Impacts of Fault Diagnosis Schemes on Distribution System Reliability

Shahram Kazemi, *Member, IEEE*, Matti Lehtonen, and Mahmud Fotuhi-Firuzabad, *Senior Member, IEEE*

***Abstract*—Design and development of fault diagnosis schemes (FDS) for electric power distribution systems are major steps in realizing the self-healing function of a smart distribution grid. The application of the FDS in the electric power distribution systems is mainly aimed at precise detecting and locating of the deteriorated components, thereby enhancing the quality and reliability of the electric power delivered to the customers. The impacts of two types of the FDS on distribution system reliability are compared and presented in this paper. The first type is a representative of the FDS which diagnoses the deteriorated components after their failing. However, the second type is a representative of the FDS which can diagnose the failing components prior to a complete breakdown and while still in the incipient failure condition. To provide quantitative measures of the reliability impacts of these FDS, the comparative and sensitivity case studies are conducted on a typical Finnish urban distribution network.**

***Index Terms*—Fault diagnosis schemes, fault management, power distribution system, reliability assessment, smart grid.**

I. Nomenclature

ASUI	Average system unavailability index.
ECOST	Expected cost of the power interruptions imposed on the customers.
EENS	Expected energy not supplied.
FDS	Fault diagnosis schemes.
FMA	Fault management activities.
NCS	Total number of the cable sections in the distribution network under study.
PAFR	Average share of the passive failure events in the total failure events of the cable sections
PARR	Average ratio of the time required for repairing the passively failed cable sections to that required for repairing the actively failed cable sections.
PFDS	Proactive fault diagnosis schemes.
RFDS	Reactive fault diagnosis schemes.
SAIDI	System average interruption duration index.
SAIFI	System average interruption frequency index.
SGS	Smart grid simulator.
r^i_{Active}	Time required to repair the cable section number i, when it encounters with an active failure condition.
r^i_{Passive}	Time required to repair the cable section number i, when it encounters with a passive failure condition.
$\lambda^i_{\mathrm{Active}}$	Active failure rate of the cable section number i.
$\lambda^i_{\mathrm{Passive}}$	Passive failure rate of the cable section number i.

Manuscript received February 21, 2011; revised June 06, 2011; accepted November 05, 2011. Date of publication February 29, 2012; date of current version May 21, 2012. This work was supported in part by the Fortum Foundation in Finland under Grant B2-11-032. Paper no. TSG-00054-2011.

S. Kazemi is with the Departments of Electrical Engineering at Sharif University of Technology, Tehran, Iran, and Aalto University, Espoo, Finland (e-mail: shahram.kazemi@ieee.org).

M. Lehtonen is with the Department of Electrical Engineering at Aalto University, Espoo, Finland (e-mail: matti.lehtonen@aalto.fi).

M. Fotuhi-Firuzabad is with the Department of Electrical Engineering at Sharif University of Technology, Tehran, Iran (e-mail: fotuhi@sharif.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2011.2176352

II. Introduction

Electric utilities have traditionally performed the fault diagnosis activities based on the customers' outage calls. Upon receiving the trouble calls from the customers, the operators look at the network configuration map and the protection design manual to determine the outage area. Then, a repair crew has to be sent to patrol the outage area. When faced with a tripped circuit breaker and no indication as to where the fault lies, a repair crew has a range of options by which the faulted section is identified. In a manually operated distribution network, either "feeder splitting and fault reignition method" or "feeder splitting and insulation test method" can be used for finding the faulted section. The diagnosis of the fault in these manners can be an unsafe, rigorous and time-consuming task, which finally results in the poor quality and reliability of electric power delivered to the customers. In order to overcome these issues, various types of the FDS have been developed across the globe [1]. Some of the FDS mainly work based on the measurements of voltages and currents signals provided by devices such as the fault passage indicators installed along the distribution feeders [2]–[4]. Other FDS normally operate based on algorithms that use measurements of voltages and currents signals provided by intelligent electronic devices located at a main substation [5]–[7]. The majority of the FDS which have been developed over the past two decades are mainly RFDS [1]. These schemes diagnose the failed component after a complete breakdown condition and following the reaction of protective devices against the over-current faults and other similar abnormal situations. Although the fault diagnosis activities can now be accomplished faster and more precisely than before, but the component failures still result in extensive outages, substantial expensive equipment repair and replacement, and unsafe conditions for the public. However, regardless of some failure modes of the components that are unavoidable (such as accidents), there are many other failure modes of the components that often develop over days to months before a complete breakdown occurs [8]. This fact has been the basic idea for developing the PFDS [9], [10]. Using the PFDS, the failing components can be detected while still in their incipient failure conditions. As a result, a repair crew can be dispatched to repair or replace the failing component, before a complete breakdown occurs. Hence, not only the quality and reliability of electric power delivered to the customers are improved but also the substantial expensive equipment repair and replacement and possible unsafe conditions can be mitigated.

Although many techniques and formulas have been purposed in the literatures for developing the FDS, but always there has been a lack of well documented materials related to the reliability impacts of such automation schemes. This issue has been the main motivation for developing this paper. It aims to compare the effects of representatives of the RFDS and the PFDS on the distribution system reliability. The paper is organized as follows. After this introduction, the reliability evaluation procedure is discussed in Section III. Next, in Section IV, the results of comparative and sensitivity case studies which have been conducted on a typical Finnish urban distribution network are presented and discussed. Finally, a conclusion is provided in Section V.

III. Reliability Evaluation Procedure

When comparing various reliability improvement measures, it is necessary to perform a course of quantitative reliability assessment studies in the related decision making process. In such studies, the processes that are followed for managing the faulted network can affect the approach to these studies. When an electric power distribution network encounters a fault condition, specific activities designated as fault management activities are required to be carried out. Typical FMA involve the following processes [11]:

- protection system reaction;
- fault notification;
- approximate fault location;
- decision making;
- repair crew dispatching and traveling;
- patrolling;
- fault isolation;
- service restoration;
- repair or replacement;
- return to normal operation.

Distribution system reliability assessment is not a difficult task as long as the detailed modeling of the FMA is not required to be considered in the related analyses. However, the reliability evaluation procedure is complicated when the procedures involved in the FMA are altered due to the characteristics

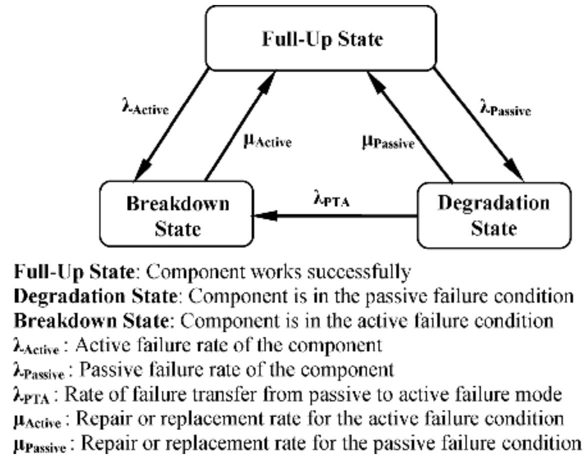

Fig. 1. A three-state Markov model for representing the failure modes of a component of an electric power distribution network.

of implemented solutions. An electric utility can invest on a specific automation scheme to perform one or some of the FMA in more efficient manner compared to what they have been doing so far. The current paper is mainly dealing with two automation schemes that have been developed and implemented in the real fields for automating two stages of the FMA, namely fault notification and approximate fault location activities. Employing either one of these automation schemes will affect the procedures of electric utilities for performing the FMA. As a result, in this situation, the detailed reliability modeling of the FMA is required to gain the desired results. In addition, a suitable reliability model should be used for representing the failure modes of the components. A three-state Markov model has been developed by the authors for reliability studies concerned in this paper, as shown in Fig. 1.

In the model shown in Fig. 1, the "Full-Up State" represents the normal operating status of a component. In contrast, the "Breakdown State" and the "Degradation State" represent the failure conditions. The breakdown state corresponds to an active failure situation in which the component encounters with a severe damage. Therefore, it is de-energized by means of protection devices and forced to the outage condition. On the other hand, the degradation state represents the passive failure situation at which the component malfunctions, but the damage is still in the incipient condition and needs more time to completely breakdowns. The component leaves its normal operating state to either the active failure state or the passive failure state by rates equal to $\boldsymbol{\lambda}_{\mathbf{Active}}$ and $\boldsymbol{\lambda}_{\mathbf{Passive}}$, respectively. A passively failed component will finally become an actively failed component if the necessary repair or replacement activities are not carried out well in advance. This phenomenon has been represented by the transition rate $\boldsymbol{\lambda}_{\mathbf{PTA}}$ in the model shown in Fig. 1. The time periods required for returning a component to its normal operating status, when it is either in the active failure state or the passive failure state, may not be the same. Therefore, two different repair or replacement rates have been assigned to the failure states, i.e., $\boldsymbol{\mu}_{\mathbf{Active}}$ and $\boldsymbol{\mu}_{\mathbf{Passive}}$. The parameters of the proposed model can be estimated from the statistical analysis of the failure cause of components and engineering practices.

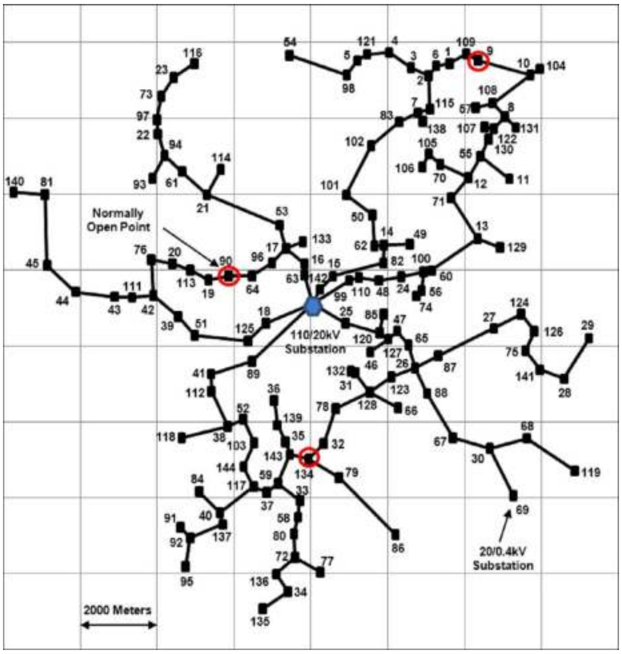

Fig. 2. Single-line diagram of a typical Finnish urban distribution network which is used as a test system for quantitative reliability assessment studies.

A software package designated as "Smart Grid Simulator" (SGS) is used for directing the reliability case studies concerned in this paper. The SGS has been developed by the first author to simulate the issues related to the smart grids. The reliability assessment module of the SGS mainly relies on the reliability evaluation techniques which have been already developed by the authors in this area, e.g., [11]–[13]. More detailed information about the reliability evaluation techniques underlying the SGS can be found in [14]. Failure modes of each component of the network under study are simulated in the SGS. For each failure mode, the detailed reactions of protection and automation schemes and their impacts on the different stages of the FMA are evaluated automatically. As a result, the time periods required for accomplishing each step of the FMA and manners in which different load points have been affected are determined. Based on these outcomes, the SGS calculates the reliability indices.

IV. Study Results

A typical Finnish urban distribution network is used in this paper as a test system for quantitative reliability assessment studies. The single-line diagram of the test system is shown in Fig. 2. Table I contains the basic data of this test system. More detailed information about this test system can be found in [14]. There are 144 distribution substations (20/0.4 kV) in this network which are supplied through 6 underground cable feeders originated from a subtransmission substation (110/20 kV).

In order to assess the reliability performance of the test system when the RFDS and the PFDS are employed, the following cases are considered in the analyses:

1) Case 1: The base case which aims to show the reliability performance of the test system when there is no automation scheme for health monitoring of the network components. In this situation, upon a component failure, the power interruptions are notified by the network operators through outage calls received from the customers. Then repair crews are sent to the outage area. They halve the downstream sections of the operated circuit breaker by opening a suitable switching device. Then an insulation test is performed to determine whether the fault is located upstream of the opened switching device or *vice versa*. This trial-and-error process is repeated until the faulted section is found. Then, the faulted section is isolated and the power service is restored for other healthy sections of the network through the proper switching actions. By the time these tasks are accomplished, the precise fault location and the repair or replacement activities are carried out. Finally, the network is returned to its normal operating status.

2) Case 2: This case represents a situation when a typical RFDS is implemented in the test system. The scheme proposed in [2] is used for such a purpose. This scheme has been developed for detecting and locating a faulted cable section in the underground cable distribution networks. When employing this scheme on the test system, although a fault still results in the circuit breaker operation and hence power interruption for customers, but the faulted cable section can be detected and located automatically. As a result, the repair crews can be sent directly to the faulted area. Then, the faulted cable section is isolated and the power service is restored for other healthy sections of the network through the proper switching actions. After accomplishing these tasks, the precise fault location and the repair activities are carried out. Finally, the network is returned to its normal operating status.

3) Case 3: This case represents a situation when a typical PFDS is implemented in the test system. The PFDS proposed in [10] is used for such a purpose, as its infrastructure has close similarities with the scheme used for Case 2. This scheme is capable of detecting and locating both active and passive failure modes of the underground cable sections. The partial discharges of the cable sections are monitored continuously in this scheme. Therefore, the passively failed cable sections can be detected and located automatically before they result in the circuit breaker operation. As a result, it might be possible to reconfigure the network such that the impacts on the customers due to ongoing fault isolation and repair activities are minimized. The efficiency of this scheme is considered to be

TABLE I
Basic Data of the Test System

Feeder Number	Num. of Distribution Substations	Num. of Switching Devices	Exposure (meters)	Peak Load (MW)	Average Load (MW)
Feeder 1	23	44	22606	1.41	1.03
Feeder 2	18	33	18474	1.55	1.13
Feeder 3	32	58	39595	1.57	1.15
Feeder 4	27	50	24871	2.19	1.60
Feeder 5	15	28	19878	1.43	1.06
Feeder 6	29	49	31587	1.25	0.91
Overall	**144**	**262**	**157011**	**9.40**	**6.88**

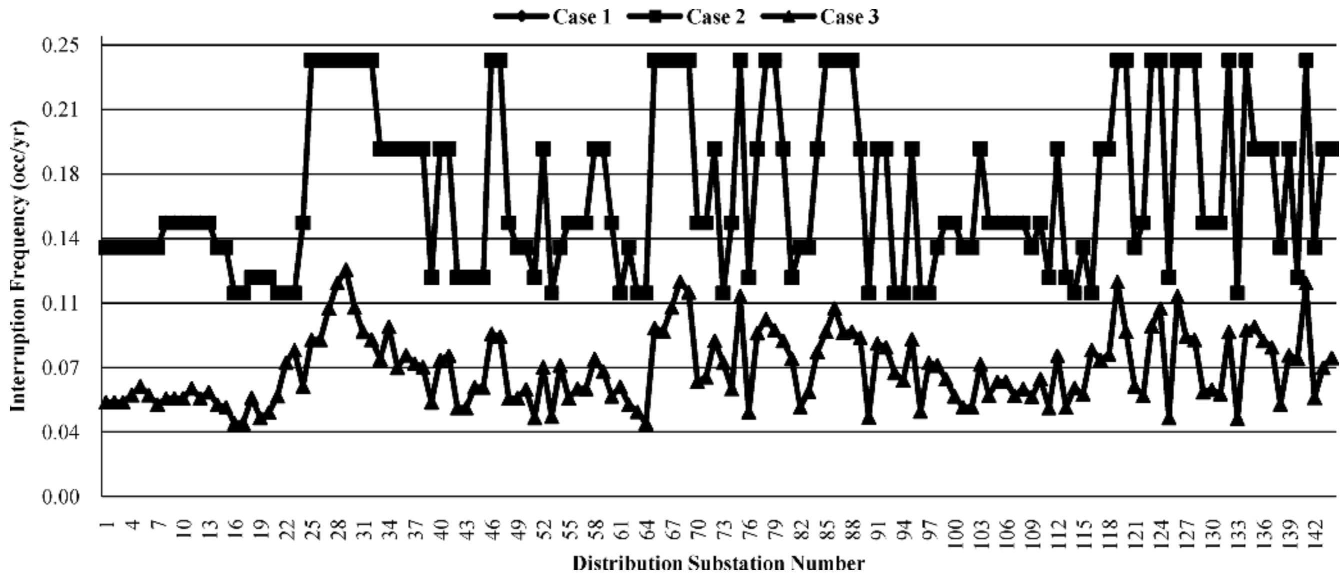

Fig. 3. Expected annual interruption frequencies (occ/yr) of distribution substations of the test system for different case studies (Note: Cases 1 and 2 have the similar results and hence they have been overlapped).

TABLE II
BASIC DATA FOR PERFORMING THE FMA IN EACH CASE STUDY

Fault Management Activity	Case 1	Case 2	Case 3
Average time required for fault notification (Seconds)	300	60	60
Average time required for approximate fault location (Seconds)	600	60	60
Average time required for decision making about the FMA (Seconds)	600	600	600
Average time required for dispatching the repair crews (Seconds)	300	300	300
Average speed of the repair crews for traveling to the faulted area (km/hr)	40	40	40
Average time required for performing insulation test on an underground cable section (Seconds)	1800	-	-
Average time required for precise fault location on an underground cable section including both pre-location and pinpointing activities (Seconds)	1800	1800	-
Average time required for manual operation of switching devices involved in the FMA (Seconds)	180	180	180
Available teams of repair crews for performing the FMA	2	2	2

about 80% [10] and is defined as the ratio of passive failure events that have been detected by the FDS over the total passive failure events. Obviously, this parameter is equal to zero for Cases 1 and 2.

The basic data required for performing the FMA in the above described case studies are assumed according to Table II. The typical data provided in Table II are based on the engineering judgments, the characteristics of the implemented FDS and also consulting with some experts in this area.

The above described FDS have been developed for diagnosing the cable faults. Therefore, to have a reasonable comparison between these case studies, the reliability studies concerned in this paper are concentrated on the cable failure events and the other components of the test system are assumed to be fully reliable. It is assumed that about 20% of the cable failure events are active failures. In addition, the time required for accomplishing the actual repair activities on a passively failed cable section is also assumed to be the same as the case when it encounters with an active failure condition. However, the impacts of these two parameters are further analyzed later in the paper.

Figs. 3–5 respectively show the expected annual interruption frequency, the expected annual interruption duration and the expected annual interruption cost indices of the distribution substations of the test system.

As expected, when employing either the RFDS or the PFDS, the reliability performance of the test system is improved. However, these improvements are more dominants in Case 3 compared to those of Case 2. As it can be seen from Fig. 3, employing the RFDS in Case 2 has no impact on the interruption frequencies of the distribution substations of the test system compare to the base case study (Case 1).

However, the interruption frequencies of the distribution substations of the test system decrease when employing the PFDS in Case 3. Actually, neither the protection system nor the RFDS implemented in Case 2 can detect the passively failed cable sections. As a result, after a period of time, the passively failed cable sections will suffer a complete breakdown. By the time this occurs, the protection system reacts against this failure condition which results in the power interruption for the customers. Only after accomplishing this process, the faulted cable section can be detected and located by the RFDS implemented in Case 2.

Figs. 4 and 5 show that employing the FDS in Case 2 and Case 3 have reduced the effects of cable faults on annual interruption durations and also annual interruption costs of distribu-

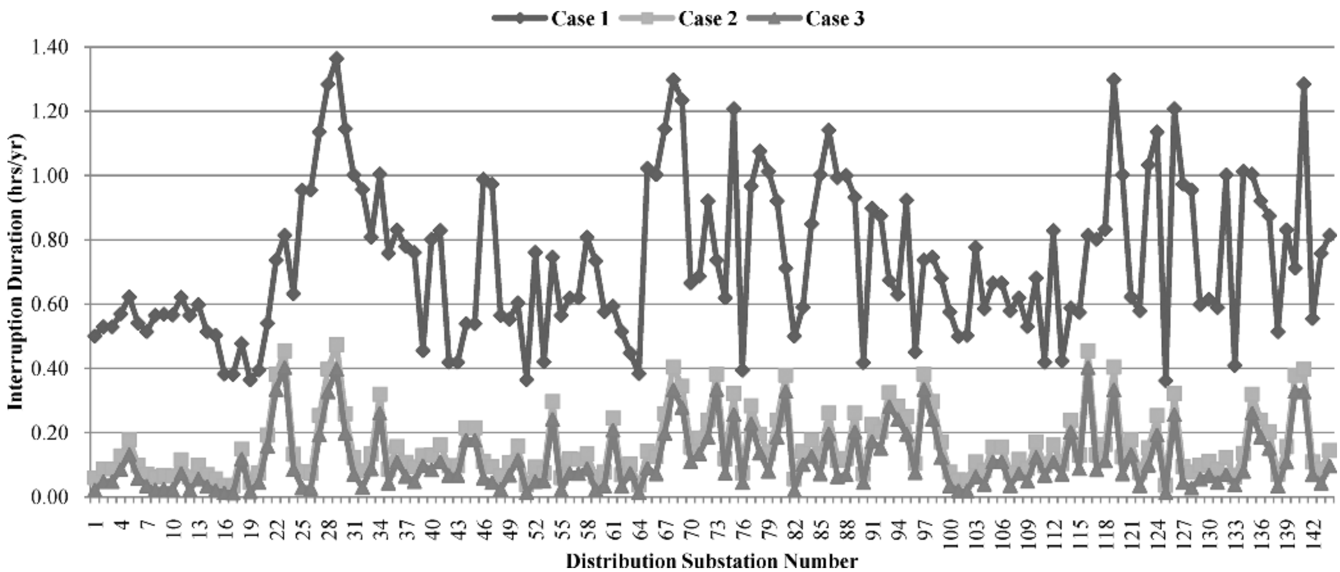

Fig. 4. Expected annual interruption durations (hrs/yr) of distribution substations of the test system for different case studies.

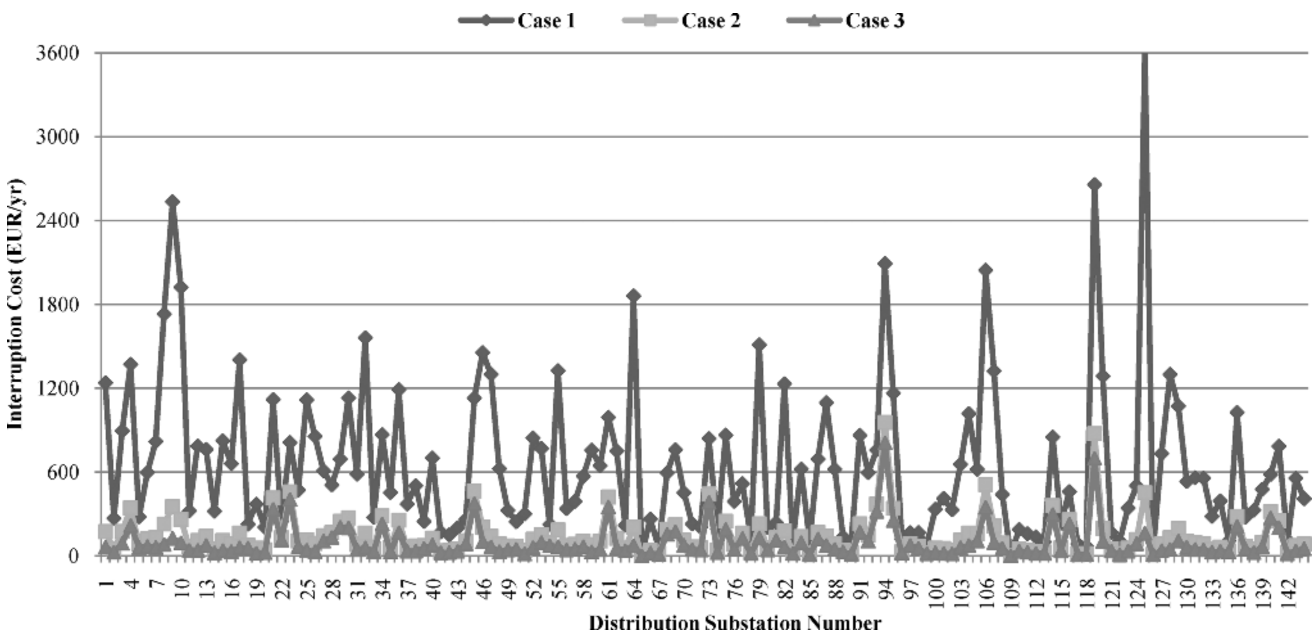

Fig. 5. Expected annual interruption costs (EUR/yr) of distribution substations of the test system for different case studies.

tion substations of the test system. However, in contrast to the RFDS used in Case 2, the PFDS employed in Case 3 can detect and locate the passively failed cable sections well in advance. Hence, the necessary fault isolation and repair activities can be done with the least impacts on the other distribution substations connected to the passively failed cable sections. As a result, the degrees of reliability improvements are much better for Case 3 compared to those of Case 2.

The system oriented reliability indices of the test system for different case studies are shown in Table III. The relative changes of these indices for different pair of case studies have also been presented in Table IV. The results shown in these tables clearly show the great impacts of the RFDS and the PFDS on reliability performance of the test system. For Case 2, SAIFI remains unchanged while the other reliability indices improve. For Case 3, however, all the reliability indices improve. These tables once more show how the PFDS can result in much better reliability performance in the test system compared to those of the RFDS.

TABLE III
SYSTEM ORIENTED RELIABILITY INDICES OF THE TEST SYSTEM

Reliability Index	Case 1	Case 2	Case 3
SAIFI (intr/sub-yr)	0.166	0.166	0.070
SAIDI (hrs/sub-yr)	0.735	0.161	0.116
ASUI (%)	0.00839	0.00184	0.00132
EENS (kWhr/yr)	3741.73	765.81	529.86
ECOST (EUR/yr)	94198	20595	13471

It is expected that employing any FDS in the distribution networks would affect the overall burden on the utility repair crews for performing the FMA. Fig. 6 shows the results of such study when either the RFDS or the PFDS are employed in the test

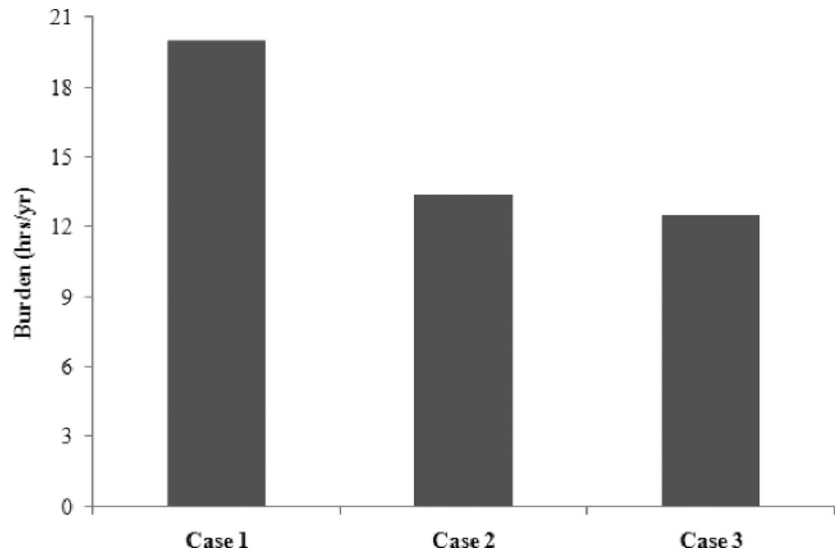

Fig. 6. Expected burden on repair crews (hrs/yr) for different case studies.

TABLE IV
RELATIVE CHANGE IN SYSTEM ORIENTED RELIABILITY INDICES (IN PERCENT)

Reliability Index	Cases 2&1	Cases 3&1	Cases 3&2
SAIFI	0.00	-57.83	-57.83
SAIDI	-78.09	-84.22	-27.95
ASUI	-78.07	-84.27	-28.26
EENS	-79.53	-85.84	-30.81
ECOST	-78.14	-85.70	-34.59

TABLE V
SENSITIVITY OF SAIFI (INTR/SUB-YR) TO DIFFERENT ATTRIBUTES OF PASSIVE FAILURE EVENTS WHEN A TYPICAL PFDS IS EMPLOYED IN THE TEST SYSTEM.

PAFR (%)	PARR (%)			
	100	80	60	40
100	0.045	0.045	0.045	0.045
80	0.070	0.070	0.070	0.070
60	0.094	0.094	0.094	0.094
40	0.118	0.118	0.118	0.118

system. This figure shows that how the RFDS implemented in Case 2 or the PFDS employed in Case 3 can affect the average hours per year that the utility repair crews should be engaged with the FMA in the test system. As the activities and hence the total time period required for fault location is decreased when employing either the RFDS or the PFDS, the overall burden on the utility repair crews is also reduced for Case 2 and Case 3 compared to that of Case 1.

Fig. 6 also shows that the burden on repair crews is about the same when either the RFDS (Case 2) or the PFDS (Case 3) is used in the test system. The reason for this is that the repair crews should be dispatched to fix the problem regardless of the fault type. As it has been assumed that the time required for performing repair activities on a passively failed cable section is the same as that of an actively failed cable section, the small difference between the results associated with Cases 2 and 3 originated from the time required for precise fault location activities, which is negligible in Case 3 (see Table II).

The results of the above described comparative case studies clearly manifest the prominent capabilities of the PFDS over the RFDS for reliability enhancement of the electric power distribution networks. The main origin for this pioneering is the capability of the PFDS in detecting and locating both passive and active failure modes of the components. For this reason, further analyzing of the PFDS when the characteristic of passive failure events are changed is of high importance. In practice, a passively failed cable section may have fewer impacts on the peripheral cables routed through the same channel or conduit compared to the case of an actively failed cable section. Therefore, the time required for accomplishing the actual repair activities on a passively failed cable section could be shorter than that of the case when it encounters with an active failure condition. In addition, the failure causes of the underground cable networks may vary from one utility to another. This issue can affect the share of passive failure events in the total failure events of the cable sections. Therefore, the following two parameters are defined for overall description of the passive failure events in the underground cable distribution networks:

$$PAFR = \frac{100}{NCS} \times \sum_{i=1}^{NCS} \frac{\lambda^i_{\text{Passive}}}{\lambda^i_{\text{Passive}} + \lambda^i_{\text{Active}}} \quad (1)$$

$$PARR = \frac{100}{NCS} \times \sum_{i=1}^{NCS} \frac{r^i_{\text{Passive}}}{r^i_{\text{Active}}}. \quad (2)$$

Tables V–IX represent the sensitivity of the system oriented reliability indices with respect to different attributes of the passive failure events. The typical PFDS described in [10] was employed in the test system when conducting these sensitivity case studies.

Table V shows that the SAIFI index is improved with increasing the value of PAFR and deteriorate for the reverse situation. However, this index remains constant for different values

TABLE VI
SENSITIVITY OF SAIDI (HRS/SUB-YR) TO DIFFERENT ATTRIBUTES OF PASSIVE FAILURE EVENTS WHEN A TYPICAL PFDS IS EMPLOYED IN THE TEST SYSTEM.

PAFR (%)	PARR (%)			
	100	80	60	40
100	0.106	0.092	0.077	0.063
80	0.116	0.104	0.092	0.081
60	0.125	0.116	0.108	0.099
40	0.134	0.129	0.123	0.117

TABLE VII
SENSITIVITY OF ASUI (%) TO DIFFERENT ATTRIBUTES OF PASSIVE FAILURE EVENTS WHEN A TYPICAL PFDS IS EMPLOYED IN THE TEST SYSTEM.

PAFR (%)	PARR (%)			
	100	80	60	40
100	0.00121	0.00105	0.00088	0.00072
80	0.00132	0.00118	0.00105	0.00092
60	0.00143	0.00132	0.00123	0.00113
40	0.00153	0.00147	0.00140	0.00133

TABLE VIII
SENSITIVITY OF EENS (KWHR/YR) TO DIFFERENT ATTRIBUTES OF PASSIVE FAILURE EVENTS WHEN A TYPICAL PFDS IS EMPLOYED IN THE TEST SYSTEM.

PAFR (%)	PARR (%)			
	100	80	60	40
100	479.17	415.41	351.65	287.89
80	529.86	478.85	427.84	376.84
60	580.54	542.29	504.03	465.78
40	631.23	605.73	580.22	554.72

TABLE IX
SENSITIVITY OF ECOST (EUR/YR) TO DIFFERENT ATTRIBUTES OF PASSIVE FAILURE EVENTS WHEN A TYPICAL PFDS IS EMPLOYED IN THE TEST SYSTEM.

PAFR (%)	PARR (%)			
	100	80	60	40
100	11884	10392	8899	7406
80	13471	12277	11082	9888
60	15058	14162	13266	12370
40	16644	16047	15450	14853

of PARR. It should be noted that even in situations where all the cable failure events are passive (i.e., $\mathrm{PAFR} = 100$), customers will still experience power interruptions. There are two main reasons for this phenomenon. The first one is the efficiency of the employed scheme in diagnosing the passively failed cable sections. The efficiency of the PFDS used in these studies is 80% [10]. This value of efficiency means that the developed scheme can diagnose about 80% of all passive failure events and the remaining 20% will finally appear as the active failure events. The active failure events then result in a power interruption for customers due to the operation of protection devices, which are counted by SAIFI. The second reason is the inherent limitations in the distribution network for isolating and repairing the failed cable sections, as it might not be possible to perform these activities without unavoidable power interruptions to some distribution substations.

TABLE X
SENSITIVITY OF BURDEN ON REPAIR CREWS (HRS/YR) TO DIFFERENT ATTRIBUTES OF PASSIVE FAILURE EVENTS WHEN A TYPICAL PFDS IS EMPLOYED IN THE TEST SYSTEM.

PAFR (%)	PARR (%)			
	100	80	60	40
100	12.52	10.72	8.92	7.12
80	12.50	11.06	9.63	8.18
60	12.49	11.40	10.33	9.24
40	12.47	11.74	11.03	10.31

In contrast to SAIFI, the other system oriented reliability indices presented in Tables VI–IX show some levels of sensitivity to both PAFR and PARR. In general, these reliability indices are improved with increasing the value of PAFR and decreasing the value of PARR and deteriorate for the reverse situations.

Table X shows the sensitivity of burden on the utility repair crews to different attributes of the passive failure events. As it can be seen from this table, for the situation where the average time required for repairing a passively failed cable section is almost the same as that of an actively failed cable section, i.e., $\mathrm{PARR} = 100$, the burden on the repair crews amplifies with increasing the share of passive failure events. However, the situation is different for cases where the average time required for repairing a passively failed cable section is less than that of an actively failed cable section. In these situations, the burdens on repair crews are lessened with increasing the value of PAFR and decreasing the value of PARR and amplified for the reverse situations. This behavior is resulted from different procedures that the utility repair crews should follow for performing the FMA when dealing with various failure modes of the cable sections. For an actively failed cable section, the repair crews first isolate the faulted cable section and then reconfigure the network in an optimal manner to restore power for distribution substations which have been affected by the fault. However, for a passive failure situation, the repair crews first reconfigure the network such that the minimum number of distribution substations would be affected from ongoing fault isolation process, then they perform the necessary fault isolation and repair activities. Normally, the time required for accomplishing the second scenario is pretty more than that required for the first scenario. Therefore, as it can be seen from the first column of Table X, with increasing the share of passive failure events, the burden on the utility repair crew is increased. However, this issue is masked in situations where the time required for performing repair activities on a passively failed cable section is less than that of an actively failed cable section, i.e., PFRR less than 100%, as this time reduction is far more than that of the previously described incremented time.

V. CONCLUSIONS

This paper aimed to compare the effects of two types of the FDS on the reliability performance of the electric power distribution systems. The first one was a representative of the RFDS and the second one was a representative of the PFDS. The SGS was used for conducting the quantitative reliability assessment studies on a typical Finnish urban distribution network when employing these FDS. The results of comparative case studies show that employing either the RFDS or the PFDS can improve the reliability performance of the electric power distribution systems. However, the extents of improvements are much better when employing the PFDS. The RFDS can detect and locate the deteriorated components after their failing and hence mainly reduce the duration of power interruptions imposed on the customers. In contrast, the PFDS can diagnose the failing components prior to the breakdown condition and while they are still in the incipient failure condition. As a result, the PFDS can reduce both frequency and duration of power interruptions experienced by the network customers. In addition, the substantial expensive equipment repair and replacement and possible unsafe condition can be mitigated by using the PFDS. The results also indicate that employing either the RFDS or the PFDS can reduce the overall burden on the utility repair crew for performing the FMA. The results of sensitivity case studies show that when either the share of passive failure events in the total failure events is considerable or where the time required for performing the repair activities on the passively failed components is far less than that of the actively failed components, the more improvement in the reliability indices are expected from the PFDS compared to the RFDS.

Acknowledgment

The authors would like to thank Dr. R. J. Millar for his great assistance on providing the data required for quantitative reliability studies concerned in this paper.

References

[1] S. Kazemi, "Commonly used automation schemes for fault management in the MV distribution networks," Dept. Electr. Eng., Aalto Univ., Espoo, Finland, Tech. Rep. VAHA1, 2009.

[2] A. Newbould, L. Hu, and K. Chapman, "Cable automation for urban distribution systems," in *Proc. 2001 IEE Conf. Develop. Power Syst. Protection*, pp. 319–322.

[3] A. Campoccia, M. L. Di Silvestre, I. Incontrera, E. R. Sanseverino, and C. Spataro, "Applicational aspects of a new diagnostic methodology for fault location in MV networks: Problems, solutions and improvements," in *Proc. 2005 Int. Conf. Future Power Syst.*, pp. 1–6.

[4] S. Bagley and D. Branca, "A new approach to find fault locations on distribution feeder circuits," in *Proc. 2007 IEEE Rural Electr. Power Conf.*, pp. B5-1–B5-4.

[5] M. S. Choi, S. J. Lee, D. S. Lee, and B. G. Jin, "A new fault location algorithm using direct circuit analysis for distribution systems," *IEEE Trans. Power Del.*, vol. 19, pp. 35–41, Jan. 2004.

[6] E. C. Senger, G. Manassero, C. Goldemberg, and E. L. Pellini, "Automated fault location system for primary distribution networks," *IEEE Trans. Power Del.*, vol. 20, pp. 1332–1340, Apr. 2005.

[7] X. Yang, M. S. Choi, S. J. Lee, C. W. Ten, and S. I. Lim, "Fault location for underground power cable using distributed parameter approach," *IEEE Trans. Power Syst.*, vol. 23, pp. 1809–1816, Nov. 2008.

[8] B. D. Russell, C. L. Benner, R. M. Cheney, C. F. Wallis, T. L. Anthony, and W. E. Muston, "Reliability improvement of distribution feeders through real-time, intelligent monitoring," in *Proc. 2009 IEEE Power Energy Soc. Gen. Meet.*, pp. 1–8.

[9] B. D. Russell and C. L. Benner, "Intelligent systems for improved reliability and failure diagnosis in distribution systems," *IEEE Trans. Smart Grid*, vol. 1, pp. 48–56, Jun. 2010.

[10] P. C. J. M. van der Wielen and E. F. Steennis, "Smartening cable connections by an intelligent health monitor system," in *Proc. 2010 IEEE Conf. Innov. Smart Grid Technol. Eur.*, pp. 1–7.

[11] S. Kazemi, M. Lehtonen, and M. Fotuhi–Firuzabad, "A comprehensive approach for reliability worth assessment of the automated fault management schemes," in *Proc. 2010 IEEE Transm. Distrib. Conf. Exhib.*, pp. 1–8.

[12] S. Kazemi, M. Fotuhi–Firuzabad, and R. Billinton, "Reliability assessment of an automated distribution system," *IET Gener., Transm., Distrib.*, vol. 1, pp. 223–233, Mar. 2007.

[13] S. Kazemi, M. Fotuhi–Firuzabad, M. Sanaye-Pasand, and M. Lehtonen, "Impacts of automatic control systems of loop restoration scheme on the distribution system reliability," *IET Gener., Transm., Distrib.*, vol. 3, pp. 891–902, Oct. 2009.

[14] S. Kazemi, "Reliability evaluation of smart distribution grids," Ph.D. dissertation, Sharif Univ. Technol., Aalto Univ. Dept. Electr. Eng., , 2011.

Shahram Kazemi (M'09) received the M.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran in 2004 and the Ph.D. and D.Sc. degrees in electrical engineering from Sharif University of Technology and Aalto University, Espoo, Finland, in 2011.

From 2003 to 2006, he was with Niroo Consulting Engineers Co., Tehran, as a Senior Researcher. He then pursued his doctoral study and research activities at Sharif University of Technology and Aalto University. His main research interest is the reliability evaluation of smart distribution grids.

Matti Lehtonen received the M.S. and Licentiate degrees in electrical engineering from Aalto University (formerly Helsinki University of Technology), Espoo, Finland, in 1984 and 1989, respectively, and the D.Sc. degree from the Tampere University of Technology, Tampere, Finland, in 1992.

Since 1987, he has been with VTT Energy, Espoo, and since 1999, he has been with the Department of Electrical Engineering at Aalto University, where he is a Professor of IT applications in power systems. His main activities include earth fault problems, and harmonic related issues and applications of information technology in distribution automation and distribution energy management.

Mahmud Fotuhi-Firuzabad (SM'99) received the B.Sc. and M.Sc. degrees in electrical engineering from Sharif University of Technology, Tehran, Iran, and Tehran University, Iran, in 1986 and 1989, respectively, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Saskatchewan, Saskatoon, Canada, in 1993 and 1997, respectively.

He worked as a Postdoctoral Fellow in the Department of Electrical Engineering, University of Saskatchewan from January 1998 to September 2000, where he conducted research in the area of power system reliability. He worked as an Assistant Professor in the same department from September 2000 to September 2001. Presently, he is a professor and Head of the Department of Electrical Engineering, Sharif University of Technology.

Dr. Fotuhi-Firuzabad is a member of the Center of Excellence in Power System Management and Control. He serves as an Editor of the IEEE TRANSACTIONS ON SMART GRID.