Impacts of Loop Restoration Strategy on Distribution System Reliability

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

Abstract-- **Implementation of Distribution Automation (DA) in electric power distribution systems can result in customer satisfaction with improved reliability, consistent quality and high-tech services. Loop Restoration Strategy (LRS) is a special DA method in the feeder level which is used by electric utilities to improve distribution system reliability. The effects of the implemented LRS on the reliability indices of a given distribution system mainly depend on its Automatic Control System (ACS). Selecting the type of ACS of LRS by electric utilities relies on the level of improvement required at load points and system oriented reliability indices. A step by step evaluation procedure is proposed in this paper to quantitatively assess the impacts of two common types of ACS of LRS on reliability indices of a distribution reliability test system.**

Index Terms—**Distribution Automation, Loop Restoration Strategy, Recloser Controls, Reliability Assessment.**

I. NOMENCLATURE

ACS	Automatic Control System
CBA	Probability that LCE of substation circuit breaker is available to perform its intended functions
DA	Distribution Automation
LCE	Local Control Equipment
LRS	Loop Restoration Strategy
MRA	Probability that LCE of normally closed recloser is available to perform its intended functions
MST	Manual Switching Time
NC	Number of Components
NLP	Number of Load Points
NRO	Number of reclosing operations to lock out
NRO_{FB}	Average number of reclosing operations to fuse blowing due to permanent fault on fuse protected lateral sections
NRO_{TFC}	Average number of reclosing operations for fault clearing due to a temporary faulty condition
TRA	Probability that LCE of normally open tie recloser is available to perform its intended functions
$ENS^S_{L_j}$	Average energy not supplied of L_j
C_i	Component number i
L_j	Load point number j
La_{L_j}	Average load connected to L_j
N_{L_j}	Number of customers of L_j
r_{C_i}	Repair time of C_i
$r^S_{L_j}$	Average sustained outage time of L_j
$U^S_{L_j}$	Average annual sustained outage time of L_j
$U^S_{C_iL_j}$	Contribution to the annual sustained outage time of L_j due to a permanent fault on C_i
$\lambda^M_{C_iL_j}$	Contribution to the momentary interruption frequency of L_j due to any faults on C_i
$\lambda^{ME}_{C_iL_j}$	Contribution to the momentary interruption event frequency of L_j due to any faults on C_i
$\lambda^S_{C_iL_j}$	Contribution to the sustained interruption frequency of L_j due to a permanent fault on C_i
$\lambda^P_{C_i}$	Average permanent failure rate of C_i
$\lambda^T_{C_i}$	Average temporary failure rate of C_i
$\lambda^S_{L_j}$	Average sustained interruption frequency of L_j
$\lambda^M_{L_j}$	Average momentary interruption frequency of L_j
$\lambda^{ME}_{L_j}$	Average momentary interruption event frequency of L_j

II. INTRODUCTION

Analysis of customer failure statistics in most utilities indicates that distribution systems make the greatest individual contribution to the unavailability of supply to customers. As distribution utilities shift from non-profit public utilities to profit-driven business enterprises, the question of how to maintain and improve service reliability while keeping electricity rates lower and protect shareholders' interests becomes more difficult to answer [1]. In an attempt to facilitate rapid response to outages as well as efficient day-to-day operation of distribution systems, some utilities have begun the implementation of DA into the design of their distribution feeders. DA can maximize customer satisfaction with improved reliability, consistent quality and high-tech services [2-4]. LRS is a special DA method in the feeder level which is used by utilities to improve distribution system

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S. Kazemi is with the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran and also a visiting researcher in the Department of Electrical Engineering, Helsinki University of Technology, Espoo, Finland (e-mail: s_kazemi@ee.sharif.edu).

M. Fotuhi-Firuzabad is with the Center of Excellence in Power System Control and Management, Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran (e-mail: fotuhi@sharif.edu).

M. Sanaye-Pasand is with the School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran (e-mail: msanaye@chamran.ut.ac.ir).

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

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reliability. The LRS is controlled and managed by its ACS. The ACS is tuned by a set of algorithms to provide automatic control operations of switching devices of LRS to remove the faulted section and restore the unfaulted sections of the feeder. The effects of implementing LRS on reliability indices of a given distribution system mainly depend on its ACS. Several kinds of these ACSs have been developed for implementing in LRS for automation of distribution systems [5-7].

Different regulatory environments put different weightings on reliability indices, such as SAIFI, SAIDI, MAIFI and MAIFI$_E$. Therefore, assessing the impacts of various ACSs of LRS on reliability indices of a given distribution system, which has special reliability targets and budget constraints, is a crucial task. An approach is proposed in this paper to quantitatively assess the impacts of two common types of ACS of LRS on distribution system reliability. The proposed technique is based on the event tree method and the concepts of conditional probability approach. In order to demonstrate the proposed technique, comparative and sensitivity studies are conducted using a distribution reliability test system.

III. LOOP RESTORATION STRATEGY

The LRS typically utilizes a predetermined number of reclosers installed in series between two distribution feeders. It is typically applied to two feeders by installing a normally open tie recloser at a tie point between two feeders, as shown in Fig. 1. Also, a normally closed sectionalizing recloser is installed on each feeder. The substation circuit breaker that operates to protect the distribution feeder has also auto-reclosing capability. This provides isolation of any faulted sector within the distribution feeder while simultaneously reestablishing service to all customers unaffected by the faulted sector within a relatively short period of time. This procedure is controlled and managed by a special ACS. In this paper, two common types of ACS with and without communication capability are considered in the analysis [5-7].

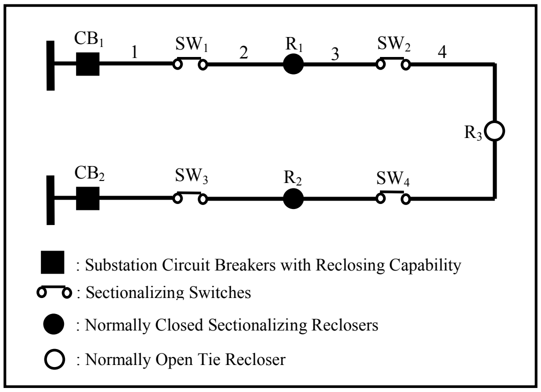

Fig. 1. Typical Configuration of Loop Restoration Strategy.

A. ACS without Communication Capability

In a LRS with this kind of ACS, operational logic for automated loop restoration is implemented through the stand alone intelligence of each switching device. There is no communication link between these switching devices. The LRS may therefore be activated when the switching devices act in accordance with the pre-defined roles of the stored instructions and extracted local information. Consider the schematic diagram of Fig. 1. The LRS equipped with an ACS without communication capability is designed to work as follows [5-7]:

- When a permanent fault occurs on section 1, substation circuit breaker CB$_1$ first opens and recloses and after re-ignition of the fault opens again and then locks out. The ACS at the normally closed sectionalizing recloser R$_1$ senses loss of the source side voltage, and the ACS at the normally open tie recloser R$_3$ senses voltage loss on its R$_1$ side. Timers of both reclosers begin to operate. The control system is designed in way that the time delay at R$_1$ expires first, and then R$_1$ opens and locks out. The time delay at R$_3$ expires next, and R$_3$ closes and restores service to the unfaulted feeder on sections between R$_1$ and R$_3$. After locating the fault, sectionalizing switch SW$_1$ can be opened and R$_1$ is closed manually and restores service to the unfaulted feeder on section 2.
- When a permanent fault occurs on section 2, a procedure similar to the case when a permanent fault occurs on section 1 will follow. Except, after fault locating, SW$_1$ can be opened and CB$_1$ is closed manually and restores service to the unfaulted feeder on section 1.
- When a permanent fault occurs on section 3**,** R$_1$ first opens and recloses and after re-ignition of the fault opens again and then locks out. Tie recloser R$_3$ senses voltage loss on its R$_1$ side. After expiration of its time delay, it closes and senses fault current, then trips and locks out. The unfaulted portion of the feeder, between CB$_1$ and R$_1$, remains in service. After fault locating, sectionalizing switch SW$_2$ can be opened and R$_3$ is closed manually and restores service to the unfaulted feeder on section 4.
- When a permanent fault occurs on section 4, R$_1$ and R$_3$ open and lock out after their fault protection sequences. The unfaulted portion of the feeder, between CB$_1$ and R$_1$, remains in service. After fault locating, SW$_2$ can be opened and R$_1$ is closed manually and restores service to the unfaulted feeder on section 3.
- When a temporary fault occurs on sections 1 or 2, CB$_1$ performs its normal reclosing sequence and remains closed once the fault is cleared. During these sequences, all customers along the feeder are momentarily interrupted.
- When a temporary fault occurs on sections 3 or 4, R$_1$ performs its normal reclosing sequence and remains closed once the fault is cleared. During these sequences, only customers between R$_1$ and R$_3$ are momentarily interrupted.

B. ACS with Communication Capability

Although the above discussed ACS of LRS is easy to implement, the following disadvantages exist. First, when a permanent fault occurs between CB$_1$ and R$_1$ or between CB$_2$ and R$_2$, the loop reconfiguration occurs after CB$_1$ or CB$_2$ performs its complete reclosing sequence (four reclosing shot in most cases). This results in blinking and effects the whole feeder severely. Second, automatic restoration to the normal system configuration is difficult to achieve. Third, if the fault occurs between R$_1$ and R$_3$ or between R$_2$ and R$_3$, the loss-of-voltage closure command by the ACS logic could cause the fault to be momentarily placed on the other feeder. These concerns are prevented with the ability to exchange data between switching devices via communication link. Reconsider the schematic diagram of Fig. 1. The LRS which is equipped with an ACS based on communication link is designed to work as follows [7]:

- When a permanent or temporary fault occurs on sections 1 or 2, CB_1 and R_1 instantly open. R_1 is activated through a command sent by CB1. Then R_3 closes and restores service to the unfaulted feeder on sections between R_1 and R_3. Substation circuit breaker CB_1 recloses in a normal fashion. If successful (in the case of a temporary fault), the loop is automatically restored to its normal situation. Otherwise (in the case of a permanent fault), CB_1 opens and locks out. After determining the fault location, SW_1 can be opened and R_1 or CB_1 is closed manually and restores service to the unfaulted feeder on the section between CB_1 and SW_1 or SW_1 and R_1, respectively. Comparing with the similar case using the ACS without communication capability, there is no need to wait until CB_1 goes through all reclosing sequences even for temporary faults. In this way, blinking impact on the whole feeder is minimized.
- When a temporary fault occurs on sections 3 or 4, R_1 performs its normal reclosing sequence and remains closed once the fault is cleared. For permanent faults on these sections, R_3 is blocked through a command sent by R_1 from closing into the fault. Contrary to the previous ACS without communication capability, it prevents the fault to be momentarily placed on the other feeder.

IV. EVALUATION PROCEDURE

A. General Concepts

A modular approach is used to evaluate the impacts of various ACSs of LRS on distribution system reliability. This approach divides the ACS into modules that can be analyzed independently. The reliability data associated with each control module can be either derived by a separate reliability analysis or obtained from a data collection scheme. For illustration purposes, the ACS for the LRS of Fig. 1 can be divided into 5 control modules, corresponding to each switching device. These control modules have no shared components and are considered to be independent. Each control module is representative of the Local Control Equipment (LCE) at the location of each switching device. The LCE contains power supply units, timers, relays, sensors, processing units and communication systems (if available). For the sake of simplicity in approaching the evaluation procedure and to put more emphasis on evaluating the impacts ACSs of LRS on the distribution system reliability, the protection system and switching devices are assumed to be fully reliable. Based on the proposed logic of the implemented ACS of LRS, the operational procedure for the fault isolation and service restoration, when a permanent or temporary fault occurs, is identified. The control process, following occurrence of a fault, involves the sequential operation logic of a set of control modules. Therefore, the consequence of the availability and unavailability of each control module on the operational procedure for fault isolation and service restoration is analyzed using the event tree method [8-10]. Using this approach, the various possible outcomes of the control processes are identified and the associated outcome and restoration probabilities are calculated. The average annual outage time and average interruption frequency of the load points are calculated using the restoration and failure probabilities based on the concepts of conditional probability approach. The system oriented reliability indices are then determined by aggregating the load point indices.

B. Classification of Interruptions and Load Points

When a fault occurs, the interruption frequency and restoration time of different load points of a feeder are not the same due to restoration logic of the implemented ACS of LRS and availability of its LCEs.

The following definitions are used for classification of interruptions in this paper [11]:

- *Momentary Interruption:* A single operation of an interrupting device that results in a voltage zero. For example, two circuit breaker or recloser operations (each operation being an open followed by a close) that momentarily interrupts service to one or more customers is defined as two momentary interruptions.
- *Momentary Interruption Event:* An interruption of duration limited to the period required to restore service by an interrupting device. Such switching operations must be completed within a specified time of five minutes or less. This definition includes all reclosing operations that occur within five minutes of the first interruption. For example, if a recloser or circuit breaker operates two, three, or four times and then holds (within the five minutes of the first operation), it shall be considered as one momentary interruption event.
- *Sustained Interruption:* Any interruption not classified as a part of a momentary event. That is, any interruption that lasts more than five minutes.

During a permanent faulty condition on a component, load points of a distribution system equipped with LRS can be divided into seven classes as follows:

Class A: load points that are not interrupted due to a fault.

Class B: load points that are interrupted due to a fault and their outage durations are equal to the time required to isolate and repair the failed component. These load points experience sustained interruptions.

Class C_1: load points that are interrupted due to a fault, but can be isolated and restored by automatic switching actions. It is considered that ACS of LRS is available, therefore outage durations of these load points are equal to the time required to isolate the fault and to restore service through a main or an alternative supply using successful automatic switching actions. These load points experience just one momentary interruption. Only LRS equipped with an ACS with communication capability has load points which are categorized in this class.

Class C_2: these load points are similar to those categorized in class C_1, but they experience momentary interruptions with frequency equal to the number of reclosing operation of upstream recloser or circuit breaker to lock out, i.e. NRO.

Class D: load points that are interrupted due to a fault, but can be isolated and restored by automatic switching actions. It is considered that ACS of LRS is unavailable, therefore outage durations of these load points are equal to the time required to isolate the fault and to restore service through a main or an alternative supply using the manual switching actions. These load points experience sustained interruptions.

Class E: load points that are interrupted due to a fault, but can be isolated and restored by manual switching actions. Outage durations of these load points are equal to the time required to isolate the fault and to restore service through a main or an alternative supply using manual switching actions. These load points experience sustained interruptions.

Class F: load points that are interrupted due to a fault, but can be isolated and restored by blowing the fuse of faulted lateral section. Outage duration of these load points is equal to the time required to isolate the fault and to restore service through reclosing operations. These load points experience NRO_{FB} momentary interruptions.

During temporary faulty condition on a component, load points of a distribution system can also be divided into four classes as follows:

Class G: load points that are not interrupted due to a fault.

Class H: load points that are interrupted due to a fault but availability or unavailability of ACS of LRS have no effect on their momentary interruption frequencies. In this case, upstream recloser or circuit breaker operations result in fault clearing. These load points experience momentary interruptions with the frequency of the required upstream recloser or circuit breaker operations for temporary fault clearing, i.e. NRO_{TFC}.

Class I: load points that are interrupted due to a fault but availability of ACS of LRS affects their momentary interruption frequencies. Only LRS equipped with an ACS with communication capability has load points which are categorized in this class. In this case, upstream circuit breaker and downstream recloser operations, which are managed by ACS, result in fault clearing. The ACS of LRS is available and these load points experience just one momentary interruption.

Class J: these load points are similar to those categorized in class I, but the ACS of LRS is unavailable. These load points experience momentary interruptions with frequency equal to the required upstream recloser or circuit breaker operations for temporary fault clearing, i.e. NRO_{TFC}.

C. Steps of Evaluation Procedure

The deduced formulas and procedure for determining the impacts of the introduced ACSs of LRS on the distribution system reliability can be summarized in the following steps:

(1) Based on the above described general concepts, for a possible permanent or temporary fault on each component of distribution system, the event trees are developed [8-10]. The sequences of events together with the associated outcomes in the operating procedure of ACS are then identified. Eventually, based on the outcomes of the developed event trees, the classes of each load point (corresponding to those classified in the pervious subsection) and their associated probabilities are determined. For illustration purposes, these parameters are presented in Tables 1 & 2 for load points connected to each section of LRS of Fig. 1 due to occurrence of a permanent or a temporary fault on section 2, respectively.

TABLE 1

CLASSES AND CORRESPONDING PROBABILITIES OF EACH LOAD POINT OF LRS OF FIG. 1, WHEN A PERMANENT FAULT OCCURS ON SECTION 2

Load Points	**ACS without Communication Capability**		**ACS with Communication Capability**	
	Class	**Probability**	**Class**	**Probability**
Sect. 1	E	1	E	1
Sect. 2	B	1	B	1
Sect. 3	C_2	MRA×TRA	C_1	CBA×MRA×TRA
	D	1-(MRA×TRA)	D	1-(CBA×MRA×TRA)
Sect. 4	C_2	MRA×TRA	C_1	CBA×MRA×TRA
	D	1-(MRA×TRA)	D	1-(CBA×MRA×TRA)
Sect. 5-8	A	1	A	1

TABLE 2

CLASSES AND CORRESPONDING PROBABILITIES OF EACH LOAD POINT OF LRS OF FIG. 1, WHEN A TEMPORARY FAULT OCCURS ON SECTION 2

Load Points	**ACS without Communication Capability**		**ACS with Communication Capability**	
	Class	**Probability**	**Class**	**Probability**
Sect. 1	H	1	H	1
Sect. 2	H	1	H	1
Sect. 3	H	1	I	CBA×MRA×TRA
			J	1-(CBA×MRA×TRA)
Sect. 4	H	1	I	CBA×MRA×TRA
			J	1-(CBA×MRA×TRA)
Sect. 5-8	G	1	G	1

(2) The contribution to the sustained, momentary and momentary interruption event frequency of L_j by a permanent and a temporary fault on C_i is determined based on the concepts of conditional probability theory and using the results obtained in Step 1:

$$\begin{aligned}\lambda^{S}_{C_iL_j} = {} & (\lambda^{P}_{C_i} \mid B^{P}_{C_iL_j}) \times P(B^{P}_{C_iL_j}) \\ & + (\lambda^{P}_{C_i} \mid D^{P}_{C_iL_j}) \times P(D^{P}_{C_iL_j}) \\ & + (\lambda^{P}_{C_i} \mid E^{P}_{C_iL_j}) \times P(E^{P}_{C_iL_j})\end{aligned} \tag{1}$$

$$\begin{aligned}\lambda^{M}_{C_iL_j} = {} & \left\{(\lambda^{P}_{C_i} \times 1) \mid C^{P}_{1C_iL_j}\right\} \times P(C^{P}_{1C_iL_j}) \\ & + \left\{(\lambda^{P}_{C_i} \times NRO) \mid C^{P}_{2C_iL_j}\right\} \times P(C^{P}_{2C_iL_j}) \\ & + \left\{(\lambda^{P}_{C_i} \times NRO_{FB}) \mid F^{P}_{C_iL_j}\right\} \times P(F^{P}_{C_iL_j}) \\ & + \left\{(\lambda^{T}_{C_i} \times NRO_{TFC}) \mid H^{T}_{C_iL_j}\right\} \times P(H^{T}_{C_iL_j}) \\ & + \left\{(\lambda^{T}_{C_i} \times 1) \mid I^{T}_{C_iL_j}\right\} \times P(I^{T}_{C_iL_j}) \\ & + \left\{(\lambda^{T}_{C_i} \times NRO_{TFC}) \mid J^{T}_{C_iL_j}\right\} \times P(J^{T}_{C_iL_j})\end{aligned} \tag{2}$$

$$\begin{aligned}\lambda^{ME}_{C_iL_j} = {} & \left\{(\lambda^{P}_{C_i}\times 1)\,|\,C^{P}_{1C_iL_j}\right\}\times P(C^{P}_{1C_iL_j}) \\ & +\left\{(\lambda^{P}_{C_i}\times 1)\,|\,C^{P}_{2C_iL_j}\right\}\times P(C^{P}_{2C_iL_j}) \\ & +\left\{(\lambda^{P}_{C_i}\times 1)\,|\,F^{P}_{C_iL_j}\right\}\times P(F^{P}_{C_iL_j}) \\ & +\left\{(\lambda^{T}_{C_i}\times 1)\,|\,H^{T}_{C_iL_j}\right\}\times P(H^{T}_{C_iL_j}) \\ & +\left\{(\lambda^{T}_{C_i}\times 1)\,|\,I^{T}_{C_iL_j}\right\}\times P(I^{T}_{C_iL_j}) \\ & +\left\{(\lambda^{T}_{C_i}\times 1)\,|\,J^{T}_{C_iL_j}\right\}\times P(J^{T}_{C_iL_j})\end{aligned} \tag{3}$$

In these equations, $B^{P}_{C_iL_j}$ and $P(B^{P}_{C_iL_j})$ are respectively the event and its associated probability, so that load point L_j due to a permanent fault on C_i is categorized as Class B. Similar notations are used for referring to other classes of load points. Superscripts P and T are respectively used for representing permanent and temporary faults on C_i.

(3) The contribution to the annual sustained outage time of L_j of a permanent fault on C_i is determined based on the concepts of conditional probability theory and using the results obtained in Step 1:

$$\begin{aligned}U^{S}_{C_iL_j} = {} & ((r_{C_i}\times\lambda^{P}_{C_i})|B^{P}_{C_iL_j})\times P(B^{P}_{C_iL_j}) \\ & +((MST\times\lambda^{P}_{C_i})|D^{P}_{C_iL_j})\times P(D^{P}_{C_iL_j}) \\ & +((MST\times\lambda^{P}_{C_i})|E^{P}_{C_iL_j})\times P(E^{P}_{C_iL_j})\end{aligned} \tag{4}$$

(4) The load-point and system oriented reliability indices are determined by analyzing the contribution associated with each failure event. For L_j, the reliability indices are deduced by aggregating the calculated $\lambda^{S}_{C_iL_j}, \lambda^{M}_{C_iL_j}, \lambda^{ME}_{C_iL_j}$ and $U^{S}_{C_iL_j}$. The load-point reliability indices are calculated as follows:

$$\lambda^{S}_{L_j} = \sum_{i=1}^{NC}\lambda^{S}_{L_jC_i} \tag{5}$$

$$\lambda^{M}_{L_j} = \sum_{i=1}^{NC}\lambda^{M}_{L_jC_i} \tag{6}$$

$$\lambda^{ME}_{L_j} = \sum_{i=1}^{NC}\lambda^{ME}_{L_jC_i} \tag{7}$$

$$U^{S}_{L_j} = \sum_{i=1}^{NC}U^{S}_{L_jC_i} \tag{8}$$

$$r^{S}_{L_j} = \frac{U^{S}_{L_j}}{\lambda^{S}_{L_j}} \tag{9}$$

$$ENS^{S}_{L_j} = U^{S}_{L_j}\times La_{L_j} \tag{10}$$

The following system oriented reliability indices can be calculated using the load point indices:

$$SAIFI = \frac{\sum_{j=1}^{NLP}(\lambda^{S}_{L_j}\times N_{L_j})}{\sum_{j=1}^{NLP}N_{L_j}} \tag{11}$$

$$SAIDI = \frac{\sum_{j=1}^{NLP}(U^{S}_{L_j}\times N_{L_j})}{\sum_{j=1}^{NLP}N_{L_j}} \tag{12}$$

$$ASAI = \frac{\sum_{j=1}^{NLP}(8760\times N_{L_j}) - \sum_{j=1}^{NLP}(U^{S}_{L_j}\times N_{L_j})}{\sum_{j=1}^{NLP}(N_{L_j}\times 8760)} \tag{13}$$

$$AENS = \frac{\sum_{j=1}^{NLP}(U^{S}_{L_j}\times La_{L_j})}{\sum_{j=1}^{NLP}N_{L_j}} = \frac{\sum_{j=1}^{NLP}ENS^{S}_{L_j}}{\sum_{j=1}^{NLP}N_{L_j}} \tag{14}$$

$$MAIFI = \frac{\sum_{j=1}^{NLP}(\lambda^{M}_{L_j}\times N_{L_j})}{\sum_{j=1}^{NLP}N_{L_j}} \tag{15}$$

$$MAIFI_{E} = \frac{\sum_{j=1}^{NLP}(\lambda^{ME}_{L_j}\times N_{L_j})}{\sum_{j=1}^{NLP}N_{L_j}} \tag{16}$$

V. STUDY RESULTS

Application of the proposed technique to a multi-load points distribution system is illustrated using the distribution reliability test system shown in Fig. 2. The test system is the distribution system connected to Bus 2 of the Roy Billinton Test System (RBTS) [12]. The required reliability data is given in [12]. A computer program has been developed to perform the necessary computations. In the study results presented in this paper, only the 11 kV feeders are considered and any failures in the 33 kV system, the 33/11 kV substation, fuses, circuit breakers, reclosers and switches are ignored. It is assumed that protection system operates successfully when required to do so. Circuit breakers and reclosers are assumed to open and isolate a fault, if required. 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 this case, a failed transformer can be replaced by the spare one within the installation time rather than leaving the load point disconnected for the repair time of the failed one. It is assumed that substation circuit breakers have reclosing capability. Also, when employing the LRS for the test system, the intermediated section switches on each feeder and loop switches are replaced by normally closed sectionalizing and normally open tie reclosers, respectively. Any two adjacent feeders which are interconnected to each other through a normally open tie recloser are considered as a LRS with its own ACS.

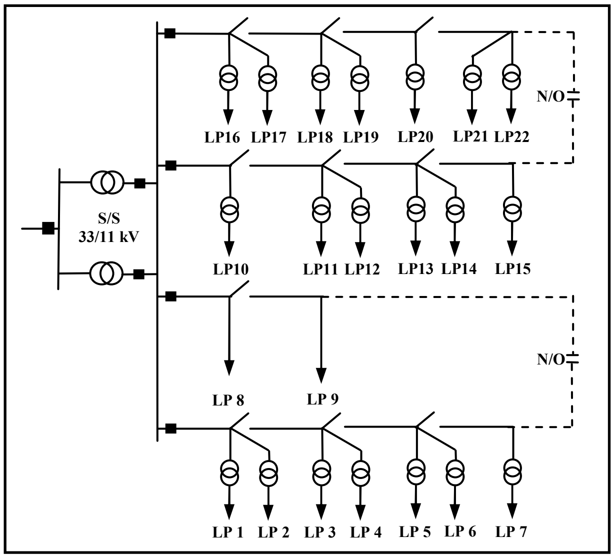

Fig. 2. The distribution reliability test system, known as RBTS – Bus 2 [12].

In order to quantitatively examine the impacts of two introduced ACSs of LRS on distribution system reliability, several comparative studies are conducted. An overall brief description of various case studies is as follows:

- **Case 1**: The LRS is not implemented.
- **Case 2**: The LRS is implemented and equipped with an ACS without communication capability.
- **Case 3**: The LRS is implemented and equipped with an ACS with communication capability.

In these case studies, the basic assumptions tabulated in Table 3 are taken into account.

TABLE 3
BASIC ASSUMPTIONS WHICH ARE CONSIDERED IN THE ANALYSES

Manual Switching Time	1 (hr)
Availability of LCE of ACS	0.99
NRO	4
NRO_{FB}	3
NRO_{TFC}	2
Ratio of Temporary to Permanent Failure Rate of Components	$\frac{\lambda_{C_i}^{T}}{\lambda_{C_i}^{P}} = 2 \quad for\ i = 1\ to\ NC$

Table 4, shows the system oriented reliability indices of the test system for comparative case studies. It can be seen from the results that the indices are improved when LRS is implemented in the test system compared to those obtained in the absence of LRS. The improvements are about the same for both LRS operated by ACSs with and without communication capability. This similarity is especially predominant in the case of reliability indices which only count the effects of sustained interruptions, like SAIFI, SAIDI, ASAI and AENS.

It is also important to perform sensitivity studies and consider the impacts on the system and load-point reliability indices while varying some of the basic assumptions.

Table 5 shows the effect of different manual switching times (MSTs) on some reliability indices of the test system. This table shows that the improvements in the reliability indices are the same for both LRS operated by ACSs with and without communication capability. However, the effects of employing LRS, for distribution system reliability improvement, are considerable when the value of MST becomes higher.

Table 6, shows the effect of ratio of temporary to permanent failure rate of components on some of the reliability indices of the test system. This table shows that as the value of ratio of temporary to permanent failure rate of distribution system components increases the effect of LRS on improving the reliability indices associated with momentary interruptions will be more considerable.

When employing LRS, load points of distribution reliability test system of Fig. 2 can be categorized into two groups. The first group are those load points located between substation circuit breakers and mid point normally closed sectionalizing reclosers, i.e. load points 1-4, 8, 10-12 and 16-19. The second group are those load points located between midpoint normally closed sectionalizing reclosers and normally open tie reclosers, i.e. load points 5-7, 9, 13-15 and 20-22.

The impacts of introduced ACSs of LRS are distinguishable from the results of Table 6. This table shows that the momentary interruption frequency and momentary interruption event frequency of the first group of load points decrease when LRS is implemented in the test system compared to the similar results in the absence of LRS. This improvement is the same for both LRS operated by ACSs with and without communication capability. However, it can be seen from the result of Table 6 that momentary interruption frequency of the second group of load points decreases when LRS equipped by an ACS with communication capability is implemented, and increases when LRS equipped by an ACS without communication capability is implemented. Table 6 also shows that the momentary interruption event frequency of the second group of load points increases by implementing LRS. This is due to the operational procedure of implemented ACS of LRS and the definition of momentary interruption events.

TABLE 4
SYSTEM ORIENTED RELIABILITY INDICES OF THE TEST SYSTEM FOR COMPARATIVE STUDIES

Reliability Indices	**Case 1**	**Case 2**	**Case 3**
SAIFI (int/cust.yr)	0.2482	0.1603	0.1603
SAIDI (hr/cust.yr)	0.7656	0.6776	0.6776
ASAI (%)	99.9912606	99.9922648	99.9922648
AENS (kwhr/cust.yr)	4.6351	4.0900	4.0900
MAIFI (int/cust.yr)	3.4718	1.8179	1.7856
MAIFI$_E$ (int.eve/cust.yr)	1.5588	0.8239	0.8239

TABLE 5
EFFECT OF DIFFERENT MANUAL SWITCHING TIMES ON SOME RELIABILITY INDICES OF THE TEST SYSTEM

Reliability Indices	**Case 1**			**Case 2**			**Case 3**		
	MST (hr)			**MST (hr)**			**MST (hr)**		
	0.5	**1.0**	**1.5**	**0.5**	**1.0**	**1.5**	**0.5**	**1.0**	**1.5**
SAIDI (hr/cust.yr)	0.6968	0.7656	0.8344	0.6528	0.6776	0.7024	0.6528	0.6776	0.7024
AENS (kwhr/cust.yr)	4.2369	4.6351	5.0334	3.9644	4.0900	4.2156	3.9644	4.0900	4.2157
Annual Outage Time of Load Point 3 (hr/yr)	0.7220	0.7902	0.8585	0.6781	0.7025	0.7269	0.6781	0.7025	0.7269
Annual Outage Time of Load Point 15 (hr/yr)	0.6586	0.7285	0.7984	0.6083	0.6278	0.6473	0.6083	0.6278	0.6473

TABLE 6
EFFECT OF RATIO OF TEMPORARY TO PERMANENT FAILURE RATE OF COMPONENTS ON SOME RELIABILITY INDICES OF THE TEST SYSTEM

Reliability Indices	**Case 1**			**Case 2**			**Case 3**		
	Ratio of Failure Rates			*Ratio of Failure Rates*			*Ratio of Failure Rates*		
	2	*3*	*4*	*2*	*3*	*4*	*2*	*3*	*4*
MAIFI (int/cust.yr)	3.4718	4.6765	5.8812	1.8179	2.4740	3.1302	1.7856	2.4342	3.0828
MAIFI$_E$ (int.eve/cust.yr)	1.5588	2.1612	2.7636	0.8239	1.1520	1.4800	0.8239	1.1520	1.4800
Momentary Interruption Frequency of LP3 (int/yr)	3.6182	4.8682	6.1182	1.8830	2.5620	3.2410	1.8830	2.5620	3.2410
Momentary Interruption Event Frequency of LP3 (int.eve/yr)	1.6227	2.2477	2.8727	0.8540	1.1935	1.5330	0.8540	1.1935	1.5330
Momentary Interruption Frequency of LP15 (int/yr)	3.1785	4.2945	5.4105	3.5735	4.6895	5.8055	2.3637	3.2027	4.0417
Momentary Interruption Event Frequency of LP15 (int.eve/yr)	1.4315	1.9895	2.5475	1.5302	2.0882	2.6462	1.5293	2.0873	2.6453

VI. CONCLUSION

This paper proposes an approach for assessing the impacts of two commonly used ACSs of LRS on the distribution system reliability. In order to demonstrate the proposed technique, comparative and sensitivity studies were conducted using a typically distribution reliability test system. Comparative studies were directed to illustrate how two common types of ACSs could affect reliability indices of a given distribution system. In addition, sensitivity analyses were performed to illustrate the impacts on reliability indices of varying the manual switching times and the ratio of temporary to permanent failure rate of distribution system components. The study results presented in this paper indicate the benefits of employing the LRS for automating a distribution network and also show the different effects of the two studied ACSs of LRS on the reliability indices associated with sustained and momentary interruptions. Although, both ACSs with and without communication capability result in acceptable reliability improvement, but effects of LRS in the distribution system reliability improvement can be even more enhanced using the ACS with communication capability. However, when comparing these two ACSs for selection, one should not just consider the reduction in reliability indices as decision making criteria. Instead, in addition to performance of these ACSs from distribution system reliability point of view, other parameters such as different weightings that regulatory puts on the reliability indices, utility's budget constraints, purchase, installation, operation and maintenance costs of LRS equipment, the number of reclosing operations of ACS procedure for fault detecting, isolating and service restoration (which severely impacts the whole feeder components and load points), automatic restoration capability to the normal system configuration (which decreases the operational cost), and also avoiding the faults occurs downstream of mid recloser to be momentarily placed on the other feeder (which improve the distribution system security and power quality) should also be taken into account.

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VIII. BIOGRAPHIES

Shahram Kazemi was born in Iran. Obtained B.Sc. Degree (with Honors) in Electrical Engineering from University of Hormozgan, Bandar-Abbas, Iran in 2002, and M.Sc. Degree (with Honors) in Electrical Engineering from Sharif University of Technology, Tehran, Iran in 2004. From 2003 to 2006 he has been with Niroo Consulting Engineers Co., Tehran, Iran as senior researcher. He is currently working toward the Ph.D. Degree in Electrical Engineering at Sharif University of Technology and as visiting researcher at Helsinki University of Technology, Espoo, Finland. His research interests include Power System Reliability and Power System Protection, Control and Automation.

Mahmud Fotuhi-Firuzabad (SM'99) was born in Iran. Obtained B.Sc. and M.Sc. Degrees in Electrical Engineering from Sharif University of Technology and Tehran University in 1986 and 1989 respectively and M.Sc. and Ph.D. Degrees in Electrical Engineering from the University of Saskatchewan in 1993 and 1997 respectively. Dr. Fotuhi-Firuzabad worked as a postdoctoral fellow in the Department of Electrical Engineering, University of Saskatchewan from Jan. 1998 to Sept. 2000 and from Sept. 2001 to Sept. 2002 where he conducted research in the area of power system reliability. He worked as an assistant professor in the same department from Sept. 2000 to Sept. 2001. Presently he is an associate professor and Head of the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. He is a member of center of excellence in power system management and control.

Majid Sanaye-Pasand (M'97, SM'05) graduated in electrical engineering in 1988, Tehran, Iran, and received his M.Sc. and Ph.D. in 1994 and 1998, Calgary, Canada, respectively. His areas of interest include power system analysis and control, digital protective relays and application of AI. He is at present an associate professor and associate chair at the School of Electrical and Computer Engineering, University of Tehran. He is a board member of Control and Intelligent Processing Center of Excellence, University of Tehran.

Matti Lehtonen received the M.S. and Licentiate Degrees in electrical engineering from the Helsinki University of Technology (HUT), Espoo, Finland, in 1984 and 1989, respectively, and the Dr. Tech. 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 HUT, where he is a Professor of IT applications in power systems. Presently he is Head of the Department of Electrical Engineering, HUT, Espoo, Finland. His main activities include earth fault problems, and harmonic related issues and applications of information technology in distribution automation and distribution energy management.