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Composite automated distribution system reliability model considering various automated substations

Hamze Hajian-Hoseinabadi [a,*], Mohamad Esmail Hamedani Golshan [a], Heydar Ali Shayanfar [b]

[a] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

Due to the fact that automation can significantly improve reliability of substation as well as distribution system, this paper presents a composite reliability assessment model of distribution system which illustrates the impacts of substations automated by various automation configurations on the reliability of primary distribution systems equipped with a specific distribution automation (DA) scheme. First, three architectures of substation automation systems (SASs), known as ring, cascading, and star, are reviewed and their reliability block diagrams (RBDs) are developed. Reliability assessments for five types of automated substations are then done using the event tree and the concept of expectation methods. Afterwards, a particular automated distribution scheme designated as the low interruption system (LIS) is reviewed and the interaction between the SAS and the DA is then modeled using the event tree methodology. Finally, by presenting explicit formulas for reliability evaluations of the automated distribution system, the composite reliability assessment models are completed. The proposed approach is applied to the five distribution system configurations.

1. Introduction

Significant reliability enhancement is one of the most important reasons cited for implementation of substation automation system (SAS) or distribution automation (DA) scheme. On the one hand, there are several previous works which consider reliability or availability of the substation control network topologies based on the fault tree analysis, event tree method, reliability block diagram (RBD) approach or tie sets methodology [1–10]. Moreover, the literatures [11,12] present approaches to quantitatively evaluate the reliability of various automated substation configurations in the presence of different SASs. Refs. [13–15] also present a step by step evaluation procedure to assess the impacts of a particular DA scheme on reliability indices of a typical distribution reliability test system. On the other hand, diverse investigations have been fulfilled to evaluate the reliability aspects of non-automated distribution systems [16–18]. Furthermore, the article [19] develops composite models which reflect the effect of non-automated substation on non-automated distribution system reliability indices. However, the impacts of automated substation on reliability indices of automated distribution system have not been comprehensively covered in the literature so far.

With this motivation, this paper develops a set of composite load point reliability assessment models that illustrate the impacts of automated substations, automated distribution systems and the interaction between them as shown in Fig. 1. First, the SAS reliability model including the three steps as functional modeling, hardware modeling, and function/hardware linking, is carried out. Second, the reliability model of the automated substation in the presence of a typical SAS is performed. Third, a specific automated distribution scheme designated as the Low Interruption System (LIS) is reviewed and its reliability model is investigated. The interaction between the SAS and the DA is then modeled. Finally, after modeling the interaction between automated substation and automated distribution system, the composite reliability evaluation models are developed by combining the previously mentioned reliability models.

2. SAS reliability model

A typical SAS usually comprises a set of components and different levels. The main components of a SAS are: human machine interface (HMI); industrial personal computer (IPC) and network control center server (NCCS); various substation IEDs; the bay control unit (BCU); power supply unit (PSU); communications facilities such as Ethernet switch (ESW), Ethernet interface (EI) and fiber optical connection (OPT). Also, a generic SAS involves three hierarchical levels (HLs) including the remote control point (HL

* Corresponding author. Tel./fax: +98 311 391 2451.
E-mail addresses: hamze.hajian@gmail.com (H. Hajian-Hoseinabadi), hgolshan@cc.iut.ac.ir (M.E.H. Golshan), hashayanfar@gmail.com (H.A. Shayanfar).

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Nomenclature

AI	Analogue Input
AST	automatic switching time
BCU	bay control unit
CB	circuit breaker
DA	distribution automation
DI	Digital Input
DO	Digital Output
EI	Ethernet interface
ESW	Ethernet switch
HL	hierarchical level
HMI	human machine interface
IPC	industrial personal computer
IED	intelligent electronic device
LIS	Low Interruption System
LS	local system
MST	manual switching time
MTTR	mean time to repair
NCC	network control center
NCCS	network control center server
OPT	optical connection
PSU	power supply unit
RBD	reliability block diagram
RTU	remote terminal unit
SAS	substation automation system
SCS	substation control system
SR	Synchronizing Relay
$A^{(i)}_{\text{SCS\&NCC}}$	availability of the combined block SCS & NCC regarding SAS architecture i
C_j	component number j
$F_{C_j,i}$ and $P(F_{C_j,i})$	event that the automation system can remove the effect on load point i of a fault on component C_j and its associated probability
$\overline{F_{C_j,i}}$ and $P(\overline{F_{C_j,i}})$	event that the automation system fails but the effect on load point i of a fault on component C_j is removed by manual switching action and its associated probability, respectively
$\overline{\overline{F_{C_j,i}}}$ and $P(\overline{\overline{F_{C_j,i}}})$	event that the effect on load point i of a fault on component C_j cannot be removed by the automation system or manual switching action and its associated probability, respectively
$F_{m,i}$	number of main sections of a primary feeder servicing load point i
N_{cb}	number of feeder circuit breakers connected at the same low voltage bus
NC	number of substation components
N_m	total number of main feeder sections connected at the same low voltage bus
P_{SAS}	availability of the substation automation
P_c	probability of a stuck condition of a breaker
P_{DA}	availability of the distribution automation
P_i	probability of success of component i
r_{C_j}	average repair time of component C_j
r_{cb}	repair time for a feeder circuit breaker
r_{li}	repair time for the lateral servicing load point i
r_m	repair time for a main feeder section
r_{ti}	repair time for the distribution transformer that services load point i
T_{MSW}	manual switching time
$U_{C_{j,i}}$	outage time of load point i due to a fault of component C_j
$U_{S,i}$	average annual outage time of load point i contributed by the substation itself
λ^a_{cb}	active failure rate of a feeder circuit breaker
λ^p_{cb}	passive failure rate of a feeder circuit breaker
λ_{C_j}	average failure rate of component C_j
$\lambda_{C_j,i}$	contribution to the failure rate of load point i due to a fault on component C_j
λ_{li}	failure rate of a lateral servicing load point i
λ_m	failure rate of the mth main section of a primary feeder
$\lambda_{S,i}$	average failure rate of load point i contributed by the substation itself
λ_{ti}	failure rate of a distribution transformer that services load point i

l), the station control point (HL 2) as well as the bay control point (HL 3). Three architectures, designated as ring, cascading, and star, are considered in this paper [8,20] as shown in Figs. 2–4. The more detailed explanations of these architectures can be found in [8].

Reliability modeling of the SAS can be done in three separate steps as follows. The first step is to create a functional model of the SAS. In this step, an event tree [12,21] is designed for automatic switching action. This event tree provides a tool to describe automatic switching action from a functional point of view. By this approach, various possible classes of switching action and their associated probabilities are identified. The following terms are used to classify the outcomes of the event tree:

- Success (S): all required functions including switchgear control, indications, synchronizing, and interlocking are fully available and the automatic switching action is completed successfully.
- Failure (F): the unavailable functions make it impossible to complete the required switching action. The reader is invited to refer [12] for more detailed explanations on how event trees are developed and interpreted. In the second step, the hardware of the SAS is modeled through RBD approach.

Also, it is assumed that the control functions are considered as available, if all bays are controllable from station level or remote. In other words, if we assume a substation with n bays, all n bays must be controllable to provide an available system. This assumption is shown as "n-out-of-n" in Fig. 5. By using the concept of RBD, we simplify the original RBDs shown in Fig. 5 to the one in Fig. 6. This new reduced RBD consists of BCU, which is put in series with the combined block diagram of ESWs, EIs, substation control system (SCS), and NCC named as SCS & NCC. In order to construct the combined block diagram of SCS & NCC, the redundant blocks associated with NCC and SCS are first merged and then, this resulting block diagram is combined with the blocks of ESWs and EIs (as series combination). Afterwards, the combined block of SCS & NCC is put in series with the block of BCU to produce the reduced RBD of each configuration.

By using the minimal path sets method, the availability of the combined block SCS & NCC regarding each architecture can be calculated as follows:

$$A^{(1)}_{\text{SCS\&NCC}} = P^2_{\text{ESW}}P^{n+1}_{\text{EI}}P_{\text{PSU}}P_{\text{IPC}}P_{\text{HMI}} + P^2_{\text{ESW}}P^{n+1}_{\text{EI}}P_{\text{PSU}}P_{\text{NCCS}} - P^3_{\text{ESW}}P^{n+2}_{\text{EI}}P_{\text{PSU}}P_{\text{IPC}}P_{\text{HMI}}P_{\text{NCCS}} \quad (1)$$

$$A^{(2)}_{\text{SCS\&NCC}} = P^n_{\text{ESW}}P^{n+1}_{\text{EI}}P_{\text{PSU}}P_{\text{IPC}}P_{\text{HMI}} + P^n_{\text{ESW}}P^{n+1}_{\text{EI}}P_{\text{PSU}}P_{\text{NCCS}} - P^n_{\text{ESW}}P^{n+2}_{\text{EI}}P_{\text{PSU}}P_{\text{IPC}}P_{\text{HMI}}P_{\text{NCCS}} \quad (2)$$

$$A^{(3)}_{\text{SCS\&NCC}} = P_{\text{ESW}}P^{n+1}_{\text{EI}}P_{\text{PSU}}P_{\text{IPC}}P_{\text{HMI}} + P_{\text{ESW}}P^{n+1}_{\text{EI}}P_{\text{PSU}}P_{\text{NCCS}} - P_{\text{ESW}}P^{n+2}_{\text{EI}}P_{\text{PSU}}P_{\text{IPC}}P_{\text{HMI}}P_{\text{NCCS}} \quad (3)$$

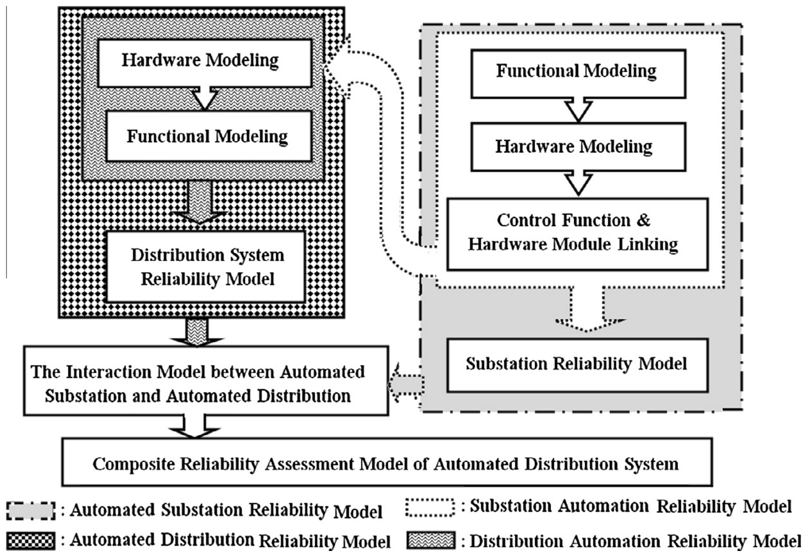


Fig. 1. Composite reliability model of automated distribution system.

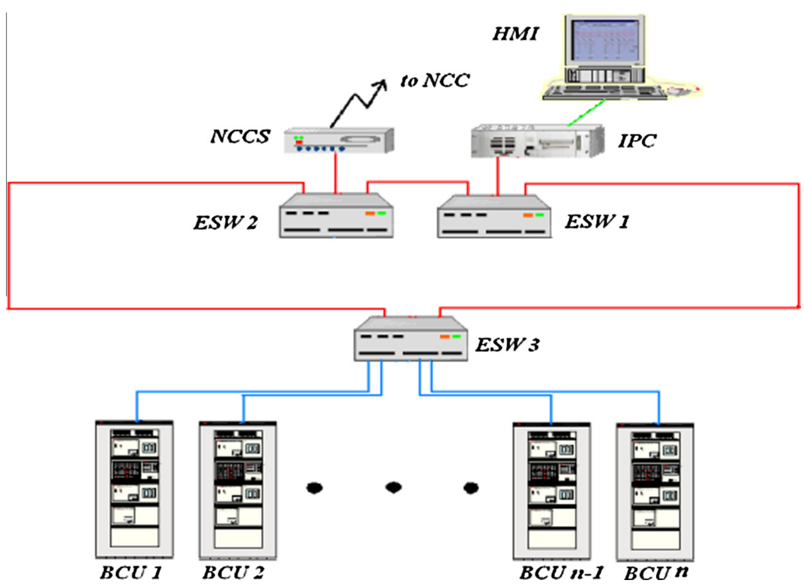


Fig. 2. Architecture 1: ring architecture.

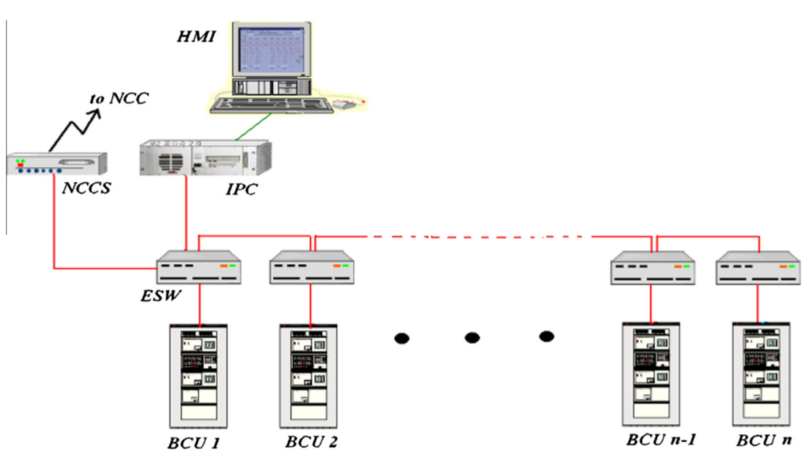


Fig. 3. Architecture 2: cascading architecture.

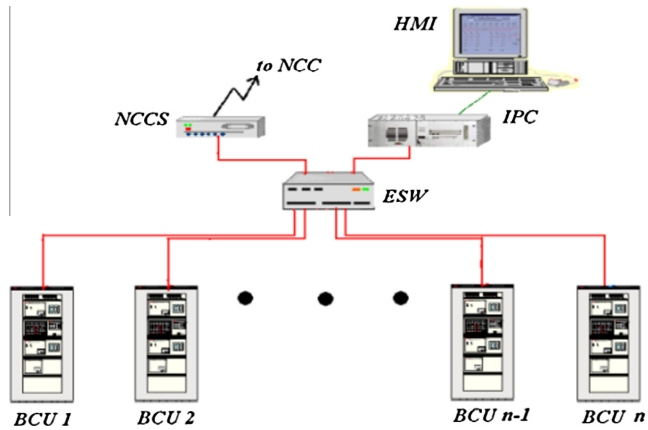
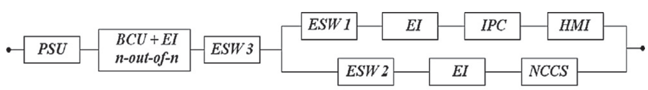
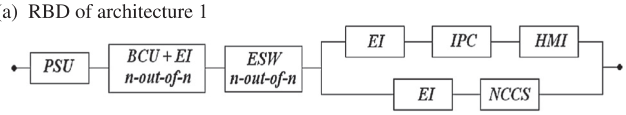


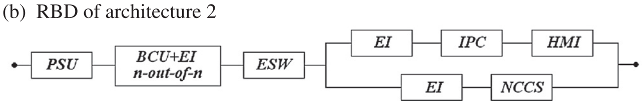
Fig. 4. Architecture 3: star architecture.



(a) RBD of architecture 1



(b) RBD of architecture 2



(c) RBD of architecture 3

Fig. 5. RBDs of various substation automation architectures.

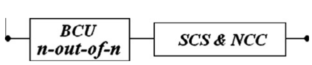


Fig. 6. Reduced RBD of each substation automation architecture.

In the third step of the SAS modeling, it is necessary to link hardware failures and their consequences in terms of failure of the functions such as switchgear control. This link can be shown in a table, as shown in Table 1 [12]. Each row of Table 1 represents a hardware module and each column represents one control function. The intersection between a row related to a hardware module and a column related to a control function is checked if failure of the hardware module causes loss of function of the control function.

The availability of the ESW is assumed to be 99.8%. The availability data of other components are also presented in Table 2 [6,12]. For these components, the time to detect and repair each failure is 48 h (MTTR = 48 h). For each SAS architecture with 10 BCUs, based on the above three steps, the probabilities associated with each class of automatic switching action including S and F are determined and shown in Table 3. It has to be noted that more detailed explanations on how these probabilities are deduced can be found in [12].

Table 2
Failure rate and unavailability of automation components.

Components	Failure rate (f/yr)	Unavailability $\times 10^{-6}$
RTU	0.087642	480
IPC, NCCS	0.070290	385
HMI, SR	0.018252	100
PSU	0.009125	50
AI board	0.007300	40
DO board	0.005475	30
DI board	0.003650	20
OPT, EI, processing unit	0.001825	10

Table 3
State availability comparison of various architectures.

Architecture	Success state (%)	Failure state (%)
Ring	98.4027	1.5973
Cascading	85.9085	14.091
Star	98.4261	1.5739

3. Automated substation reliability model

When the automatic switching time (AST) is less than 5 min, if a permanent fault on component C_j affects load point i, the following three different cases may occur:

(1) The automation system can successfully remove the effect on load point i of a fault on component C_j in less than 5 min. This condition imposes no sustained interruption on load point i.
(2) The automation system fails but the effect on load point i of a fault on component C_j can be removed by manual switching action. This condition imposes a sustained interruption on load point i by the average failure rate of component C_j and also, by manual switching time.
(3) The effect on load point i of a fault on component C_j cannot be removed by any switching action. This condition imposes a sustained interruption on load point i by average failure rate of component C_j as well as average repair time of component C_j.

The deduced formulas and procedures for determining the impacts of the introduced SAS on the substation reliability can be summarized in the following steps:

Table 1
Control function and hardware module linking.

			Control function Switchgear control	Synchronizing	Interlocking	Indication
Hardware module						
Substation and remote control level, PSU, processing unit			⊗		⊗	⊗
Bay control level	Bay 1	Analogue Input (AI) board				⊗
		Digital Input (DI) board		⊗	⊗	⊗
		Digital Output (DO) board	⊗	⊗	⊗	
		Synchronizing Relay (SR)		⊗		

(1) Determine the contribution to the sustained interruption frequency and annual outage time of load point i by component C_j on the basis of the concept of expectation method and the restoration probabilities identified in section II as [11–13]:

$$\lambda_{C_j,i} = 0 \times P(F_{C_j,i}) + \lambda_{C_j} \times P(\overline{F_{C_j,i}}) + \lambda_{C_j} \times P(\overline{\overline{F_{C_j,i}}}) \quad (4)$$

$$U_{C_j,i} = 0 \times P(F_{C_j,i}) + (\lambda_{C_j} \times T_{MSW}) \times P(\overline{F_{C_j,i}}) + (\lambda_{C_j} \times r_{C_j}) \times P(\overline{\overline{F_{C_j,i}}}) \quad (5)$$

(2) Deduce reliability indices. The load point indices can be deduced by analyzing the contribution associated with each failure event as follows:

$$\lambda_{S,i} = \sum_{j=1}^{NC} \lambda_{C_j,i}, \quad U_{S,i} = \sum_{j=1}^{NC} U_{C_j,i} \quad (6)$$

4. Distribution automation reliability model

After modeling the automated substation, the reliability model of distribution automation is now reviewed. Distribution automation is achieved through a SAS, remote control switches, remote terminal units (RTUs) and a communication system such as fiber optic cable. A communication system links the SAS and RTUs, enabling the switches to be controlled and supervised from the substation. In the following, we give details of a typical DA and its reliability assessment procedure.

4.1. Low Interruption System (LIS)

DA can be adopted using various approaches. This different approach to further minimize service interruption is designated as the "Low Interruption System" automated scheme. This approach is based on the fact that the majority of faults on distribution lines are not too large to be interrupted by the section switches. As a result, with fault, service interruptions on the un-faulted sections can be prevented by interrupting the fault current using the section switches. The more descriptions of LIS automated scheme and its main components can be found in [22].

4.2. Isolation of faulted section

Fig. 7a shows a small distribution system with the LIS automated scheme in the feeder. The system consists of several section switches (S) used to segment the feeder into sections. These switches are controlled by the RTU located beside them. The BCU installed at the substation provides supervisory monitoring and control for feeder circuit breaker (CB). When a fault occurs, the faulted section is isolated without the tripping of the CB in the substation because the fault current can be interrupted by the switch. Consequently, un-faulted sections are not affected by the fault. The isolation procedure is shown in Fig. 7b.

4.3. Reliability evaluation procedure of DA

Reliability assessment of the LIS automated scheme is presented in the [13]. It can be summarized in the following steps:

(1) The LIS automated scheme is a complex control system which contains various automation components and control actions. Therefore, the reliability evolution of this system can be a complicated process. For this reason, a modular approach is performed to assess the impacts of SAS as well as DA on distribution system reliability. This approach divides the automation system into modules which may contain a small or large number of individual components. These modules, having no shared components, are considered to be independent. As a result, the reliability of these modules can be analyzed independently. In the next step, all the modules are combined and analyzed using the event tree method. According to the modular approach, the control system for the LIS automated scheme of Fig. 7a is divided into 4 modules including three local system (LS) modules plus one SAS unit, as depicted in Fig. 7c. Each LS module is representative of the local automation equipment at the location of each switching device. In other words, each LS module contains the RTUs, communication systems, power supply units, switching devices, and fault detectors. Overall, it is obvious that an automated scheme with n switching devices has $(n + 1)$ independent modules including (n) LS modules plus one SAS unit.

(2) In this step, an event tree is designed in terms of the control component modules. If failure events occur in the control operating systems, the automation system will continue trying to restore as many load points as possible. For example, let us assume that a fault occurs between S1 and S2 in Fig. 7a. An event tree can be developed for the control procedure in terms of its component modules as shown in Fig. 7d. The paths leading to the required outcome are first identified. The probability of occurrence of each relevant path is the product of the event probabilities in the path. Finally, it is necessary is to sum the probabilities of outcomes leading to the restoration of a particular load point.

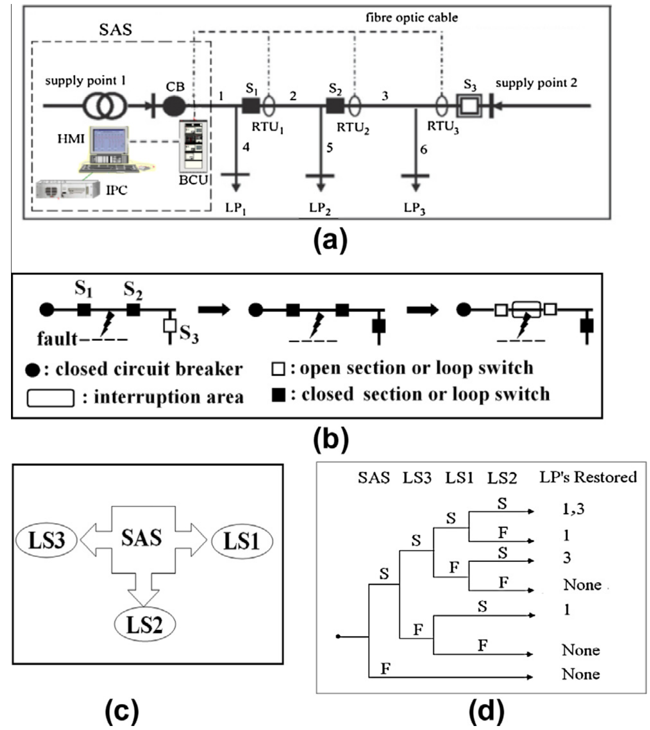


Fig. 7. (a) Typical configuration of the LIS, (b) isolation procedure on a fault between S1 and S2, (c) system modules of Fig. 7a, and (d) event tree procedure when a fault occurs between S1 and S2 (S = success, F = failure).

After discussing reliability models of automated substation and DA, a composite model for reliability assessment of the automated distribution system supplied by the automated substations is presented in the following section.

5. Composite automated distribution system reliability model

The literature [19] develops a set of composite distribution system reliability evaluation models that can be only applied to a non-automated distribution system. However, we expand them and present a set of enhanced equations which reflect the effect of automated distribution substations equipped with various SASs, primary distribution systems equipped with the specific DA, and the interaction between them.

First, five types of distribution systems, designated as link arrangement, basic radial, open/closed loop, and primary network system, which are the RBT Bus4 system [23], are shown in Figs. 8–11, respectively. The more detailed explanations of these configurations can be found in [19].

When a fault occurs, interruption frequency and restoration time of a specific load point can be varied due to the operating procedure speed of the implemented SAS, DA as well as availability of the automatic control functions of the applied control system. For example, if an active failure occurs on a feeder CB, all the feeder breakers connected at the same low voltage bus must trip out. The low voltage bus then loses continuity of supply, and the load points supplied by the bus suffer an outage event. However, if SAS is available and AST is less than 5 min, the switching operations required to restore service can be achieved automatically and therefore, the faulted CB is isolated and the other tripped ones are re-closed immediately. As a result, the load points supplied by the de-energized bus do not suffer any sustained interruptions. The definitions and classifications of interruptions can be found in [24]. As another example, when a fault occurs, the SAS transmits a control signal to the RTU to close the normally open loop switch. Next, the SAS transmits a control signal to open switches on the source and load sides of the faulted section. All these operations are completed before the CB trips out. According to these explanations, the composite load point reliability indices of the automated distribution system design K, which is represented as λ_{LPi}^{K} and U_{LPi}^{K}, can be expressed as Eqs. (7–13). $m \notin f_i\,(m \notin d_i)$ denotes that the main feeder (the main section) serving load point i is excluded. Also, in these equation, $m \leqslant m_i$ represents the main section located upstream of load point i, and $m_i + 1 \leqslant m \leqslant F_{m,i}$ is downstream of load point i.

6. Case studies and discussions

The application of the reliability assessment models presented in the previous sections is illustrated using three SAS architectures, five substation designs (shown in Fig. 12) and five distribution networks (Figs. 8–11). The reliability data of substation equipments are presented in Table 4 [12,19]. Moreover, the required reliability parameters and load point data regarding the distribution systems are given in [23]. It is assumed that the disconnect switches in Figs. 8–11 are completely reliable for simplicity. Also, all CBs

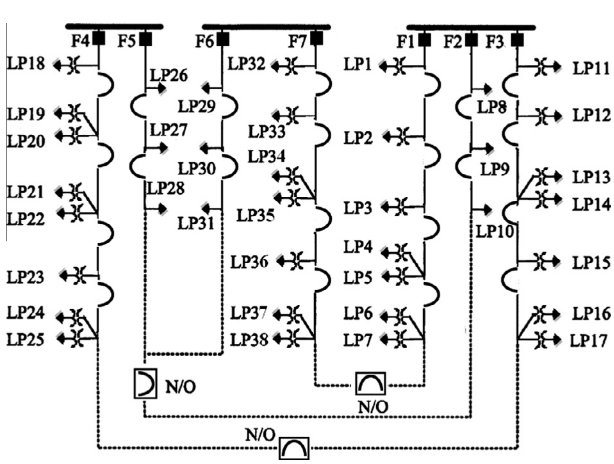


Fig. 8. Design A: Link arrangement system.

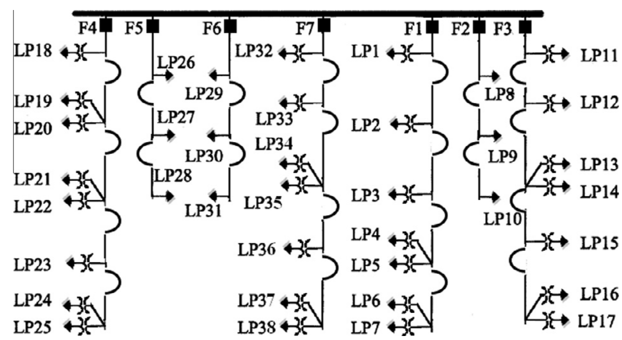


Fig. 9. Design B: Basic radial system.

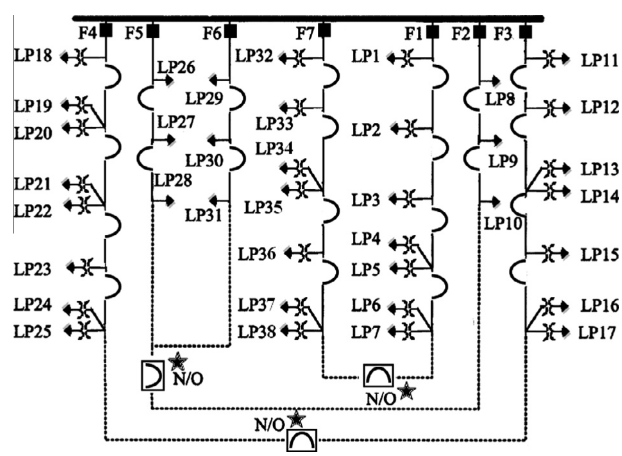


Fig. 10. Design C: Open loop system, design D: Closed loop system (the switches marked with ∗should be replaced with normally closed breakers).

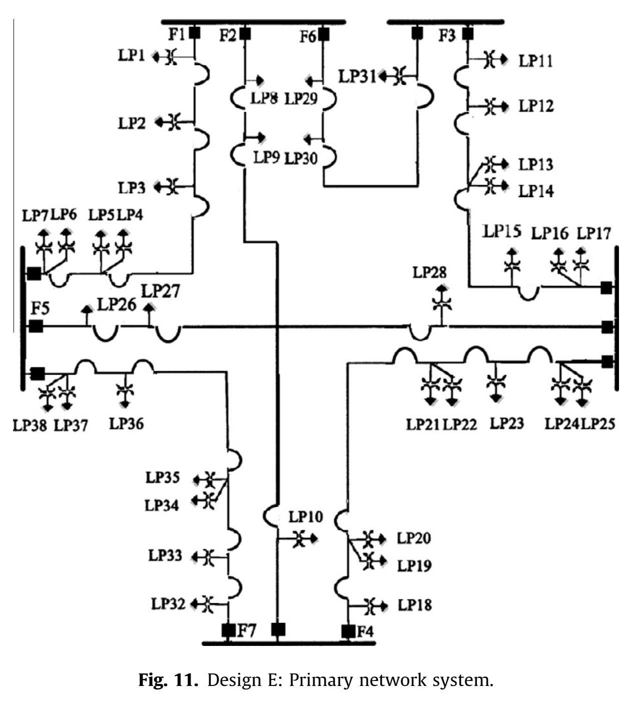


Fig. 11. Design E: Primary network system.

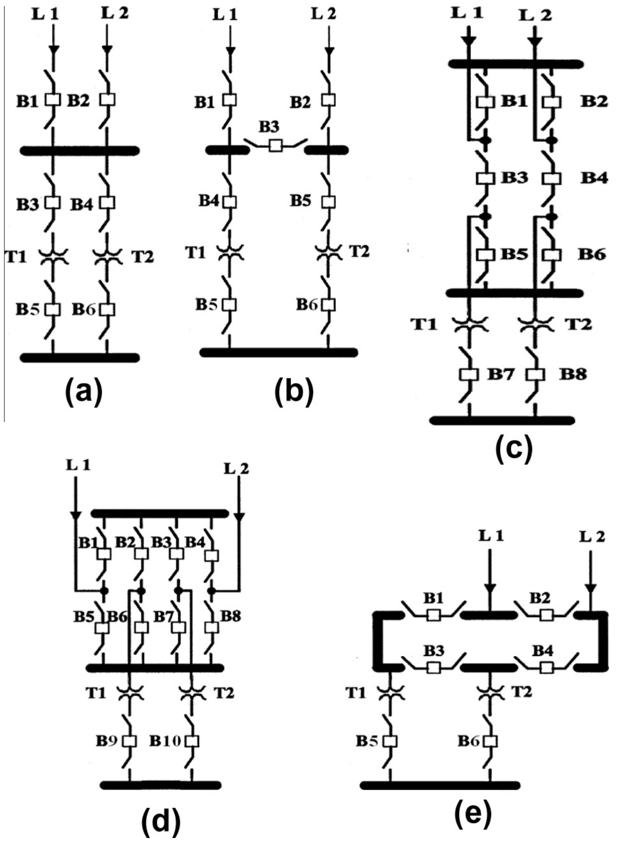


Fig. 12. Single line diagrams of five substation configurations. (a: single bus (design a), b: sectionalized single bus (design b), c: breaker-and-a-half (design c), d: double bus double breaker (design d), and e: ring bus (design e)).

Table 4
Substation components reliability data.

Components	λ_A (/yr)	λ_P (/yr)	λ_M (/yr)	MTTR (h)	MTTM (h)	P_c
Transformer	0.04	–	1.0	40	120	–
Breaker	0.01	0.01	1.0	12	96	0.05
Bus bar	0.01	–	0.5	6	8	–

shown in Fig. 12 are assumed to be normally closed. On the other hand, in the studies presented in this paper, any failures in the fuses, section and loop switches are ignored. It is also assumed that a spare transformer is available for the low voltage transformer in order to reduce the effect of transformer failure. In order to assess the impacts of the five automated substations on the distribution system reliability, various comparative case studies are conducted. A classification of these case studies is tabulated in Table 5. In all these cases, it is assumed that the total manual switching time is 1 h. This is the time required to restore the interrupted load points between the supply point and the point of isolation before the repair process has been completed. Automation features are not included in the study results presented for cases α.β.1. In cases α.β.2, α.β.3, and α.β.4, the SAS but not DA is implemented. Finally, the impacts of using automation features on system reliability indices are illustrated in cases α.β.5 to α.β.7. Table 6 shows the basic load point indices of LP7 for all case studies described in Table 5. Furthermore, Fig. 13 presents system reliability indices for the five types of primary distribution system in combination with three configurations of mentioned substations. Based on the results, several remarks can be drawn: Table 4 shows that interruption frequency and the annual outage time of LP7 decrease significantly when SAS is implemented in the test systems. This improvement is the same for both architectures of star and ring, although in the case of cascading configuration, this enhancement is rather smaller. For example, comparison of cases α.β.1 and α.β.2 in Table 4 shows that the decrease in the annual down time ranges from 4.4% (designs E) to 21.6% (design C.a). Also, Table 4 shows that the failure rate index of load point 7 in distribution system design E has a 9.1% decrease and the similar value in design C.a has a 41.1% decrease. Concurrently employing both the SAS and DA will considerably improve the load point and system reliability worth indices. For example, comparing the results shown in Table 4 for cases α.β.1 and α.β.7 shows that the failure rate of load point 7 in distribution system design A.e has a 72.2% decrease and the similar value in design C.d has a 77.4% decrease. Furthermore, it can be seen that the trend of reliability improvements for system is similar to load point indices shown in Table 4. Comparing cases D.a.1 and D.a.4, which presents the impact of the SAS (in the absence of the DA) on distribution reliability indices, shows 39.5% and 20.4% decrease in SAIFI and SAIDI, respectively. This improvement can be predominantly higher when both automation systems (SAS and DA) are implemented. For instance, comparing cases C.e.1 and C.e.7 shows 77.1% and 40.8% decrease in SAIFI and SAIDI, respectively. Furthermore, the system reliability indices are significantly affected by DA more than SAS. Moreover, SAIFI is more sensitive to automation features than SAIDI. The primary network supplied by the substation equipped with star/ring SAS has better reliability indices than the others, while non-automated basic radial produces the worst case.

$$\begin{aligned}\lambda^{A,C}_{LPi} = {} & \underbrace{\lambda_{S,i}}_{\text{effect of substation}} + \underbrace{(1-P_{SAS})N_{cb}\lambda^{a}_{cb}}_{\text{effect of primary protection}} \\ & + \underbrace{(1-P_{SAS})P_c\sum\nolimits_{m=1,m\notin f_i}^{N_m}(\lambda_m)}_{\text{effect of backup protection}} \\ & + \underbrace{(1-P_{SAS})\lambda^{p}_{cb} + (1-P_{DA})\sum\nolimits_{m=1,m\notin d_i}^{F_{m,i}}(\lambda_m) + \lambda_m + \lambda_{ti} + \lambda_{li}}_{\text{effect of primary distribution system}} \end{aligned} \quad (7)$$

$$\begin{aligned}U^{A,C}_{LPi} = {} & \underbrace{U_{S,i}}_{\text{effect of substation}} + \underbrace{(1-P_{SAS})N_{cb}\lambda^{a}_{cb}T_{MSW}}_{\text{effect of primary protction}} \\ & + \underbrace{(1-P_{SAS})P_c\sum\nolimits_{m=1,m\notin f_i}^{N_m}(\lambda_m T_{MSW})}_{\text{effect of backup protection}} \\ & + \underbrace{(1-P_{SAS})\lambda^{p}_{cb}T_{MSW} + (1-P_{DA})\sum\nolimits_{m=1,m\notin d_i}^{F_{m,i}}(\lambda_m T_{MSW}) + \lambda_m r_m + \lambda_{ti} r_{ti} + \lambda_{li} r_{li}}_{\text{effect of primary distribution system}} \end{aligned} \quad (8)$$

Table 5
Classification of case studies (α = A, B, C, D, or E; β = a, b, c, d, or e).

Distribution network type	Substation design	No automation	With SAS					
			Without DA			With DA		
			Ring	Cascading	Star	Ring	Cascading	Star
α	β	α.β.1	α.β.2	α.β.3	α.β.4	α.β.5	α.β.6	α.β.7

Table 6
Load point reliability indices of LP7 regarding various cases $\delta.\eta$.

	λ_{LPi} (f/yr)							U_{LPi} (min/yr)						
δ	η = 1	2	3	4	5	6	7	1	2	3	4	5	6	7
A.a	0.6002	0.4289	0.4484	0.4289	0.1732	0.2218	0.1731	67.209	56.935	58.103	56.933	41.592	44.508	41.586
A.b	0.5631	0.4205	0.4367	0.4204	0.1648	0.2101	0.1647	64.987	56.429	57.402	56.427	41.088	43.806	41.082
A.c	0.5465	0.4121	0.4274	0.4121	0.1564	0.2008	0.1563	63.988	55.927	56.843	55.925	40.584	43.248	40.578
A.d	0.5467	0.4071	0.4230	0.4071	0.1514	0.1963	0.1513	64.005	55.625	56.578	55.623	40.284	42.978	40.278
A.e	0.5686	0.4137	0.4313	0.4137	0.1580	0.2047	0.1579	65.318	56.024	57.08	56.021	40.68	43.482	40.674
B.a	0.7322	0.4507	0.4827	0.4506	0.4507	0.4827	0.4506	159.42	142.53	144.45	142.53	142.54	144.46	142.53
B.b	0.6951	0.4423	0.4710	0.4422	0.4423	0.4710	0.4422	156.69	141.52	143.25	141.52	141.52	143.24	141.51
B.c	0.6785	0.4339	0.4617	0.4338	0.4339	0.4617	0.4338	153.57	138.90	140.56	138.89	138.89	140.56	138.89
B.d	0.6787	0.4289	0.4573	0.4288	0.4289	0.4573	0.4288	153.89	138.90	140.61	138.90	138.90	140.60	138.90
B.e	0.7006	0.4355	0.4656	0.4354	0.4355	0.4656	0.4354	155.18	139.27	141.08	139.27	139.27	141.08	139.27
C.a	0.7322	0.4310	0.4653	0.4309	0.1753	0.2386	0.1752	83.820	65.752	67.806	65.748	50.412	54.210	50.406
C.b	0.6951	0.4226	0.4536	0.4225	0.1669	0.2269	0.1668	81.093	64.741	66.600	64.737	49.398	53.004	49.392
C.c	0.6785	0.4142	0.4442	0.4141	0.1585	0.2176	0.1584	77.970	62.114	63.916	62.110	46.770	50.322	46.764
C.d	0.6787	0.4092	0.4398	0.4091	0.1535	0.2132	0.1534	78.294	62.121	63.959	62.117	46.782	50.364	46.770
C.e	0.7006	0.4158	0.4482	0.4158	0.1601	0.2216	0.1600	79.578	62.490	64.432	62.486	47.148	50.838	47.142
D.a	0.7122	0.4307	0.4627	0.4306	0.1749	0.2359	0.1747	82.620	65.733	67.653	65.729	50.382	54.048	50.376
D.b	0.6751	0.4223	0.4510	0.4222	0.1664	0.2243	0.1663	79.893	64.722	66.447	64.718	49.374	52.842	49.368
D.c	0.6585	0.4139	0.4417	0.4138	0.1581	0.2149	0.1579	76.770	62.095	63.763	62.092	46.746	50.154	46.734
D.d	0.6587	0.4089	0.4373	0.4088	0.1530	0.2105	0.1529	77.094	62.102	63.806	62.098	46.752	50.202	46.746
D.e	0.6806	0.4155	0.4456	0.4154	0.1597	0.2189	0.1596	78.378	62.471	64.279	62.467	47.124	50.676	47.112
E.a	0.4300	0.3906	0.3951	0.3906	0.1348	0.1684	0.1347	57.000	54.638	54.907	54.638	39.288	41.304	39.282
E.b	0.4300	0.3906	0.3951	0.3906	0.1348	0.1684	0.1347	57.000	54.638	54.907	54.638	39.288	41.304	39.282
E.c	0.4300	0.3906	0.3951	0.3906	0.1348	0.1684	0.1347	57.000	54.638	54.907	54.638	39.288	41.304	39.282
E.d	0.4300	0.3906	0.3951	0.3906	0.1348	0.1684	0.1347	57.000	54.638	54.907	54.638	39.288	41.304	39.282
E.e	0.4300	0.3906	0.3951	0.3906	0.1348	0.1684	0.1347	57.000	54.638	54.907	54.638	39.288	41.304	39.282

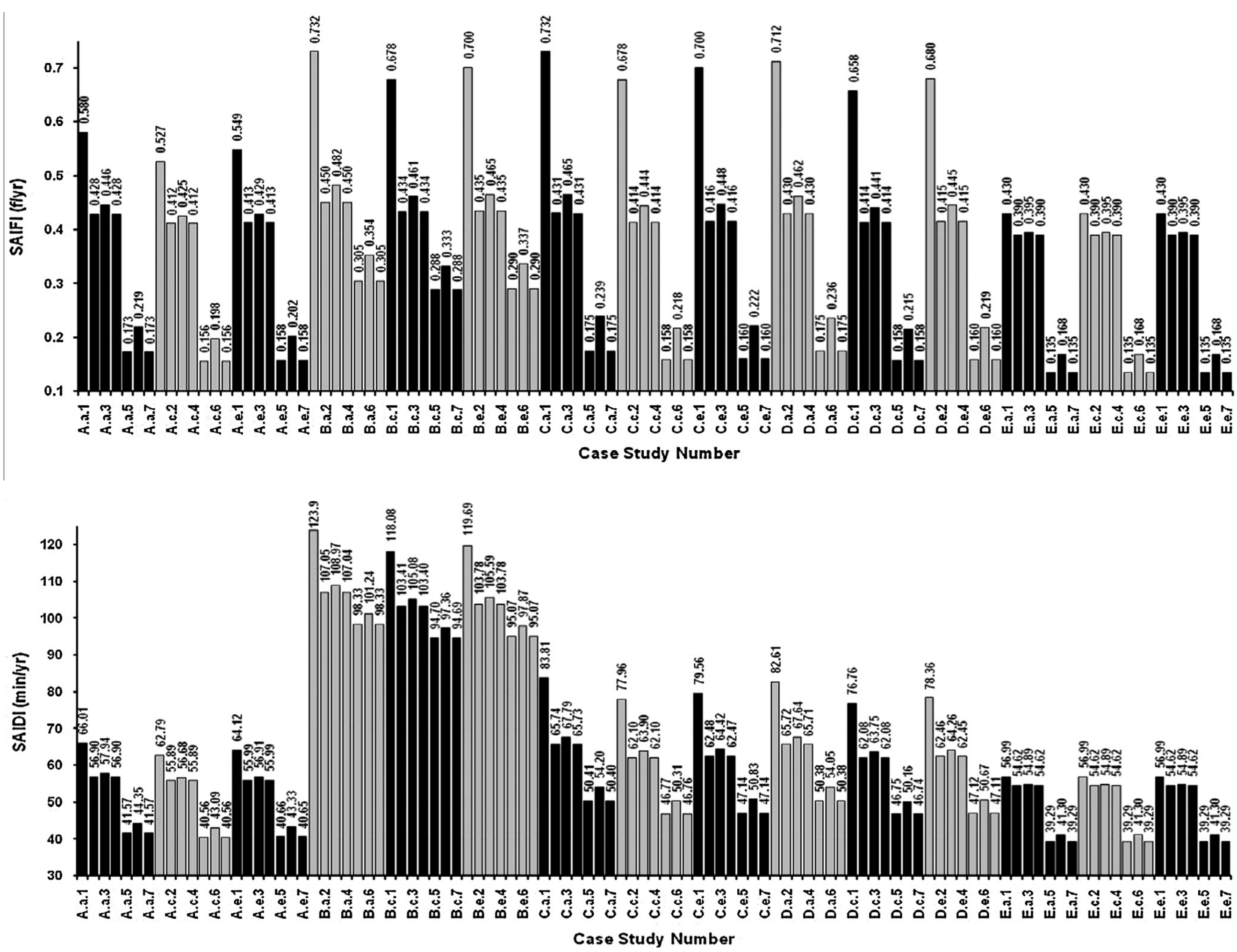


Fig. 13. System indices comparison for various case studies.

$$\lambda_{LPi}^{B} = \underbrace{\lambda_{S,i}}_{effect\ of\ substation} + \underbrace{\lambda_{cb}^{a}((1-P_{SAS})(N_{cb}-1)+1)}_{effect\ of\ primary\ protction} + \underbrace{(1-P_{SAS})P_c\sum_{m=1,m\notin f_i}^{N_m}(\lambda_m)}_{effect\ of\ backup\ protection} + \underbrace{\lambda_{cb}^{p} + \sum_{m=1}^{m_i}(\lambda_m) + (1-P_{DA})\sum_{m=m_i+1}^{F_{m,i}}(\lambda_m) + \lambda_{ti} + \lambda_{li}}_{effect\ of\ primary\ distribution\ system} \quad (9)$$

$$U_{LPi}^{B} = \underbrace{U_{S,i}}_{effect\ of\ substation} + \underbrace{\lambda_{cb}^{a}((1-P_{SAS})(N_{cb}-1)T_{MSW}+r_{cb})}_{effect\ of\ primary\ protction} + \underbrace{(1-P_{SAS})P_c\sum_{m=1,m\notin f_i}^{N_m}(\lambda_m T_{MSW})}_{effect\ of\ backup\ protection} + \underbrace{\lambda_{cb}^{p}r_{cb} + \sum_{m=1}^{m_i}(\lambda_m r_m) + (1-P_{DA})\sum_{m=m_i+1}^{F_{m,i}}(\lambda_m T_{MSW}) + \lambda_{ti}r_{ti} + \lambda_{li}r_{li}}_{effect\ of\ primary\ distribution\ system} \quad (10)$$

$$\lambda_{LPi}^{D} = \underbrace{\lambda_{S,i}}_{effect\ of\ substation} + \underbrace{(1-P_{SAS})N_{cb}\lambda_{cb}^{a}}_{effect\ of\ primary\ protction} + \underbrace{(1-P_{SAS})P_c\sum_{m=1,m\notin f_i}^{N_m}(\lambda_m)}_{effect\ of\ backup\ protection} + \underbrace{(1-P_{DA})\sum_{m=1,m\notin d_i}^{F_{m,i}}(\lambda_m) + \lambda_m + \lambda_{ti} + \lambda_{li}}_{effect\ of\ primary\ distribution\ system} \quad (11)$$

$$U_{LPi}^{D} = \underbrace{U_{S,i}}_{effect\ of\ substation} + \underbrace{(1-P_{SAS})N_{cb}\lambda_{cb}^{a}T_{MSW}}_{effect\ of\ primary\ protction} + \underbrace{(1-P_{SAS})P_c\sum_{m=1,m\notin f_i}^{N_m}(\lambda_m T_{MSW})}_{effect\ of\ backup\ protection} + \underbrace{(1-P_{DA})\sum_{m=1,m\notin d_i}^{F_{m,i}}(\lambda_m T_{MSW}) + \lambda_m r_m + \lambda_{ti}r_{ti} + \lambda_{li}r_{li}}_{effect\ of\ primary\ distribution\ system} \quad (12)$$

$$\lambda_{LPi}^{E} = \underbrace{\lambda_{S,i}}_{effect\ of\ substation} + \underbrace{2(1-P_{SAS})\lambda_{cb}^{a}}_{effect\ of\ primary\ protction} + \underbrace{(1-P_{DA})\sum_{m=1,m\notin d_i}^{F_{m,i}}(\lambda_m) + \lambda_m + \lambda_{ti} + \lambda_{li}}_{effect\ of\ primary\ distribution\ system,\quad U_{LPi}^{E}=U_{S,i}} + \underbrace{2(1-P_{SAS})\lambda_{cb}^{a}T_{MSW}}_{effect\ of\ primary\ protction} + \underbrace{(1-P_{DA})\sum_{m=1,m\notin d_i}^{F_{m,i}}(\lambda_m T_{MSW}) + \lambda_m r_m + \lambda_{ti}r_{ti} + \lambda_{li}r_{li}}_{effect\ of\ primary\ distribution\ system} \quad (13)$$

7. Conclusion

This paper comprehensively proposes a set of composite reliability evaluation models taking into account the effects of substation automation systems, a particular distribution automation scheme, automated substations, automated primary distribution systems, and the interaction between them. In order to demonstrate the proposed technique, various comparative studies were directed using three configurations of SASs, five automated substations, a specific automated distribution scheme designated the LIS, and five types of distribution system. As the first fact, the results show that SAS can play an important role in the enhancement of the system reliability indices. This improvement is the same for both architectures of star and ring, although in the case of cascading configuration, this enhancement is smaller. Moreover, the study results indicate that the load point and system reliability indices are significantly improved by implementing both DA and SAS schemes. For example, in the absence of any kinds of automation systems, the basic radial type has the worst reliability indices; however, when this configuration is equipped with SAS and DA, its indices are better than those of the non-automated primary network system. The results also reflect the fact that the automated primary network supplied by the substations equipped with star/ ring SAS has the higher reliability than others, next is the automated link arrangement supplied by the automated substation designs c/d, and the worst case is non-automated basic radial distribution system. Overall, the proposed method is practical to rank various automated distribution systems based on their reliability, indicating the benefits of employing the automated substation for the distribution system performance improvement.

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