Reliability Evaluation of Distribution Structures Considering the Presence of False Trips

Sajeesh Babu, Patrik Hilber, *Senior Member, IEEE*, Ebrahim Shayesteh, *Member, IEEE*, and Lars E. Enarsson

***Abstract*—This paper presents a method for modelling the different modes of failures in a substation and feeder architecture along with updating the possible false tripping scenarios in it. A traditional approach to collectively assess the failure modes using reliability block diagram is reviewed, and the method is updated to count in the unaccounted false tripping scenarios. A generalizable radial feeder branching structure is adopted and the effect of total feeder length and number of feeders from each busbar is examined and modelled with the help of the updated reliability block diagram. The modelled trends are also studied from real-world substation architectures. Thus, the analysis attains an improved estimation of the complex hidden failure probabilities combining theoretical and practical models.**

***Index Terms*—Circuit breakers, control equipment, failure rate modelling, power distribution faults, power system control, power system reliability, substation protection.**

NOMENCLATURE

i, j	Feeder section notation.
n	Total number of feeder sections.
L_i	Feeder line leading to load end i.
B_i	Breaker component i.
C_i	Conductor component i.
α, β, δ	Probability terms considered to define the failure rate contributions from different causes.
λ_{Li}	Net failure rate for feeder line Li.
λ_{Bi}	Failure rate for breaker component Bi.
λ_{Ci}	Failure rate for conductor component Ci.
λ_{Lsyi}	Failure rate contribution to Li from sympathetic trips
λ_{gi}	Failure rate contribution to Li from breaker operation failure.

I. INTRODUCTION

POWER system automation involves the introduction of a number of intelligent components and sub-systems connecting and communicating with the existing grid. Assessing the influences on system reliability from these components which are employed to monitor and safely manage the grid, is a complex yet significant task. It is important to test and understand whether the investments in advanced automation systems are enhancing the system reliability to the desired levels.

The basic knowledge required to understand, model and analyse power system reliability from component to system level with the help of statistical and probabilistic methods is covered in [1]. Implementation of these methods is widely practiced in research intended to improve the reliable performance of power networks; for example [2-4]. However, in real-world implementations, critical yet intricate power network equipment such as protection systems can have operational failures from causes that are unaccounted for, in system design. Apart from flaws in physical components and the impact of external agents, these failures can initiate from incorrect manipulation by control equipment, missing communications, lack of situation awareness of human operators and other reasons [5]. Modelling of such correlated events with consideration to the cause, mode and nature of the events has not been conducted yet in required detail. This paper hence investigates the complex faults occurring in such systems and calculates their corresponding frequency in practical cases.

Here, the area of focus is operation of protection systems and breaker components. The different types and scenarios of faults occurring in practical protection systems are observed in [6-8]. Within this scope, improved understanding is required regarding different failure scenarios relating to circuit breakers and especially their corresponding probabilities. In order to address this, an approach to model effective failure rate expected at load end of a radial feeder network is developed in this paper and compared with real-world case statistics. Various fault probabilities in such systems are calculated using Reliability Block Diagram (RBD) approach.

A detailed review of power system reliability analysis with a focus on identifying the important works concerning the primary grid and the control and protection equipment is done in [5]. The association of protection system reliability with the primary equipment is a focus in the review. Improvement in maintenance scheduling with the knowledge of circuit breaker and relay failures is used in [9] to formulate an updated probabilistic maintenance plan and then tested on the Finnish power grid. Fail to operate and undesired trip are the protection system failure modes investigated in [10, 11]. Focusing on component interaction and readiness of components, further breakdown of the failure modes is carried out in [10]. This paper achieves breakdown of failure modes through observations on practical systems considering probable causes of failures. The role of protection system failures in cascading failure events is observed in [11], where adequacy and vulnerability based analysis on IEEE Reliability Test System is conducted to identify the weak links in the system. A subset of such cases is considered in this paper as overlapping failure events. While [11] calculates hidden

Manuscript accepted July 23, 2016. Paper ID TSG-01299-2015

S. Babu, P. Hilber and E. Shayesteh are with the School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden (e-mail: sbabu@ kth.se).

L. E. Enarsson is with Ellevio AB, Stockholm.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSG.2016.2609684, IEEE Transactions on Smart Grid

failure probabilities in the test system, this paper study them on distribution architectures. Structured approaches to determine these hidden failure probabilities rather than from guesswork based on failure statistics are found to be very rare in background literature during the state of the art study and hence the suggested approach is of significance.

II. Failure Modes

Most of the power system components can be classified into two divisions, the primary and the secondary equipment [5]. Primary equipment is responsible for the actual transfer of energy from the generating units to customer locations, while the secondary side deals with the monitoring, measuring and control of the primary system. Studies on the performance of distribution systems and corresponding failure event records reveal that about one third of failures recorded at these voltage levels are associated with the secondary system [12]. Mal-operation of a protection system can be through false tripping and failing to trip when required. Among this, failure to respond to actual fault signals could lead to isolation of larger areas from power supply depending on the fault location and grid design. For example, a whole substation outage can have more number of disconnected customers than failures confined to one or more outgoing feeders from the same station [13]. Analysis of recorded fault registers used by power utilities suggests that even faults occurring on these outgoing feeder lines can escalate through false tripping of breakers in other protection zones due to the aforementioned causes.

The different modes of failure during operation that can take place in a substation called active failure events, passive failure events, stuck-condition of breakers and overlapping failure events [8], are outlined below.

A. Active failure events

All types of primary grid components can undergo active failures such as short circuit faults in conductors and breakers. When an active failure event occurs, the appropriate circuit breaker in charge of the fault location as per grid design detects the fault through its corresponding secondary equipment and isolates the fault area. The impact and restoration time required for active faults depends on the fault location. The probability of active failure events is usually higher than other failure modes [7]. Breakers that undergo component failure are disconnected along with the nearby lines by a backup breaker which often is the station breaker.

B. Passive failure events

Passive failure events or open circuit faults do not produce fault currents to operate a circuit breaker. This distinction is important because there can be cases where a passive opening of a conductor component escalates to a short circuit condition as the open conductor often come in contact with ground or other primary component sections. Other examples of passive failures could be open circuits caused by error in protection systems or even due to lack of situation awareness from the operator. Often in power system calculations such events are assumed to be rare [1]. Note that, when a false trigger from secondary equipment is causing a passive failure event, the general assumption of considering the primary component as the culprit component leads to wrong estimations. For example, consider an error in the protection scheme producing a false trip signal to a breaker.

C. Stuck condition of breakers

The ratio of the number of failed operations of a breaker due to stuck condition to its total number of operations is called stuck condition probability of a breaker [8]. Physical stuck condition or the failure of the breaker control to correctly deliver the proper trip signal can cause non-operation of the breaker when required. It is important to classify the stuck condition cases according to the culprit component especially because preventive maintenance is the key to minimise stuck condition events.

D. Overlapping failure events

The completely or partially failed or even under repair condition of a component, if associated with a successive failure event in the network, is called an overlapping failure. During calculations with such events, short disconnections and failures of higher order than two are usually neglected [14] and this is followed in this paper.

Automation introduced in power system depends on higher quantity and improved quality of communication. Relatively high communication traffic in practical systems can also result in errors and spurious signals. Also, operation of the secondary equipment in automated systems is very complex [5]. Hence the frequency of overlapping failures resulting from miss-communications is expected to increase in advanced power systems.

III. Theory and Development of Updated RBD

This section presents how the modes of failures discussed above are counted in the modelling in this paper. The layout of distribution substations can widely vary depending on system requirements, economic constraints, size and distribution of customers and secondary stations. Here, a generalised reference structure with scalability is adopted and the traditional RBD analysis of the structure is reviewed. Later on, additional failure cases observed in automated systems are included thus updating the RBD. The important aspect captured in this paper is the adoption of RBD for modelling the correlated events considering the impact of respective events.

A. Reference branching feeder structure

See the reference feeder structure shown in Figure 1, where a number of feeder lines named L_1, L_2, .. L_n are feeding from the station busbar represented by the horizontal line. The station breaker B_0 is located on the other side of the busbar. The feeder protection breakers and conductor components in each feeder are marked respectively as B_1, B_2, .. B_n and C_1, C_2, .. C_n.

The RBD representation of the reference branching feeder structure is illustrated in Figure 2. It shows how the reliability

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSG.2016.2609684, IEEE Transactions on Smart Grid

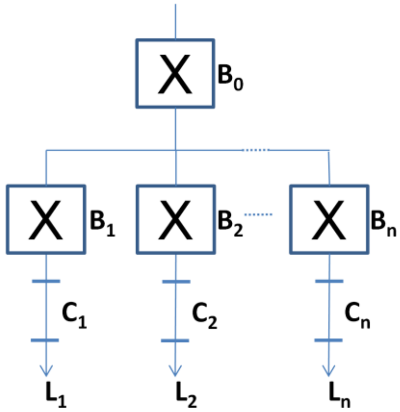

Fig. 1 Branching feeder structure. B, C and L indicate breaker component, conductor component and feeder line respectively. B_0 is the station breaker.

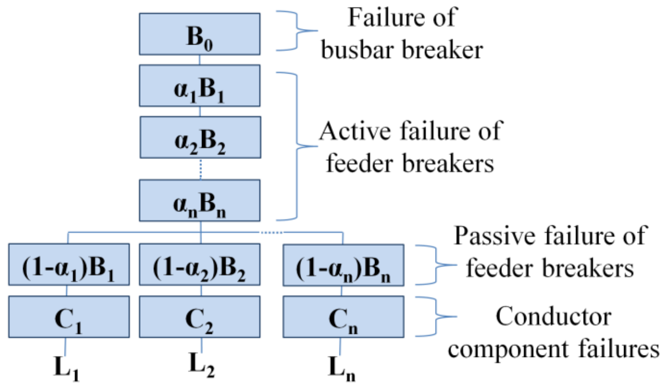

Fig. 2. RBD of the branching feeder structure considering both active and passive failure events. α represents the ratio of active failures of a breaker to the total failures.

impacts of the components as per the failure modes. Certain failure modes discussed in Section II, especially those from overlapping failures are included and discussed as the RBD is updated in Section III.B. Note that, the stuck condition of a breaker from a reliability perspective can be modelled as an overlapping failure case where the reason for stuck condition determines the culprit component. A physical stuck condition may be identified as an active component failure. The other possible scenarios based on the culprit components are discussed and included later in the paper. Figure 2 illustrates how active and passive failures affect the customer ends of the feeder lines distinguishing whether each case affect all station customers or only those in a feeder section. As component failures of breakers are isolated by a backup breaker near the station, an active breaker failure affects all the station customers and hence the corresponding placement in RBD. However, passive open circuiting and conductor failures ideally affect only the respective feeders.

While conducting failure rate calculations the representative block in the RBD can be replaced by corresponding failure rates of the blocks. The probability term α is introduced to indicate the ratio of active failure events to the total failure events of breaker components. Here α can be in the interval [0, 1] depending whether none or all failures respectively are active failures. Hence $(1-\alpha)$ could similarly represent the portion of passive failures relating the breaker. If i represents the feeder line number for any breaker component B_i, then

$$\alpha_i = \frac{active\, failure\, frequency\, of\, B_i}{total\, failure\, frequency\, of\, B_i} \qquad (1)$$

As mentioned in section II.A, in practical systems active failures are more frequent than passive events. Hence the practical value of α_i should be more close to 1 than 0. Also note that as per reliability considerations, active and passive failures of conductor components will affect the corresponding feeder lines only, since feeder protection breakers can isolate the active conductor failures. Hence the total effect is considered combined as conductor component failures (See Figure 2). Since failures of order higher than two are ignored, approximate net failure rate calculations can be conducted on the RBD, counting together the individual failure rates of blocks affecting each feeder end [15]. Hence for a feeder line L_i, the net failure rate as per the RBD is

$$\lambda_{L_i} \approx \lambda_{B_0} + (1-\alpha_i)\lambda_{B_i} + \lambda_{C_i} + \textstyle\sum_j \alpha_j \lambda_{B_j} \qquad (2)$$

For a system with components which never or rarely undergoes passive failures, $\alpha_i \approx 1$. If passive failures are neglected, Equation (2) represents that the overall failure rate expected for a load point is the sum of the component failure rates of all the breakers and that of the conductor line connecting to the corresponding load point [15].

B. Outages due to false trips

Protection failures are classified in to two types, namely fail to operate and undesired tripping [10]. In addition to the modelled active and passive failure modes from the reference structure, this paper takes into account mainly two types of false tripping events which occur in overlap with faults in either conductors or breakers.

While designing protection schemes for distribution systems, protection zones are defined and the breakers are assigned to protection zones such that minimal cascading of contingencies occur. However, as mentioned in section II.D, due to complexities of secondary equipment, overlapping failure events often occur in real-world distribution systems. Probability of false trips in practical distribution grids could vary depending on different aspects such as degree of automation present, quality of maintenance, quality of design of protection systems and degree of situation awareness of human operator [16, 17]. These factors act as tuning parameters that adjust the false trip probabilities in individual systems. As the degree of automation is expected to increase significantly in power system operation, neglecting these false trip probabilities can cause significant errors in reliability calculations. Experience from fault record inspection and protection engineering can be utilised to estimate undesired trip probabilities specific to systems with various degrees of automation complexity.

The RBD structure given in Figure 2 does not take these probabilities into account and hence should be updated. In this section, such faults are introduced and then the approach advances to include them in the model.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSG.2016.2609684, IEEE Transactions on Smart Grid

1) Sympathetic tripping

Sympathetic tripping is a type of undesired tripping. During sympathetic tripping, the breaker in a healthy section of the power system where no actual fault exists, trips because of the undesired response of the secondary system to a fault in a line in the proximity [18, 19]. The healthy section which got sympathetically disconnected needs only a short restoration time as no actual fault exists in this section. However, corrective maintenance actions should be considered on the secondary system which triggered this false trip overlapping with faults in the neighbouring section. The longer component repair time should then only affect the actual faulty section. An example case based on Figure 1 could be an actual short circuit fault in C_1 that ideally should only affect L_1 by tripping B_1 but, B_2 sympathetically tripped thus disconnecting L_2 also.

In the calculation here, a new probability term δ in the interval [0, 1] is introduced to assess the contribution of sympathetic trips in a feeder line overlapping faults in neighbouring feeder line conductors. For any feeder line j, the probability of sympathetic trips overlapping with a fault in conductor C_j is

$$\delta_j = \frac{sympathetic\ trip\ frequency\ overlapping\ with\ failure\ of\ C_j}{total\ failure\ frequency\ of\ C_j} \quad (3)$$

If all faults in a component trigger sympathetic trip then δ will be 1 and if none then 0. The effective contribution to failure rate of feeder line i from sympathetic trips in conductors of n parallel feeders with undesired trip affecting probability is

$$\lambda_{Lsy_i} = \sum_{j=1}^{n, j\neq i} \delta_j \lambda_{C_j} \quad (4)$$

The component block representation of the individual terms on the right hand side of Equation (4) can be observed in Figure 3. Here, note that sympathetic faults are not assumed to overlap on a breaker fault, such as short circuit in a breaker component. This is because the active failure of the feeder breakers in the reference branching feeder structure requires the station breaker to isolate the fault thus already disconnecting all the feeders from supply.

2) Breaker operation failure

This is a protection failure case where the breaker responsible for the fault location fails to operate. There are multiple scenarios that could result in this state where a fault is not isolated by a nearby breaker, but by the backup breaker which are normally set at a lower response sensitivity to the same fault location [20]. Stuck condition, physical under-sensitivity, secondary system failure and over-sensitivity of backup protection system are such scenarios. Component ageing, thermal effects, material failure, wrong secondary equipment manoeuvres, software errors and lack of operator's situation awareness can be the causes behind these scenarios [21]. The net impact of breaker operation failures on the overall failure rate experienced at each feeder end is calculated

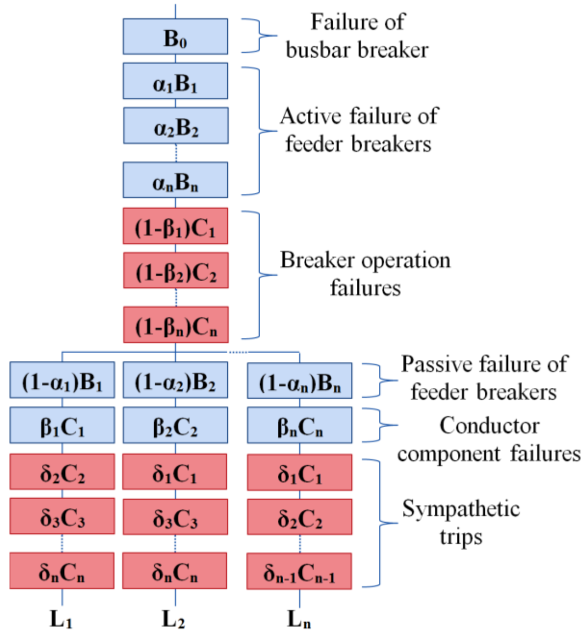

Fig. 3. Updated RBD counting in sympathetic tripping and breaker operation failure represented by component blocks and probability indices.

here with the help of a probability term β. For a conductor C_j the corresponding

$$\beta_j = \frac{active\ failure\ frequency\ of\ C_j}{total\ failure\ frequency\ of\ C_j} \quad (5)$$

Note that $(1-\beta_j)$ corresponds to the probability that a fault in conductor C_j escalates and causes the opening of station breaker B_0; hence disconnecting all feeder lines in branching feeder structure. Here β can be in the interval [0, 1] depending whether none or all failures respectively are only active component failures

So, the net impact on failure rate of feeder line i from such breaker operation failures overlapping with fault in conductor components in feeder lines is calculated as

$$\lambda_{Lg_i} = \sum_j (1-\beta_j)\lambda_{C_j} \quad (6)$$

Similar to the case of sympathetic trips, breaker operation failures overlapping with conductor component failures only are considered here. Individual component blocks representing the right hand side of Equation (6) can be observed in Figure 3. However, in practical distribution stations more than one station breaker could be present and care should be given to individually identify the probability of breaker operation failure associating to each station breaker.

C. Updated RBD for reference branching feeder structure

Figure 3 has accommodated the discussed failure modes and false trip states on the reference structure. Considering the contingency scenarios discussed until now (and remarked on Figure 3) as the total set of possible failure scenarios, the expression for the overall failure rate experienced at the end of each feeder line i can be expressed as

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSG.2016.2609684, IEEE Transactions on Smart Grid

$$\lambda_{L_i} \approx \lambda_{B_0} + (1-\alpha_i)\lambda_{B_i} + \beta_i\lambda_{C_i} + \sum_j[(\alpha_j\lambda_{B_j}) + (1-\beta_j)\lambda_{C_j}] + \sum_{j=1}^{n,j\neq i}\delta_j\lambda_{C_j} \quad (7)$$

Since failures of order higher than two are ignored, approximate net failure rate calculations can be done with Equation (7). For a fictitious system where all contingency scenarios other than active failures are absent, the designed RBD structure should adopt the values such that $\sum\alpha=1$; $\sum\beta=1$; *and* $\sum\delta=0$. Equation (7) updated for this case will be a basic failure rate model ignoring the false trip probabilities, given by

$$\lambda_{L_i} \approx \lambda_{B_0} + \lambda_{C_i} + \sum_j \lambda_{B_j} \quad (8)$$

IV. Comparison Approach and Models

Associating the equation derived from the updated RBD with failure rate of primary grid components, the variations in net failure rate experienced in different station designs can be calculated. As the number of parallel feeder lines increases, the number of constituent blocks in the resulting RBD also increases. Increase in complexity with more number of components which can undergo failure also increases the probabilities of secondary system related mal-operations. Such consequential variations derived from the model addressed from here onwards as the simulation model, are described in Section IV.A.

Similar observations entirely assessed from a real-world case called here onwards as the data model, are compared with the simulation model. This procedure demands a detailed data investigation on existing distribution system architectures and consolidation of both performance and system design related data. This is discussed in Section IV.B. The comparison of the calculations from both models can reveal the proportion of hidden failure probabilities in practical distribution systems. Here, optimisation and comparison of trends of System Average Interruption Frequency Index (SAIFI) against varying feeder capacity of busbars in substations are specifically used to calculate these probabilities.

A. Simulation Model

Figure 4 is the layout showing the main components in a substation connected to a busbar from which feeder lines branch out as in the reference feeder structure. The component layout in practical substations can differ in design and corresponding net station failure rate should be calculated. In Figure 1, there exists only one station breaker above the busbar. Here busbars at both ends of station are marked as BB_1 and BB_2. B_{01} and B_{02} are the station breakers placed on either sides if the transformer T_1. The branching feeders similar to the reference structure feed from BB_2.

In the simulation model Equation (7) is implemented with appropriate values for component failure rates in a sample distribution system as shown in Table I. Note that the failure rates corresponding to the station components shown in Figure 4 are also included to the net station failure rate calculation similar to that for B_0 in the reference feeder structure. Initially

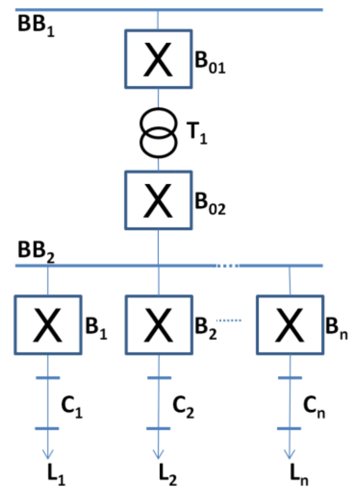

Fig. 4. Substation components and outgoing parallel feeders.

the constraint values for the hidden failure probabilities α, β and δ are kept as in the case of basic failure rate model as assumed to arrive at Equation (8). Also, a clear distinction whether the updated false trip scenarios affect either a subset or all the feeder ends is applied though Equation (7).

The hidden failure probabilities are modelled as optimisation constraints so that comparison data model modifies the effective constraint values to practical ranges of the probabilities. Other than these constraints in the constructed model, an independent parameter exists which is the length of the conductors in feeders connected to each busbar. This is why the failure rate of conductor components in feeders is recognised in 'failures per kilometre per year'.

To make the calculated trends from the simulation model comparable with the observed trends from the data model, the independent variable should be adopted from the same set of cases. Hence the feeder layout data from Table II is used as a common platform for both the simulation and data model.

The distribution of SAIFI contribution to all the customers feeding from a busbar against the number of parallel feeders in the physical layout of the same busbar is observed through the modelling, from station level. The data collection was conducted at a utility by network experts and there are options to make isolated views of feeders, busbars and stations along with only the connected customers in each respective case. Thus SAIFI contribution from these sections is also observable. For example, net failure rate and SAIFI affecting each included feeders and thus collectively busbars 1 of staion 1 are calculated for the simulation model using Equation (7) and feeder arrangement of station 1. This data point relates to the corresponding feeder count per busbar and thus the effective feeder length as recognised from Table II.

TABLE I
COMPONENT RELIABILITY DATA [2, 22]

Components	Failure rate (failure/year)	Failure rate (failure/km*year)
Busbar (BB)	0.01	
Circuit Breaker	0.0106	
Transformer	0.0222	
Conductor Line	-	0.018

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSG.2016.2609684, IEEE Transactions on Smart Grid

As the variations are modelled with the variable length of conductor, linearity is assumed for the fitting trends. Figure 5 shows this distribution for all the busbar schemes listed in Table II, when the hidden failure probabilities are as in the case of basic failure rate model ($\alpha=1;\ \beta=1;$ *and* $\delta=0$).

B. Data Model

This section introduces the consolidated results from a detailed data collection from different parts of the electric grid in Stockholm municipality, Sweden. Distribution substations and respective feeder connections of different size, layout and customer distributions from different localities were studied and corresponding data from network and utility internal sources were collected. Reported reliability performance indices relating to customers of all stations were also collected. The estimations from statistics on the interruption frequencies for all the busbars and the layout specifications of the feeders were associated. This allowed considering each busbar as a data point in the model analysis.

The Stockholm municipality, by nature of the terrain and customer size and customer occupied localities, is divided into three sub-areas; here termed as area 1, area 2 and area 3. To have an average representation of the observed grid, three stations of varying design from each of these sub-areas were studied. Table II consolidates the data hence collected and calculated for the model. The first three substations are in area 1, substation 4 to 6 in area 2 and substation 7 to 9 in area 3.

Area 1 consists of densely populated inner city environment with a high power demand per area unit. Reliability in area 1 is relatively higher than the other two. The dense power demand in combination with the limitations of medium voltage cables demand the substations in area 1 to be designed with a relatively large amount of bays, each feeding a separate medium voltage line. This renders a relatively short average cable length per feeder of just over 1000 meter. Area 2 is characterized by a suburban setting. Average length per feeder in area 2 is approximately 3500 meter, resulting in higher earth fault currents than in Area 1. Area 3 consists mainly of large apartment buildings, shops and other businesses but also

TABLE II
SUBSTATION AND FEEDER LAYOUT DATA

Substation	Total number of feeders	Station level SAIFI (failure/customer *year)	Average feeder length per station (km)	Net failure rate for feeder component (failure/year)	Number of separated busbars	Busbar	Number of feeders per busbar	Busbar level SAIFI (failure/customer *year)
1	43	0.134	1.467	0.02641	4	1	10	0.031163
						2	9	0.028047
						3	12	0.037395
						4	12	0.037395
2	44	0.602	2.047	0.03685	8	5	7	0.095773
						6	7	0.095773
						7	6	0.082091
						8	6	0.082091
						9	3	0.041045
						10	3	0.041045
						11	06	0.082091
						12	6	0.082091
3	48	0.103	1.303	0.02345	8	13	8	0.017167
						14	8	0.017167
						15	4	0.008583
						16	4	0.008583
						17	4	0.008583
						18	4	0.008583
						19	8	0.017167
						20	8	0.017167
4	15	0.271	3.169	0.05704	2	23	7	0.126467
						24	8	0.144533
5	12	0.192	6.062	0.10912	2	25	6	0.096000
						26	6	0.096000
6	18	0.456	2.156	0.03881	2	27	9	0.228000
						28	9	0.228000
7	30	0.418	4.057	0.07303	2	31	15	0.209000
						32	15	0.209000
8	26	0.451	3.796	0.06833	2	33	13	0.225500
						34	13	0.225500
9	14	0.158	5.513	0.09923	2	35	8	0.090286
						36	6	0.067714

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSG.2016.2609684, IEEE Transactions on Smart Grid

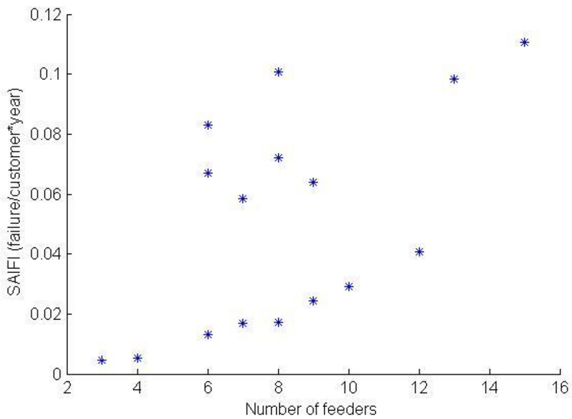

Fig. 5 . Simulated busbar level SAIFI contribution datapoints against number of feeders per busbar

of a relatively high proportion of green areas. Area 3 has the poorest reliability. The average length per feeder is higher and adds up to just over 5500 meter, considerably longer than Area 1 and Area 2. The long feeder length also results in rather high earth fault currents for the stations in Area 3, in comparison to the other areas.

The SAIFI observations for the customers from all the stations, distributed to the busbar data points should include the consequential contribution of all practical failure modes. The observations made from the data from Table II, and the identified trends are given in Figure 6. Each data point corresponds to one busbar. For example, busbar level SAIFI contribution affecting busbars 1 of station 1 is given in Table II and this data point relates to the corresponding feeder count per busbar. The data points from Figure 5 and corresponding trend line are also cast on Figure 6 for comparison.

It is evident from the comparison of the trend lines that, in practical systems, more number of failures affect the data points than active component failures alone. The relatively poorer performance of the observed real-world data compared to the basic failure rate model strongly suggests the presence of hidden failures and indicates the respective probabilities.

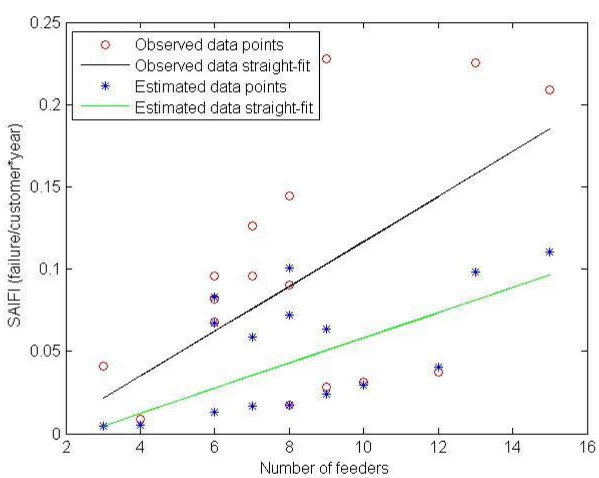

Fig. 6. Observed trend of busbar level SAIFI against number of feeders per busbar from the data for the existing system along with the simulated basic failure data rate model with $\alpha=1; \beta=1;$ *and* $\delta=0$.

Further discussion of the modelled data sets and analysis of trends are conducted in the next section.

V. Analysis and Discussion

The ranges of the hidden failure probabilities are initially analysed. As discussed in Section III.A, active failures are expected to be more frequent than other failure modes. Hence, practical values of α and β should be closer to 1 than 0. Similarly, when passive and overlapping failures are considered as rare events $(1-\alpha)$ and δ should be closer to 0 than 1. These probabilities can be derived through the comparative curve fitting optimisation. Thus α, β and δ were derived to be 0.99, 0.82 and 0.038 respectively. Figure 7 shows the trend line curve fitting after the optimal minimization. The line on top (black) represents the trend of the real-world data set observed and the simulated line below (green) is fitted to settle the optimisation constraints α, β and δ.

Even though the constraints are derived specific to the adopted model with the reference feeder structure, the resultant values fall in a practical range. Note that, in an ideal scenario, addition of parallel feeders is not expected to degrade the performance of neighbouring lines. Often this is not the case in practical systems, due to occurrence of false trips and overlapping failure events as discussed. While the modelled sympathetic trips overlapping with conductor component failures affect an additional set of customers, the breaker operation failures cascade conductor contingencies to a larger scale.

To test the identified failure probabilities, the effective proportion of secondary system related failures in the analysed case, can be separated from the whole set and compared with findings from other researches and system studies. As per the updated RBD model, three false trip categories relatable to protection system were present; passive failure events, sympathetic trips and breaker operation failures Figure 8 shows an extracted secondary related failure observation along with the total SAIFI estimation. About 36.63% of failures are thus identified to be associated to the protection system, using

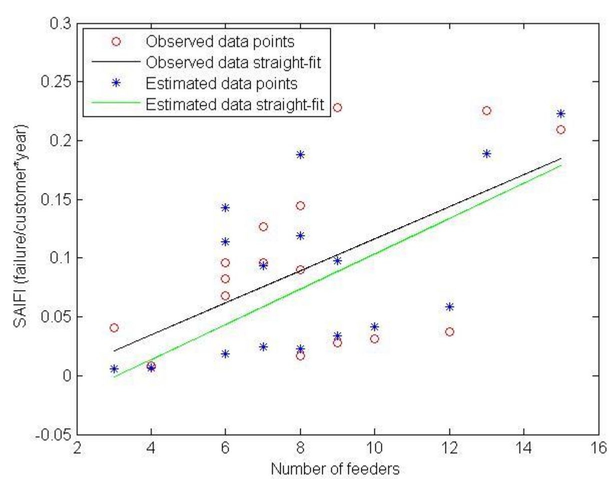

Fig. 7. Curve fitting optimisation with the observed data trend settles the simulated data at $\alpha=0.99$; $\beta=0.82$; and $\delta=0.038$.

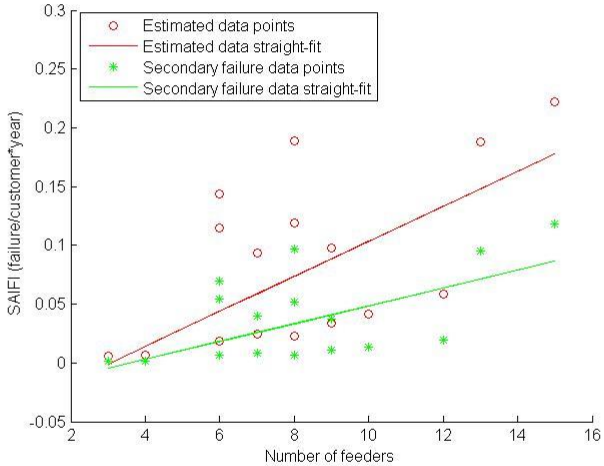

Fig. 8. Ratio of estimated total SAIFI and and SAIFI due to secondary equipment faults against number of feedes per busbar.

average calculation and this observation strongly abides with the observations by energy researchers on ten years of protection system failure statistics from [12]. The obtained understanding of secondary system impact and hidden failure probabilities can potentially provide significant improvement to maintenance and investment planning.

VI. Conclusion

The failure modes relating substation and feeder architectures along with the resultant RBD modelling were reviewed and updated with false trip scenarios present in practical systems with automation. Overlapping failure scenarios, such as sympathetic tripping and breaker operation failure were identified, and the respective contingency cascading modes were analysed. Representative probabilities were used to formulate the degree of impact on net failure rate on feeder lines due to these failure scenarios. The hidden failure probabilities derived through α, β and δ are critical since the overlapping events, even when rare, affect a larger portion of customers.

Theoretical approach and practical observations were used to construct two respective models. The models were compared, and the presence of false trips in the studied system was verified. The corresponding hidden failure probabilities were quantified. The degree of impact of secondary systems on the performance of substation architectures was derived and tested against observations from protection system failure statistics by other researchers. A strong correlation was hence confirmed.

The paper, thus takes forward the understanding of correlated failure events in power systems. The research is ongoing with extending the model to further generalizable cases, network design optimisation and economic analysis for improved maintenance decision making.

VII. Acknowledgement

The authors would like to thank the Energiforsk AB, risk analysis program for funding the project and Ellevio AB for access to case study data.

References

[1] R. Billinton and R. N. Allan, *Reliability evaluation of power systems* vol. 2: Plenum press New York, 1984.

[2] H. Hajian-Hoseinabadi, "Impacts of Automated Control Systems on Substation Reliability," *IEEE Transactions on Power Delivery*, vol. 26, pp. 1681-1691, Jul 2011.

[3] L. Pottonen, U. Pulkkinen, and M. Koskinen, "A Method for Analysing the Effect of Substation Failures on Power System Reliability," *15th PSCC, Liege*, pp. 22-26, 2005.

[4] L. R. C. Ferreira, P. A. Crossley, and R. N. Allan, "The impact of functional integration on the reliability of substation protection and control systems," *IEEE Transactions on Power Delivery*, vol. 16, pp. 83-88, 2001.

[5] S. Babu, P. Hilber, and J. H. Jurgensen, "On the status of reliability studies involving primary and secondary equipment applied to power system," in *International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)* 2014, pp. 1-6.

[6] R. Allan, "Effects of protection systems operation and failures in composite system reliability evaluation," *International Journal of Electrical Power & Energy Systems*, vol. 10, pp. 180-189, 1988.

[7] D. Dong-Li, W. Xiao-Yue, and D. Hong-Zhong, "Reliability Evaluation in Substations Considering Operating Conditions and Failure Modes," *IEEE Transactions on Power Delivery*, vol. 27, pp. 309-316, 2012.

[8] J. Meeuwsen and W. Kling, "Effects of preventive maintenance on circuit breakers and protection systems upon substation reliability," *Electric power systems research*, vol. 40, pp. 181-188, 1997.

[9] J. Lamponen, L. Haarla, and R. Hirvonen, "Component importance driven test scheduling for circuit breakers and protective relays," in *PowerTech, 2015 IEEE Eindhoven*, 2015, pp. 1-5.

[10] J. Kai and C. Singh, "New Models and Concepts for Power System Reliability Evaluation Including Protection System Failures," *IEEE Transactions on Power Systems* vol. 26, pp. 1845-1855, 2011.

[11] Y. Xingbin and C. Singh, "A practical approach for integrated power system vulnerability analysis with protection failures," *Power Systems, IEEE Transactions on*, vol. 19, pp. 1811-1820, 2004.

[12] G. Kjølle, Y. Aabø, B. Hjartsjø, and S. Statnett, "Fault statistics as a basis for designing cost-effective protection and control solutions," in *Proc. 2002 CIGRE Session*, 2002.

[13] J. Meeuwsen and W. Kling, "Substation reliability evaluation including switching actions with redundant components," *Power Delivery, IEEE Transactions on*, vol. 12, pp. 1472-1479, 1997.

[14] D. Nack, "Reliability of substation configurations," *Iowa State University*, pp. 7-8, 2005.

[15] R. Billinton and R. N. Allan, *Reliability evaluation of engineering systems*: Springer, 1992.

[16] A. Liew, "Nuisance trippings of residual current circuit breakers or ground fault protectors of power sources connected to computer and electronic loads," *Electric Power Systems Research*, vol. 20, pp. 23-30, 1990.

[17] C. Roldán-Porta, G. Escrivá-Escrivá, F. J. Cárcel-Carrasco, and C. Roldán-Blay, "Nuisance tripping of residual current circuit breakers: A practical case," *Electric Power Systems Research*, vol. 106, pp. 180-187, 2014.

[18] J. Roberts, T. L. Stulo, and A. Reyes, "Sympathetic Tripping Problem Analysis and Solutions," in *24th Annual Western Protective Relay Conference, Spokane, Washington*, 1997.

[19] A. B. Othman, A. A. Z. M. Mamdoh, and Y. H. Kamal, "Prevention of sympathetic tripping phenomena on power system by fault level management," in *Transmission and Distribution Conference and Exposition, 2008. T&# x00026; D. IEEE/PES*, 2008, pp. 1-14.

[20] X. Yiyan, M. Thakhar, J. C. Theron, and D. P. Erwin, "Review of the Breaker Failure Protection practices in Utilities," in *65th Annual Conference for Protective Relay Engineers*, 2012, pp. 260-268.

[21] S. B. Rafi, M. Fotuhi-Firuzabad, and T. S. Sidhu, "Reliability Enhancement in Switching Substations Using Fault Current Limiters," in *International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)* 2006, pp. 1-5.

[22] J. Setreus, P. Hilber, S. Arnborg, and N. Taylor, "Identifying Critical Components for Transmission System Reliability," *IEEE Transactions on Power Systems* vol. 27, pp. 2106-2115, 2012.