A Modeling Approach for Dependability Analysis of Smart Distribution Grids

Tesfaye Amare, Bjarne E. Helvik, Poul E. Heegaard
Information Security and Communication Technology
NTNU – Norwegian University of Science and Technology, Trondheim, Norway
Email: tesfayez, bjarne, poulh@ntnu.no

***Abstract*—The distribution grids are among the most critical infrastructures which integrates advanced control and communication technologies atop of power systems. This paper presents a comprehensive modeling framework suited to study the resiliency and dependability of the next generation distribution grid. It focuses on revealing insight in the complex interaction and dependencies between the ICT based control system and the power-grid. It looks into the role of automation and new technologies in future distribution grids. The objective is through a quantitative assessment to identify vulnerabilities and to study alternative design principles and architecture of the automated distribution grids. The modeling framework is general and modular based on a stochastic activity networks using the Mobius tool. For illustration, a case study is included at the end.**

I. INTRODUCTION

Smart distribution grid is a modern electric power infrastructure which integrates advanced control and communication technologies in power systems. It is among the most critical infrastructure which can be considered as a system of systems. More ICT-based control system is about to be introduced. Architectural changes such as the deployment of multiple micro-grids within the distribution grid has been also increasingly introduced into the distribution grid. The micro-grids with their own local controllers continually interact to each other and they are also capable of operating independently during some situations. There will be strong interdependencies between the power grid and the ICT based support system. As a result, the resulting quality (performance and dependability) for an end-user is demanding to assess.

This paper aims to presenting a modeling framework that is suited to study the resiliency and dependability of the 'next generation' distribution grid. The main focus is to include the complex interaction and dependencies between the ICT based control system and the physical grid (sub)systems. The intended use, beyond performing a quantitative assessment, is to identify vulnerabilities, provide insight which may guide design principles and architectures of the automated distribution grids.

Significant previous work have been carried out towards this objective, mostly by simulation. However, Menasch and others have presented a Markov model taking into account into account the dependency of the communication infrastructure during power lines failures [1], [2], [3]. A limitation of the analytical approach is the ability to include a wide range of ICT and power components, as well as the dynamic and structural complexity of such systems. Most simulation studies do either put emphasis on i) the ICT based control infrastructure [4], [5], [5], [6], [7], [8], [9], [10], e.g., focusing on cyber attacks [8], [9] or an SDN driven ICT infrastructure on top of the power grid [10], [11], or on ii) the power dynamics [12], [13], [14], [15], [16]. However, there will be a strong coupling and dependence between communication and control systems and power grid that may induce large scale failures due to cascading effects as discussed in [17], [18]. Hence, it is important to establish a comprehensive modeling framework of the structure and the mutual dynamics of both (sub)systems.

Buldyrev, Gao & al. addresses these issues using a point to point interdependency models where a power node fails if the communication node associated to it fails and vice versa [19], [20]. More recent papers by Parandehgheibi & al. [21], [22], though focusing on specific scenarios, showed that 'point-wise' failure model is not appropriate.

Chiaradonna & al. [14], [15], [16] presented a compositional stochastic modeling framework for distribution grid with a focus on dependencies between the control and the physical grid. Though the paper presented a generic model, it still doesn't provide an equal emphasis on the two (sub)systems. It concentrates more on modeling the detail behavior/dynamics of the power grid by capturing system states using Power, Current and Voltage values.

The framework proposed in this paper has a simpler abstraction of the physical grid, but with an extended emphasis on modeling the failure processes and dynamics on the communication and control infrastructure. This approach is chosen for scalability and for modeling new emerging technologies, operational and architectural changes and automation in the distribution grid.

The remainder of this paper is organized as follows. Sect. II presents the smart distribution grid layout comprising the ICT support system and physical grid with the generic assumptions considered. Sect. III introduces the proposed Modeling framework. Then, in Sect. IV a case study scenario showing the effect of automation and introduction of new technologies in fault identification, location and service restoration of distribution grids is presented with an illustration of simulation result. Finally, Section V gives the conclusive remarks and future works.

II. SYSTEM DESCRIPTION

This section describes the main components, operational behaviors of the distribution grid and some major assumptions considered in the modelling framework. A distribution grid that consists of a physical grid with typical voltage levels below 33 kV and an advanced ICT based support system to enhance its operation is considered.

A. System Topology

The framework is generic and flexible. A distributed architecture consisting micro-grids, a centralized controller architecture with one controller at the substation, or a combination of the two can be used. An example is shown in Figure 11 which provides an overview of cyber-physical distribution grid used for the case study in section IV. The grid can be viewed as consisting of two planes; the physical grid and the ICT based control system. It is assumed that power flow is bidirectional where power can flow from the substation to the customer side and vice versa. The physical grid consists the following main components:

- Feeders: Medium and Low voltage power lines carrying power between substation and customers.
- Substation unit/Generator: main source of energy to the distribution grid. This is used to model the power supply from the transmission grid.
- Distributed Generators: locally installed energy supply to the distribution grid. These are used to model locally controlled renewable, flexible energy source such as wind turbine and solar panels.
- Transformers: used to step up/down voltage.

The plane on top of the physical grid is the ICT based support system. It mainly consists:

- Controllers: These can be a central controller at the substation responsible for an overall monitoring and management of the distribution grid or a local controller monitoring local components in a distributed control architecture.
- Sensors: devices such as Merging Units that are used to monitor and transmit information to control units e.g., controllers and Protection IEDs.
- Actuators: devices such as switches and isolators that are used to regulate (connect and disconnect) power grid components eg. feeders.
- Protection IEDs: devices such as relays installed on the power lines which are assumed to take measures during a failure in the physical grid. These devices are assumed to exchange information among each other and make a decision based on the information received from sensors.
- Smart meters: used to monitor and control customer side equipments and power usage for e.g., during demand response negotiation.

The sensors, control and protection devices are connected to local controllers through a wide area network as the operator often needs to have a full control on the quality of the communication for operational activities involving these devices. Meanwhile, customer side devices (Smart meters) can also be assumed to be connected to a controller through the Internet for scalability reasons as well as for the fact that there are no stringent requirements for operations involving customers such as demand response.

B. Outline of System Behaviour

The major principles and operational behaviours mainly related to failure process and service restoration showing the interdependency between the ICT based control system and the physical grid are discussed below.

All components from both the ICT based control system and the physical grid could fail permanently from random accidental faults which needs to be repaired by a maintenance crew. In addition to the permanent failures, temporary failures are also considered for some ICT based components such as protection IEDs/relays. Though it is not included on this paper, the framework is also suitable to consider simultaneous/weather related failures as well as malicious attacks. For controllers, considering some functionalities to be added due to the introduction of new ICT based components, software failures are also taken into account where a simple restart could neutralize it or it could end up as a permanent failure. The failure processes for all components is assumed to be a Poissonian process. In this study, omission type of failure semantics are considered on both (sub)systems. The framework is also easily extendable for considering other failure semantics such as value and timing failure semantics.

Once a failure occur in a physical grid component, the fault isolation and detection is dependent on the state of associated ICT based component. If the ICT based component is working, it will neutralize/isolate it safely followed by controllers locating the fault and handling the service restoration. Otherwise, if the responsible ICT components are not working, the failure is assumed to propagate failing neighbour power lines (could be up to substation unit) which covers a relatively larger section of the grid unless the ICT components in neighbour lines are in a working state to isolate the failed component.

When a component from the ICT based infrastructure fails, it won't have an immediate consequence on the physical grid. However, their failure will propagate to the physical grid if there is a need to use the failed ICT infrastructure before it get repaired.

After detection of a failure, the controller is responsible for reconfiguration of the grid topology, redistribution of power and updating system state. Distributed generators can be used as a backup during failure restoration. Besides, load shedding as well as demand response (i.e. negotiating with customers to lower their demand) can also be considered if there is a shortage of power supply.

A limited repair resource is considered where there is one maintenance crew at the (sub)systems. For physical grid components, the repair process comprises time to locate the failure which highly depends on the availability of ICT infrastructure during the failure and time needed for handling the maintenance.

III. MODELING FRAMEWORK

A Stochastic activity network model [23] is developed to study the Smart distribution grid. The model is developed using the Mobius tool [24]. It is a general and composable stochastic model, which is built from atomic block models.

One template, an atomic model, is developed for each type of components in the distribution grid. An example is shown in Figure 1. An instance for each of the components is then created using an indexed extended places in the atomic models. This is similar to the concept of colored tokens where the movement of one token represent a behavior of one component. Extended places are special elements in the SAN formalism that allows the model to handle the representation of structures and arrays of primitive data-types(places) [24]. Each position (place) in this array contains a certain number of tokens, and the state of one component is determined by the number of tokens (marking) in a given position of the extended places.

An atomic model, say a Protection IED, learns about the state of other atomic models such as the feeder through the unconnected places as shown at the top of Figure 1. These extended places are shared among two or more atomic models and are used to model the dependencies and interconnection between components as discussed in section III-C and section III-D. Input gates are used to control the enabling of activities while Output gates are used to define the marking changes that will occur when an activity completes. An Output gate changing the marking in the shared extended places is used to communicate information among atomic models. The overall distribution grid is modelled by connecting the atomic sub-models using a 'Join' composed model formalism as shown in Figure 10.

A. Atomic models

Atomic model templates are developed for the individual components of the ICT based control system and the physical grid. These are described in the following subsections.

The ICT based control system comprises seven atomic sub models; Controllers (C), Protection IED, Intelligent Switch (IS), Merging Unit (MU), Communication Links (Comm), Switches/Routers (Switch) and Smart Meters (SM).

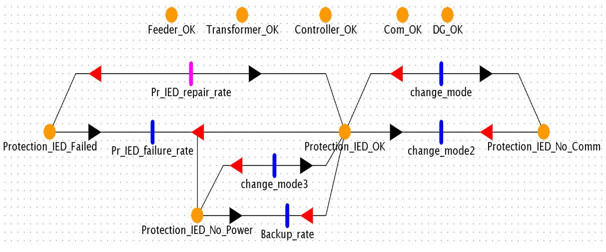

Fig. 1. An atomic model of Protection-IED.

1) Protection IED: Figure 1 shows the atomic model for a Protection IED which is used to model advanced protection devices such as digital relays. It consists of four extended places; Working (PR_IED_Ok), failed power supply - No power (PR_IED_No_Power), failure in communication link - No communication (PR_IED_No_Comm) and Permanent failure (PR_IED_Failed). From initial working state in PR_IED_Ok, a protection IED could end up in a PR_IED_No_Comm state if all the communication nodes/links towards it are not in their working state. A Protection IED could also have a local communication to sensors and actuators it monitors while there is no communication path towards neighbouring protection IEDs or towards the controller. Such cases are modeled by different markings of the PR_IED_No_Comm and PR_IED_Ok extended places.

A working state in PR_IED_OK can either instantly or after some battery time switch to a no power state in PR_IED_No_Power if its power supply is lost i.e. the feeder providing power supply is no more in its working state. Protection IEDs could fail from all other state to a failed state in PR_IED_Failed which needs maintenance. The failure rate in active states (such as PR_IED_Ok) can be set to a higher value than passive states (such as PR_IED_No_power) by using a conditional failure transitions.

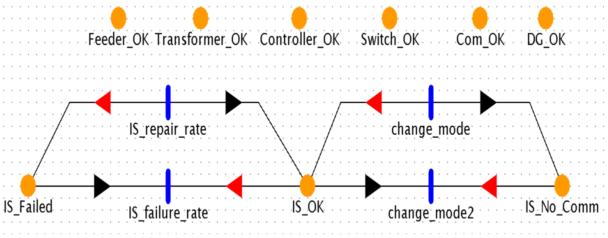

Fig. 2. An atomic model of Intelligent Switch.

2) Intelligent Switch: Figure 2 shows the atomic model for an Intelligent Switch (IS) which is used to model advanced breakers, normally open or close switches that can be remotely operated or tripped. It consists of three extended places; Working (IS_Ok), failure in communication link- No communication (IS_No_Comm) and permanent failure state (IS_Failed). From the initial working state in IS_Ok, an Intelligent Switch could end up in a No communication state in IS_No_Comm if all the communication nodes/links towards it are not in their working state. An Intelligent Switch could also have a local communication with protection IEDs while there is no communication path towards the controller. Such cases are modeled by different markings of the IS_No_Comm and IS_Ok extended places. Intelligent Switches could fail from all other states to a failed state (IS_Failed) which needs maintenance by a repair crew.

3) Merging Unit: Figure 3 shows the atomic model for a Merging Unit (MU) which is used to model advanced sensors such as current/voltage transformers that can digitize the original current and voltage signals and send them through a communication network. The Merging Unit model

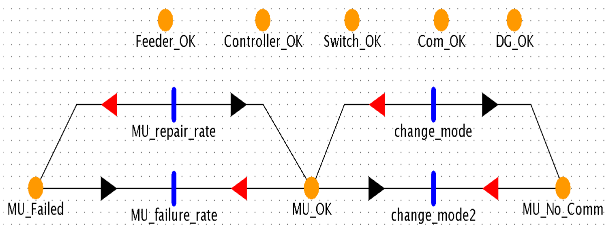

Fig. 3. An atomic model of Merging Unit.

consists of three extended places; Working (MU_Ok), failure in communication link- No communication (MU_No_Comm) and permanent failure (MU_Failed). The model's behaviour is similar to the behaviour of Intelligent Switches discussed above.

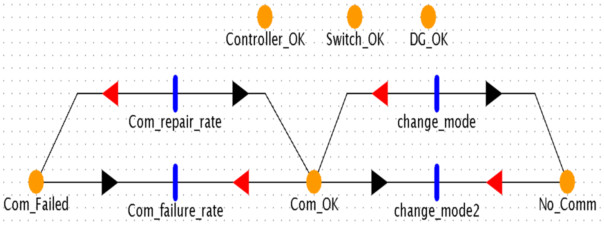

Fig. 4. An atomic model of Communication links.

4) Communication Link: Figure 4 shows the atomic model for Communication links that are used to connect all ICT based components in the grid. It consists of three extended places; Working (Comm_Ok), failure in Switches/routers to which the communication link attached to - No communication (No_Comm) and Permanent failure (Comm_Failed). From initial working state in Comm_Ok, a Communication link could end up in a No_Comm state if all the switches/routers to which the communication link attached to are not in their working state. There could also be a situation where there is a local communication to/and from the connected switch, but without communication beyond the switch/router. Such cases, providing partial service, are modeled by different markings of the No_Comm and Comm_Ok extended places. Communication links could fail from all other states to a failed state (Comm_Failed) which needs maintenance by a repair crew.

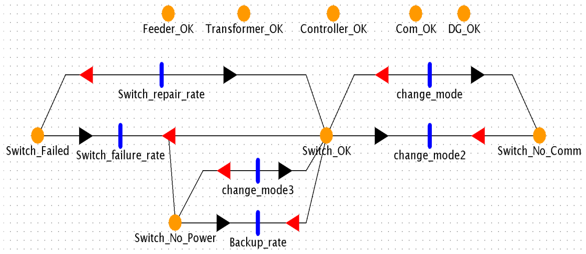

Fig. 5. An atomic model of a Switch.

5) Switch/Router: An atomic model for Switches and/or Routers is shown in Figure 5. It consists of four extended places; Working (Switch_Ok), failed power supply - No power (Switch_No_Power), failure in communication link- No communication (Switch_No_Comm) and Permanent failure (Switch_Failed). The transitions between the extended places are similar to the transitions discussed above in Protection IED atomic model.

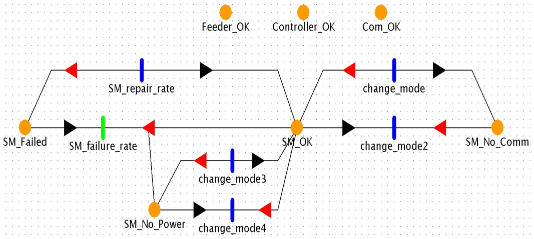

Fig. 6. An atomic model of a smart meter

6) Smart Meter: Similarly, Smart meters, shown in Figure 6, are also modeled by four extended places; Working states in (SM_Ok), failure in communication link - No communication (SM_No_Comm), Permanent failure (SM_Failed) and No power (SM_No_power). The transitions between the extended places are similar to the transitions discussed above in Protection IED atomic model.

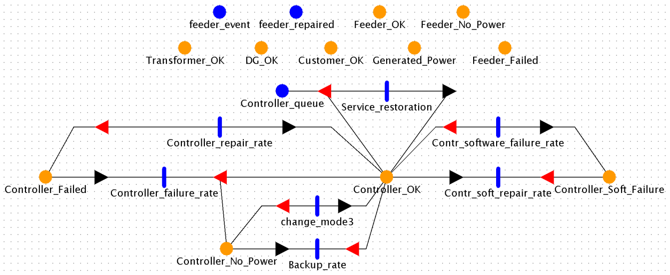

Fig. 7. An atomic model of a controller

7) Controllers: Figure 7 shows the atomic model for the Controller. It consists of four extended places; Working state (Controller_Ok), Software failure (Controller_Soft_Fail), Permanent failure (Controller_Failed) and No power state (Controller_No_Power). A software failure in controllers is either restored by a restart or it might lead to a permanent failure. The controller could fail permanently from all other state which needs maintenance by repair crew. If the power supply of the controller is lost, the controller changes its state from a working state in Controller_Ok to a no power state in Switch_No_Power after holding for some battery time. Whenever there are faults in major components, the controller is informed through Controller_queue and it will check the stability, reconfigure the topology, manage/regulate all the components and update the system state. Major tasks such as demand response and reconfiguration are assumed to take some time.

Similarly, atomic models for the physical grid are developed for feeders, transformers and distributed generators (DG).

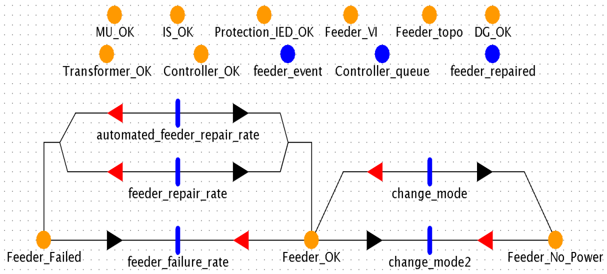

Fig. 8. An atomic model of a Feeder

8) Feeders: Figure 8 shows the atomic model for the feeders. It consists of three extended places; Working (Feeder_Ok), Permanent failure (Feeder_Failed) and No power (Feeder_No_power). Failure of a feeder in a working state is either handled by the responsible protection IED (safe fail) if the ICT based control infrastructure is in a working state or it might lead to a failure cascading into upstream feeders if the associated ICT based protection system is also failed. These two failure situations are modelled by different markings in the Feeder_Failed extended place. The feeder could also fail permanently from all other state which needs maintenance by repair crew. Here also, the failure rate in active states (such as Feeder_Ok) can be set to a higher value than passive states such as Feeder_No_power. A feeder in a working state will instantly switch to 'No Power' state if the feeder from which it gets power is not in a working state.

The repair time in a feeder is composed of a time needed to locate the fault and time needed to do the actual maintenance. Time needed to locate the failure is assumed to be dependent on the failure situation modeled in the failed states in Feeder_Failed extended places. A repair of feeder where the ICT support system has also failed will take a longer time. Transformers can also be modeled using a similar atomic model.

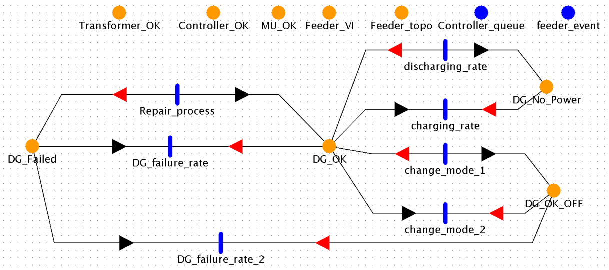

Fig. 9. An atomic model of a Distributed Generator(DG)

9) Distributed Generators: Distributed generators, shown in Figure 9 are modeled by four extended places; Working states (DG_Ok), off state (DG_Ok_OFF), Permanent failure (DG_Failed) and a No power state(DG_No_power). The model assumes that Distributed generator's initial state is 'DG_OFF'. It can be turned on and off by a controller when there is a need/shortage of power. Turning on and off the Distributed generators can also be set regularly based on the load pattern. From the working 'DG_Ok' states, Distributed generators might end up either in 'DG_No_power' state if it has been used continually until it run out of power or in off state in DG_Ok_OFF if the controller decide to turn off it. Distributed generators could also fail permanently from all other states where the failure rate in active states (such as DG_Ok) can be set to a higher value than passive states such as DG_Ok_OFF and DG_No_power.

B. Composed model

The overall distribution grid is modelled by connecting the submodels using a 'Join' composed model formalism as shown in Figure 10. The dependencies as well as interconnection between components are modeled using shared states/places as discussed in the following sections.

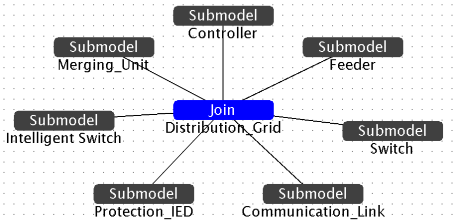

Fig. 10. Composed model of distribution grid

C. Topology modeling

The structure and interconnection between all the components is modeled using shared places. These places are defined in the composed model and are shared among all atomic submodels whose normal operation is dependent on these places. If the enabling conditions for an activity/transition between states in a component is dependent on the state of another component, the extended place that contain the state of the other component will be defined as a shared place and a condition can be set in the first component using this shared place. Besides, a special extended place Feeder_topo is used to keep track of topology/structural information so that each feeder component can look into this array and learn about the topology i.e., to which feeder it is connected to.

As an example, let us consider the feeder model shown in Figure 8 and assume that this specific component is connected to (getting power from) a transformer. Feeder_Ok is shared among a Feeder atomic sub - model and a Transformer atomic sub- model. The Feeder model will instantly switch (modify the markings) from working state in Feeder_Ok to a no power state in Feeder_No_power if the specific transformer to which the feeder is connected leave its working state. This is done by defining an enabling condition for the transition in the Feeder dependent on the shared extended place Transformer_Ok so that Feeder can look into the component (in this case the transformer) from which it gets power supply. In this way, a failure in one component propagates through out the structure unless there are mitigation and protection mechanisms such as by controllers. Such approach makes it flexible and easy to add and/or remove components in modeling the topology and interconnection among physical grid components as well as ICT based control systems.

D. Interdependency between Power and ICT based control system

The interdependency between Power grid and ICT control systems is also modeled using shared places. The model of physical grid components include shared places from the ICT component to which they depend on for their normal operation. Similarly, places from the physical grid components are also included in the model of ICT based control system components to model power supply dependency of ICT components on the physical grid. As an example, looking into the atomic model of the controller on Figure 7, the transition from Working state in Controller_Ok to a no power state in Controller_No_Power is programmed to be dependent on a specific power line feeder to which the controller is connected to. i.e. the transition will be enabled and executed if the failed feeder could not be maintained within a backup battery time. And similarly, the transition from no power state in Controller_No_Power back to the working state in Controller_Ok is also made to be dependent on the working sate of the feeder and it will be enabled as soon as the underlying power node is maintained.

E. Reward model/Metrics

Reward models are used to study the dependability and survivability of the distribution grid. In this study, we compute metrics related to Availability of the service and down times (SAIDI indexes) experienced by loads. Metrics are obtained by assigning a reward to states of interest and statistics will be collected every time the system visits this state. The final result, often a mean value, is proportional to the time the component/system stays in that state.

The measurement can be made on any components, but the study focuses on customer/load side measurements at the smart meters. There can be a variety of measures of interest to final customers and the service provider. In this paper, the following two main metrics are used.

- Availability of Service/power: to measure the availability of the service to an end user/load. This can be obtained by assigning a reward of one when the smart meter of an end user is in a working state. In the presentation of numerical results, the unavailability is used, $U = 1 - A$.
- Service downtime (SAIDI): to measure time the end user lose access to the service/power This is also obtained using reward model on smart meters. It is possible to measure aggregated values for the entire system or measure the individual SAIDI values/distributions experienced at any point/load which can give some architectural and topological insight.

IV. CASE STUDY

To illustrate the capabilities/features of the proposed framework, the role of automation in Fault Location, Isolation and Service Restoration (FLISR) in distribution grids is investigated. A sensitivity analysis is used to study the benefit of automation and the effect of new advanced ICT based component failures in the availability of the service/power to end users. See [25], [26], [27], [28] for further information about FLISR.

The FLISR operation consits of two stages; i) detection, fault location and isolation, and ii) service restoration [27]. The following subsections details these stages.

Fault Location Detection and Isolation: When a failure occurs in a working state of a feeder, the appropriate protection IED in charge of the fault location, as per the grid design, detects the fault through its corresponding secondary equipment (Merging units). If the associated ICT support system is working, it isolates the fault area using intelligent switches. If the ICT based control system is failed, the failure will propagate into upstream feeders/components and it may also fail the whole distribution grid. The impact and restoration time required for such active faults depends on the ICT based control's ability in detecting, locating and isolating the fault.

Service Restoration: After fault detection and isolation Using Merging units and Protection IEDs, the substation based controller is responsible to restore power to the maximum possible out-of-service loads/end users within a short time. The restoration process is also dependent on ICT based control system as the controller needs to find suitable backup feeders and transfer the loads in out-of-service areas using remotely controlled intelligent switches. In the proposed framework, the controller prepares a restoration plan that can keep the stability and meet operational constraints of the grid. For this study, a set of alternative topologies are pre-determined and the controller selects a topology that can provide power to most customers.

The physical distribution grid topology from [29] shown in Figure 11, is modified to include new ICT based components and used in this study. The physical grid that consists 16 feeders has a radial topology with normally open intelligent switches providing redundancy between some feeders. Based on IEC 61850 standard topology in [30], the communication network shown in Figure 12 is used for ICT based control system. The ICT based control architecture comprises 6 Protection IEDs, 16 Merging Units, 16 Intelligent switches, 8 switches, 48 communication lines and one substation based controller.

It is hypothesized that automation of grids improves reliability by reducing the fault detection and repair times. However this is to our knowledge not thoroughly investigated. In this scenario, the fault detection times (repair times) of feeders are varied to study this. Similarly, the failure rate for protection IEDs, relays and Merging unit is varied to conduct a sensitivity analysis. The failure and repair rates of the grid components are based on [31] and [25] and are presented in Table I. Random times are assumed to be negatively exponentially distributed. For controllers, switches and protection relays, a two hour backup battery is considered during power outages.

Mobius tool supports both numerical solver and simulation

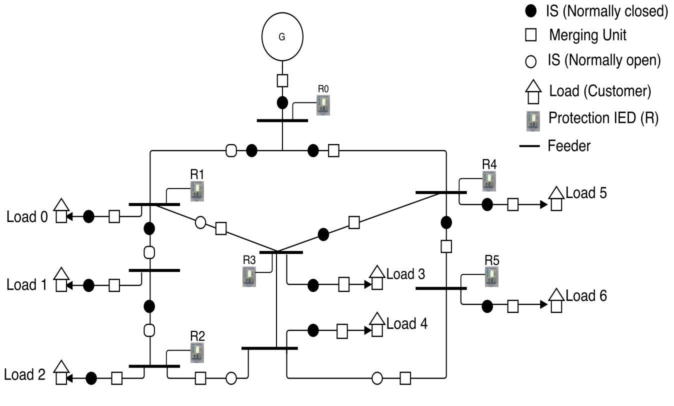

Fig. 11. Distribution grid topology.

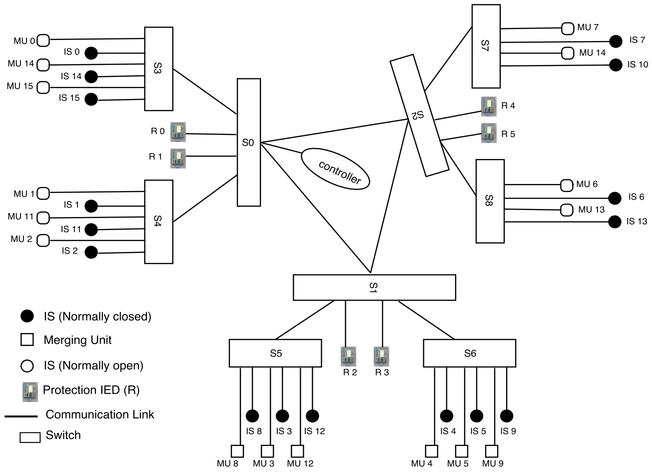

Fig. 12. ICT based control system architecture.

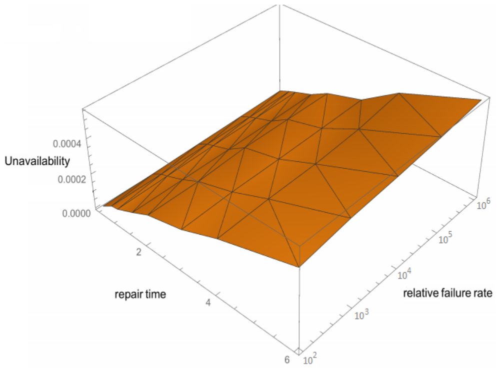

Fig. 13. Unavailability of Load 4. The x-axis is repair time and y axis is the ratio of varying failure rate for protection IED relative to the value in Table I.

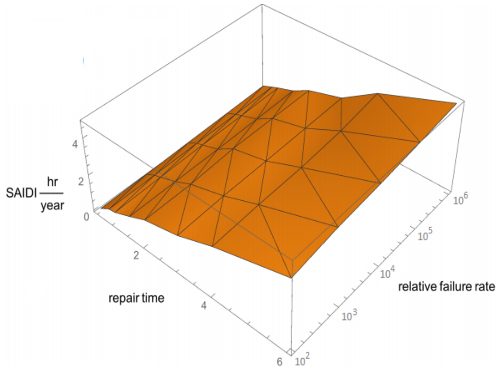

Fig. 14. SAIDI values of Load 4. of Load 4. The x-axis is repair time and y axis is the ratio of varying failure rate for protection IED relative to the value in Table I.

with built-in error control measurements. Since the size of the system makes it difficult to use numerical solvers, we have used the simulation solver. The grid is simulated for 90 years and a replication of 20 is used to get a confidence interval range of 10^{-5} and 10^{-6}. The whole simulation, including replications takes around two to ten minutes depending on the ICT component failure rates used. The result for all end users is similar and we have used end user/load 4 as a representative. The resulting Availability of power for end user/load 4 is shown in Figure 13 and the SAIDI values are shown in Figure 14. The results indicate clearly that the Availability and SAIDI indices are improved significantly for end users if the new ICT based support system is able to lower the repair time needed for feeders. Considering the assumed dependence of FLISR function on ICT support system, the unavailability is far less sensitive to changes in the failure rate of the new ICT based components as shown in Figure 13. It shows that an increase in availability of the service (lower unavailability) is more dependent on the ability of components to detect and locate failures in a short time (lower repair time) than the dependence on the failure rates of the new ICT based components. This might be due to the conventional, but not entirely realistic assumption, that ICT failures will not induce failure into the power system. It is assumed that the ICT failures could only influence the failure handling of the power system.

TABLE I
FAILURE RATE AND REPAIR TIME OF THE GRID COMPONENTS

Component type	**Component failure rate (failure/year)**	**Component repair rate (hr/failure)**
Feeder	0.07 per Km	6
Protection IED	0.023	2
Merging Unit	0.0268	2
Intelligent Switch	0.03	2
Communication line	0.068	3
Switches/router	0.2	3
Controller (permanent failures)	0.2	2.5
Controller(Software failures)	12	0.3

V. CONCLUDING REMARKS

In advancing smart distribution grids, there will be a strong and complex coupling and dependence between the communication system and the physical grid. This paper has presented a comprehensive and unified approach that provides a balanced view of both communication and power grid subsystems. It is scalable and suited for modeling new emerging technologies that may go into the distribution grid, as well as further autonomic operations, operational and architectural changes. The modelling framework is illustrated by a simple, but realistic, case where the role of automation of Fault Location, Isolation and Service Restoration (FLISR) is investigated.

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