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DIGITAL TWIN ARCHITECTURE: A NEW APPROACH TO SMART METERING UPGRADE AND DEPLOYMENT

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Abstract:
Users and providers of smart grid power are connected by smart meters. With the growth of smart grid use such as response to user demand, peak valley time of use pricing, prevention of electricity theft, power quality observation, and peer-to-peer (P2P) trading of electrical energy, smart meters have emerged as a hotspot for research. Previous research on energy consumer smart meters primarily examined new smart grid features or applications, many of which are still being studied. Upgrades to user-deployed smart meters will be necessary in the future, since the service models and communication protocols used in smart grid applications are likely to be revised or changed. Although upgrading smart meters would be difficult due to their resource constraints, it has not received much attention. This study offers a Digital Twin driven service architecture as a solution to reduce the need for user-side smart meter upgrades. The architecture being proposed maximizes the stability of user-side smart meters by developing application-oriented communication protocols and service models in Digital Twin virtual agents.

Keywords: *Smart Meter, Digital Twin, Smart Grid, Micro-controller unit*

I. Introduction

Renewable energy sources, including solar, wind, and hydropower, are not the same as fossil fuel-based power plants. (Niaz et al., 2022). Variables that are natural have a huge effect on the quantity of clean energy produced, making it difficult to sustain consistent power production. This can cause fluctuations in the electrical grid, which seriously jeopardizes the reliability of systems with centralized power supplies. It is certain that the widespread use of dispersed renewable energy sources, including solar, wind, and hydropower, will make it more challenging to support centralized electric power infrastructure and keep up with growth expected in the future. (Kader et al., 2022) Systems of distributed power supplies are increasingly becoming a viable option for improving power supply efficiency and dependability. It is critical that issues such as potential computational resource shortages, the difficulties with system updates and the high cost of smart meters for users are promptly addressed. Traditional power networks enable information to flow to power consumers only in one direction, while smart grids facilitate two-way flow. (Zhou et al., 2013). The current smart grid requires power users to comply with grid commands and adjust power supply based on user data, but it has not yet reached sufficient development, and future changes are expected. (Mollah et al., 2021). Future developments will require us to implement more sophisticated features like load identification, electricity theft prevention, demand response, P2P energy trading, privacy protection, and network topology for the time division billing of the smart meter, the electricity supply, ladder billing, and late power-off features.

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Smart meters are necessary for information sharing between consumers and the electricity system. Using the IR46 standard. (Sun et al., 2019) suggests "a smart meter structure made up of four Microcontroller Units (MCU): a metering MCU, a management MCU, an identity MCU, and a load control MCU". In the dissertation, they looked at each component's operation and assessed how well the multi-MCU smart meter performed in a testing setting. The smart grid's power users are connected to it through smart meters. An essential component of the smart grid are smart meters. Currently, the majority of smart meters use the Microcontroller Unit (MCU) in addition to a unique Metering Chip architecture. Although this arrangement will perform the essential tasks of smart meters, it's is not very scalable. You cannot improve on the current structure, replacing them is the only option available. Because smart meters are essential for the dependability and efficiency of the smart grid, they need to undertake more functions due to the continuous improvement in social requirements. Smart meters as they are, are no more adequate for the needs of the future, therefore a fresh structure is needed. The current smart meters' processing power is limited, causing economic losses and labor costs. Large-scale replacements can hinder rapid iteration, leading to valuable applications that cannot be implemented in a timely manner. Therefore, it is necessary to have a smart meter framework that is inexpensive and simple to update. This will enable the rapid development of smart grids (SG) and ensure the continued success of the smart grid (Chen et al., 2023). (Song et al., 2019) worked on a twin MCU smart meter that satisfies the IR46 standard. In order to operate independently, they divided the metering and management chips and concentrated on figuring out the process of updating the software in this type of setup. The IR46 standard is being promoted, which adds complexity to the hardware and software of smart meters as well as to the procedures used to assess their quality (Xiangqi et al., 2019) suggested a software design scheme based on a single chip that can realize the functional division of a single Radio-Frequency Identification (RFID) semi-active technology by separating the metering module from other modules based on an MCU. (Peng et al., 2019) developed a "closed-loop feedback correction" model to increase the effectiveness and caliber of the development process by strictly controlling the important components and risk areas in the creation of smart meters. This study presents a Digital Twin (DT) method for using smart meters, which aims to address the issue of smart meters being costly and challenging to upgrade. The primary novelties in this research are:

•To produce a digital twin state, this structure maps the physical meters' states using the container.

•Application-focused Models of communication and services are transferred from the physical meter to the relevant Digital Twin by means of Digital Twin technology, which creates a specific proxy Digital Twin for every physical meter on the edge system or cloud. The physical meter simply has three essential features: time-sensitive function, one-on-one communication with the DT, and basic energy metering.

•Through the improvement of the appropriate proxy DT, the reduction of user marketing requirements, and the enhancement of smart meter computing power, we would have advanced smart meters.

The remainder of the sections of this study are broken down as follows: This study first examines the notion of Smart Meters, their functions and the different types that exist. Second, we looked at Digital Twin concept and application. Third, the paper delved into the proposed architecture of using Digital Twin to mirror the demand side smart meters,

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communicate with their pair and with the utility side. Furthers studies outside of this, will investigate and examine the experimental results to further confirm the efficacy of this approach on the user side of the smart grid in real-time applications.

I. Smart Meters

The smart meter is one of the most important parts of the smart grid. The electrical grid system consist of the generator, the transmission, the distribution, and the consumption of electricity. Electricity is transported from a small number of central generators to numerous load centers that have consumers or clients in conventional power networks. (Chen et al., 2023). A smart grid is a kind of power grid that enables the creation of an advanced automated and distributed energy delivery network by permitting the passage of unusual power and two-way information. (Kabalci & Kabalci, 2019). A smart meter is a sophisticated energy meter that collects data from electrical devices used by consumers, computes their energy use, and then transmits extra data to the utility provider for better billing and monitoring. A smart meter can capture real-time energy use statistics and detect electrical factors like voltage and frequency. The smart meter and the utility central system may send and receive information to and from each other. Smart meters may also be used to monitor and manage user electrical gadgets in order to control loads and demands inside the facility. Additionally, they are equipped with the built-in capacity to remotely detach and reconnect particular loads.

The smart meter uses a variety of sensing devices and control methods that are backed by a specific network infrastructure for communications. The information obtained from smart meters consists of unique meter identity, time of data, power use numbers, and other necessary information. A smart meter can detect power use and collect diagnostic data from household equipment, determine the specifications, transfer the information to utilities, and then get back control signals to maximize the customer's power usage and bill in accordance with the results. A smart meter may occasionally be able to interact with some neighboring smart meters. From customer's standpoint, smart meters have a variety of possible advantages. For instance, users can control their energy usage to lower their electricity bills by estimating bills using the information gathered. From the utility's point of view, real-time pricing may be implemented using the data gathered from smart meters. This allows the firms to set a maximum amount of electricity that consumers can consume and urge them to cut back during times of peak load. It is possible for the system administrator to remotely cut off or reconnect a delivery of power to any consumer with the appropriate mechanism, allowing them to optimize power flows based on data received from demand sides.

Functions of a smart meter

The typical expectations for a smart meter include the following features: programming, security, display, billing, load management, data recording, collecting, and storage; two-way communication

The technologies and designs of smart meter systems vary, but they all work according to a generally simple procedure. By using a Local Area Network (LAN), smart meters gather data from end users and send it to a data collection system. Depending on the need of the data demand, this transmission process might be carried out once a day or as frequently as every 15 minutes. The data is then transmitted by the collector once it has been retrieved. The WAN is used by the utility central collection system after further processing of the data. Signals or commands can be delivered straight to the meters, client premises, or distribution device because the communications path is two-way (Ajenikoko & Olaomi, 2014).

There are two major kinds of technologies by which smart meters communicate: Power Line Carrier (PLC) and Radio Frequency (RF). There are numerous benefits and downsides associated with the use of Smart Grid. The utilities chose the finest innovation depending on their company interest. Selecting the appropriate technology necessitates a careful assessment and study of the current requirements and the potential advantages for business. (Ajenikoko & Olaomi, 2014).

A. Radio Frequency – RF

A smart meter collects measurement information from users and sends them to a data center by wireless radio transmission. After that, the data is prepared and transferred to the utilities data systems gathered in one location using a variety of techniques. These details are used for operational and commercial reasons; billing for utilities and managing outages, and other systems. There are two different types of RF technologies:

Mesh Technology: The smart meters connect with one another at the collecting point to create a LAN cloud. The collector uses a range of WAN protocols to transmit the data to the utility data center. The benefits of mesh radio technology, include its broad bandwidth, tolerable latency, and usual operating frequency of 915 MHz. While, the geography, long-distance problems in isolated locations, and private communications are some of its drawbacks.

Point to Point Technology: With the use of this technology, smart meters may have direct communication with a designated collector, usually a tower. The utility control center receives the information from the tower collector via a number of channels for processing. . Some benefits of point-to-point radio frequency technology include greater throughput, low or no latency, wide bandwidth, direct connection with every endpoint, and the ability to cross longer distances. Certain drawbacks to point-to-point radio frequency technology include terrain and long-distance problems, proprietary communications, and a reduced level of interface with Distribution Automation (DA) devices (Abrahamsen et al., 2021; Baimel et al., 2016; Castro, 2022)

B. Power Line Carrier – PLC

The utility power lines can be employed to send the data that the smart meter has acquired to the utility data center. After that, more processing and analysis are done on the provided data. The utility makes use of this data for future and operational needs. PLC technology has certain benefits, such as increasing rural lines' cost-effectiveness and enabling long-distance or remote work. Although it has a few drawbacks, such as a longer data transmission time than wireless, less bandwidth, and a higher cost in urban areas (*The Role of Radio Frequency Communication in Smart Metering Systems*, n.d.)

II. Digital Twin Approach

The idea of DTs was proposed fairly early on, but it was not taken seriously at the time because of a lack of technology and cognitive capacity. With the growth of cloud computing, Machine Learning as well as Internet of Things (IoT) in recent years, DTs have progressively gained popularity in research. The main goal of the DT is to use a network connection to establish a close link between the items in the two places by creating a model of the physical element in the real world within the virtual environment.

Tao et al. (2018) thoroughly examined the idea of DTs and came up with the following characteristics:

Representation and relevance: Virtual representations ought to resemble real-world objects as closely as feasible. When developing mapping models, it is important to take into account the fact that certain physical entity features may not be useful in certain application circumstances.

Mapp-ability: Every significant feature and event ought to be included in the virtual model.
Reproducibility: Each physical element that has been virtualized ought to be able to be duplicated in the virtual environment.
Entanglement: The network establishes close connections between every DT. Any modifications to the real world should be promptly reflected in the virtual representation.

Persistence: Physical items and virtual models ought to have the ability to stay in sync for an extended period of time. The virtual image ought to have the capacity to harmonize the state of the physical device once the link is reestablished, even in the event that connection is broken.

Memory: A significant amount of data will be produced as physical entities operate. Virtual pictures ought to be able to hold a large amount of data in storage.

(Vrabič et al., 2018) defined a digital twin as a digital replica of a physical item or assembly that is based on service data and integrated simulation. The digital copy stores data obtained from several sources during the course of the lifespan of a product. This information is regularly updated and provided in a variety of ways to help with decision-making by projecting future conditions in the design and operating settings.

(Fuller et al., 2020; Singh et al., 2021) defined three terms that will assist in recognizing the prevalent misunderstandings found in the literature. Nonetheless, a number of misconceptions are common and they are not exclusive to these particular instances.

1) Digital Model: A digital depiction of a real object is known as a digital model; automatically generated data must not be transferred from the digital model to the physical model in order for a digital model to be appropriately defined. Digital models include construction blueprints, product designs, and development, to name a few. The absence of any kind of information interchange between the digital model and the physical system is a key characteristic. This implies that after the digital model is produced, modifications introduced to the real object have no bearing whatsoever on the digital model.
2) Digital Shadow: An item with a flow in a single direction between its physical and digital forms is called a digital shadow. It is the digital item that changes when the physical object changes rather than the reverse.
3) Digital Twin: When an existing physical entity and its digital replica are in total connection, they are called "Digital Twin" if data flows between them. The digital object automatically changes in reaction to modifications made to the physical thing, and vice versa.

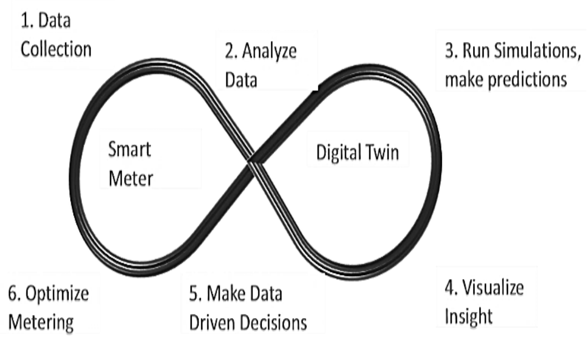

Fig. 1: interaction between smart meter and its digital twin

APPLICATIONS OF DIGITAL TWIN

Instances of Digital Twins applications are vast. This part of the paper will first look at the possible uses for digital twins, covering the

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fields, industries, and particular issues with the technology.

1) ***Smart cities***: The rising advancements in connectivity through IoT have led to a yearly increase in the use and potential effectiveness of Digital Twins inside smart cities. As more smart cities are built, communities become increasingly interconnected, which increases the demand for digital twins. Furthermore, the more information we collect from IoT sensors integrated into our essential municipal services, the more opportunities this will create for research into the development of sophisticated AI algorithms (Mylonas et al., 2021; Singh et al., 2021). Future-proofing in several ways greatly benefits from a smart city's services and infrastructures having sensors and being able to be observed by Internet of Things devices. It can be applied to support ongoing developments of future smart cities as well as to the design and growth of already-existing smart cities. Apart from the benefits associated with organizing, there are additional advantages related to energy saving. This information provides a great understanding of the distribution and usage of our utilities (Raes et al., 2021). The use of digital twin technologies is possible in the development of smart city technology. By making it possible to create a living testbed inside a virtual twin, it can aid in development that can be used to test various scenarios and, secondly, enable digital twins to absorb environmental changes through the analysis of data changes. Monitoring and data analytics can be performed with the obtained data. As smart cities grow and link more people and generate more useable data, the potential for digital twins expands (Qian, 2022).

2) ***Manufacturing***: The industrial environment is the next known use for digital twins. Producers are increasingly using digital twins in smart city construction due to financial incentives and the need for efficient product management and monitoring. (Qian, 2022). The notion of a digital twin for industrial processes is made possible by the Fourth Industrial Revolution, which makes use of device connectivity, and the current expansion is consistent with this idea. The Digital Twin is capable of providing feedback from the production line and real-time machine performance data. The manufacturer can anticipate problems earlier thanks to it. By enhancing feedback and connectivity across devices, the adoption of digital twins improves performance and dependability (Attaran et al., 2023). Digital twins and AI algorithms together have the ability to produce results with higher accuracy due to the device's capacity to store enormous amounts of data needed for examination of performance and forecasts. Another area that has a variety of uses for Digital Twins is the building industry. A building or other construction may utilize a digital twin during the planning phase. The technology is utilized for creating smart city structures and can also be continuously used for real-time prediction and monitoring purposes by applying virtual adjustments to real ones, the usage of digital twins and data analytics may boost accuracy when predicting and maintaining buildings and structures. The ability to apply algorithms in real-time within the Digital Twin prior to the physical structure provides the construction team with increased accuracy during simulations. As opposed to low detail static blueprint models, the idea of real-time simulation has been a prevalent goal observed thus far in the field of digital twins. Although there is a rationale for employing these models, their predictability and learnability are limited because they do not incorporate real-time parameters. The Digital Twin may apply deep learning and machine learning methods in addition to learning and monitoring concurrently (Corallo et al., 2021; Publication, 2020; Qian, 2022; Soori et al., 2024).

3) ***Healthcare:*** Digital twin technology can also be applied in the healthcare industry. The advancement of technology has significantly

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impacted healthcare, enabling the achievement of previously unattainable goals like high precision surgery. Because IoT devices are more affordable and simpler to install, connection has increased. Because of the growing connectivity, the potential uses of Digital Twin usage in the healthcare sector are only growing. One possible use is a person's digital twin that offers a real-time bodily examination. A more practical purpose for digital twins nowadays is to mimic the actions of specific medications. In a different application, a digital twin is used to assist with the planning and execution of surgical procedures. Healthcare providers such as hospitals, physicians, researchers, and others can use a digital twin to mimic settings that are unique to their requirements, whether they are real-time or predict future enhancements and applications. This is similar to other applications in the healthcare business. Furthermore, by combining the Digital Twin with AI algorithms, more intelligent predictions and decisions may be made. Patient care is greatly impacted by many healthcare applications that do not directly involve the patient but are nevertheless helpful for continued care and treatment. (Katsoulakis et al., 2024; Vallée, 2023). Despite the fact that digital twins are still in their infancy, there is a lot of promise for managing beds, entire wards, and hospitals using them. In the healthcare industry, because it could mean the difference between life and death, the ability to simulate and react in real-time is even more important. The digital twin in the medical setting could potentially aid in predictive maintenance and ongoing equipment repair, utilizing AI and real-time data for life-saving decisions. (Angulo et al., 2020; Kamel Boulos & Zhang, 2021; Sahal et al., 2022).

III. Digital Twin Architecture

This section details the proposed system model and proposes a Digital Twin architecture to simplify smart meter upgrades.

A. The proposed system model

The model of the suggested design, which includes the user, the generation, the transmission, and the distribution, is shown in Fig. 2. A DT, which may be implemented in the cloud or on an edge system, is added to the standard smart grid information infrastructure, which consists of the Wide Area Network (WAN), the Neighborhood Area Network (NAN), and the Local Area Network (LAN). This reduces the need for user-side smart meter upgrades.

Each DT functions as a specialized communication and service agent for a user-side smart meter in the proposed system; DT A' and B' service smart meters A and B, respectively. To avoid interfering with each other's operations, the DTs are segregated from one another. DTs communicate with one another using a virtual network in order to facilitate cooperation amongst neighborhood smart meters.

Furthermore, the DTs employ a one-to-one communication interface to connect with each user-side smart meter. If necessary, they can also exchange data on behalf of the smart meter with application servers, other smart meter users, and users themselves. Application-oriented functionalities that user-side smart meters are currently required to implement are thus handled by the DT. Only the DT, not the user-side smart meters, need to be updated if the smart grid apps change.

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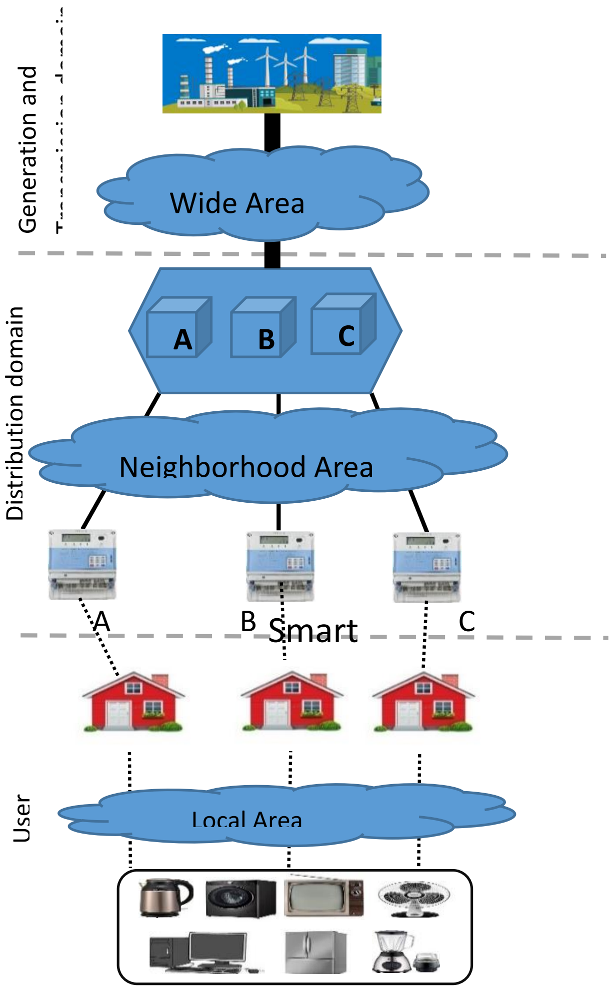

Fig. 2: Proposed System Model

B. The layered architecture

The DT architecture is shown in Fig. 3. The five layers are organized in a bottom-up fashion and they include: 1. the infrastructure layer, 2. a virtualization layer, 3. a communication layer, 4. a computation layer, and 5. an application layer. Below is a description of their roles.

Infrastructure support is given by the infrastructure layer. It is mostly made up of user-side smart meters and NANs. The dedicated DT and smart meters communicate through a NAN. The features that are built into smart meters should be as simple as possible to minimize the need for updates. Only three categories of fundamental operations are included in the suggested architecture: time-sensitive operations, electrical operations (including energy metering and electrical monitoring), and communication interfaces. User-side energy management systems (EMS) and the dedicated DT are connected via the communication interface. The DT now have access to all other functions. Every effort has to be made to simplify the user-side smart meter's functionalities.

Each DT acts as a specific user-side smart meter agent within the virtualization layer, which operates in isolated environment. The physical elements of a computer system include memory, CPUs, devices for input and output, and flash drives. These are simulated by virtual hardware at this layer. On top of the virtual hardware is the operating system kernel, which contains drivers, a scheduler, and a filing system. The application and communication layers, which are the higher layers, are also housed in the virtualization layer.

Every component of the suggested architecture is in communication with every other component. Each virtual container supports four modes of communication: one-to-one with the consumer smart meter, communication with consumer EMSs, communication with peer DTs, and communication with the utility, depending on the roles that the user-side smart meters play. Below is a more detailed description of these:

- The DT mimics the actions of a physical user-side smart meter and acts as its dedicated agent while interacting with the utility. It accomplishes this by adhering to a standard (like Open Automated Demand Response) protocol for utility and smart meter communication. The DT behaves just like an actual user-side smart meter, so the utility is unaware that it is talking with it. The suggested service design can be supported without the utility needing to be upgraded, ensuring system consistency.

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- One to one communication is necessary between two DTs since each one acts as the agent of a single user-side smart meter. There are just three forms of communication required for smart grid applications: writing, forwarding, and reading. Writing allows the container to send commands (such as the requirement to make certain configurations) to the smart meter; forwarding enables the message to be sent from the smart meter straight to a user-side EMS without requiring local processing; and reading allows a DT to read or monitor data from the smart meter. Messages to and from the smart meters are made simpler in this way. One-to-one communication with the DT is made simpler and less complex, which minimizes security and authentication difficulties.

  Direct contact between the DT and user-side facilities is made possible via the communication interface with user-side EMSs, independent of the smart meter. This is a reflection of the fact that some smart meters are unable to connect to user-side EMSs, which prevents them from taking part in demand response initiatives. Many electrical appliances in the user domain can be remotely monitored and controlled via the Internet. The facilities can participate in demand-side management even in the absence of a user-side smart meter by enabling communication between the container and user-side facilities.

- Message exchanges between DTs are made possible via the intra-DT communication interface. In order to maintain and operate the smart grid, cooperation between dispersed energy resources and electricity customers is crucial due to its power distribution systems. This role is moved to the DT in the suggested design. An intra-DT communication interface is the implementation of the communication interface seen in conventional smart meters. Using the proposed technology is made possible by DT communication, which follows the same protocol as smart meter communication. Additionally, because NAN technologies have restrictions, smart meters have limited communication bandwidth. The bandwidth and data transfer rate of the virtual network that facilitates communication between DTs are significantly higher.

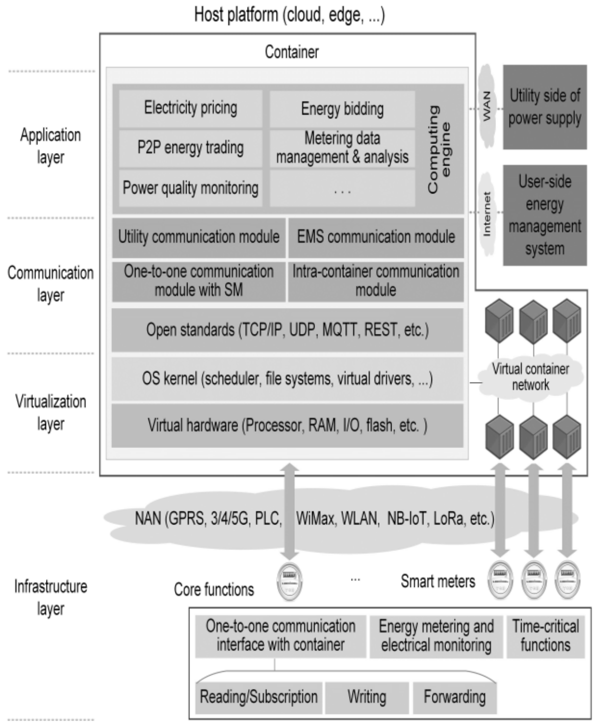

Fig.3: A layered approach to the Architecture.

Smart grids applications, such as peer-to-peer energy trading, block chain, smart metering data management and analysis, energy bidding, power quality monitoring, and electricity pricing and incentives, in the distribution grid are supported by the application layer. User-side smart meters were used to support these applications, but DTs are now used instead. Furthermore, a computing engine offers the light computational powers needed for smart grid applications, such as

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learning-based analysis, data encryption, and lightweight optimization. The utility creates and implements the computing engine; users can choose what they need from the variety of alternatives available.

Conclusion

Digital twins are a potent instrument that bridges the gap between the digital and physical worlds in the fast-paced world of technology innovation. Digital twins, which began at the nexus of engineering, simulation, and data science, have traveled an incredible path from conception to revolutionary application. The transformation of industries has been brought about by the development of digital twins, which have gone from modeling individual parts to modeling entire systems, with power grids emerging as a major winner. These complex networks—which are essential to modern life—face a number of difficulties, such as grid stability and the application of sustainable energy. With the ability to provide real-time insights, predictive analytics, optimized operations, and increased disaster resilience, digital twins have opened the door to a new era in grid management. Yet, challenges loom on the horizon. The quality and integration of data, complexities of modelling, security concerns, high initial investments, and the need for cultural change demand prudent navigation. As the energy landscape evolves, embracing digital twins requires strategic planning, collaboration, and a commitment to overcoming challenges. In the journey ahead, power grid operators can harness the full potential of digital twins. The cost of vast changes in technology, implementation and deployment as it concerns smart metering can be substantially minimized if this approaches is fully developed.

Further study will be done to test and show its full potentials.

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