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Composite automated distribution system reliability model considering various automated substations

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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

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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
$A^{(i)}_{\mathrm{SCS\&NCC}}$	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 *m*th 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:

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

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

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