Availability and Resiliency Analysis of Modern Distribution Grids Using Stochastic Reward Nets

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***Abstract*—This paper presents a method to evaluate the availability and resiliency of a modern distribution grid using Stochastic Reward Petri Nets (SRNs). SRNs are a modelling formalism used to evaluate the complex dependencies of components during fault recovery. The method is verified using the RBTS Bus 2 Test system and then applied to an enhanced version of the distribution grid which employs remote communications and distribution automation to hasten the recovery process. Sensitivity analysis is applied to the enhanced version of the test system to demonstrate improvements in recovery time and reduction in downtime with respect to to component failure. Finally, resiliency analysis is performed to the enhanced system to evaluate the systems ability to recover from unexpected and severe events and demonstrate the improvements that this technology provides.**

***Index Terms*—Distribution grid, availability, resiliency, SAIDI, smart grid**

I. Introduction

In recent years there has been a large amount of innovation in power distribution grids and their protection systems. One area of focus is the reduction in the impact of faults by improving the recovery process when faults occur . Distribution grids are generally assembled in a mesh structure and operated in a radial manner. This means that there are multiple paths that can be used to deliver power to each load point on a grid, but only a single path is online at any time due to the utilisation of distributed sectionalising switches. This strategy is employed to reduce the overall downtime experienced by customers. When a component fails the grid operators can use sectionalising switches to restore power to a portion of the affected customers through alternate routes, without needing to repair the failed component. This methodology is known as Fault Detection, Isolation and Repair (FDIR) and is a key part of distribution automation schemes.

The purpose of FDIR is to reduce the total impact on customers served by a distribution grid due to failure. An important application of reliable communications in modern distribution grids is to automate this reconfiguration process with remotely controlled switches and sensors. Automation of the reconfiguration process has resulted in a major reduction of the time it takes to restore customer power because of the reduction in time it takes to locate a fault and the time it takes to reconfigure the grid. In some cases this process has reduced the outage time of customers to minutes or even seconds. In one case in the USA, 40,000 out of 80,000 customers had their power restored within 2 seconds after a wide-spread failure due to distribution automation [1]. The deployment of remotely controlled switches and sensors onto the smart grid has made them resemble distributed computer systems. Because of this, techniques from the field of distributed computing are able to be applied to evaluate the reliability and resilience of distribution grids.

Abstracting a distribution grid to model its availability using a state-based Continuous-Time Markov Chain (CTMC) is an error-prone and tedious process [2]. This is due to the complexity of the large number of states which must be considered. Stochastic Reward Nets (SRNs) are an improvement to CTMCs that contain connected graphs which contain two types of node; places and transitions. Each place contains zero or more tokens which move between places when transitions *fire*. SRNs use logic-based functions to ma system. They provide the ability to analyse individual parts of complex distribution grids by deconstructing them into separate components. Each component exists separately, but its dependencies on other components can be modelled using logic-based guard functions. This removes the need to explicitly define every permutation of the possible system states, because these are automatically generated using the formalism. A reward function can also be defined to determine the availability of a system.

SRNs expand on stochastic Petri nets (SPNs) by augmenting them with output measures specified with reward functions [2]. They provide a high-level interface for the concise specification of large, complex systems. This paper utilises SRNs to evaluate modern smart grid technology. Specifically, the contribution of near-instantaneous post-fault reconfiguration provided by reliable communications is evaluated. For this paper, we will consider near-instantaneous reconfiguration, which is of the order of seconds, as instantaneous. It is shown how this technology improves the day-to-day performance, measured by the System Average Interruption Duration Index (SAIDI) [3], which represents the average outage time of each customer per year. Finally, it is shown how reliable communications can enhance the resilience of a distribution grid to unpredictable events such as severe weather.

Section I-A discusses related work. Section II introduces the system being analysed and the concepts of SRNs. Sections III and IV employ SRNs to conduct a sensitivity and resiliency

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analysis of the system and presents and discusses the results. Section V concludes the paper.

A. Related Work

There are several examples of SPNs applied to distribution grids for a number of purposes, ranging from fault-diagnosis to load-transfer optimisation [4]. Works similar to the topics of this paper include [5], which presents a method to identify faults, [6], which assesses unavailability of SCADA communications and [7] which evaluates the reliability of small power systems using Fluid SPNs. Reliability and availability analysis of distribution grids using SPNs is a largely untouched method. This paper demonstrates that applying reward functions to stochastic Petri nets (to develop SRNs) in order to model availability of power distribution systems is straightforward and valuable insight can be gained from doing so.

II. System Availability Model

The system being modelled for this paper is Feeder 1 and Feeder 2 of the Roy Billinton Test System (RBTS) Bus 2 Test System [8], shown in Figure 1. Note that each lateral (L2, L3 etc) has a mechanical fuse at its junction with the feeder.

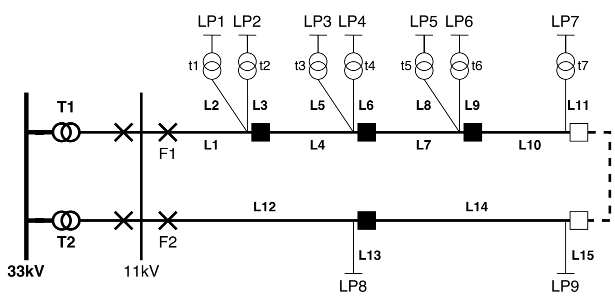

Fig. 1: Feeder 1 and 2 of the RBTS Bus 2 distribution grid test system, adapted from [8].

The component parameters for the RBTS Bus 2 can be found in the test system paper [8]. Assumptions for this system are summarised as follows:

- Protection and reconfiguration equipment cannot fail.
- Fault protection devices (CBs, fuses) operate instantly.
- All failures are detected by the protection equipment.
- All failure rates are unchanging in time and are exponentially distributed.
- The fault isolation rate remains constant regardless of how many components have already failed.

Availability analysis of Feeder 1 is performed using SRNs. This has been chosen because the variation in its load point topology illustrate all of the interesting features of the analysis. There are numerous software packages available to evaluate SRN models. The authors have used SHARPE [9] and SPNP [10] to evaluate the SRN in this paper. These packages use the given model to generate a reachability graph of the system, based on the transitions, places, arcs and defined reward functions. This reachability graph is a CTMC which can be solved using numerical techniques which are described in detail in [2].

A. Demonstration of Method

This section demonstrates that assembling the SRN for the RBTS Bus 2 test system produces the same availability results as are given in the paper, if the same assumptions are made. It constructs a SRN for load point 3, which is denoted LP3, and present the results for the remaining load points in a table.

The components relevant to LP3 are:

- Supply feeder lines (L1, L4, L7 and L10)
- Lateral line (L5)
- 11/0.415kV transformer (t3)
- Substation and 33kV system
- Interconnecting ring main
- Redundant supply feeder via ring main (L12, L14)

For this example the substation and 33kV section of the system are perfectly reliable and thus not included in the availabilty model.

This SRN is created to model the availability of LP3. As such simplifications of the system can be made. Firstly, from the perspective of LP3, the lines of Feeder 2 provide an alternate supply when lines before LP3 along Feeder 1 fail and are isolated. These Feeder 2 lines can be modelled as in series because failure of either of these removes their ability to provide an alternate supply. They can modelled as a two-state component of the SRN. This component is labelled F2 and is part e in the SRN diagram

Each load point connects to the main feeder through a lateral. These are composed of a fuse, a line, in some cases a transformer. A failure in any of these components is immediately disconnected from the system by the fuse. This means that the failure of any component on a lateral only affects the load point that the failed lateral supplies. For LP3, the line L5 and transformer t3 make up the lateral. They are in series, and as such they can be combined into a two-state SRN. This component is labelled Lat3 and is part d in the SRN diagram

Each line component along Feeder 1 can fail, and when this occurs it can be isolated using normally-closed switches. There is one of these switches placed between each labelled line. These are illustrated in the detail of Figure 1. When a failure occurs on any of the feeder lines on either feeder, the circuit breaker at the base of the feeder detects the fault current and opens. This disconnects the failed component, along with the rest of the feeder, from the source, deenergising every load point supplied. Along both feeders there are normally-closed sectionalising switches which can be operated when a line is deenergised. When a fault occurs, they are employed to isolate the faulted component from the rest of the system. The ring main unit connecting the two feeders can be used to supply load points beyond the failed component, along the feeder. This process is referred to as fault isolation. After a failure is repaired, the reverse occurs. The ring main disconnects the two feeders and the open sectionalisers are closed. This process is assumed to take the same amount of time as the fault isolation. These components are parts a,b,c and f for lines L1, L4, L7 and L10 respectively.

Because feeder lines require isolation before they can be repaired, they require more than a two-state system to represent each of them. For the system presented here, there are four *places* used to represent four possible states of each feeder line. Load point 3 has four relevant 4-place feeder line components. These are all similarly shaped, with different failure rates, repair times and reconfiguration times. The 4-state component modelling line 1 follows:

- P_{L1_ok} is the default place and represents the state where the line is operating as intended.
- P_{L1_failed} represents failure of line L1. It is entered at rate $\lambda_{L1} = 1/MTTF_{L1}$, from place P_{L1_ok}.
- $P_{L1\_isolated}$ represents the state where sectionalisers and ring mains have isolated the failed line and provided alternate supply to the load point if possible. This state is entered from P_{L1_failed} at rate $i = 1/MTTI$, where $MTTI$ is the mean time to isolate the failed component and operate the ring main if needed. i is the isolation rate.
- $P_{L1\_repaired}$ represents the state where the line is still isolated, but has been repaired. It is entered at rate $\mu'_{L1} = \frac{1}{(MTTR_{L1})-2MTTI)]}$ from $P_{L1\_isolated}$. $MTTR_{L1}$ is the mean time to repair for L1. The time taken to isolate the component $(MTTI = 1/i)$ and the time required to reconnect the component $(MTTI)$ is included in the MTTR metric but these steps have been separated in this SRN, so the time taken to do so must be subtracted to have the correct repair rate.
- P_{L1_ok} is entered from $P_{L1\_repaired}$ at rate i. This transition models the reconnection of a feeder line to the feeder after it has been repaired.

These above conditions create the SRN of LP3 shown in Figure 2.

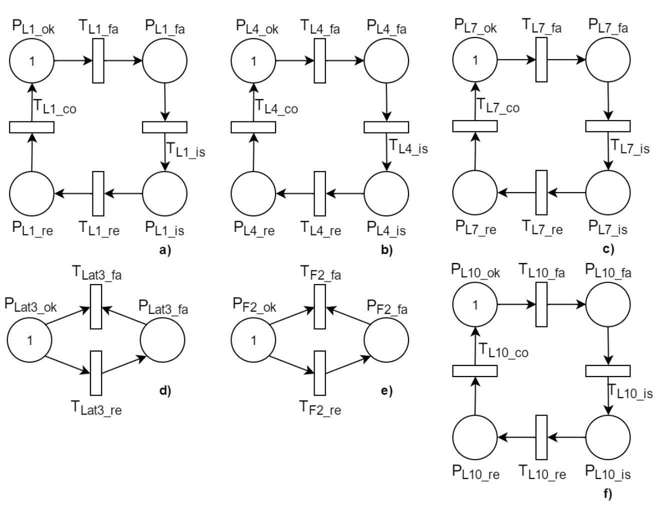

Fig. 2: SRN used to model availability of LP3 on Feeder 1

Based on the SRN defined here, a reward function is created to determine when load point LP3 is online, in order to calculate availability. For LP3 to be online it requires the lateral Lat3 and the line L4 to be online. This is because there are no switches available to isolate LP3 from L4. If these two components are online, there are two cases where LP3 is online. The first where LP3 is connected to the substation through Feeder 1. For this condition to be met, there must be an unbroken path to the source, and no components along the feeder which would cause the circuit breaker to operate (i.e. no components with a token in the P_{Lx_failed} place. The alternative case which would allow LP3 to be online is if it is supplied through Feeder 2. This requires Feeder 2 to be online, the lines connecting LP3 to the ring main to be online, and the remaining feeder lines to not be in a failed state. These configurations produce the reward function for LP3's availability shown in Table I amongst the functions for the other 7 load points in the modelled system.

This SRN was evaluated with SHARPE, using the rates described in the RBTS Bus 2 test system, and the same availability values are calculated for this as are given for the test system.

III. Availability and Sensitivity Analysis

For this paper, the aim is to evaluate the improvements obtained by enhancing the reconfiguration process which takes place after a fault occurs. Reconfiguration is used to restore service to as many load points in the system as possible, by using distributed switches to separate load points from the faulted component and connect them to alternate sources, or through alternate paths.

The method described in Section II-A has been applied to all the load points of Feeder 1 of the RBTS Bus 2 test system. The results are presented in as downtime (hr/yr) and can be seen in the second column of Table II. The same analysis was conducted on the system with the reconfiguration time (for both isolation and reconnection) set to zero. The results for this can be seen in the third column.

A. Sensitivity Analysis

The sensitivity of the load point downtime (in hours per year) to component failure rate is now assessed for both delayed and instantaneous reconfiguration. For the RBTS, the time taken to reconfigure after a fault is 1 hour. Figure 3 shows the downtime for LP3 when varying each feeder line MTTF, for both delayed and instantaneous reconfiguration. While each line MTTF is being changes, the remaining are kept at there defined value.

To evaluate the contribution of instantaneous reconfiguration to system availability, a sensitivity analysis of the system SAIDI to MTTF of each feeder line, for both delayed reconfiguration (1hr) and instantaneous reconfigurations is conducted. Figure 4 shows the contribution of each component to the system SAIDI value.

Analysis reveals two features in Figures 3 and 4. It can be seen that there is a constant reduction in downtime for all feeder line MTTF values, caused by the hastened reconfiguration. Secondly, after instantaneous reconfiguration is

TABLE I: Availability reward function for LP3

<table>
<tr><th>Function</th><th>Definition</th></tr>
<tr><td>$ss\_avail\_LP3()$</td><td>if(#P_{L4_ok}==1 && #P_{Lat3_ok}==1 && (#P_{L1_ok}==1 && #P_{L7_failed}==0 && #P_{L10_failed}==0)
|| (#P_{L1_failed}==0 && #P_{L7_ok}==1 && #P_{L10_ok}==1 && #P_{F2_ok}==1)) 1 else 0</td></tr>
</table>

TABLE II: Downtime of each load point for system with delayed and instantaneous reconfiguration in hr/yr

Load Point	Delayed	Instantaneous
1	3.58	3.34
2	3.64	3.40
3	3.64	3.40
4	3.58	3.34
5	3.64	3.40
6	3.63	3.40
7	3.60	3.40

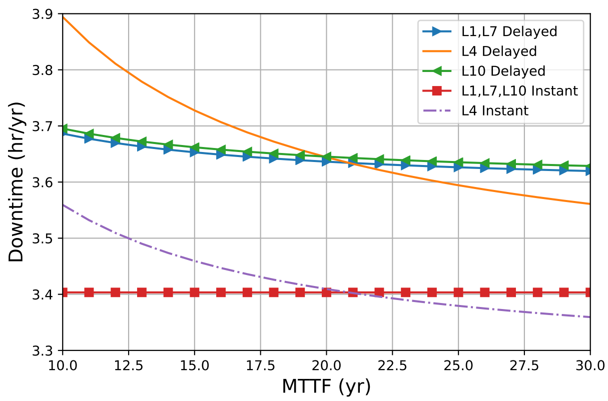

Fig. 3: Downtime of LP1 for varied feeder line MTTF, for delayed and instantaneous reconfiguration

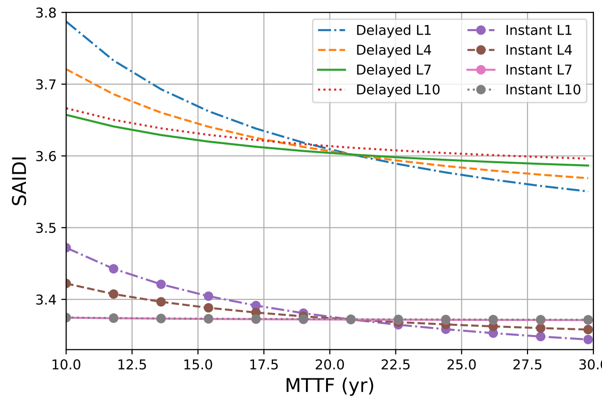

Fig. 4: SAIDI of Feeder 1 for varied feeder line MTTF, for delayed and instantaneous reconfiguration

introduced, LP3 becomes immune to failures which occur on feeder lines that it can be separated from. The contribution of instantaneous reconfiguration may be limited by the topology of the grid. This is because sectionalisers can only assist in isolating a load point from a failed component if they are placed in a location between the two. Additionally, reconfiguration is only a portion of the recovery process. For load points which can't be isolated from a fault, the only reduction in outage time gained from hasted reconfiguratioon results from the repairs beginning faster.

This technique allows us to observe from a system perspective how the protection and reconfiguration equipment of a distribution grid assists in fault recovery. It is able to highlight the overall contribution that can be made by both the topology of protection equipment on a grid, and also by the speed in which it operates. This methodology can be used to optimise where distribution grid reconfiguration devices are deployed in order to reduce outage time for as many customers as possible.

IV. Availability Resilience Analysis

Resiliency can be assessed by introducing parametric changes to a system by reducing the MTTF of a component to far below normal range. The system availability is then assessed to determine how this parametric change has affected it. If the change in availability is small, it can be said that the system availability is resilient to the MTTF of the altered component [11]. This analysis provides valuable insight into how the system can withstand abnormal events such as severe weather or earthquakes.

Figure 5 presents the results for the resiliency analysis of feeder line L4. It shows four different configurations and presents these for each load point. The first is the downtime of the load point when all component MTTF values are normal and reconfiguration time is unadjusted. The second is the downtime of the load point when the MTTF of each component is 1% of its normal value, and hence very unreliable. The third is the system with normal component MTTF values, but with instantaneous reconfiguration and the final is where the MTTF is 1% of its normal value and the reconfiguration is instantaneous.

From this figure it can be seen that the introduction of instantaneous reconfiguration after a fault means that the failed components can be quickly isolated and the resulting outage time reduced to negligible amounts. The exceptions to this are components which cannot be isolated from the load points LP3 and LP4, and the full duration of the repair must be endured when these components fail. Instant reconfiguration removes the effect of a failure of a component on any load point which can be isolated from it. Based on this analysis, it can be seen that load point downtime is resilient to feeder line failures which are able to be disconnected from the load point.

The contribution of post-fault instantaneous reconfiguration on system resiliency in the form of changes in SAIDI can

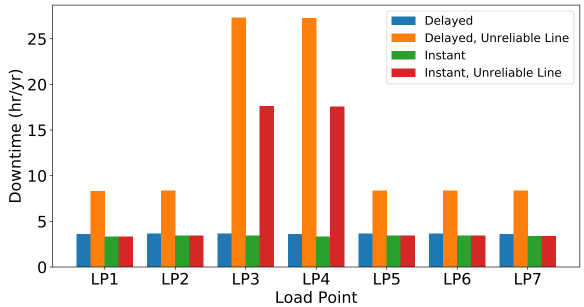

Fig. 5: Downtime of each load point before and after setting L4 MTTF to 1% of its value, with delayed and instant reconfiguration.

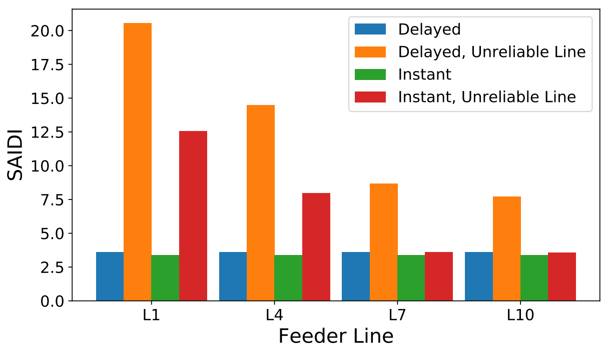

Fig. 6: Feeder 1 SAIDI, before and after setting each component MTTF to 1% of value, with delayed and instant reconfiguration.

be seen in Figure 6. This has the same four configurations presented in Figure 5, but for system SAIDI, and for each feeder line MTTF that has been changed. It displays the contribution of instantaneous reconfiguration to system SAIDI resilience against the reduction of MTTF of an individual component to 1% of current value. The key feature of this figure is the increase in SAIDI when the parametric change is introduced to each component. This step is always smaller when instantaneous reconfiguration is used. The step is very small when the reconfiguration is instantaneous for faults in L7 and L10. This is due to the majority of customers supplied by the feeder being connected to LP1, LP2 and LP3. Hence most of the population is immune to faults along L7 and L10. With the introduction of instantaneous reconfiguration after a fault, the SAIDI of this feeder is more resilient.

SRNs can assess system resilience by inspecting how a severe change in a single components reliability affects the system as a whole, thus determining how resilient the grid is to failures in the altered component. This methodology in its current form gives an indication of resilience, but does not provide an overall numerical value for system resilience. As such, it cannot be used yet for optimisation of resilience in a distribution in a distribution network in its current form. This is future work for the authors.

V. Conclusion

In this paper Stochastic Reward Nets are presented as a method to assess modern advances of the distribution grid. They are used to evaluate the availability and resiliency improvements gained by enhancing fault recovery techniques, specifically by deploying remote switching and distribution automation making post-failure reconfiguration instantaneous. Sensitivity analysis reveals the contribution of instantaneous reconfiguration is a steady reduction in the downtime of all load points because the repair process is shorter. It also reveals instantaneous reconfiguration makes load points immune to failures that they can be separated from using distributed switches. Resiliency analysis is presented and reveals that correctly placed sectionalisers improve distribution grid resilience because they can isolate faults from the majority of customers supplied by the feeder, particularly if the reconfiguration is instantaneous. SRNs can be used to deconstruct distribution grid in a straightforward way in order to assess the contribution that modern technology has to improving the availability of distribution grids. This paper assesses the addition of remote sectionalisers and distribution automation. Future work for this techniques includes assessing the contribution of distributed generation and microgrid systems.

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