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Review and retrofitted architectures to form reliable smart microgrid networks for urban buildings

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Abstract: Smart microgrid initiatives for recent urbanisation at power distribution level need an integrated and interoperable environment that can work collectively with local energy systems and utility grid. This is achieved through the design of an architecture by using contemporary information and communication technology. System architecture provides a common work process that span across all the critical subsystems of a building for better informed decisions with reduced human interventions. Two key aspects of architecture development are, the way of its presentation and network reliability. The architecture should be clear in its presentation for the understanding of various stakeholders and possess fault tolerant communication mechanisms to have high network reliability. Considering aforementioned aspects, this study presents review of state-of-the-art architectures developed by IEEE-1547, ISA-95, National Institute of Standards and Technology, IEC-61850 for smart microgrids formation and suggests retrofitted architectures to improve architecture clarity by presenting in a more lucid way and network reliability by the concept of redundant communication paths.

1 Introduction

Buildings of industries, universities, special economic zones, etc., are emerging as the critical consumers in the power systems due to recent urbanisation. The management and engineering operations of these buildings typically include electrical (utility-grid/diesel-generators/renewables/building-loads), consumer operations, heating ventilation and air conditioning, etc. Systems designed for the control of those isolated units are independent with each other in view of architecture and/or control laws. Thus, absence of an integrated unit is a major challenge facing by building operations to deploy smart grid environment at power distribution level, named as 'smart microgrids'.

Smart microgrids are emerging recently that leads to the growth of the smart building electric power system (EPS) architecture using 'information and communication technology (ICT)' and 'automation and control philosophies'. It is almost impossible to manage a large industry to optimise its operations without automation solutions [1]. It mainly involves sensing instruments for tracking system variables (such as temperature, frequency, voltage, current, etc.) and take the control action based on the predefined logic. This activates the output elements such as actuators and human machine interface (HMI) for monitoring and control actions. All these units are integrated together and forms as a smart microgrid architecture [2].

The fundamental definition of a system architecture was given by IEEE-1471 as 'the fundamental organisation of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution' [3]. As per this, the description of any architecture is based on its topologies (or viewpoints) those specify a group of explicit concerns of interest to the specific set of stakeholders. The architecture shall also include the ways in which these concerns are conveyed and addressed. In brief, as shown in Fig. 1, an architecture should include the system models along with descriptions (procedures, principles and policies) and provide the feasibility of drawing various topologies to address different stakeholder concerns [4]. Two types of topologies can be drawn for any architecture, namely, physical topology that defines the physical outline of cables and equipment, and logical topology that defines how the data is transmitted from one module to another [5, 6].

1.1 Motivations and problem description

Based on IEEE-1471 architectural description, various architectures for the formation of smart microgrids are developed by IEEE-1547 [7], ISA-95 [8], National Institute of Standards and Technology (NIST) [9, 10], IEC-61850 [11, 12], etc., guidelines. These are continuously updating and does not limiting options for innovation to address new requirements, which provide more features to the consumers to encourage smart microgrids formations. Some of the key challenges yet to be addressed in these architectures, are given as follows [13].

1.1.1 Lack of awareness and clarity: Best practices and matured standards are available readily those can be applied to deploy smart grids at higher level. The main issue comes with the adoption of those standards for customer level at distribution systems. This require thorough awareness of those standards for the people involved in the deployment, operation, and maintenance of smart microgrids for buildings. Besides, different stakeholders are responsible for different parts of the system, and thereby, may understand the system incorrectly. Individually, they may make different choices about evolution and use. These challenges require a clear representation of the system architecture that can provide options to explore various viewpoints to ensure accurate understanding of the architecture for various stakeholders.

1.1.2 Technical challenges: From the technical point of view, the focus is required to manage the integration of new equipment that has a lower life span than system's traditionally installed assets. Similarly, interoperability of that new equipment and already installed equipment need to be addressed. The fundamental architecture for monitoring and information exchange in distribution systems was given by IEEE-1547.3. However, the data exchange between the distributed resource (DR) controller and equipment or entities internal to the local power system are not addressed. Besides, many potential paths for data exchange among various elements in the network, the requirements for

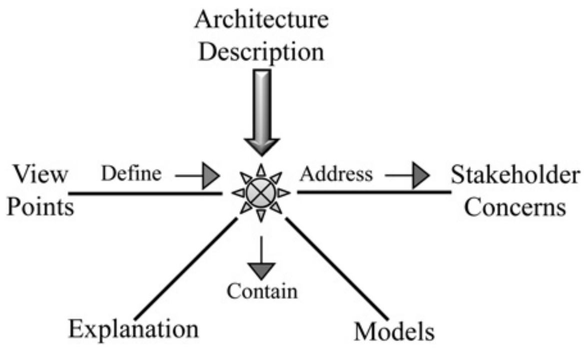

Fig. 1 *General description of a system architecture*

protection, safety, data reliability, and new asset interconnection are also yet to be addressed.

To address some of the aforementioned key concerns in state-of-the-art architectures for smart micrograms deployment, this paper suggests retrofitted architectures based on IEEE-1547 and IEC-61850 to improve the architecture clarity and network reliability. System modelling and simulations are carried out through OPNET tool to validate the reliability aspect of the proposed architecture.

1.2 Literature review

This section presents some of the attempts made in the literature for the development of smart distribution system architecture with the aspects of distribution management, network energy management, routing arrangements, data management, security requirements, functional and planning issues, monitoring and control, etc. This paper specifically focus on the aspects of architecture topologies to improve the clarity in its presentation based on IEEE-1547 and network reliability improvements based on IEC-61850.

Leite and Mantovani [14] presented the design and development of an architecture to simulate the smart distribution management system with seven layers of communication infrastructure. This system was useful to generate real-time power system scenarios at distribution level with a wide range of load demands that is ideal for developing new planning, operation, and control schemes. Parker *et al.* [15] presented an analytical method that quantify the overall utility function to optimise the packet probing rate to evaluate the delay and loss parameters of broadband networks. This is by considering all the measurements as numerical samples and are designed optimally by the use of statistical techniques. Wang *et al.* [16] presented an integrated control scheme to reduce the network energy consumption. This increase the efficiency of control information exchange among different network domains and introduced possibility for the implementation of different routing methods and control over quality of service. Kamrul *et al.* [17] presented a resilient routing arrangement called as smart failure insensitive routing to reduce key issues associated with slowness of routing convergence after a failure in network has occurred.

Ansari *et al.* [18] presented an embedded computing mathematical model using Monte–Carlo technique for the energy scheme performance evaluation. This estimates the network reliability and helps in maintaining network resiliency over duty-cycle protocol effects. Various initiatives for the design of smartgrid networks were presented in [19–21]. Data-centric building management system design that use named data networking and information-centric networking architecture was presented in [19]. Communication technologies and issues presented in their execution including gateway deployment, network topology, routing algorithms, and security were explained in [20]. Major challenges for their deployment including compatibility design, security assurance, timeliness management, and cognitive spectrum access were also discussed. The security requirements for the smartgrid communication networks were identified and presented novel mechanisms to meet those requirements [21].

Sidhu *et al.* [22] presented the fundamental features of IEC-61850 in terms of functional hierarchy, communication architecture, and process. The challenges for the development of new communication architectures and possible solutions, by addressing the functional and planning issues in overall substation were presented. Similarly, a comprehensive survey of the critical networking challenges presented in the design of smartgrid communication networks and routing protocols, various technologies and architectures to address these challenges were described in [23]. Reddy *et al.* [24] presented an architecture for the real-time modelling of the renewable or alternative energy based hybrid energy system formations at power distribution level using commercial off the shelf components such as programmable logic controller (PLC) and supervisory control and data acquisition (SCADA). This improves system fidelity and real time control capabilities. Madureira *et al.* [25] presented a hierarchical decentralised management and control architecture for electrical distribution system. This architecture provides the advanced functionalities such as voltage control coordination between the low and medium voltage sides, and exploiting distributed generation abilities with traditional voltage control methods.

Architectures for a smart house to develop smartgrids at distribution level were further discussed in [26]. Lopez *et al.* [27] presented a monitoring system architecture to achieve energy efficiency in the neighbourhood of a distribution power system infrastructure. This is integrated using machine-to-machine based platform and is being developed under the European project ENERsip. The development of hardware and software modules and the validation of the system was also outlined. Portela *et al.* [28] presented an ICT architecture to develop smartgrids at power distribution level. It defines the security and privacy enhancing measures applied to consumer's business operations. This system enables demand side management for residential houses. Liu *et al.* [29] presented the design of a smartgrid architecture with two distinct accountable communication protocols for both home area network and neighbourhood area network. Further, renewable energy based microgrids design with the schemes for the optimisation of units, system sizing, energy transactions, and control were described in [30–32].

1.3 Organisation of the paper

The rest of the paper is organised as follows. Section 2 gives the description of state-of-the-art conventional architectures available for the integration of DRs to form smart microgrids, Section 3 gives the description of proposed retrofitted architectures for the integration of DRs to form smart microgrids, Section 4 gives the modelling and simulations for the validation of proposed retrofitted IEC-61850 architecture, followed by simulation results presented in Section 5 and concluding comments presented in Section 6. The limitations and future scope are given in Section 7.

2 Conventional architectures for the integration of DRs to form smart microgrids

This section provides the description about conventional state-of-the-art architectures developed by various international forums namely, IEEE, ISA, NIST, and IEC for the formation of smart power systems.

2.1 IEEE-1547 architecture description

IEEE-1547.3-2007/1547.4-2011 architecture is mainly concerned with MIC ('Monitoring, Information exchange, and Control') among the DR controllers and outside environment. However, the methods and concepts shall be useful to designers and developers of communication systems for energy management system (EMS), EPS, SCADA, loads, protection, and revenue metering. In general,

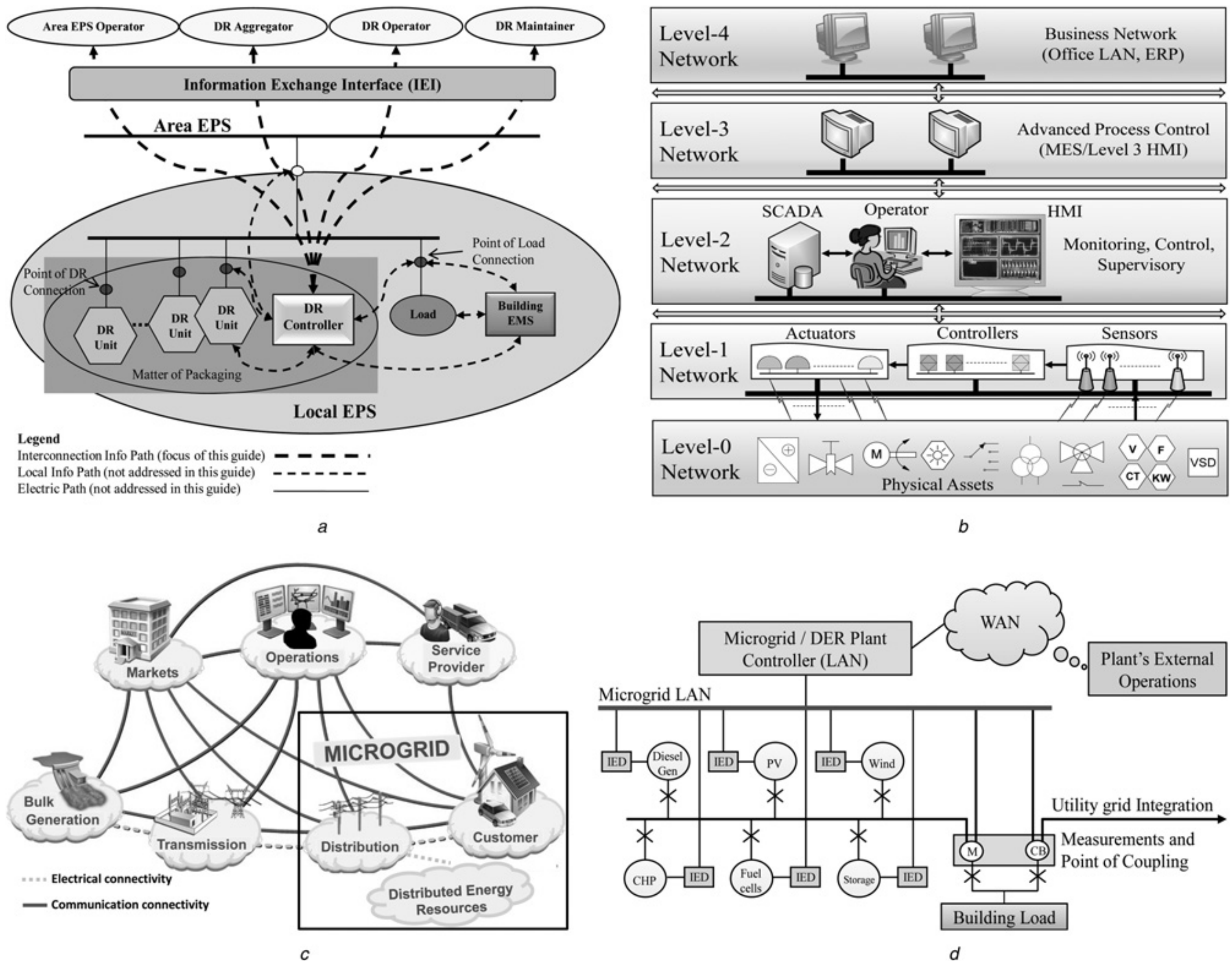

Fig. 2 *Smart distribution system architectures*

a IEEE-1547.3 architecture
b ISA-95 architecture
c NIST architecture
d IEC-61850 architecture

the architecture for MIC of DRs is proposed to assist the interoperability of DRs and help DR stakeholders to implement MIC to support business and technical operations and transactions between stakeholders. The architecture design is mainly to denote the possible implantation of a system with various topologies [33, 34]. Also, the new DRs introduces new controllers, systems to the already existing automation system, and both these new and existing systems shall communicate with each other for reliable and safe EPS operation. IEEE-1547 provide use-case methodology and examples (DR unit scheduling, dispatch, ancillary services, maintenance, and reactive supply) rather than addressing the technical or economic viability of specific types of DRs [7]. Fig. 2*a* provides IEEE-1547 architecture for MIC of DR interconnection.

In Fig. 2*a*, upper ovals (area EPS operator, DR aggregator, DR operator, and DR maintainer) denotes the stakeholder roles, who needs information exchange with DR system, to know about its inter-connection with that local EPS. Hexagons denote the DR units. There might be one or more DR elements at the site, but, there should be at least one controller that can perform control and monitoring function. The DR systems and controllers can be installed in various configurations. The controller has the intelligence to collaborate with site equipment and stakeholders. These may be packaged separately or together depending on the manufacturer business policy and client's requirements. The bottom small oval denotes a load. Some loads may have local facility EMS controller to optimise their operations. An intelligent building's facility controller 'EMS' is denoted with rectangle. This collaborates with DR operator to ensure proper interaction between DR controller and EMS. Electrical and communication connections are represented by solid and dashed lines respectively. The information exchange interface represents information exchange equivalent to 'point of common coupling' in electrical system.

2.2 ISA-95 architecture description

ISA-95 is an international guideline for the integration of control systems and enterprise. It is used to determine which information

Table 1 Network levels of ISA-95 architecture

Network level	Functionality
Level_0	Defining the actual physical production process.
Level_1	Defining activities involved in manipulating and sensing the physical process.
Level_2	Defining the activities of controlling and monitoring the physical processes.
Level_3	Defining the work flow activities to produce the estimated end products.
Level_4	Defining the activities that are related to the business and its management.

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Table 2 Brief description of 7-domains of NIST smartgrid model

Domain	Actors	Interface	Primary purpose
Bulk generation	Generators, storage devices.	Operations, markets, and transmission domains.	Electricity generation from various other energies like nuclear fission to chemical combustion, wind, solar, geothermal heat, water, etc.
Transmission	RTUs, relays, AMIs, PMUs, power quality & fault recorders, HMIs.	Operations, markets, bulk generation, and distribution domains.	Bulk transmission of stable electrical power from generation to distribution domains through various substations. Operated by regional transmission operator.
Distribution	Capacitor banks, reclosers, sectionalisers, storage devices, relays.	Operations, markets, transmission, and customer domains	Reliability of the distribution domain is to be improved with the usage of advanced facilities like, distributed generation, storage, demand response, and load control.
Customer	AMI, communication gateway, electric vehicles, etc.	Operations, markets, service provider, and distribution domains	Providing communication for devices in customer premises using HANs to enable them to manage the energy generation and usage.
Markets	DERs and aggregators.	Generation, transmission, distribution, customers, operations, and service providers.	To perform pricing or balancing demand and supply for the smooth operation of the power system.
Operations	DER operators	Generation, transmission, distribution, customers, markets, and service providers.	To do network operation, control, monitoring, fault management, operation statistics, feedback analysis, and training for dispatchers.
Service provider	Organisations that provide services to electrical utilities and customers.	Customers, markets, and operations.	To perform various tasks to support the business process of power system generation, distribution, customers. Enhancing customer services in home energy generation/ management for enabling economic growth.

is to be exchanged among systems for finance, sales, logistics and the systems for production, quality, and maintenance [8, 35, 36]. ISA calls an industrial network as 'manufacturing and control system' and defines it as the combination of hardware and software systems like distributed control system (DCS), SCADA, PLC, sensing instruments, monitoring and diagnostics along with associated human interface, control network, safety, manufacturing process functionality to continuous, batch, discrete, processes [37]. It is recommended to isolate business network from industrial network via a firewall, to limit the access, and provide security from outside cyber-attacks. Industrial network is further divided into multiple sub-networks mainly to reduce unwanted network traffic in critical control network and enhance the speed of response by reducing the network latency. Although, industrial best practices recommend isolating industrial and business networks, integration of these networks yield several benefits. Based on these aspects, ISA-95 developed a network architecture described as follows.

ISA-95 recommends different levels of networks as described in Fig. 2*b* and Table 1 to achieve better integration of business to industrial network for optimum plant operation without compromising security. DCS/PLC forms the Level-1 and Level-2 networks. These two networks are combined together and called as 'process control network (PCN)'. Level-3 and Level-4 are combined and known as 'plant information network'. Protocols used for establishing PCN are AS-interface (Actuator Sensor Interface, AS-i), DeviceNet, Ethernet Industrial Protocol (EtherNet/IP), and Foundation Fieldbus H_1, H_2, and HSE. From the security and quality of service perspective, Level-3 network must be isolated from Level-2 by a router. The nodes that usually reside at Level-3 network are advanced process control, domain controller, applications, advanced alarming etc. Level-3 is used for managing manufacturing operations like production scheduling, tracking, dispatch etc. Level-4 is for business logistics management.

2.3 Modified NIST architecture involving microgrids

Under 'Energy Independence and Security Act' in 2007 [38], the NIST, has to coordinate smartgrid framework development that includes model standards and protocols for the information management to realise interoperability of system and devices [9]. This helps in identifying the actors and possible communication paths in the smartgrid [10]. The joint committee of CENELEC (European Committee for Electrotechnical Standardisation), European Committee for Standardisation, and European Telecommunications Standards Institute developed a smartgrid architecture that includes microgrids as shown in Fig. 2*c* by modifying the fundamental NIST model [39, 40]. The main difference between the two models is specialised in the way of distributed energy resource (DER) usage (Section 6.3.3. of [40]). It describes the contribution of 7-domains (markets, operations, service providers, generation, transmission, distribution, and customers) in the overall smartgrid operation as given in Table 2.

The customer domain is segregated with 3-types of consumers namely, domestic (<20 kW), commercial (20–200 kW), and industrial (>200 kW). Due to recent urbanisation era, the industrial and commercial consumers are increasing vastly and thereby creating huge burden on the utility grid. To reduce this burden, many decentralised microgrids are being formed at distribution level across the world. With the availability of contemporary technologies, the networks for distribution are now built with extensive control and monitoring devices, interconnections, and DERs for generating and storing power. Besides, the progress of recent communication gateways enable features like control and monitoring of local generation, remote control, in-house display for usage, data logging, interfacing with building management system.

2.4 IEC-61850 architecture description

The communication technologies for the integration of intelligent electronic devices (IEDs), HMI, and other engineering applications in a substation automation network has moved from proprietary to the open standard based architectures. With this intent, IEC-61850 standard was developed along with a customisation to substation automation on already existing energy and commercially available communication guideline such as IEEE-802.2/802.3 and OSI/ISO layers [41]. It enables interoperability of IEDs in the substation network. It also provides an easy way to interface various systems that can provide facility for remote and local control, substation and equipment health monitoring, protection, and asset management. It is an open, flexible, and future proofing standard that supports communication between devices in power distribution and transmission systems [12, 42]. Fig. 2*d* represents the architecture of DER based microgrid [43]. The system is developed with IEDs that support IEC-61850 communication. IEDs constitute logic node (LN) and device (LD) that communicates for data exchange [44].

The IED communication layers are shown in Fig. 3 [45]. The type-4 raw data samples and generic object oriented substation events-GOOSE (block, trip, interlock, etc.) messages (type-1, 1A) are time critical and hence, they are directly drawn to Ethernet layer. It gives the benefit of improved performance over real time messages by shortening the Ethernet frame as there is no upper layer protocol overheads and reduces the processing time. Medium speed message of type-2, command message of type-7), low speed

Layer	Channel				
Application	Client-Server MMS protocol suite	Time synchronization GSSE	GOOSE	Link redundancy module	Raw data samples
Transport	TCP	UDP			
Network	IP				
Link	Ethernet (IEC/ISO 8802-3)				
Physical	Physical medium (fiber optics, twisted-pair copper, coaxial cable)				

Fig. 3 *IEC-61850 layers in communication architecture*

message of type-3, and the file transfer tasks of type-5 are denoted as client-server communications and assigned to manufacturing message specification (MMS) protocol suits. MMS and generic substation state events (GSSE) has TCP/IP stack before the Ethernet layer. Server-client communication exchanges the information such as event record, fault records, measured value, etc. Type-6 time synchronisation messages are communicated to all IEDs in the substation by UDP/IP.

3 Proposed retrofitted architectures for the integration of DRs to form smart microgrids

As described in Section 1, the proposed retrofitted architectures focus on the following two aspects.

• Topologies to improve the clarity of presentation and understanding of IEEE-1547 architecture.
• Redundant architecture to improve the network reliability of IEC-61850 architecture.

3.1 Proposed topologies for IEEE-1547.3 architecture

As per IEEE-1471, the explanation of any architecture hinges over the idea of topology or viewpoint, which specifies a group of explicit concerns of interest to the specific set of stakeholders, and the ways in which these concerns were conveyed and addressed. The fundamental architecture for MIC of DRs was given by IEEE-1547.3. However, the following points were not addressed in the guideline.

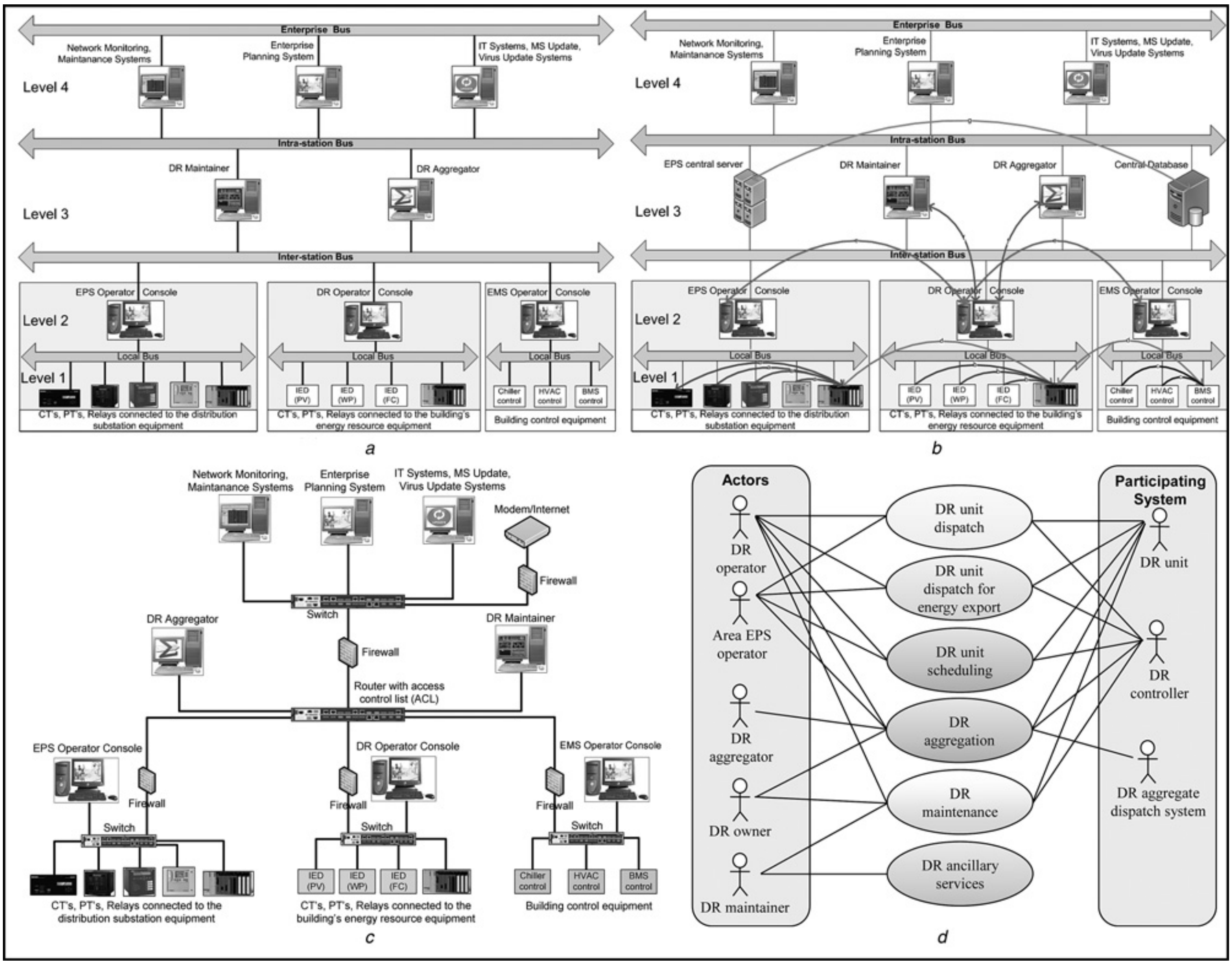

Fig. 4 *Proposed topologies for IEEE-1547.3*

a Conceptual topology
b Concurrent topology
c Network topology
d Requirements topology

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- The data exchange between the DR controller and equipment or entities internal to the local EPS.
- Guidelines for the development of specific viewpoints and paths for data exchange.
- Requirements for protection, safety, interconnection, or local and area EPS operation functions.

Keeping aforementioned constraints in view, and as a solution for the critical concerns, this paper proposes conceptual, concurrent, network, and requirements topologies as shown in Fig. 4, to improve the clarity and understanding for various stakeholders about IEEE-1547 architecture. A large number of models can potentially be employed in these topologies, but each centres around one or a small number of models that gives the essential character of the topology.

3.1.1 Conceptual topology: Conceptual topology represents decomposition of the system into number of subsystems that gives most basic description of the system. This expresses the system architecture in terms of arrangement of all its critical components and their connectivity. This helps to ensure that all the key components and functionalities have been considered by the architect team. These components are chosen so as to meet domain level responsibilities and ensure that the conceptual model remains rooted in problem domain from which the system requirements are drawn. Fig. 4*a* shows the conceptual model of a smart building power system that is developed based on the hierarchical arrangement of all its internal components.

3.1.2 Concurrent topology: Concurrent topology shown in Fig. 4*b* expresses the run-time structure of the system in terms of concurrently executing components. The models in this topology range from high-level and coarse-grained subsystems, down to detailed threading models. A thorough treatment of the system architecture in concurrent topology ensure that the key issues in DRs such as, performance, robustness, and scalability are addressed. This topology mainly outlines, what are the devices/ systems that are to be operated in parallel.

3.1.3 Network topology: The network topology shows the overall system positioning relative to typical modern software development life cycle. Proposed network topology for a smart distribution system is shown in Fig. 4*c*. This topology mainly helps to systems and networks people in the building operations to understand the connectivity between in-house devices that helps in design of building's local area network.

3.1.4 Requirements topology: The requirements topology gives the system requirements and context in a manner that highlights and focuses attention on the architecturally significant requirements. Specific use cases, quality attributes, and architectural risks are called out and explored during the process of creating requirements topology. Fig. 4*d* shows the requirements topology use-case representation, where, it represents the interactions of external actors and system components. This captures and refines the important requirements that serves for the architecture shaping. This works as the two-way model, where the architecture is tested with the requirements and/or the requirements are updated as per the architecture. Regularly, non-functional requirements are supposed to shape the system architecture. This is true to a great extent as specified requirements in some points such as performance, scalability, reliability, capacity and security can have significant impact on the system structure along with the other constraints such as limitations on cost, development skills, feasibility, etc.

3.2 Proposed retrofitted IEC-61850 architecture

Substation automation networks are increasingly installed with the devices adhering to IEC-61850 communication standards. Substation equipment are considered as critical infrastructure, and hence the expectation on the availability is high. This high levels of availability in substations are usually required for the electronic and communication devices. As per the nature of the application, the communication latency of the substation events shall be very high based on the criticality of information carried in the network. IEC-61850 communication is based on Ethernet and hence carries some disadvantages like very fast switchover and recovery in the event of link/switch failures and its inability to deliver an appropriate redundancy at physical network and link level. Communication redundancy is required in IEC-61850 scenario especially in the aspects of system protection. The failure to transfer a command from one protection unit to another may lead to catastrophic failure that may turn into equipment burning.

IEC 61850-7-420 guideline on 'communication systems and networks for power utility automation for DERs' gives a foundation for conceptual organisation of DER logical nodes and devices and information modelling. It recommends that the protection systems and DER controllers should be tightly coupled with electrical connection point at the load and circuit breakers. Hence, the expectation on the communication system is to deliver a packet within 4 ms. Hence, to improve the availability of the system, it is proposed to design a redundant path for the communication. The redundancy can be developed at the device (IED) level and/or link (network) level. This paper introduces the link level redundancy into the IEC-61850 conceptual organisation of the microgrid. Again, link level redundancy in the network can be realised either by having redundant media (with single IP and MAC, but with two media links) or redundant ports (IED with redundant IP and MAC and with redundant network interfaces). Fig. 5*a* shows the retrofitted IEC-61850 architecture for improving the network reliability in smart distribution systems. This paper simulates redundant port type communications to achieve the redundancy.

3.2.1 Procedure for link failure detection: The failure detection in the network is carried through the observation of diagnostic packets. Each IED sends diagnostic packets periodically through both (normal and redundant) interfaces to the other IEDs. Each of these packet is assigned with a sequence number. Each IED observes these diagnostic packets received from the peer IEDs in the network and discard the duplicate diagnostic packets generated based on the sequence number. A packet missing at any point of time from any interface denotes the failure of the link/ network. IED compares the current sequence number of the packet with previous number. If the difference between any two sequence numbers is more than the threshold value, then the failure of the link is declared. The corresponding time taken ($T_{\rm fd}$) for fault detection is calculated based on (1). $T_{\rm fd}$ is the interval between the instant at which a failure happened and the instant at which a fault is detected.

$$T_{\rm fd} = (2 + T_{\rm th,max}) \times T_{\rm pul} + T_{\rm prodelay} + T_{\rm Pvariation} \quad (\sec) \qquad (1)$$

where, $T_{\rm th,max}$ is maximum threshold that indicates maximum number of successive diagnostic packets lost over any one interface. $T_{\rm pul}$ is pulse interval that indicates time interval denoting how often an IED need to send a packet message out on its interface. $T_{\rm Pvariation}$ and $T_{\rm prodelay}$ are the configuration parameters specific to the network.

4 Modelling and simulation for the validation of proposed retrofitted IEC-61850 architecture

Redundant links provide alternative communication paths for IEDs. With this feature, the networks can be developed such that no single communication link from/to the LDs within that network. This can also facilitates for continuous access and monitoring of communication paths among various IEDs. The link failures are caused by the failure of various components in communication subsystems. Each IED that participate in the network can detect faults and can take the corrective measure based on those failures.

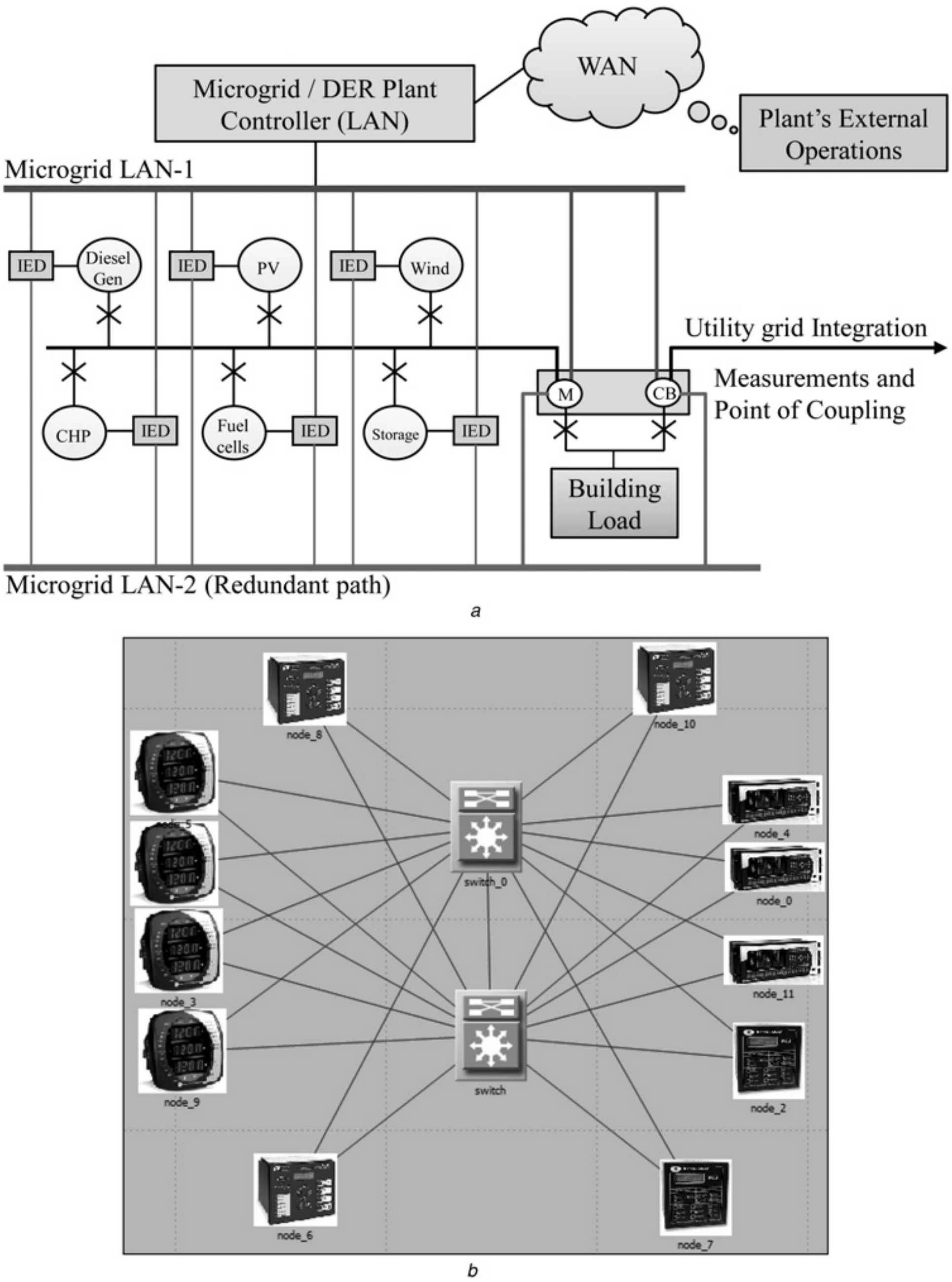

Fig. 5 *Retrofitted IEC-61850 architecture*

a Conceptual organisation
b OPNET simulation model

This failure detection and recovery is handled by each IED rather than by some centralisation. Hence, it is required for each IED to publish link's status periodically to all other IEDs in the network. Therefore, all the participated IEDs can get knowledge about all other IEDs. This information helps to identify alternate paths in the case of communication link failures.

OPNET modeller is used to analyse the effectiveness of the proposed architecture over link failures in the network. It provides three levels of models namely, network, node, and process models connected in a hierarchy [46, 47]. The network model is developed by the combination of various nodes and each node model is developed with the combination of various process models.

Fig. 5*b* shows the network model of the retrofitted IEC-61850. The simulation is done with the consideration of 12 IEDs interfaced via two different switches in redundant fashion. The IEDs in the network represents the LNs of DRs such as energy sources, protection equipment, meters, remote terminal units (RTUs), etc. For the simulation purpose, the system model inside all IEDs is deliberated as similar even though the LNs, LDs, etc., specifications may vary in real systems.

IED node is modelled with the application that provides the IED MMS services. These are developed in process 'data_srv' of Fig. 6 and simulates the server-client based environment. Link redundancy module (LRM) shown in Fig. 7 is to generate GOOSE packets and publish in the network. Diagnostic packets are created and sent to all registered nodes. The LRM is designed with child process models and is invoked at run time. This is responsible for transmitting the diagnostic packets in the network and maintaining the link status list.

Link failure model is designed as shown in Fig. 8. This model fails randomly selected links with the user inputs such as start time, stop time, and repetition time. Link status list model shown in Fig. 9 gets initialised and starts publishing the packets. This is updated with the sequence number and threshold.

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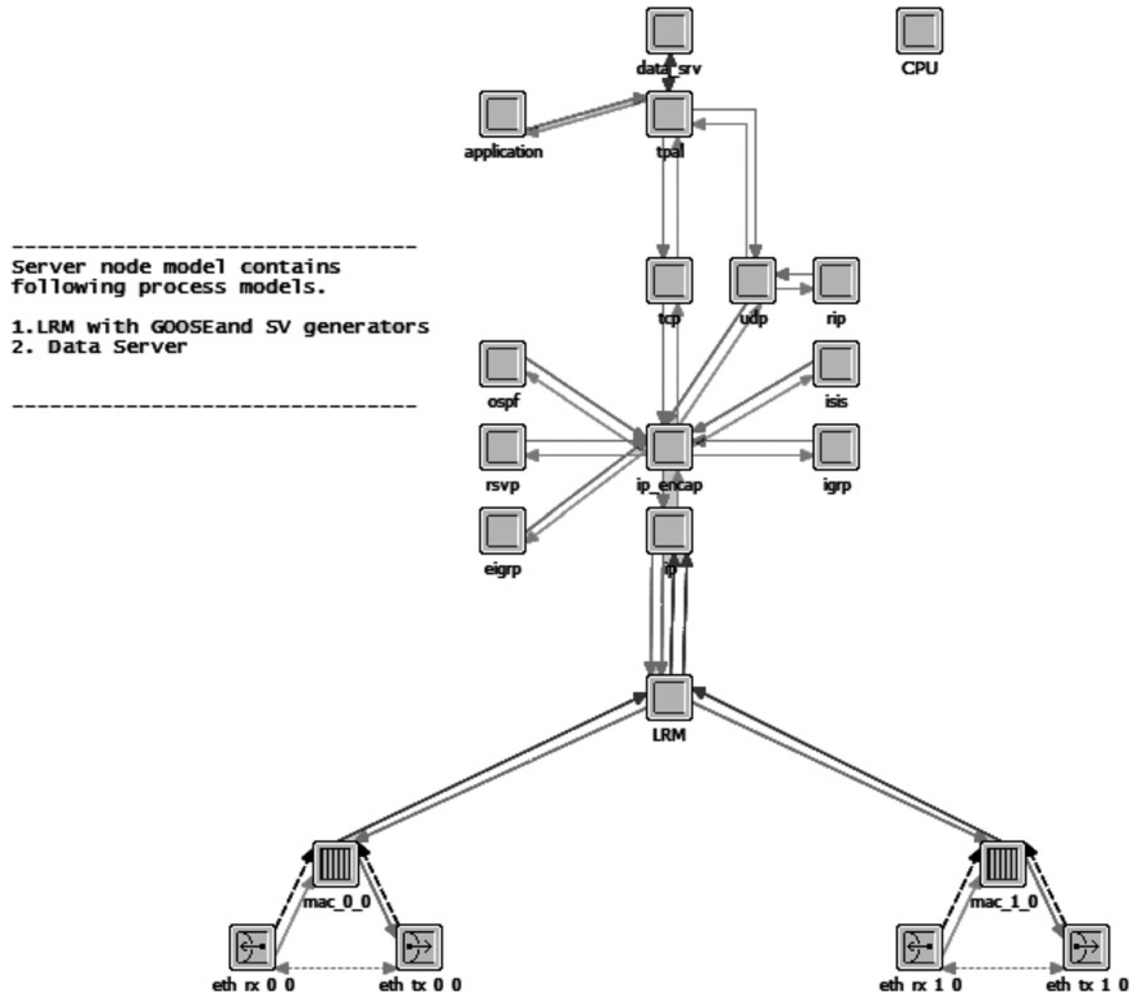

Fig. 6 *Simulation model of an IED node in the network*

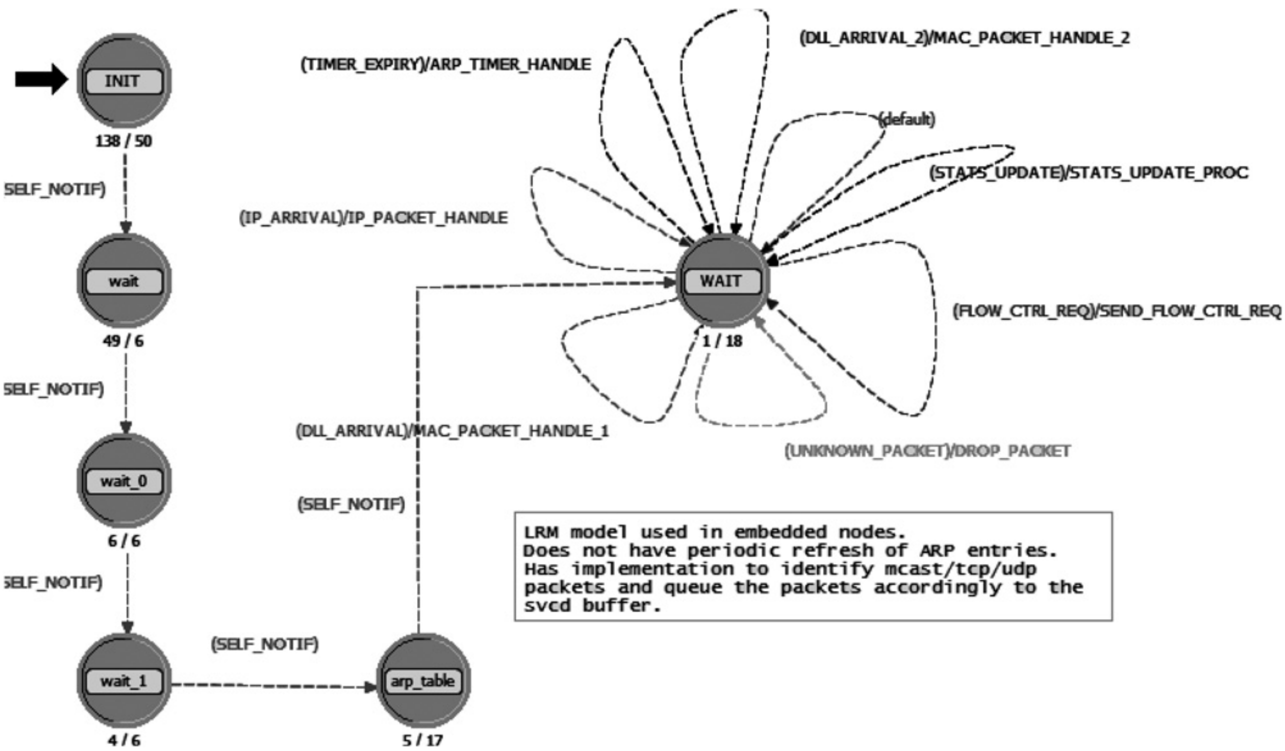

Fig. 7 *Simulation model of LRM and GOOSE process model*

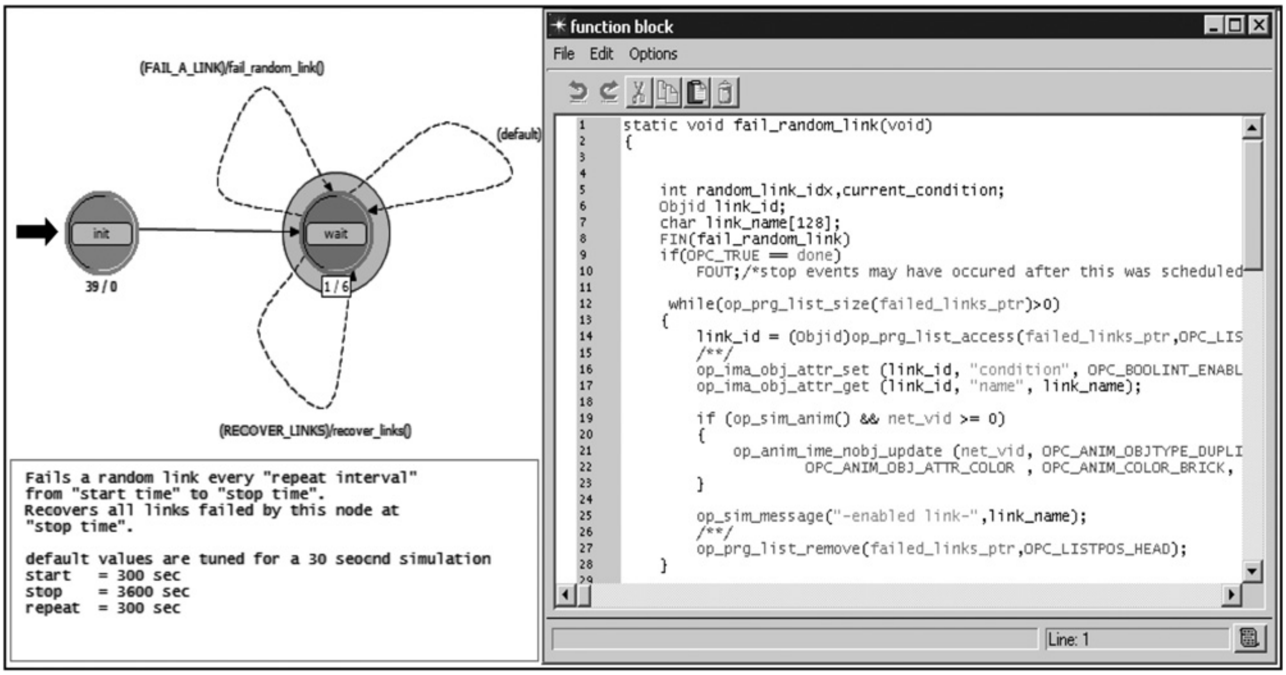

Fig. 8 *Simulation model of link failure process model*

5 Simulation results

Fig. 10*a* represents the response of the continuous traffic sent by one IED and received at another IED. The link failure is denoted in the second trend from top of the diagram. This link failure immediately pushes the IED to transmit the communication via other switch. Therefore, as shown in the third trend, a sudden rise in the traffic can be seen at second switch. The send and received traffic can be observed from top and bottom trends. It can be observed that there is no loss in the traffic even though there is a link failure.

The results of the random link failure simulations are shown in Fig. 10*b*. Albeit, random link failure unit performs concurrently with other units, for illustration of the functionality, the results are separately shown. Fig. 10*b* has the trends of the communication between the links. Deep valleys in the result specifies the link failures. The top trend specifies the link failure occurred at port 1 (A) of IED1. The first failure happened at around 900th s for the interval of 300 s. The second failure happened at 2000th s for the interval of 600 s within the total simulation of 3600 s duration. A similar failure is applied in same simulation period across different links in different timings.

Behaviour of the network under multiple link failures is indicated in Fig. 10*c*. The system is capable of providing the alternative communication paths for some faults and the failure is unavoidable if the faults are more or equal to 2. However, the network recovers immediately after the link recovery. From the result, it is observed that there is no further delay for the communication recovery after the link recovery.

The results represented in Fig. 10*d* are similar to the results represented in Fig. 10*c*, with a difference to show the packet drops. The packet drops are measured for various link failures and found there is no packet drop in case of single failure. It is seen in the event of both link failures namely, random link failures and as well as multiple link failures are considered.

6 Conclusions

In this paper, various topologies and architectures for the design of smart microgrids at power distribution systems are elucidated. The selection of any topology or architecture is based on the customer requirements and the complexity of the system. The study started with the analysis of state-of-the-art architectures available for the

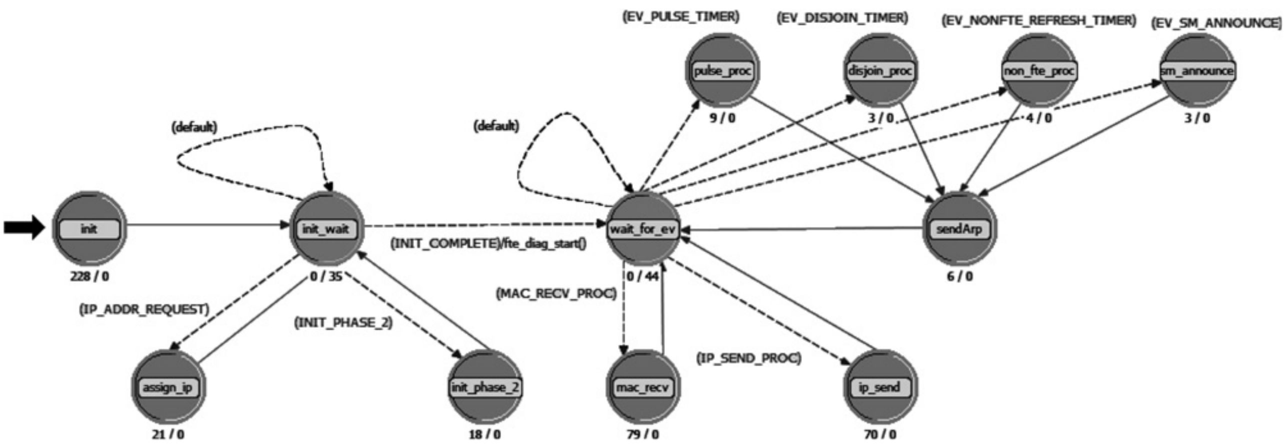

Fig. 9 *Simulation model of link status list process model*

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integration of DRs to form smart microgrids and presented the concerns yet to be resolved in those architectures. To augment the fundamental architectures developed by IEEE-1547 and IEC-61850, this paper suggested retrofitted architectures to improve the clarity in the architecture presentation for the understanding of various stakeholders and network reliability through redundant communication concepts. The cumulative merits of the proposed concepts in this paper are given as follows.

- Various important topologies namely, conceptual topology, concurrent topology, network topology, and requirements topology are derived. These can help in understanding IEEE-1547.3 guideline easily from the point of view of various stakeholders of the distribution system.
- From the simulation results shown in Fig. 10, it is observed that the system reliability was improved with the proposed network model under multiple and random link failures. Hence, the

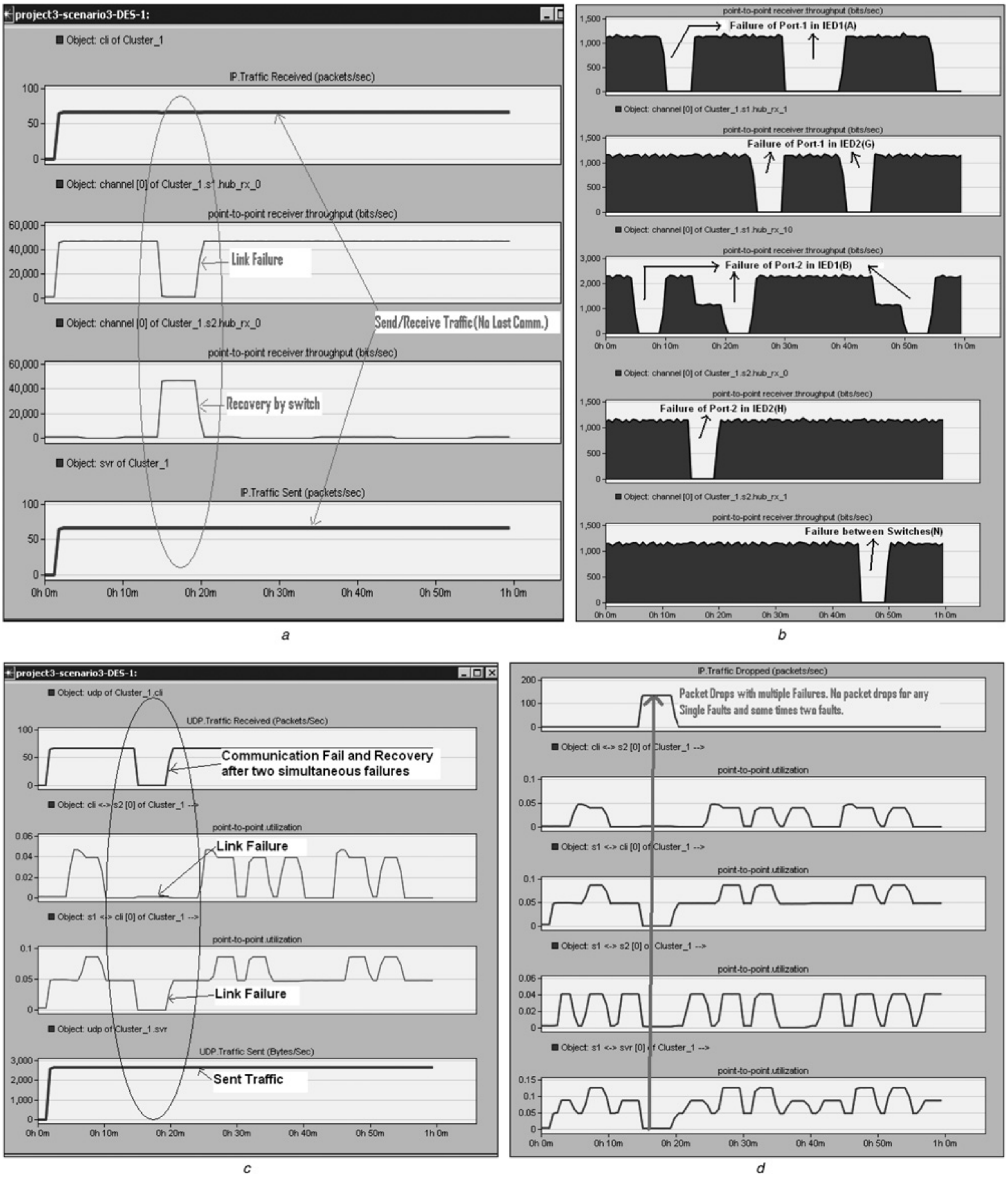

Fig. 10 *Simulation results of*

a Link fault recovery
b Random link failures simulation
c Fault recovery from multiple failures
d Packet drops due to multiple link failures

redundancy concepts found to be suitable for improving IEC-61850 architecture to tolerate the communication link failures. This improves overall system availability while tolerating certain faults in the network without reducing or degrading the functional behaviour of the IEDs.

Hence, these architectures helps in development of reliant smart microgrids for the buildings by increasing the system availability and thereby reducing the human supervisions. This facilitates the distribution systems to remotely monitor and control its assets continuously. This can further helps in effective utilisation of available resources and thereby reduces the utility grid dependency.

7 Limitations and future scope

Besides, the aforementioned advantages of the suggested concepts in this paper, it may have the following limitations and can be revised in the future with similar aspects.

• It requires 2 copies of diagnostic packets, one for the data communication, and another is to check that the directly connected link is down or not. Alternative methods can be identified to develop same functionality of the system with single copy of diagnostic packet.

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