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Akka as a tool for modelling and managing a smart grid system

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Abstract. The article addresses big data processing challenges, fault tolerance, and consumer interaction in a smart grid network management system. It analyses the use of Akka for agent-based modelling of smart grid systems, which enables the creation of distributed, resilient systems that can efficiently scale and recover from failures. The article describes how the hierarchical structure of Akka actors can improve the management of disparate components within a smart grid system, allowing developers to create complex interaction and management models. The approach ensures multithreading and asynchronous operation, geographic distribution of management nodes, and enhanced system security, allowing the simulation of system hierarchy down to the level of the end device or user, which is crucial for overall system reliability.

Keywords: smart grid, Akka, agent modelling, hierarchical control system

1. Introduction

1.1. Smart grid development context and challenges

Smart grids integrate advanced technologies to enable two-way communication between energy providers and consumers, optimising resource usage, enhancing the quality of electricity supply, and improving the overall efficiency of the energy system. By using a comprehensive approach that combines monitoring and analytics, smart grids enable more accurate models for predicting and managing electricity demand, which is crucial for responding to society's changing energy needs [1, 13].

The core principles underlying the concept of smart grids are the decentralisation of electricity generation and the resilience of the energy network infrastructure. Decentralisation allows for integrating various renewable energy sources, such as solar panels and wind turbines, directly into the grid, reducing reliance on centralised energy generation sources. This approach [1] allows for a more precise description of the system's environmental impact, providing formal grounds for describing and formalising the structural elements of the network while enhancing overall resilience to external factors and ensuring reliable, uninterrupted electricity supply.

The structure of a smart grid represents a complex system integrating various energy sources, transmission and distribution subnetworks, consumer systems, and advanced management and monitoring systems. This integration optimises energy production, distribution, and consumption and supports society's sustainable energy future. The development of smart grid management systems faces several challenges, including integrating renewable energy sources, ensuring cybersecurity, handling

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large volumes of data, maintaining fault tolerance, and ensuring efficient consumer interaction.

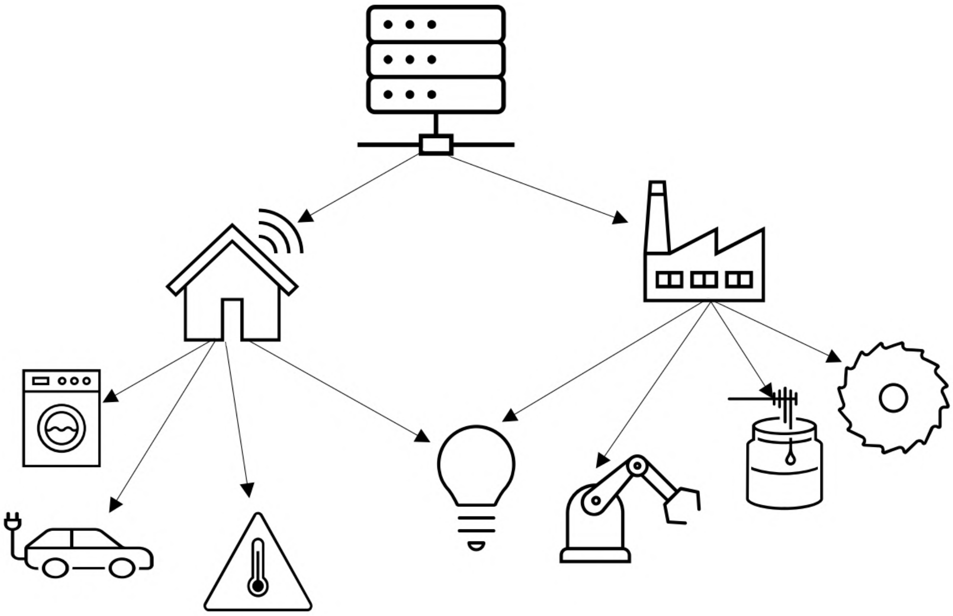

Figure 1: Sensors and actuators in a smart grid network.

The integration of diverse energy sources requires new approaches to managing energy flows. In contrast, the cybersecurity of individual control nodes and energy equipment is critical for protection against cyberattacks and unauthorised access. The vast amounts of data generated by smart grids require effective methods for collecting, storing, and analysing information. The need for high system reliability in emergencies imposes several constraints on the range of permissible management strategies. Therefore, developing interfaces and protocols for engaging consumers in demand management processes is a current challenge for optimising the use of energy resources. These features call for a comprehensive approach and innovative solutions to create effective and reliable smart grid management systems [1, 19].

For instance, renewable energy generation [6] requires complex coordination and seamless integration with existing energy network nodes to ensure the power supply stability. Therefore, control and monitoring systems play a crucial role in detecting and responding to changes in demand and supply [22].

1.2. Agent-based modelling with Akka

Agent-based modelling [23], as a computational model for representing entities as autonomous agents and simulating their interactions, can be applied to modelling smart grid networks. Agents may include end-users, individual parts of the power grid, subsystems, and the system as a whole. In intelligent networks, agent-based entities (such as suppliers, utilities, regulators, and consumers) often operate independently of one another, incorporating a significant portion of decision-making logic regarding further interaction with smart grid subsystems on their side. It is important to note that the object of interaction can also be represented as an agent with its state. Accordingly, agent-based modelling allows for formalising agents' autonomous behaviour, objectives, and interrelationships.

The asynchronous interaction of multiple agents within a smart electrical grid must be taken into account, as it is dynamic and influenced by environmental changes, electricity exchange processes, and the hierarchical ranking of micro-agents (individual consumers) and macro-agents (utility companies, regulators, etc.) and their social connections. This approach enables the exploration of societal influence on the energy sector and captures corresponding reactions to pricing and technical constraints.

Agent-based modelling can be used as a testbed for analysing new design approaches for smart grid networks, particularly in tasks such as system response to demand-supply changes and distributed energy generation [4, 24, 27, 31].

The Akka framework is well-suited for smart grid network modelling due to the following features:

1. Akka is built on the actor model, a mathematical framework for parallel computing. This enables the representation of asynchronous interactions between distributed network nodes through mathematical primitives and corresponding structural dependencies.
2. Akka operates with actors, which are universal, independent, and multi-level structural units within a hierarchical actor system. Each actor has its state and can be used to model any subject-object entities within the power grid and their interactions and relationships. Actors can only change their state, influencing the system indirectly through message exchanges, which require synchronisation based on state locking.
3. The actor system can integrate external information sources, such as sensors or switches, to assess and respond to environmental changes. The hierarchical nature of the actor system and its ability to encapsulate domain relationships independently from other actor system groups allow for physical distribution or replication of smart grid subsystems across different servers.
4. The actor messages do not have direct access to the state and behaviour of the actor object [2], allowing for parallelisation of processes that execute internal logic and minimising the impact of the internal state of an actor on the state of the entire actor system. This enables developers to abstract from the issue of competing threads while maintaining flexibility in modelling objects and entities within the power grid [16, 20].

1.3. Comparison with alternative technologies

While many existing technologies and frameworks can be applied to distributed system design, Akka offers a combination of particularly well-suited features for modelling and managing smart grid systems. In contrast to microservices-based approaches (e.g., Spring Cloud [21, 28]), which focus primarily on service orchestration and RESTful communication, Akka provides a native concurrency model through actors, which encapsulate state and behaviour, communicating exclusively via asynchronous message passing [8].

Distributed data platforms such as Hazelcast or communication frameworks like JGroups offer state sharing and group communication capabilities. Still, they lack built-in support for hierarchical actor supervision, fault isolation, and actor-level recovery strategies [15, 18]. Akka Cluster and Akka Sharding further enable physical distribution and elasticity in computation, which are essential for geographically dispersed smart grid control systems [2, 7].

In addition, autonomous agent platforms (e.g., JADE, Jason, Repast) typically lack the same level of integration with modern concurrency models. They may not offer direct support for the high-level abstractions needed for real-time system coordination [3, 10, 17]. The Akka Toolkit actor model is a conceptual and practical foundation for designing resilient distributed systems where each component is self-contained and fault-tolerant by design [2, 7].

Next, we will discuss the smart grid network modelling using Akka, specifically focusing on the actor model, actor systems, and their messaging interactions. The research question driving this work is: How effectively can an Akka-based actor model simulate and manage the dynamic interactions, scalability, and fault tolerance requirements of a distributed smart grid network? The objectives of this study are to evaluate the framework's performance in terms of scalability, resilience, and real-time self-balancing capabilities within simulated smart grid environments.

2. Akka as a tool for smart grid network modelling

The advantages described by Akka enable the design of distributed systems that can operate across multiple remote servers. This is crucial for smart grids, where numerous agents interact in real-time. Akka offers resilience by design: if one actor fails due to a critical error, this failure does not affect other actors in the system. An actor can recover its state after failures and utilise multithreading and asynchronous processes to optimise server resources. This is particularly important for handling large volumes of data, which can be represented as messages in a smart grid. One of Akka's key features is its scalability, allowing new actors – and consequently, new servers – to be added [2, 20].

The actor is an abstraction, allowing it to be implemented according to network requirements, without restricting software and hardware developers' tools by their choice. The abstraction of the model permits the operation of high-level concepts such as energy generation sources, power transmission methods, relays, end-users, and the interaction protocols of network nodes and subsystems.

The multi-level structure of the actor system allows for modelling individual physical entities and incorporating the properties of entire subsystems. These entities can include sensors that collect data on energy consumption and actuators that respond to changes in the energy system. Actuators receive messages from a central node or other actors and decide subsequent low-level control strategies.

Described components of the network, such as power plants and substations, can be reused and extended. This allows developers to standardise and formalise the structural interaction processes between different system nodes. Standardisation simplifies the integration and expansion processes of the power grid.

For accurate modelling of actor systems and smart grid networks, it is important to define parameters for components and subsystems such as:

- variable power output of power plants;
- active energy consumption by residential, industrial, and commercial facilities, considering peak loads at different times of the day;
- average active energy loss in distribution networks, particularly substations;
- impact and output values of individual nodes in the energy network during emergencies;
- physical and software-based forms of information transmission between actor nodes. It is necessary to predefine the types of command and information messages within the smart network and the criteria for energy transmission between its subsystems [12, 14].

The described components, in the form of hardware and software implementations based on actors, can be used to model an intelligent power system (figure 2) that meets specified requirements and follows the hierarchical distributed structure of the system as a taxonomy of actor groups and subgroups. These subgroups manage and coordinate the energy network in a specific region, locality, district, or household and allow for modelling the system's behaviour during non-standard inter-node interactions, such as emergencies.

In the next section, smart grid network management based on Akka will be discussed, considering the modelling features and limitations mentioned earlier in the article.

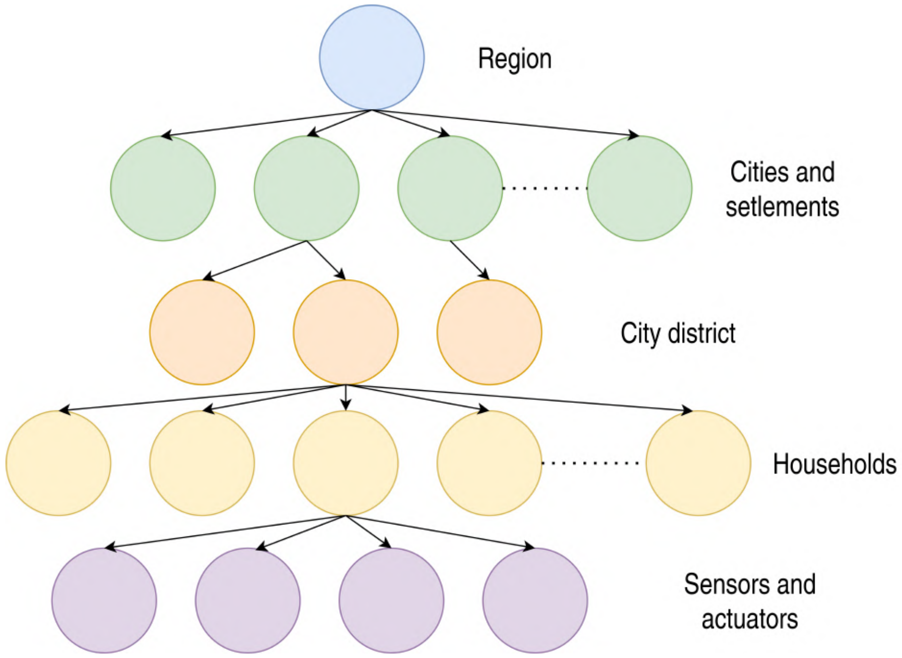

Figure 2: Hierarchical structure of actors in the smart grid system.

3. Akka as a tool for managing smart grid networks

While the previous section focuses on using Akka to model smart grid architectures and behaviours, these exact modelling mechanisms form the foundation for managing real-world smart grid networks. The actor-based architecture supports the simulation of network states and interactions and their deployment in live control systems. This dual use stems from Akka providing runtime constructs, such as fault-tolerant actors, supervision strategies, and distributed deployment, applicable in simulation environments and production-level smart grid management infrastructure. Thus, this section illustrates how these modelling principles are directly transferable to real-time system management. A similar modelling approach is used for managing smart grid systems. The hierarchy of smart grid management allows for the implementation of the following operations when assigning specific tasks to a group of actuators:

1. Prohibition of operation execution, followed by the substitution of the current management strategy with an alternative-type control strategy;
2. Authorisation for a group of actuators to execute an operation, with subsequent adjustment of results and consequences according to the current management strategy;
3. Postponement of the current operation while maintaining the existing management strategy until a decision is made regarding the prohibition or authorisation of the operation by the group of actuators.

This allows developers of smart grid systems to create complex models in which actors interact with each other, exchanging messages and coordinating their actions to ensure the optimal functioning of the energy network. The hierarchical structure of actor-based networks enhances the efficiency of controlling and managing smart grid system components at various levels.

Connecting households to the smart grid network increases the number of active sensors and actuators, generating a load on the accounting and management system. Temporary disconnections of certain nodes in the system may be used to enhance computational capacity and maintain specific subsystems. Loss of control by the management system over a portion of the network's subsystems is an emergency due to the critical nature of the electric power infrastructure. It is advisable to utilise Akka Cluster and Cluster Sharding technologies to prevent and mitigate the disconnection of part of the computational infrastructure [2, 16, 20]. These technologies allow for the placement or replication of actors from one node to another, redistributing and restructuring actor groupings in response to changes in the number of managing nodes, thereby managing the load on the control system by connecting and disconnecting nodes (figure 3).

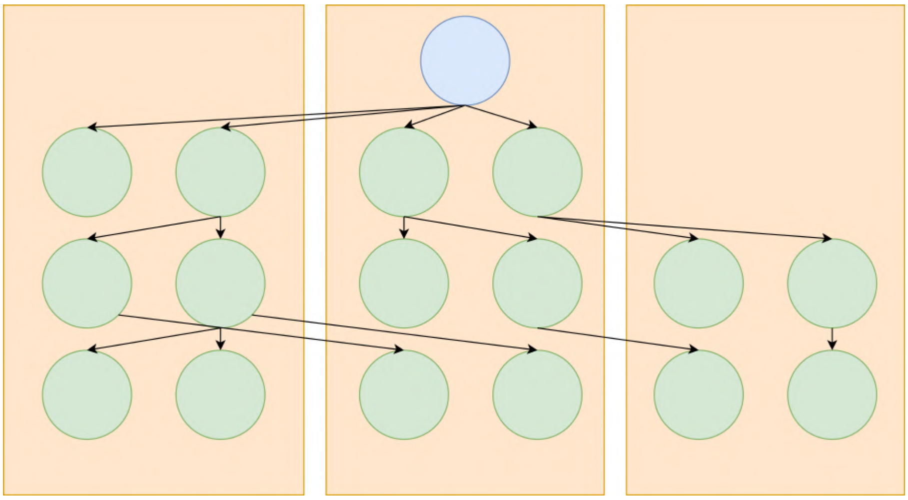

Figure 3: Distribution of actors in the Akka cluster.

With increased computational capacity for the control system, it becomes possible to dynamically integrate nodes into the network without system shutdowns, manual workload redistribution, or servicing individual nodes. This facilitates the manipulation of smart grid subsystems while minimising disruptions to the overall system.

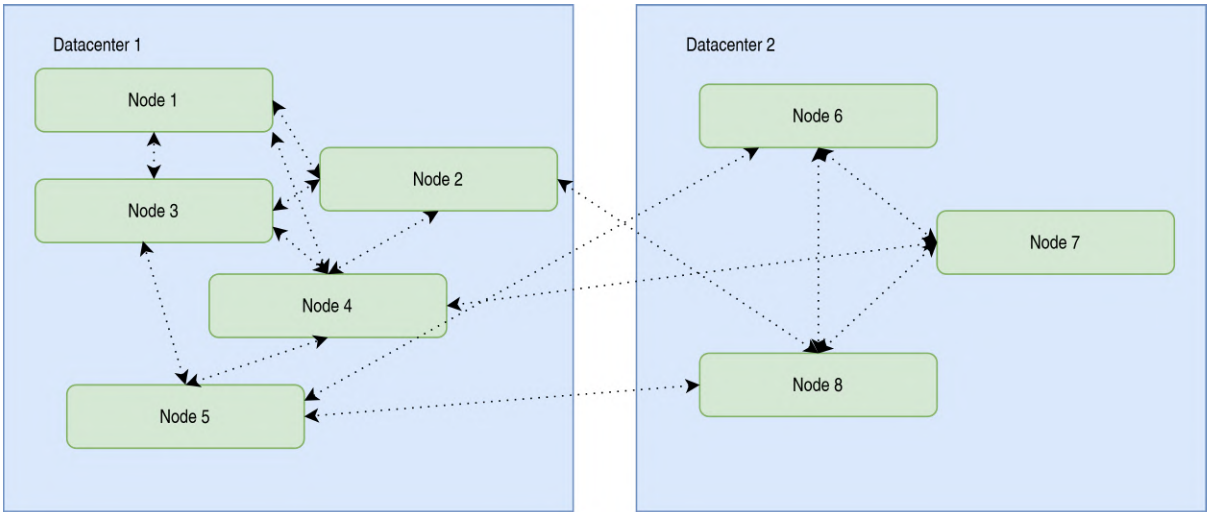

Figure 4: Schematic representation of communication among geographically distributed nodes in the smart grid control system based on Akka cluster.

The geographical distribution of the control system elements is critically important to ensure flexibility and resilience in the smart grid network. As well as to minimise the risk of system-wide failure. Akka Cluster, and more specifically its component – Multi-DC Cluster [2, 9] – enables the physical separation of control centres across different locations, thereby minimising the risk of simultaneous system outages (figure 4).

4. Simulation of self-balancing distributed electrical grids

4.1. Simulation Objectives and framework

For modelling purposes, the authors utilised Vigilant Hawk [26], an actor-based framework they developed using the Akka toolkit. Akka is the underlying actor-based runtime, offering concurrency and message delivery capabilities. In contrast, Vigilant Hawk encapsulates the domain-specific simulation logic, including actor behaviours, state management routines, and the coordination mechanisms essential for modelling decentralised smart grid environments. The framework facilitates modelling the asynchronous behaviour of distributed peer-to-peer smart grids, offering a generative nature and flexibility to represent the nodes of the distributed electrical network within the context of self-balancing mechanisms using the actor model.

The framework was designed to model clustered high-load systems, such as distributed electrical grids. In this framework, distributed electrical grid systems are modelled using CRDTs [25] to represent the states of cluster nodes. Using CRDTs provides eventual consistency without the need for coordination, helping to prevent bottlenecks and increase the efficiency of distributed systems. Each cluster node operates as an autonomous Akka actor, encapsulating its internal state [29] and interacting with other nodes solely through asynchronous message passing, avoiding execution blocking [5]. The actor concept allows for modelling each grid node, including generators, substations, and consumers. This actor-based isolation simplifies the management of mutable state and prevents shared memory contention, contributing to overall system robustness. The asynchronous communication model ensures that nodes remain responsive under load while waiting for external inputs or performing concurrent operations. Message handlers of actors process asynchronous events such as power demand shifts and redistribution decisions. Local state updates are processed independently by each node and disseminated via a distributed replication mechanism. The actor logic includes decision-making for energy redistribution, prioritising neighbouring nodes – typically influenced by spatial proximity – and handling transient failures. The simulation framework uses Akka's supervision model and built-in fault tolerance mechanisms to emulate node isolation and recovery scenarios. This decentralised approach ensures that state synchronisation emerges naturally, without centralised coordination.

The simulated cluster consists of electrical unit nodes, each identified by a unique region identifier. Each node also tracks its nominal and actual power, maintains two sets of identifiers for other units, and keeps records of electricity borrowed from and returned to these units. Each node is responsible for publishing changes to its state Replicator and reading updates from other nodes whenever changes occur.

Our experiment has 50 nodes, which we consider a typical number for households. Through an external influence, we increase the actual power in the observed node of the system so that its actual power is greater than the nominal, which requires borrowing power from a neighbouring node. We observe the state of the electrical grid as a whole over time from the perspective of a random node in the system as the grid balances itself (nodes experiencing a power shortage transition to a normal state by borrowing power from neighbouring nodes). Thus, we create a system-wide view from the perspective of a single node, allowing for the calculation of messaging based on dynamic distancing. The simulation results are illustrated in figure 5, with time zero marking the moment when all nodes achieve an initial state of balance. It is defined by the full synchronisation of system states and the efficient communication of state changes through transmissions (figure 5).

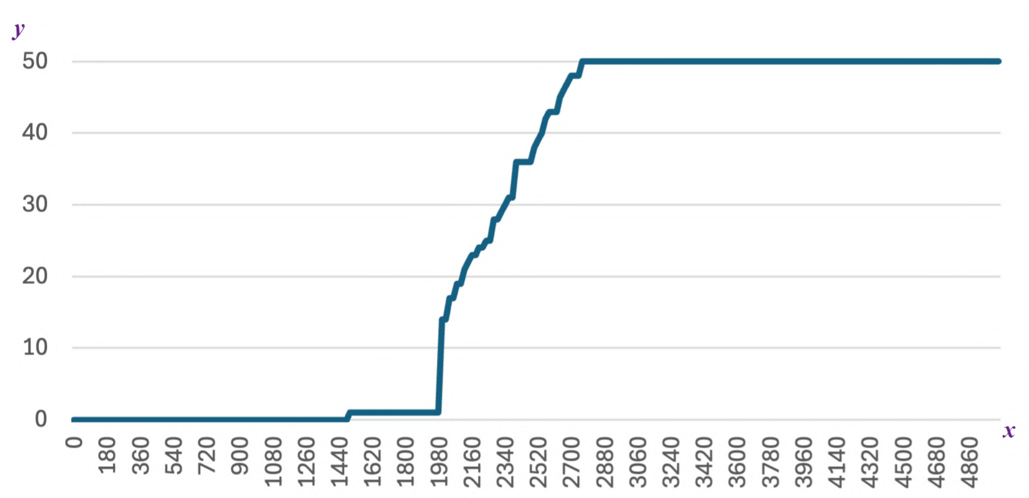

Figure 5: Simulation results of grid self-balancing.

In figure 5, on the x-axis, the number of nodes n (statically bounded) is presented, and on the y-axis, the time t in milliseconds.

During the preliminary phase, several alternative simulation scenarios were considered to evaluate the proposed actor-based system's robustness and adaptability.

One alternative scenario involved a uniform synchronous load change, where all nodes simultaneously increased their power consumption by the same amount. While this configuration created a clean and predictable test environment, it failed to introduce localised imbalances. As a result, the system did not experience demand-supply mismatches between nodes, meaning that key coordination mechanisms were not activated.

A second alternative introduced a randomised load distribution, in which nominal and actual power values were assigned stochastically across all nodes. Although this setup introduced variability and stress into the system, the resulting behaviour was difficult to interpret. In particular, it complicated the identification of causal relationships and made it challenging to assess the effectiveness of decentralised coordination.

The final selected scenario was designed to emulate a localised imbalance, in which one node exhibited a power deficit relative to its nominal capacity. In contrast, all other nodes remained in a stable state. This configuration was the most effective in demonstrating the model's essential capabilities – specifically, decentralised decision-making, efficient propagation of replicated state, and the system's ability to autonomously detect and respond to node-level power discrepancies without relying on centralised control.

4.2. Motivation for developing Vigilant Hawk

The development of the Vigilant Hawk framework was motivated by the need for a simulation tool capable of modelling large-scale, asynchronous, and self-balancing smart grid systems with high fidelity. Traditional discrete event simulation (DES) tools such as OMNeT++, AnyLogic, or Simulink offer powerful event scheduling mechanisms but often fall short in modelling concurrent, fault-tolerant, and distributed agent-based systems with real-time responsiveness [11, 30].

Unlike general-purpose simulators, Vigilant Hawk leverages Akka's actor model to represent each grid node as an isolated, concurrent entity with its own state, ensuring fault isolation and message-driven coordination. The integration of CRDTs further allows the system to achieve strong eventual consistency without centralised coordination. This combination makes Vigilant Hawk uniquely capable of simulating real-world dynamics such as dynamic node failures, asynchronous communication delays, and decentralised energy redistribution – all of which are critical for edge-oriented smart grid architectures.

5. Conclusions

Akka is a promising framework for modelling smart grid networks and developing corresponding management systems. It enables adding and removing network nodes without halting the management infrastructure during significant load increases. It provides the capability to geographically distribute the control system nodes at the physical level, thereby enhancing the resilience of accounting capabilities. The actor model underlying Akka allows for the simulation of the smart grid hierarchy down to the end-user level, representing individual components of the energy network (such as meters, actuators, etc.), subsystems, and the system as a whole in the form of actors.

Using the actor-based framework, leveraging the Akka toolkit, has proven advantageous in modelling smart grids' asynchronous and concurrent nature. The actor model's inherent support for scalability, fault tolerance, and high concurrency aligns well with the requirements of modern electrical grids, which are increasingly distributed and subjected to high loads. By encapsulating each grid node as an independent actor with isolated state management, we have minimised the risks associated with shared mutable states and have enhanced the system's resilience to node failures. The experimental results confirm that the Akka toolkit can effectively model and manage smart grid systems.

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Declaration on generative AI: The authors used ChatGPT-4o (OpenAI) and Grammarly to refine language and improve text clarity. They carefully reviewed, validated, and edited all content generated with these tools to ensure accuracy, consistency, and compliance with academic standards. No AI tools were used to generate scientific data, analysis, or results.

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