs.

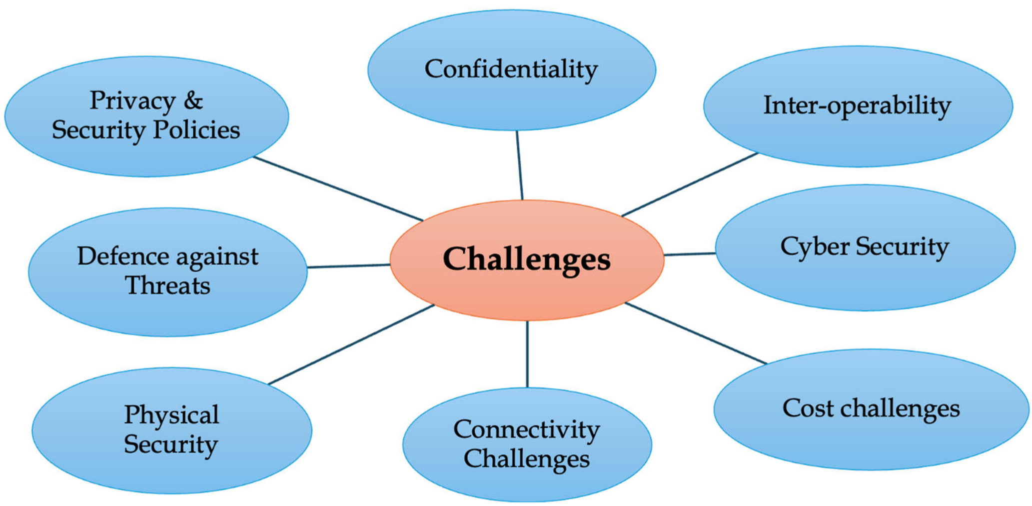

Figure 1.4 Various challenges faced by SG development.

1.6.1 Cost Challenges

The biggest challenge to the development and implementation of SGs is cost. The main cost elements in SG development are associated with the transmission and distribution system, metering, and critical technologies. As per the economic analysis and financial feasibility, studies the cost of the development for SG infrastructure is paramount which is ultimately disadvantageous to the developing countries. Smartening of the traditional grid requires the integration of additional sensors to the infrastructure which is an expensive investment to be undertaken by distribution grid operators.

1.6.2 Cyber Security

There are increased possibilities of remote operation of smart grids since the grids are large-scale system with participants widely spread between power plants and electricity consumers and devices geographically. This requires protection of resources against theft, abuse, and malicious activities. The Electric Power Research Institute has identified power system cyber security as one of the greatest issues of smart grids. It is necessary to identify loopholes in smart grids, exploited by attackers and carryout Threats Analysis by integrating Systems Security Threat Models. There are various approaches used to address cyber-physical security issue for Wide-Area Monitoring and protection and control which are vulnerable to a coordinated cyber-attack. Hence, it is necessary to assess the SG security by review of its methodology to identify weaknesses. Since SGs are deployed across the value chain, there is an increase in points of interconnection with other information networks which exposes the system to the potential threat of cyber-attack on important power management systems and infrastructure. The SG is heavily dependent on ICT which ultimately increases the complexity and the number channels for possible cyber-attacks. The cyber-attacks may target the distribution infrastructure not necessarily to cause power blackouts but other destructive disruptive activities like energy meter manipulation, blackmail, power supply disruptions, damage of equipment, damage of distribution or customer equipment. Therefore, it is necessary to ensure that cyber security is an essential aspect of any SG design and operations. Interoperability and cyber security can be achieved only through rigorous implementation of various standards.

1.6.3 Interoperability

The communication infrastructure for SG should meet specifications in terms of time synchronisation, data delivery efficiency, latency reliability, and multicast support. Additionally, the main challenge in networking communications in SG is interoperability. Rigorous implementation of applicable standards is an effective measure to achieve interoperability. The NIST has put in place interoperability standards in areas like advanced metering infrastructure (AMI), end-to-end security, metering, communication between control centres, substation automation and protection, EMS interfaces, power system control operations information security, PMU communications, electrical and physical interconnections between utility and DG, security for intelligent electronic devices (IEDs), cyber security standards and guidelines for federal information systems and bulk power systems, HAN device communication, measurement, and information model and SGIP catalogue of standards.

Each country should develop their standards for smooth implementation of SG considering their existing standards and for easy implementation. However, internationally accepted standards and security should also be put in by all countries involved in the SG implementation to make the power grid a homogeneous global grid.

1.6.4 Confidentiality Challenges

Access Control and Identity Management is needed for the confidentiality of data transmitted via SGs. There is a need for authentication to verify the identity of the receivers and avoid any disruption or exploitation. Only authenticated users should be allowed access to the control centre for transmission, and distribution grids.

1.6.5 Privacy and Security Policies

With wide scale interconnectivity and system access including the growth of IoT associated with SG development, privacy, and development of far policies for all stakeholders is a real challenge as objectives and needs may differ and even conflict among stakeholder. Therefore, there is a huge necessity for suitable security policies to establish relationships between the consumers, utilities, generating companies, transmission firms, and third parties, although applying security and privacy policies in a manner that does not lead to dissatisfaction which is a complex affair.

1.6.6 Defence against Threat

The SGs have inherent vulnerabilities against which it must be protected. This can be achieved by building an effective, layered defence system for the protection of the SG infrastructure. This defence or protection against threats or vulnerabilities gives the network segmentation and access control to defend against denial-of-service (DoS). Technologies used include firewall, virtual private network (VPN), intrusion prevention system (IPS). This leads to extra investment in technology and resources adding to system costs.

1.6.7 Physical Security

SG systems have thousands or millions of widely spread remote points and networks. This the challenge of policing or physical protection from theft, sabotage and illegal or unauthorised access. Therefore, physical protection is a real challenge for SGs. Additionally, the wider geographical dispersion of the many assets and systems makes it difficult to access all of the terminals for both maintenance and protection

1.6.8 Connectivity Challenges

This refers to the communications connectivity and interchange within the SG infrastructure and between users or stakeholders. The current trend in communication technology is undergoing a transition from analog to digital and to an Internet-like distributed environment where large number of devices are interconnected. Not all regions, devices or users have access to modern and effective internet and communication infrastructure especially where the services a public accesses and not limited to the grid system.

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