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Artificial intelligence and blockchain technology for secure smart grid and power distribution Automation: A State-of-the-Art Review

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ABSTRACT

Artificial Intelligence (AI) integrated with Blockchain distributed ledger technology (BDLT) has become the most attractive research area in the domain of renewable energy and related power automations. However, the increased use of renewable energy-enabled devices raised various challenging problems, such as smart grid-based control management, power distribution, and automations. In this manner, the collaborative approach of blockchain, AI, and wireless sensor networks (WSN) provides a secure platform for control centers to estimate state, which helps to detect and analysis of bad data movement. There are various emerging issues in the field of Blockchain-AI in a renewable environment that poses a serious impact on the technological evaluation, for example, monitoring of contingency, optimal power flow, network reconfiguration, and the commitment of security-constrained units, and control auto-generation. So, in this paper, we perform a systematic review of the state-of-the-art integrated artificial intelligence and blockchain-enabled scheduling, management, optimization, privacy, and security of the smart grid and power distribution automation. One of the focusing aspects of this research is the real-time analysis of the physical layer of the smart grid. However, in this paper, we design a framework of a unified and abstracted state-space, in which the system analysis involves malicious attacks and maintain an effective generalized defense hierarchy in real-time. The current mechanism of analysis of smart grid-enabled physical layer-based malicious attacks is categorized into their associative and targeted components. Thus, we present three different pseudo-smart contracts and digital signatures with consensus policies; that provide an understanding of the new registry of renewable smart grids details, participating stakeholders and their roles, and an updated power distribution automation ledger. We then highlighted the list of emerging power distribution automation-related limitations along with the informational management approaches that present the existing state-of-the-art in this domain, including data-driven, target defense, computation, preservation, etc. Finally, we discuss open research issues and future directions of the smart grid and automation of power distribution security and privacy.

Introduction

The rapid advancement in information and communication technology creates a new paradigm in the current trend of electric-power grid utilization and related executions. However, these days electromagnetic controlled mechanisms use an electronically controlled

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network for the purpose of improving traditional electric-power grid technological transmission [1]. This procedure helps in the transformation of the traditional electric-power grid into smart grid technology along with the power distribution management hierarchy [2]. For instance, a smart grid network integrates power distribution and communication in a dual channel to flow electric supplies and related operations. Due to this versatility of the smart grid, it is become easier to install the current power grid ecosystem with less space consumption compared to the previous system. In addition, the major objective of this new design concept of smart grid is to make the system more observable and allows to create a controlled environment for assets management with robust performance in terms of resource optimization. The security of the power distribution system, especially in the operations of the economical domain provides efficient planning and maintenance [3]. This technological improvement considers the development of the level of micro-grid, which eventually connects all the participating micro-grids to create a large network [4]. Thus, these solutions of smart grids provide reliability in power distribution and transmission in the developing countries, such as no cost to maintain a large electrical infrastructure [5].

In United State of America (USA), the rate of carbon dioxide emitted in transportation increased by more than 23% compared to the previous 2020–2021 years, according to the report of the US environmental protection agency. Whereas the share of electricity generation is included, which boosted up to 47% [6]. It is due to the opening of a number of startups and small/medium-size enterprises (SMEs), which demand more resources in terms of electricity. In order to maintain economic growth, smart grid technology plays a vital role in creating a platform that helps in the distribution of electric power efficiently and effectively. However, by deploying this, the rate of greenhouse gases and pollution reduces, especially the reduction of nitro-oxide in the air, which is harmful to the human body [7]. Most importantly, it is more efficient to calculate the demands and the need for customer utilization. In addition, it helps in the decision-making of energy selling prices and related fluctuations in an economical manner.

In the urbanization of developing countries, the demand for energy consumption increases while the number of Internet of Things (IoT) devices massively growing by both the end of manufacturing and utilization [8]. On the other side, it impacts the environment, which becomes one of the critical aspects of land surface changes. There is no standard manageable platform present, which is unable left unattempted. It is a critical problem that needs concern, not only solve by providing sustainable and renewable energy but also retain the environmental changes [9]. However, big cities consume energy almost 79%, which is responsible for greenhouse gas emissions of more than 79%. In fact, the introduction of the smart grid not only provides electrical benefits but environmental prospects as well. The current central control ecosystem for power distribution uses smart power-grid technology, which takes a long time to manage electric operations. A similar structure of electric grid is used globally for electric power supplies and distribution with the advancement of dynamic and principles-controlled mechanisms. The current power grid technology is only focused on a few preliminaries, such as generation, distribution, and control of electric-power supplies, as shown in Fig. 1. Whereas the present form of the electric grid is inefficient, unreliable, consumes more transmission delay, failure to control, and poor power quality with inadequate supplies of electricity. There is a lack of privacy and security issues while monitoring and controlling the grid system dynamically in real-time [10]. It is evaluated as a real-time challenging problem that creates opportunities to propose new solutions. Considering these problems, the regulatory authority requires a proper infrastructure that overhauls electric power supplies.

By analyzing this lack of inefficiency and reliability, Artificial intelligence (AI)-enabled machine learning (ML) techniques, including supervised, semi-supervised, and unsupervised learning can be used [11]. To expand the scope and context of dynamic monitoring and controlling of smart grid technology by enabling ML developments and customizing operational executions and responses as per the requirements. In addition, the integration of artificial intelligence with power distribution technology creates a new paradigm for the development of real-time generation, controlling, distributing, and monitoring of electric power supplies. The existing ledger management of the power distribution uses a smart grid indicates a critical analysis of a few aspects, such as cloud scalability, redundancy, third-party involvement, and management optimization. For this reason, proper infrastructure development of scalable storage requires efficiently preserving the records of reading of power/energy consumption and billing. And so, this paper addresses the implementation of a standard process hierarchy of smart grid and power distribution using AI-enabling technologies to manage, organize, and optimize digital ledger strategies. By employing receive and post method, the system analysis the consumed units and exchanges records with the participating stakeholders and competent authorities. The evaluation of productivity and performance of power distribution is another consideration prospect [12].

Recently, blockchain distributed technology has been used to enable a secure network infrastructure solution to the enterprises' current systems and process hierarchy to realize integrity, transparency, privacy, and security [13]. And so, the development and deployment of a

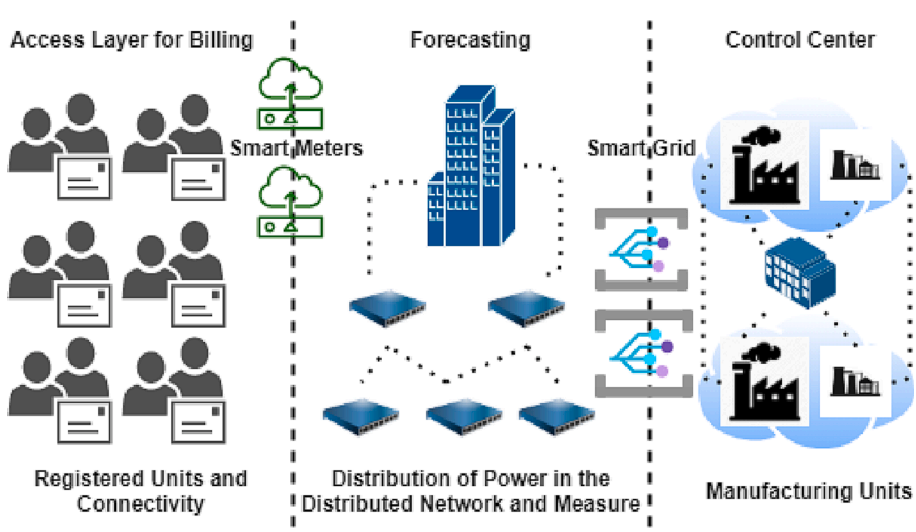

Fig. 1. The Existing Power Distributed Automation Procedure.

distributed application (DApp) make accessing information easier along with the enhancement in the blockchain-enabled APIs creating a system more efficient and reliable in every aspect of designing distributed information systems [14,15]. In a smart grid and power distribution environment, blockchain can be used to secure the infrastructure of a distributed network, encrypt information, and preserve records and events of nodes' execution details. This blockchain-enabled storage is completely based on an immutable nature, which preserves the ledger to enable a transparent process of information investigation [16]. In addition, the blockchain enabling distributed ledger environment provides chronological structure to preserve records of the event of node transaction executions of smart grid and power distribution fluctuations. For execution and deliverance, the consortium public/private network is deployed with two different channels. However, a script of chain codes schedule, control, manage and organize a number of operations through DApp to achieve the autonomous executions of power distribution in a smart grid. This distributed decentralized technology helps in the ledger privacy and security and allows to design transparent environment which is hard to tamper with or forged. With the integration of NuCypher threshold re-encryption, individual transactional information is encrypted with hashes [17]; while exchanging among stakeholders; it changes whenever dispatched.

This paper highlights the existing environment of smart grid technology along with current privacy security infrastructure-related gaps. By analyzing these scenarios, this paper provides possible solutions for scheduling, managing, organizing, and optimizing power distribution-related issues with security concerns in smart grids using AI and blockchain-enabling technologies. However, we propose B-PDA, a novel and secure framework for smart grid-based power distribution automation. It ensures the integrity and privacy of the overall transaction executions towards the deliverance in the immutable storage in the form of encrypted blocks. The main objectives and contributions are discussed as follows:

- This study presents a systematic survey of the current smart grid technology.
- Blockchain ledger with an AI-enabled secure framework for a smart grid is proposed.
- Hierarchy of Power distribution and streamline-optimized automation is discussed.
- A Multi-Proof-of-Work and Proof-of-Stack are designed for novel data scheduling.
- Finally, the list of open issues with conceptualized solutions are discussed.

The remainder of this paper is structured and organized as follows. In Section 2, we study a number of related published materials, the context of smart grid, and the survey of previous articles while extracting a list of involving limitations. Section 3 discusses disruptive distributed electric-power management and the role of blockchain technology in securing the infrastructure. B-PDA, a blockchain and AI-enabled distributed modular framework, is presented. A lightweight power distributed management infrastructure is presented along with the automation of the smart grid and its effects on the distributed environment through pseudo-implementation of smart contracts in Section 4. The list of implementation challenges with open research issues solutions is described in Section 5. Finally, we conclude this research paper, along with the discussion of future assumptions in Section 6.

Smart grid

In the era of digitization, the concept of a smart electric grid is tuned with a few improvements that describe the hierarchy of a distributed network which includes smart transformers, transmission lines, distributed substations with other electric accessories such as smart meters, etc. [18]. All these listed equipment is used for the deliverance of electric/power supplies from generators/plants to the commercial organization and consumers scales. However, to automate the ecosystem between industrial manufacturing units towards the consumers [18,19]. The smart grid performs a vital role that consists of a digital system, operational controls, automation, and computing resources which make the system perform two-way communication between the provider (such as electric suppliers/organizations) and consumers [20], as shown in Fig. 2.

As compared to the previous systems, the energy power suppliers are the only person that knows the failure of power and related fluctuation faced by the consumers, and it will be resolved when users call [21,22]. Whereas the smart grid technology responds directly while automatically receiving data of power failure. The role of the service provider is crucial; however, it manages request for electric supply fails and provide auto-respond to the affected areas because of the wireless sensor network capability, and the components of the smart grid provide real-time data. It collects data from the power generators, transformers, distributed networks, transmission load, and then the smart meters that are placed on the end-user side, as shown in Fig. 2 [23]. According to the report of the American Agency of Sustainable Energy, the use of renewable energy is increasingly growing day-to-day, where the role of the smart grid is remarkable, while energy generation is to manage load and distribution [24,25]. There are a few working operations/objectives of smart grid technology discussed as follows, which make the ecosystem more efficient and reliable [24-26]:

- To fully automate bidirectional communication between nodes (node-to-node intercommunication) and integrate all components of electric power in a single platform.
- To automate operational controls of power generation, distribution, load management, faults, and repairs.
- To provide enhanced software systems for dynamic monitoring, management panels, and decision supports strategies.
- To associate with accurate measurements and sensing systems that collect, examine, analyze, manage, organize, optimize, and dispatch.

Applicational context

Deployment of digital technology in the grid environment ensures efficiency, reliability, and accessibility among the participating stakeholders. It provides all the utilities to the consumers, which calculates the usage of the resources that make the economy stable of the nation [27,28]. With this development, the overall transition of the smart grid improves the ecosystem by upgradation in terms of it becoming perilous

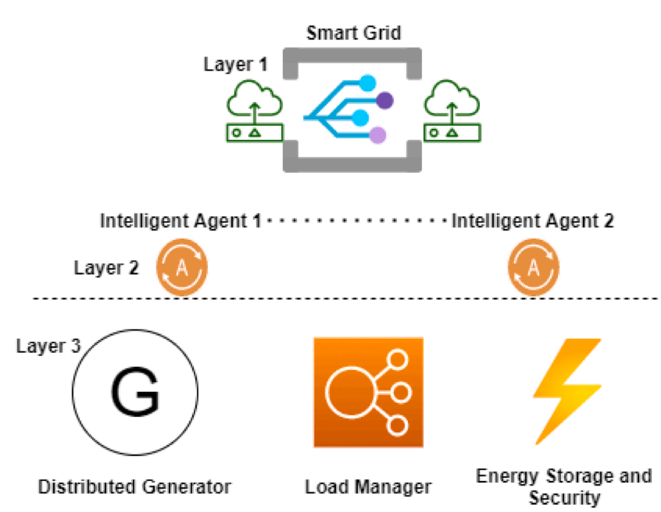

Fig. 2. Generalize Working Operations of Smart Grid.

to execute testing; and so, it develops and maintains standards in accordance with the threshold of defined regulatory protocols [29]. However, various advantages occur while the technology integrates with other state-of-the-art methods. A few lists of benefits are highlighted as follows:

- With the integration of AI machine learning techniques, the system improves the efficiency of distribution and related transmission of electric power.
- It is highly capable of restoring electric power quickly when it fails due to faults.
- It applies low cost in maintenance, operational management, load balancing, and distribution of electric power among the consumers.
- It reduces the peak demand concept and power tariff-related issues.
- It allows for the integration of renewable energy in a better manner with the use of a self-power generation mechanism.
- It enhances privacy security while transmitting.

By utilizing these major aspects of the smart grid, the expert technicians can design several distributed applications such as [29,30]:

- A novel and secure adeptness of transmission channels
- Resource consumption monitoring
- Measure the impact of disturbance in channels, feeders, and breakage
- Analysis of peak demand and streamline automation
- A large-scale load balancer application for integrated renewable energy

Smart grid and security technologies

The large-scale area field sensors and communication lines are explored to an increased level of network threats in the smart grid environment [30]. The current communication channels are vulnerable to adversaries that can alter operational control and measurement-related signals. It is because the existing systems rely on centralized network systems, which are based on a client–server-enabled architecture that considers an unsecure manner of information transmission in terms of security and privacy. For a countermeasure, The Research Institute of Electric Power and Renewable Energy has conducted a recent impact (from 2014 to 2022) analysis of the ecosystem related to

Table 1
Recent Literature of Smart Grid with CPS, AI, and Blockchain.

Research Methods	Research Result and Discussion	Open Challenges/ Limitations/ Issues	Research Benefits/Differences
A role of fifth generation (5G) network for smart energy management and distribution [31]	This paper discussed the international trends in fifth-generation network applications for smart manufacturing, such as reducing energy resource utilization for research and development, testing bedding, and work deliverance in the centralized network environment.	• Centralized network infrastructure Impacts operational management and high-class services Security and privacy preservation issue	• Support sustainable development goal Context of big data discussed 5G Lab's manufacturing requirement
A secure infrastructure to empowering sustainable energy using AI-assisted network [32]	The proposed study explored the futuristic growth of global energy consumption, energy information administration-related issues, and the role of renewable energy in 2050.	• Futuristic assumptions Renewable energy system utilization Role of green energy is discussed Power system adaptation issue	• The use of blockchain and AI for the betterment of renewable energy consumptionCreate secure business-to-consumer (B2C) environment Ledger protection limitation
An artificial intelligence-enabled secure framework design for integration system of smart grid using APEBC mechanism [33]	The author of this paper discussed a novel cloud-based storage for electric power data security and privacy. In addition, the study presents an authenticated privacy ethereum-enabled blockchain mechanism for ledger protection that maintain transparency and integrity.	• Outsourced data collection Cloud-server-enabled information security Permissionless network architecture Bitcoin-enabled mechanism for energy data transmission	• Public ledger Blockchain EthereumHash encryption (SHA-256) Cloud-based data storage Encoded policy attribute for encryption
Smart grid-enabled energy efficiency in smart homes [34]	In this paper, the authors highlighted the use of smart grid technology from its advent to the recent environment, where the technology enables several benefits, such as enhancing the automation of energy resource management, power distribution, fault analysis, assets, demand optimization, and distributed monitoring.	• Real-time capacity to monitoring and measurement Use of AI and blockchain Cloud-enabled preservation Data streamlining and automation limitation Weak security	• High guest fees applied in chain testing and deployment Create empowering environment using AI machine learning
A ring signature mechanism for smart grid multiauthority traceability with blockchain [35]	This paper proposed a novel ring signature scheme for multi-authentication that secures energy data traceability with tamper resistance in the blockchain distributed network environment. The proposed distributed application (DApp) of ring signatures is associated with the smart grid-based system.	• Traditional electric grid technology used An unsecure process hierarchy of data transmission is designed High resource consumption	• No IoT connectivity Unsecure node-to-node interconnectivity Intercommunication on-chain and off-chain channels
A smart grid for green energy management [36]	This paper explored the evolution of smart grid technology in the light of renewable energy penetration with the integration of AI, cloud computing, IoT, industrial manufacturing units, cyber-physical system, and blockchain.	• Security and privacy concerns Scope of data issue Energy power supplies streamline and automation limitation Permissionless infrastructure presented Cloud-enabled third-party involvement	• A design of monolithic system presented Power distribution automation Intelligent operational control discussed Weak process hierarchy used

the data transparency, integrity, provenance, dynamic monitoring flows, preservation protection, and controls [17,28,29]. In the assessment, we analyze various malicious attack-related scenarios with the list of corresponding electric power and energy-based failures, such as line trips, synchronous lines off, and actions of controlled operations are discussed (as mentioned in Table 1).

However, the network equipment is leveraged as a message spoofing in the corresponding assessment. In this scenario, a threatening agent deploys that performs a countermeasure of spoofing attacks and injects an anti-virus mechanism to retain message integrity in the network environment (such as a router, switcher, etc.). But, all these countermeasures of the centralized network are designed manually, which directly affects the system performance and reliability. So, in this case, we present different research articles for different operational counters of smart grid and power distribution automation (as highlighted in Table 1) that help to design better solutions and make technology towards maturity.

Comparative analysis

In this context, we address a large scale of work that has been dedicated to the current network control management of the smart grid. It includes relay, automated feeders, fault indicators, regulatory of voltage management, lead tap, transformer-enabled supplies and control, and distributed monitoring, with many warnings becoming standardized [9,37-39], as mentioned in Table 2. And so, new vulnerabilities have been unveiled that impact the quality, efficiency, and reliability of the ecosystem. To tackle this, the security of the cyber-physical system with blockchain robust the privacy protection of individual transactions of smart grid. Without integration of the technologies alone can only provide a broad solution, neither incorporating the whole [37-39]. However, in this systematic analysis, we investigate the existing systems of the smart grid and separate the list of involving problems related to network transmission, fault analysis, distribution, and remote access with privacy and security. The recent developments of effective defense strategies in the smart grid are also highlighted in this process. With the progressive research frontier (from 2014 to 2022) of smart grid with the cyber-physical system, AI and Blockchain are discussed as follows:

In the smart grid environment, distributed power automation plays a vital role as a monolithic ecosystem mechanism with the process hierarchy of electric generation, transmission, load balancing, distribution, and measurement. There are various physical systems incorporated through the transmission channels, and sub-units that initiate transactions are deployed. These physical systems are interconnected, which allows for integration and coordination of heterogeneous nodes for the sake of computation, information, and communication in a reliable manner [47-50]. However, these mentioned requirements rely on the Internet of Things (IoT)-enabled cyber-physical infrastructure to make secure the transactions of physical systems of sustainable energy. For instance, real-time analysis, measurement, and computation are constantly generated and dispatched via the protected network (communication) channel [48,50]. The designed system consists of an energy management system with a bad data detector, including details of interconnected nodes, energy generation streamlining, assets & demand optimization, product certificate, and conformity acceptance, as shown in Table 3.

Distributed Energy-Power management and other integrated technologies

With the use of distributed energy power resource management architecture, the system is able to manage distributed systems operations by means of grids related transactions that are mainly based on the distributed constraints of energy resources and monitoring [60-65]. In this manner, the technology provides a new paradigm to maintain the voltage of the grid, optimization of the power flow, and facilitate local grid load management [65]. While associated with virtual power plants, a smart industrial design provides an active optimization and operational control of power production and consumption strategies. For instance, the main highlights of working executions are discussed as follows: (i) it allows stabilization of grid frequency, (ii) energy trading and measurement, (iii) assets, peak load, and demand optimization, and (iv) portfolio management [66-70]. However, the security and privacy of the technology are weak, and analyzing vulnerabilities in the smart grid environment has attached in increasing order that impacts the quality and efficiency. The general approach is to learn individual malicious attacks against the system components. In this scenario, this paper categorizes different information technologies by their operations, such as where the ecosystem faced issues, challenges, and limitations in recent times. And so, it highlights the lack of standardization in the process of event transaction executions. First, Information collection and execution technology refers to the application of distributed networks (on-chain and off-chain) that deal with the data flow and information execution at the same end. Second, Operational management technologies refer to the monitoring, controlling, and preserving of details in a distributed manner [71-85]. While integrating these two categories of information technology in energy distribution management and automation reduces the risk of energy generation, load management, fault detection, demand & supply, distribution, optimization, privacy preservation, and security.

The defense mechanism of the current system is absolutely an ongoing research concern, in which a large number of works have been addressed in distributed energy resource management and related privacy preservation [86-97]. But still, no standard process hierarchy along with analysis mechanisms are proposed that mitigate such types of challenging issues in the distribution transactions of energy resources. For instance, some data security and privacy preservation of energy technologies with blockchain are discussed as follows:

Related survey of data security and privacy preservation with blockchain

The collaboration of blockchain and AI with smart grid & power

Table 2
Systematic Review of Smart Grid Technology.

Categories	Years 2014 References [40]	2015 [41]	2016 [42]	2017 [43]	2018 [19]	2019 [28]	2020 [44]	2021 [45]	2022 [46]	Our Proposed Systematic Review Present Framework
Network Control and Management	✓		✓	✓		✓	✓	✓	✓	✓
Smart Relay	✓	✓			✓		✓	✓	✓	✓
Automated Feeder (for Switches)		✓		✓			✓		✓	✓
Smart Fault Indicators			✓	✓		✓		✓		✓
Voltage Regulator and Automation	✓	✓		✓	✓	✓			✓	✓
Load Tap Changer		✓	✓		✓		✓		✓	✓
Distributed Secure Monitoring Feeders	✓		✓		✓	✓	✓	✓		✓
Remote Transformer Management				✓	✓		✓		✓	✓

Table 3
Systematic Review of Power Distribution Automation.

Categories	Years 2014 References [51]	2015 [52]	2016 [53]	2017 [54]	2018 [55]	2019 [56]	2020 [57]	2021 [58]	2022 [59]	Our Proposed Systematic Review Present Framework
Interconnected Nodes and Automation	✓		✓			✓		✓	✓	✓
Energy Generation and Streamlining		✓		✓		✓	✓		✓	✓
Asset Optimization	✓	✓	✓			✓		✓	✓	✓
Power Distribution and System Management	✓	✓		✓	✓		✓	✓	✓	✓
Distributed Control and Monitoring					✓					✓
Secure Communication Network						✓				✓
Demand Optimization	✓	✓		✓	✓		✓		✓	✓
Product Certificate and Conformity Acceptance	✓		✓		✓		✓	✓	✓	✓

distribution is becoming a significant key solution for facilitating comprehensive privacy and security functionalities [98-100]. However, the adaptation of blockchain technology is envisioned almost all over the world, various organizations are moving towards the distributed ledger environment because of data security, privacy, and protection. The end-to-end encryption and due to the distributed transactional processor of blockchain schedule a process hierarchy of events of nodes transactions executions in a secure manner with low-cost guarantee [101-104]. In the domain of smart grid and energy trending, blockchain solves a number of complex matters of energy resources management, such as transparency and trustworthiness with the robust performance platform it provides while exchanging energy transactions running with the complex data over the distributed network. Chain codes are designed, creates, and deploy that exclude the need for manual approval, and construct an easy environment that monetizes distributed development of energy transfer and related connections flow of controls, energy-financial transactions, etc.

A smart grid with blockchain reduces the fraudulent related issues because a unique certificate is issued for achieving the generators as well as consumers. It creates trust between the node-to-node transactions for the energy trending. A Peer-to-Peer network handles all these requests for energy resource utilization and preserves them on the protected

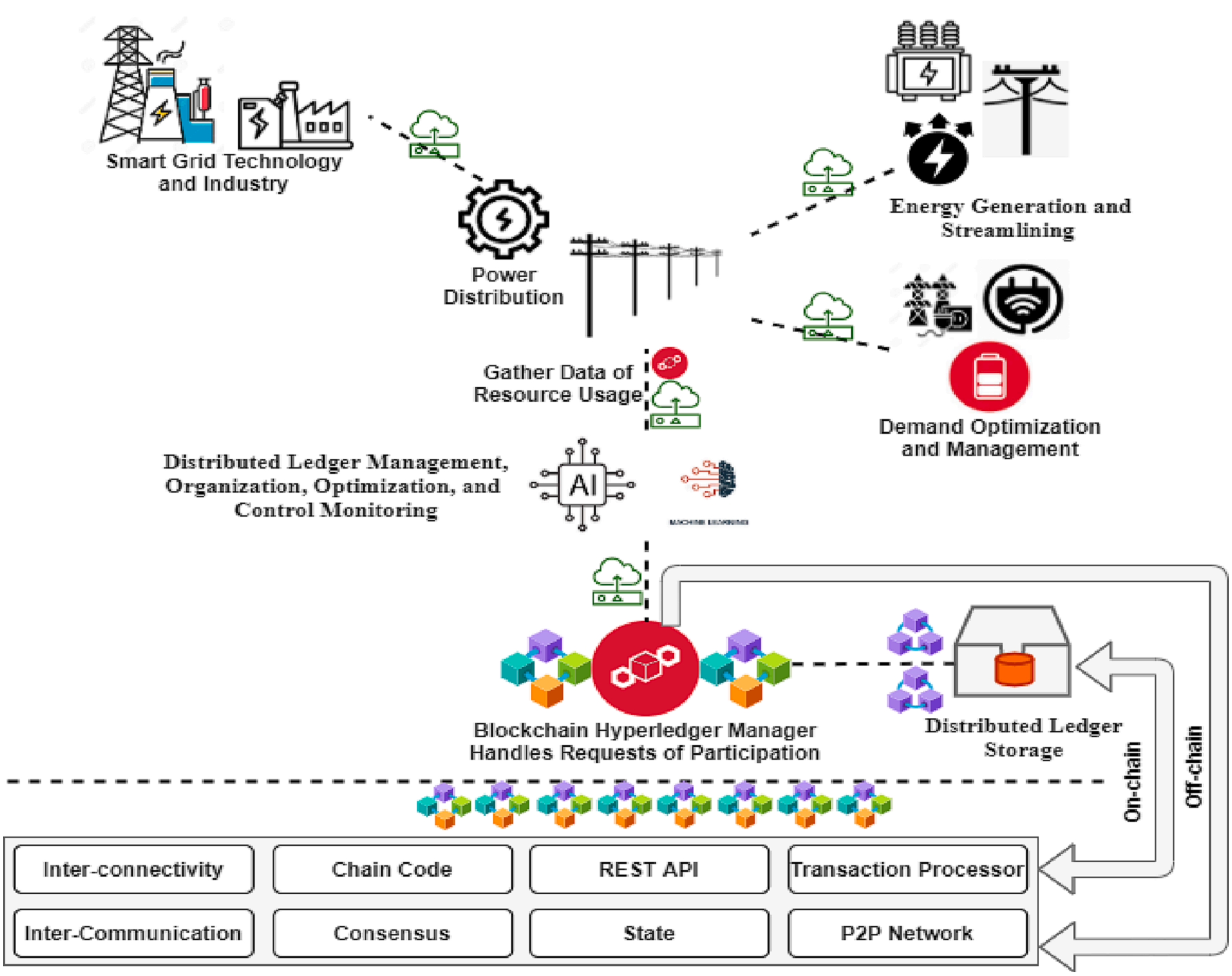

Fig. 3. Proposed B-PDA, A Blockchain Hyperledger and AI-enabled Distributed Framework.

immutable ledger, where all the copies are dispatched in the chain (a form of blocks) in chronological order over the distributed consortium network. Whereas all the nodes have interconnected that share the addresses and related information with the other participating devices.

In the current smart grid environment, there are various attacks involved that affects data integrity, confidentiality, transparency, provenance, dynamic monitoring, and control access are highlighted as follows [98-104]:

- Data availability attacks
- Control signal attacks
- Load redistribution attacks
- Measurement attacks
- Pricing attacks
- Control signal measurement attacks

A proposed integrated technological framework for secure smart grid and distributed power management automation

Fig. 3 presents a proper hierarchy of the proposed B-PDA, a blockchain hyperledger and AI-enabled framework for secure transactions executions of smart grid and related power distribution automation. In this B-PDA, a novel process hierarchy (lifecycle) is designed that collect request from the energy generation units to the consumer delivery. This lifecycle consists of collection (request of industrial units' generation), examination (generation to load management), analysis (load management), management (load balancer), organization (load balancer to power consumption), optimization (power resource management), distribution (energy dispatched), and billing (consumer usage). However, the proposed framework initiates operations when receiving data on energy generation using wireless sensor networks from the industrial units which associate with the smart grids, as shown in Fig. 3. In the middle, there is a power distribution unit deployed. The major objective of this unit is to manage load and reduce the cost of energy distribution; to do this, the B-PDA categorized the working operations into two different parts, such as energy generation and streamlining and demand optimization and management. Energy generation and streamlining manage the cost of power consumption and schedule in accordance with the defined demand of areas' usages. On the other side, demand optimization and management examine and analyze assets and demand of electric power usage continuously and optimize fluctuations by using AI-enabled machine learning-based artificial neural network (ANN) mechanism, as shown in Fig. 3. The mathematical expression of thresholding is: (threshold value for optimization = 1 if (the total number of assets and demand = to the weight >= optimize (down (0))) and if (the total number of assets and demand = to the weight <= optimize (Up (1)))). Basically, both the sub-folds of power distribution are dependent on each other.

With the integration of an AI-enabled machine learning-based mechanism (ANN), the B-PDA gathers data on resource usage constantly with the use of the B-PDA process hierarchy. The purpose is to maintain a process of distributed ledger management (such as information preservation and billing details), organization, optimization, and control monitoring in a secure and protected manner. Designing a proper structure of billing/usage of consumer end using AI machine learning is categorized into three subdomains, such as generation, load & distribution, and optimization & billing, as shown in Fig. 4. First, intelligent agents have deployed the handle requests of the smart grid and measure the usage while distributing energy resources. After the approval of the request by the agents, the power distribution units exchange resources with the distributed generators. The generators are generated energy according to the required demand, where the balancer manages the load and dispatch power to the consumer through buses and preserves the detail of dispatched in the designed blockchain-enabled immutable storage, as shown in Fig. 3. However, smart meters are deployed on the consumer end to calculate the usage of power consumption. These measurements are cross-checking the preserved details of dispatching and generate an authenticated bill (that reduces the cost of the additional charges in billing from both parties).

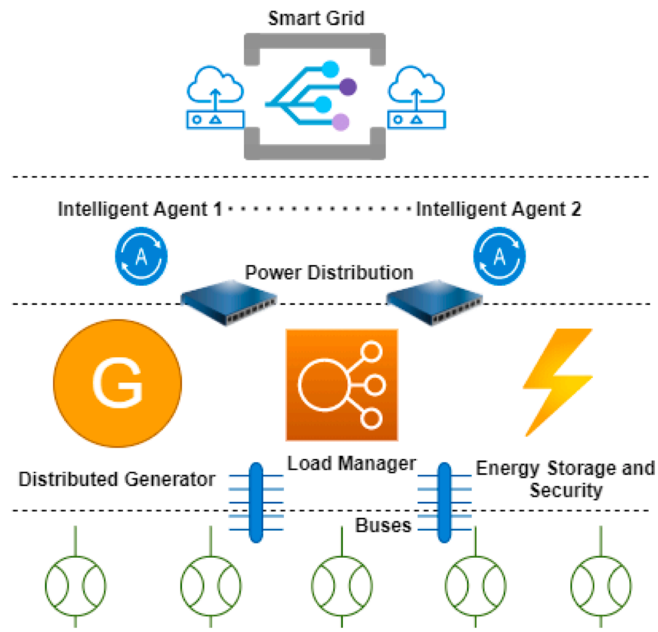

Fig. 4. Working Operation of B-PDA Smart Grid and Billing.

The remaining blockchain hyperledger-enabled objectives of the proposed B-PDA is discussed as follows:

1. **Distributed Peer-to-Peer Network:** In a P2P network, an ordering service of hyperledger initiates the proposal of smart grid-enabled transactions. Where the request is endorsed by the peer nodes on the designed distributed network for power distribution automation. The transactions of energy blocks contain details of generation, distribution, load management, and deliverance. And so, these transactions are submitted with a digital signature and protect the ledger using NuCypher proxy re-encryption to secure the peers for endorsement. It is then forwarded to the hyperledger orderer, exchanges details of ordering services to the committer, and records each activity in the blockchain immutable storage. Through the completion of this process, the details are shared with the committer on the hyperledger for validation. For this purpose, the KAFKA validation mechanism of blockchain hyperledger is used to verify with the help of defined consensus (PoS, PoW, etc.) protocols.
2. **Certificate Authority:** This proposed B-PDA presents a conceptual design of the B-PDA certificate authority (B-PDACA) network using hyperledger technology for creating a trusted stakeholder participation environment. After that, all these registered stakeholders are sent a request to the manager of power distribution only if they have a root certificate identifier. All rights reserved of B-PDACA goes to the Ministry of Renewable Energy and Water Management, which shared certificate authority with the state/city vice, that binds power distribution peers and orderer on its own. By allocating unique identifiers to the individual in the consortium network that mimic participating responses and initiate chain transactions and exchanges, which are signed by stakeholders' using the private key for ledger verification and using the public key for deliverance.
3. **Smart Contracts and Consensus Policies:** In the consortium network, different functions of chain codes are designed that enable transaction automation in an encrypted manner. The major purpose is to invoke individual blocks of transaction execution on the secure distributed network. It also handles the number of requests, schedules, manages, optimizes, and executes operations through the

DApp. However, the multi-proof-of-work and the proof-of-stack consensus are deployed that aim to reduce the workload by separating categories of the request into on-chain (handle implicit transactions) and off-chain (explicit transactions of the node) channels and executes (as mentioned in Table 4). In the designing of a consortium network, the multi-proof-of-work with proof-of-stack consensus mechanisms are collaborated with to handle both side transactions, such as public chain and private chain. According to pseudo-implementation (shown in Table 4, Fig. 5), it can perform better in terms of lightweight transaction executions with efficiency as compared to state-of-the-art consensuses, such as Proof of Elapsed Time (PoET). The PoET, a private permissioned consensus protocol based on a lottery system, enables events of node transactions to be executed in accordance with the schedule time-based randomly. The drawback of this consensus is that it only handles private transactions, which are used for enterprises' fully permissioned infrastructure.

Table 4
Pseudo-Implementation of Smart Contracts/Chaincodes.

Data Initialization: Design hierarchy of smart grid and power distribution automation (B-PDA) for data scheduling, managing, and preserving

Blockchain Manager responsible to build chain and initiate procedure of data exchange
Assumptions: Blockchain Manager is the responsible to grand permission to access ledger (only once)
Responsible for IoT-device registration
Verify and validate request of the participating stakeholders
Manage intercommunication and interconnectivity of nodes
Maintain data in the blockchain immutable storage (Filecoin)
Variable Declaration: File[z].x
int main():
device registration,
devReg();
user registration,
stkReg();
process hierarchy,
pHchy();
data collection,
dCol();
data exchange,
dExc();
data security,
dSec();
add new transaction details,
recLedger();
log preservation,
dataPreserve();
update record,
updExchange();
share updated detail and share,
shDetails();
Blockchain timestamp[run];
Smart Contract Execution Procedure:
if IoT device is not register:
then, add in devReg();
verify and validate (Only once);
after, check **if** participating stakeholder is not register:
then, add in stkReg();
else check error, update, change state, and share
terminate;
close;
if new node transactions!= recLedger():
protected with dSec();
and, executed as per pHchy();
then, exchange recorded details among the participants;
request of update transaction == updExchange():
as per multi-PoW and PoS policies: stkReg(devReg()), recLedger(dataPreserve()), and shDetails();
digital signature 51% vote;
shDetails();
else check error, update, change state, and share
stop;
close;
else check error, update, change state, and share
stop;
close;
Output: stkReg(devReg()), recLedger(dataPreserve()), and updExchange(shDetails())

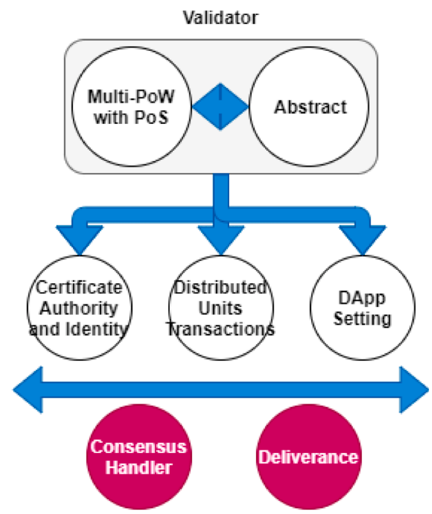

Fig. 5. Working Operation of the Proposed multi-PoW with PoS Consensus mechanims.

4. **Distributed Ledger Preservation and Hashing:** A block-based transaction is executed over the consortium network that separates requests according to the customized endorsed policies (as mentioned in Table 4) into the ordering and committer. It provides a sequential procedure for execution of transactions towards preservation (each log), such as managing new ledger/records that occur are stored in the Blockchain immutable storage (Filecoin) and updates. It protects every information travel in the chain of B-PDA using the NuCypher proxy re-encryption mechanism, which also enhances ledger integrity and confidentiality.
5. **Node Inter-Connectivity:** The proposed B-PDA restricts the direct path of transaction deliverance. It is because the transactions need to get approval from the manager of the power distribution ledger. To secure the channel, we design a consortium environment while using distinct channels of on-chain and off-chain. And so, it provides an interoperable platform that handles a number of inter-chain and outer-chain node-to-node communication. The information shared between nodes includes transaction details/logs, resource utilization, new participation, and an updated ledger, which is inaccessible directly to the participating stakeholders in the central network. It is one of the advantages to design an improved smart grid technology with distributed ledger infrastructure.

Open research issues and possible solution

In this section, we filtered various types of open research issues and challenges while integrating different technologies of information systems to build the strong infrastructure of smart grid and power distributions. For instance, there are several distributed frameworks, architectures, and methods proposed previously; that address power distribution and management-related features in the smart grid environment but a few yet remain addressed, which are discussed as follows:

Scope of distributed data privacy and streamlining

In the environment of the smart grid, there various critical problems emerge that impact directly power data management and distribution, one of the main is the automation of data registration and organization in the centralized server-based storage system with security. For instance, the data management of a centralized system is cost-efficient but there is no security and privacy to protect the ledger. While connecting to the nodes through the server networks, it required additional resources to transmit data in terms of bandwidth consumption. It is because of the load of the traffic of package transmission in a single dedicated channel. However, blockchain distributed ledger technology provides a secure environment, where data can travel from one end to the participating interconnected nodes in a distributed manner [105-109]. For instance, a blockchain hyperledger network is considered a costly related technology because of security scalability and distributed storage. Undoubtedly, the hyperledger-enabled modular infrastructure achieves integrity, transparency, provenance, and trustworthiness by constantly simulating distributed node transactions and incorporating energy-related data management logs. In this manner, the other participating stakeholders can get information about new transactions or any updates of the power distribution with a single touch regardless of whether to direct activities individually by the manager. Blockchain Sawtooth avoids third-party concerns to exchange the energy usage details with the consumers in the chain of a decentralized network.

Power distribution automation and compliance related problems

With the existing tools and techniques of smart grid-enabled power distribution creates different types of errors, including fault tolerance and automation, while the digital record preservation in the central storage relies on vendor-based solutions [107,108]. Substantially, there are various inappropriate applications used with portable Internet of Things (IoT) devices to collect readings of energy usage by the consumers and examine the fluctuation through different artificial intelligence-based machine learning techniques and dispatching bills via distributed network [109]. The competent authority needs to consider the collaboration mechanism while using the advantage of third-party solutions. It should be integrated before it follows the defined protocols of the ministry of sustainable energy and water management.

Node-to-Node intercommunication limitations

The traditional centralized server-enabled network management consumes more resources compared to the current decentralized network structure in terms of intercommunication costs between nodes and bandwidth usage. And so, there is the only way to exchange information and preserve logs in the client–server-based storage that leads to information leakage [105,106]. For instance, no proper way is presented previously that resists cyberattack and makes transactions of power distribution susceptible to alteration and tampering. This is because we need to collaborate with and update the standard of integration hierarchy for the third-part distributed storage, such as IPFS, Filecoin, etc. However, it connects with the hyperledger modular infrastructure that alleviates emerging challenges by providing a secure lifecycle. It includes power usage, examination, analysis, management, organization, and dispatch among the participating stakeholders automatically with the use of chain codes [107,108]. This complete procedure handles through the distributed application (DApp), which deploys various chain code operations (functions) that aid overall patterns of grid management in turn to the protected information delivering and exchanging, reducing resource consumption, privacy, and security.

Distributed billing and ledger preservation

Till now, there is not any standard structure presented that provides transparency between the power distribution manager and consumers in a distributed network environment. Blockchain Hyperledger cannot be able to provide standard individual predefined policies of data/billing transparency; if it required so, we could customize hyperledger procedure of data management and ledger optimization with tuned verification protocols of distributed storage. A consensus verification policy is also redesigned, such as proof-of-work (PoW), and proof-of-stack (PoS), that provide an efficient hierarchy of process execution and deliverance in terms of privacy protection and security. It allows for creating a modular infrastructure of data/billing storage, management, and dispatch in a transparent manner with possible traceability of records. By using blockchain with customized hyperledger consensus, platform modularity enables ecosystems to be tracked individual transactions of distributed billing and management at every step. It is possible because of the design and deployed chain codes of hyperledger, as shown in Table 3. This complete environment provides improved power distribution and billing/ledger management structure, which handles far better registries related processes with good results compared to other state-of-the-art methods.

Lack of standard and Regulatory-Related issues

There are various smart grid operations, such as power distribution and related automation contributing to the lack of regulatory standards for sustainable energy management and dispatching. The existing lifecycle associated with the process layer of the distributed network from generation to consumer feedback is inefficient and unreliable. As a result, an unavoidable impact on energy quality with their stability in transmission raises several cases that create consequences of power fluctuations and mismanagement [105-107]. However, by standardizing the power grid distribution processes, hyperledger modular infrastructure with an artificial neural network enforcing a standard approach and enhances the quality. And so, it improves the process of distribution, management, organization, and optimization of the final results [108,109].

Conclusion

This paper discusses the sequential enhancement in smart grid technology and its power distribution automation achieved in the past ten years (from more than a hundred research articles). In addition, the paper also addresses the unsolved problems of technology that need concern for technological maturity. Due to this, various state-of-the-art studies propose different prospects to improve power distribution automation; but to do this, distinct implementation challenges arise that impact the efficiency and effectiveness of the ecosystems are highlighted. Thus, a dynamic examination of interconnected nodes of stakeholders' devices during energy-related transmission in the distributed network is presented. However, security and privacy are the primary concerns while transmission. And so, details of processed data are recorded in the storage using the standardized process hierarchy of IoT technology and organized. In this paper, we propose a novel and secure blockchain-enabled artificial intelligence-based distributed modular framework for dynamic power distribution automation of smart grids, namely B-PDA. A consortium infrastructure of a Peer-to-Peer (P2P) network is designed to manage the process of private as well as public node transactions in a secure manner.

Through the procedure of distribution, this proposed structure handles inter-chain and outer-chain transactions using a blockchain hyperledger inter-communication strategy. For transaction protection, a NuCypher threshold proxy re-encryption is integrated with the designed framework that manages more efficient deliverance along acknowledgment. For instance, to automate transactions of nodes, pseudo-implementation of chain codes is presented, which aim to add a new consumer registry, transactions details of usage, updates about the rate fluctuation and billing, and dynamic monitoring. The multi-consensus protocols are associated with the chain codes to improve the process of data sharing and exchanging in the chain. And so, it alleviates the resource utilization of B-PDA in the P2P environment, such as multi-PoW and PoS for management, organization, and optimization. Finally, the adaptation of B-PDA in real-time is one of the better options for sustainable energy industries because it provides far more efficient data integrity, transparency, provenance, trustworthiness, and process execution platform compared to other state-of-the-art methods.

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Authors Contributions

- Abdullah Ayub Khan has written-original draft, prepared as-well-as organized this research paper,
- Abdullah Ayub Khan, Asif Ali Laghari, Mamoon Rashid, Hang Li, Abdul Rehman Javed, and Thippa Reddy Gadekallu have examined, analyzed, suggested, reviewed, rewrote, performed the survey and related literature analysis tasks, edited, investigated, hyperledger architectural designed, and explored various blockchain-enabling tools, artificial intelligence, and blockchain hyperledger technology.

All authors of the paper read and agreed to this published (online) version.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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