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Research paper

Distribution networks reliability assessment considering distributed automation system with penetration of DG units and SOP devices

M.B. Shafik [a,b], Zakaria M.S. Elbarbary [c,*], Bu Siqi [b], Ahmed M. Azmy [d], Mohamed G. Hussien [d,e]

[a] Department of Electrical Engineering - Faculty of Engineering- Kafrelsheikh University, Kafrelsheikh, 33516, Egypt
[b] Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, 999077, Hong Kong, China
[c] Department of Electrical Engineering, College of Engineering, King Khalid University, Abha, Saudi Arabia
[d] Department of Electrical Power and Machines Engineering, Faculty of Engineering, Tanta University, Tanta, 31527, Egypt
[e] School of Mechanical Engineering and Automation, Harbin Institute of Technology (Shenzhen), Shenzhen, China

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ABSTRACT

The electric utility industry is moving towards a deregulated and competitive market to meet customer expectations. So, system performance and reliability assessments are getting targeted more than before. Several performance measures of reliability are developed in the literature. In this research, the NEPLAN Simulator reliability analysis module is used to determine all the reliability indices in different cases of study considering the effect of the Advanced Distributed Automation System (ADAS). The analysis also benefits from the presence of Penetration of Distributed Generation (DG) units and Soft Open Points (SOP) to enhance system reliability alongside power quality. Therefore, this paper provides a methodology based on a cost/benefit study for distribution networks to define the best location of DG units and SOP devices that leads to better reliability indices. The objectives of the study are demonstrated and investigated through Bus 4 of the standard reliability Roy Bollington Test System (RBTS). NEPLAN uses a tool to apply the Reliability Centered Maintenance (RCM) strategy, which leads to a substantial reduction of maintenance expenses. Simulation results indicate a significant reduction in system reliability cost by 65.8% with significant enhancement in the average of all reliability indices and at each load point too such as Customer Average Interruption Duration Index (CAIDI) which is improved from 40.899 to 29.883, Energy not supplied also is declined by 52.34%. It is also worth saying that, even using DG units or SOP devices separately leads to positive results but the best outcomes are obtained with an appropriate combination of both.

1. Introduction

The electric utility industry is moving toward a deregulated and competitive environment in which utilities must have accurate system performance information to ensure that maintenance money is spent wisely, and customer expectations are met. To measure system performance, the electric utility industry has developed several performance metrics to ensure reliability. These reliability indices include power outage duration, power outage frequency, system availability, and response time; however, it should be noted that system reliability is not the same as power quality. System reliability refers to sustained interruptions and short duration interruptions (Standards, 2020). Much research has been done in the literature on distribution system reliability assessment. In Li et al. (2018), Su et al. (2019), Zhi-jian et al. (2016), Abdullah (2012), Falaghi and Haghifam (2005), Ding et al. (2010) and Sun et al. (2020), methods to evaluate the reliability of distribution networks considering distributed network access are investigated. These papers presented methods for evaluating grid reliability considering various characteristics of distributed power supply and conventional power supply. Some research papers addressed the impact of the random output of DG units such as wind or solar, while others focused on showing their significant impact on the reliability indices in islanded operation. However, most of this work assumed that the location of DG units was always fixed, and other considerations were made.

Other research focused on reliability index evaluation methods such as Monte Carlo simulation techniques or analytical methods, using new and efficient simulators with their superior capabilities in design and analysis. An overview of reliability assessment techniques for modern distribution networks is provided in Escalera et al. (2018), where a comprehensive comparison is made between different reliability assessment techniques and models.

* Corresponding author.
E-mail address: albrbry@kku.edu.sa (Z.M.S. Elbarbary).

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Normal solutions to improve reliability in DNs are (Moslehi and Kumar, 2010):

- Ring operation (mesh network) allows parts of a network to work as a ring supplied from different points. This can be achieved by using Tie switches between adjacent feeders.
- Reliability is key for any company — it is vital to have planned and continuous maintenance of the assets in order to reduce failures. Additionally, installing additional security devices can help to improve reliability.
- The effect of the evolution of DNs towards smarter grids and more sustainable energy systems has a substantial impact on system reliability.
- Energy storage technologies can be used to mitigate the fluctuations of renewable generation and extend their contribution to supply restoration.
- Also, applying of Demand Response (DR) techniques can help in optionally decreasing the peak demand selectively and preserve the supply security under emergencies (Escalera et al., 2018).
- Use of SOP devices as a new technology for power quality support in place of Tie switches (Shafik et al., 2019, 2020b) and, so, it can make mesh loop between two feeders or conserve system radiality by disconnecting a specific branch.
- Automation, especially ADAS directly affects the time process of Fault Location, Isolation, and Service Restoration (FLISR) so, ADAS enhances all system reliability indices.

A computer and communication-based system called the Advanced Distribution Automation System (ADAS) is outfitted with the appropriate hardware and software features for remote monitoring and control of the substations for major distribution feeders from a central distributed control center (Shafik et al., 2020a). A real-time adjustment to changing loads, distributed generation, and breakdown states within the distribution grid is the aim of distribution automation in the utility grid, often without operator interaction (Heidari et al., 2017; Khatib-Tohidkhaneh et al., 2020). These applications are available on ADAS, and the main ones are FLISR, Volt/Var control, protection coordination analysis, feeder load balancing, and fault locator (PacWorld, 2020). Many Numerous studies looked at in the literature examined ADAS. A distributed automation architecture for distribution networks has been thoroughly examined in Angioni et al. (2018),from design to implementation. The communication layer, information layer, and component layer are the three layers that make up the architecture. Then they evaluated it using a variety of indices, but it is important to note that it is an optimistic design that requires a trustworthy and clever DN in addition to a cost analysis and careful planning. In Girón et al. (2018), an approach for evaluating the impact of automating the DNs dependability is presented. Where, they focused on the important role of the communication system capabilities to enhance the performance of the automation system and, consequently, the system reliability similar to study in Zhou et al. (2014) with the application of IEC 61850 for distribution network automation with distributed control (Yip et al., 2018). The applications of the distribution automation system in power supply enterprises are exploited in numerous papers (Xiaoxi et al., 2009; Deng et al., 2012), especially the service of FLISR (Du et al., 2014; Kawano et al., 2015).

In the literature, many methods, including the ETAP® software package and DIgSILENT® power factory, are used to evaluate reliability indices. However, NEPLAN® (NEPLAN, 2020) is recommended as one of the most comprehensive planning, optimization, and simulation tools in this study for electrical networks (transmission, distribution, generation, and industrial), distributed or renewable energy systems, smart grids, and generation, as well as gas, water, and heating applications. Depending on the type of system under consideration, several methodologies are needed for distribution system analysis. These fundamental methods are beneficial for studying radial distribution systems. For rings or mesh systems, however, more sophisticated strategies are needed; a thorough examination of these techniques may be found in Escalera et al. (2018). So, NEPLAN is proposed to benefit from its capabilities in designing and analyzing such complicated systems (DNs equipped with ADAS, DG units, and SOP devices).

It worth to mention that inserting the DG units should be planned according to techno-economic study. This is due to the intermittent nature of such resources, where the generated power mainly depends on weather conditions such as solar irradiation, average sun hours, wind availability and speed, etc. (Hoseinzadeh and Astiaso Garcia, 2022). So, hybrid renewable energy resources (HRERs) are developed as a cost-effective solution for more environmental and technical issues in electrical energy generation especially in rural areas (Hoseinzadeh et al., 2023, 2022).

2. Problem statement and objectives

The main DN's problem that comes after power quality is system service reliability improvement to satisfy customer demand, so, it is important to measure system reliability and search for methods to alleviate it. But ideally new technologies and devices, mainly used to enhance power quality such as penetration of DG units and power electronic devices, could be utilized to enhance system reliability. It has already been shown that the ADAS can directly make the system more reliable when it is associated with the smart substation to measure and evaluate the effect of this on system reliability. There are a set of indices that must be extracted, and this can be done using NEPLAN simulator. Motivated by all the previously mentioned points, the ultimate goal of this research is to enhance the operation of MV distribution networks using a distribution automation system. Therefore, this research is targeting the following objectives:

- Developing a generic framework and strategy for ADAS design and implementation to get the grid self-healing and reliability improvement.
- Investigating how the proposed automation system improves the reliability level of the distribution network via a reliability assessment study.
- Investigating the effect of DG units and SOP devices used for power quality enhancement to alleviate the system reliability in both manual and automatic operation.
- Utilizing NEPLAN software efficient designing (full control on all parameters) and analyzing its capabilities in distribution network's reliability evaluation.

3. Typical ADAS structure

The ADAS scheme shown in Fig. 1 for the distribution network under study is the substation-centralized scheme labeled SC-ADAS. SC-ADAS components are distributed between the field area and the control center in the substation. In the field there is a Feeder Remote Terminal Unit (FRTU) that contains field devices such as circuit breakers and controllers with a certain level of automation. These field devices are ready to respond to the control signals of a distributed control center equipped with intelligent software to analyze feedback and forecast data and make appropriate decisions for the ADAS. Information is gathered by the intelligent S/S and this information is then processed to locate and generate a sequence of switching actions to isolate the fault. Then the healthy customers are reintegrated into the network by running FLISR algorithms at the primary hub. The communication system plays a crucial role in the quality and performance of ADAS depending on the field infrastructure where it can be wired/wireless or a combination.

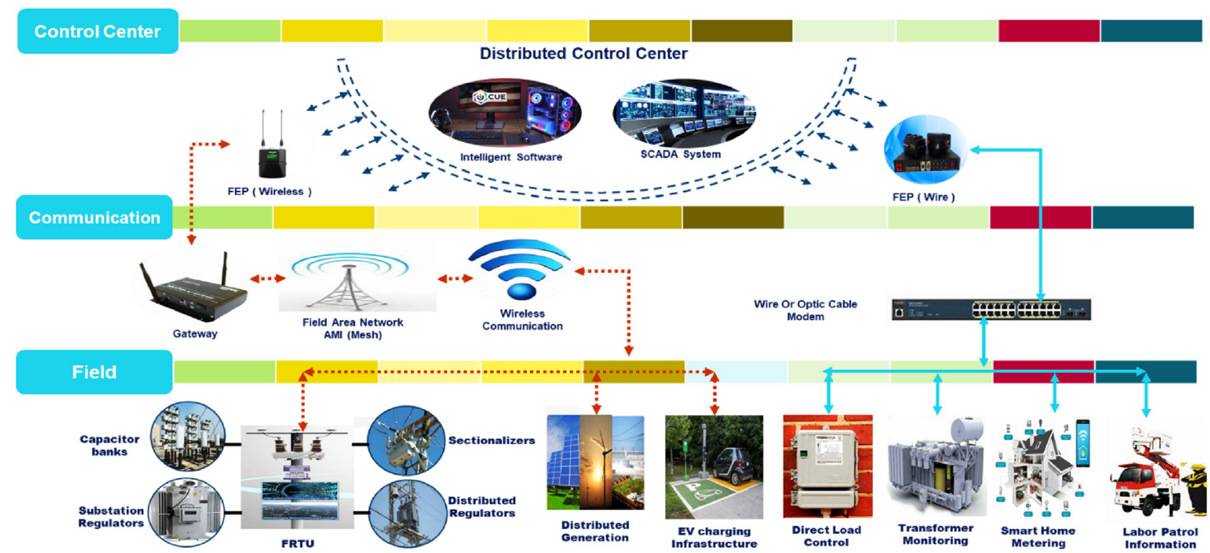

Fig. 1. Substation-centralized ADAS structure.

4. Reliability assessment study

4.1. Reliability indices

IEEE the Standard Association's P1366 — Guide for electric power distribution reliability indices helps in understanding and identifying electric power distribution reliability indices and the factors that affect their calculation (Anon, 2012). P1366 provides a set of definitions of terms and formulas for calculating reliability indices, which can be classified and explained as follows:

i. *Load Point Indices*

■ Load Point average FR (λ_i: 1/yr.) is given in Eq. (1):

$$\lambda_i = \sum_{j\epsilon N_e} \lambda_{e,j} \tag{1}$$

where, λ_e is FR of element i due to a set of failures N_e ($j\epsilon N_e$) that directly interrupt load at the point i.

■ Load Point annual outage duration (U_i: h/yr.) is given in Eq. (2):

$$U_i = \sum_{j\epsilon N_e} \lambda_{e,j}.\gamma_{i,j} \tag{2}$$

where, $\gamma_{i,j}$ is outage duration of element i due to a set of failures N_e ($j\epsilon N_e$) that directly interrupt load at the point i.

■ Load Point average outage duration (γ_i: h) is given in Eq. (3):

$$\gamma_i = \frac{U_i}{\lambda_i} \tag{3}$$

Other load indices are determined by NEPLAN, which is system load interruption frequency 'F: 1/yr.', system load interruption mean duration 'T: h', system load interruption probability 'Q: min/yr.', total interrupted load power 'P: MW/ yr.', Total load energy not supplied 'W: MWh/ yr.', and Total load interruption costs 'C: $/yr.'.

ii. *Total System Indices*

■ System Average Interruption Frequency Index ($SAIFI$: 1/yr.) is given as:

$$SAIFI = \frac{\sum N_i}{N_T} \tag{4}$$

Where N_i is the total number of interrupted customers while N_T is the total number of customers served.

■ System Average Interruption Duration Index ($SAIDI$: min/yr.) is given as:

$$SAIDI = \frac{\sum \gamma_i.N_i}{N_T} \tag{5}$$

Where γ_i is average outage duration (or restoration time) at load point i but in minutes.

■ Customer Average Interruption Duration Index ($CAIDI$: h) is given as:

$$CAIDI = \frac{\sum \gamma_i.N_i}{N_i}, \text{ while } SAIFI = \frac{SAIDI}{CAIDI} \tag{6}$$

■ Average Service Availability Index ($ASAI$: %) is given as:

$$ASAI = \frac{\text{Customer hours of available service}}{\text{customer hours demand}} \tag{7}$$

■ Average service unavailability index ($ASUI$: %) is given as:

$$ASUI = 1 - ASAI \tag{8}$$

■ Average Energy Not Supplied index ($AENSI$: MW h/customer/ yr.) is given in Eq. (9):

$$AENSI = \frac{U_i.P_i}{N_T} \tag{9}$$

Where P_i is load demand (MW) at load point i

4.2. Reliability assessment technique

NEPLAN Electricity is a user-friendly software tool with a graphical interface and a modular concept. It is based on international standards such as IEC, ANSI, IEEE etc. and can handle both AC and DC networks with high accuracy and performance, including very large networks (over 500,000 busbars) (NEPLAN, 2020). NEPLAN Electricity is divided into a series of interconnected software packages based on their functionality. Each package contains a number of modules such as:

1. Base modules: Load Flow/Contingency Analysis, Short Circuit Analysis, Load Flow Time Simulation, Motor Startup, Arc Calculation, Cable Dimensioning, Overhead Line/Cable

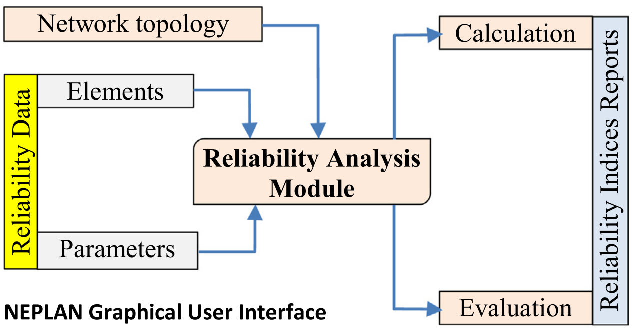

Fig. 2. Block diagram of the reliability assessment study.

Parameter Calculation, Grid Reduction, Net Transfer Capability, Voltage Stability.

2. Power Quality Module: Reliability analysis, harmonic analysis, flicker analysis, voltage sags.

The reliability analysis module is an efficient tool for determining the frequency, average duration, and cost of network component failures that cause supply interruptions (Mokoka and Awodele, 2013). Fig. 2 shows the reliability assessment block diagram, which contains the required data for reliability assessment. In the NEPLAN graphical user interface, the reliability analysis module is fed with the network topology of the system under study, the reliability data of the network elements, and the parameters that control the assessment processes, such as the calculation mechanism and the SwitchBay configuration. Then, the reliability calculations are evaluated based on different failure modes and the reliability metrics of the overall system are presented in the form of tables and graphs.

Table 1
Summary of modified RBTS-Bus 4 system data.

Data	Value
Load Points	38
Sectionalized switches	51
Feeder Sections	67
Feeders	7
DG units	25 MW, Unity PF
SOP device	LFR: 20 MW, 10 MVar, VR: ±10%
Number of customers	4779
Total Load	40 MW
MV Transformer	22/11 kV, 30 MVA (IEC 60909, Dyn11)
LV Transformer	11/0.4 kV, 1 MVA (IEC 60909, Dyn1)

5. Research methodology

5.1. Proposed distribution network configuration and construction utilizing DG units and SOP devices

Roy Bollington Test System (RBTS) Bus 4 (Abiri-Jahromi et al., 2012) is a standard system to test associated reliability problems solution. This system is modified as shown in Fig. 3 while it is fed from a primary substation connected to three supplying points where each supply point is connected to a set of feeders. Table 1 provides a summary of system data such as a set of load points, feeders, customers, and feeder sections (Lines or Cables). Notably, the network is connected to the main substation via Medium Voltage (MV) transformer and loads are connected to feeders through Low Voltage (LV) transformers selected according to IEC standards. Detailed data of loads at each load point and feeders' sections are mentioned in Heidari et al. (2017).

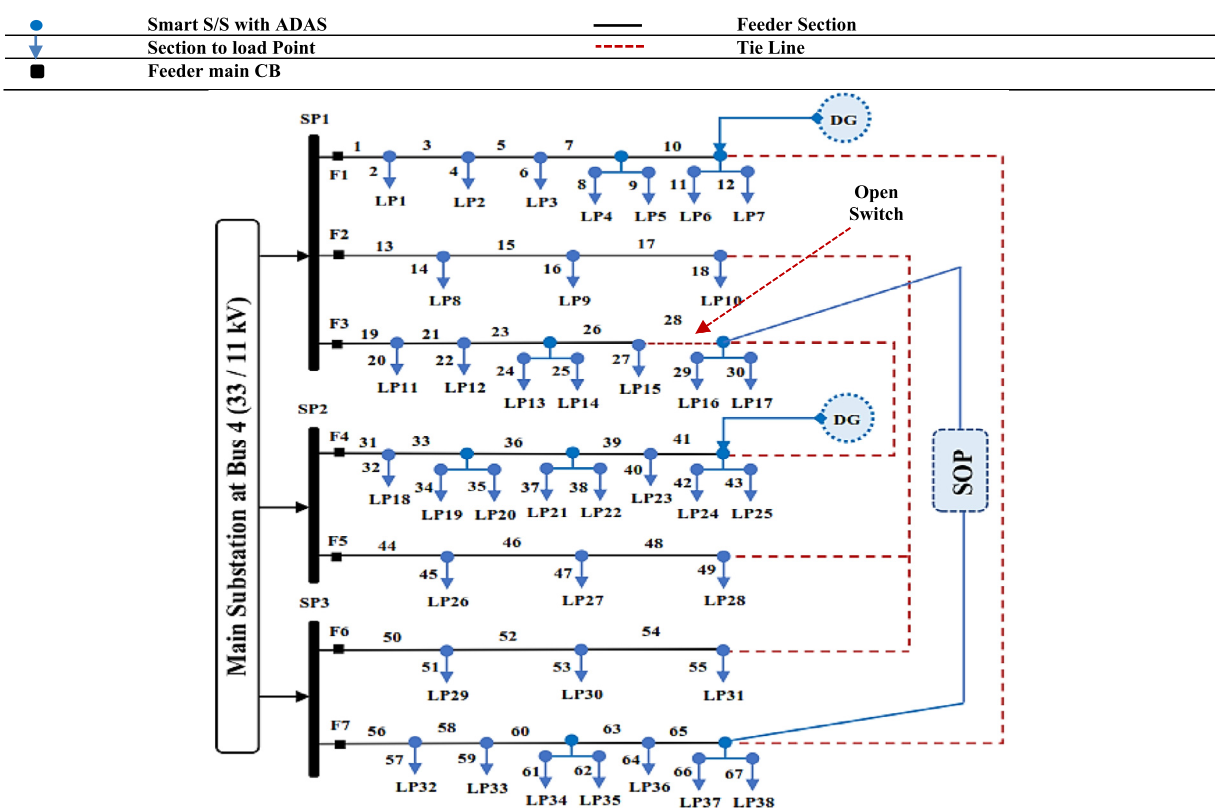

Fig. 3. RBTS-Bus 4 network configuration.

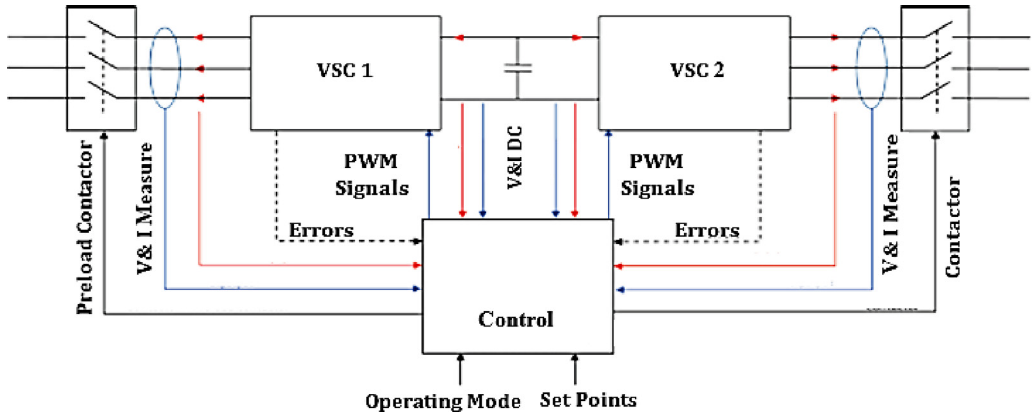

Fig. 4. SOP configuration block diagram.

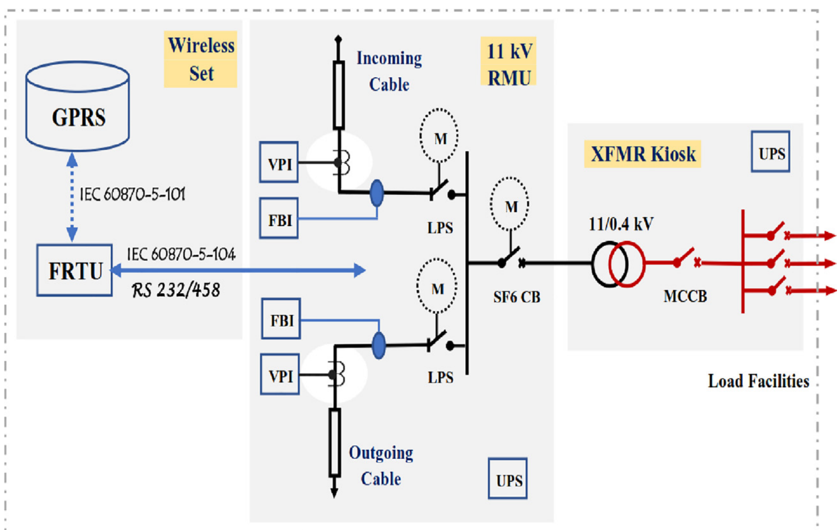

Fig. 5. Typical configuration of smart S/S with ADAS equipment (Hoseinzadeh et al., 2022).

5.2. Modeling and specifications of DG units and SOP devices

Insertion of a single DG unit or multiple DGs at different locations in the distribution system increases total system reliability while the reliability of the distribution system remains unchanged with varying the size of the DG unit (Ahmad et al., 2017). So, when modeling DG units in NEPLAN the type (Solar or wind) is not defined but is assumed to have automatic generation control to share in the network for supplying load with a fixed amount of power (50 MW) directly at one or two feeder sections end.

SOP is defined as a power electronic device, generally consisting of two back-to-back mounted voltage source inverters, and the SOP can control both active and reactive power flow between two feeders with the capability of load balancing and reactive power compensation (Shafik et al., 2019). SOP devices have different models like the UPFC model and Back-to-back voltage source converters (VSC) based SOP. The proposed operating mode is a static mode with P-Q control mode for VSC_2 and VDC-Q mode for VSC_1 (Shafik et al., 2019) to achieve smooth control of voltage and active/reactive power flow in steady state. SOP's main role in the DNs is to enhance system power quality but its presence can improve the total system reliability as it can provide the closed-loop (Ring) operation between feeders or keep system radiality. So, in this study, we will focus on the allocation of only one SOP device to improve total system reliability. The proposed UPFC configuration used in NEPLAN is illustrated in Fig. 4 while line flow regulation is 20 MW, 10 MVar, Voltage regulation is ±10%. SOP with UPFC configuration directly affects the reliability indices specially Energy not supplied to loads and loads interruption probability.

5.3. Typical configuration of smart S/S with ADAS equipment

The existing traditional S/Ss are retrofitted with smart equipment suitable for ADAS such as fault passage indicators (FPIs), motorized load break switches (LBSs), voltage presence indicators (VPIs) and Feeder Remote Terminal Unit (FRTU-IEC 60870-5-104 standards) (Elkadeem et al., 2018), as seen in Fig. 5. Loads are fed via an 11/0.4 kV transformer (XFMR-IEC 60909, Dyn1 standards).

FRTUs-IEC 60870-5-104 standards) (Elkadeem et al., 2018)" as seen in Fig. 5 act as local controllers for field devices and as a gateway between field devices and the main unit via general packet radio service (GPRS-IEC 60870-5-101 standard) as a cost-effective network. As the main component of ADAS, FRTU can monitor all sub-station equipment and acquire all parameters in respect of all incoming and outgoing feeders on real-time basis and the status signals of the devices which is about planning, executing, forecasting, implementation, and maintenance etc. So,

1. FRTU directly affects Fault location, isolation, and service restoration (FLISR) so, Presence of FRTU in the field affects

Table 2
NEPLAN reliability parameters.

Parameter	Setting
System state analysis	Connection Check
Duration for remote Switching	5 min
Duration for manual Switching	120 min
SwitchBay configuration	BB-Disc-> (BB: Bus Bay)
Considered Failure modes	All
Loading Limits	Long Term (100%)
Short circuit indicators	Local/Remote (Access time: 2 min)
Minimum Load shedding step	20%
Maximum No. of LS iterations	3
under voltage load shedding	Activated
FLISR	Activated
DG Possible influence on operation	stand-alone island operation
SOP	Implies Ring Operation

the Duration for remote Switching Table 2 (5 min instead of 120 M for the manual operation).

2. FLISR mode is activated and the duration for remote Switching is defined in NEPLAN reliability study parameters considering the effect of FRTU. Detailed description can be found in Elkadeem et al. (2018) while authors defined in Fig. 8 the switching time to be less than 5 min.
3. Simulation of the fault locating process in Table 3 (Which all set in the NEPLAN parameters) depends on the role of FRTU in monitoring and control all the field components.

5.4. NEPLAN reliability assessment framework

The basic framework for reliability assessment process executed via NEPLAN shown in Fig. 6 starts with reading data. Data input is divided into three categories: network data that include elements parameters: buses, nodes, supply, loads, … etc., reliability parameters which comprises duration of manual and automatic switching, switchbay configuration, failure models, … etc., and elements reliability data that involves elements failure rate and outage time, loads interruption cost curves, … etc. After processing the data, NEPLAN starts building failure combinations for each element and each failure model and then, the calculation of each element in each stage is performed. Finally, NEPLAN evaluates total system load and generation reliability indices and report results.

5.5. System reliability parameters and data types

Data and parameters associated with the reliability study are detailed in the following tables. Table 2 illustrates reliability data needed to be identified for the NEPLAN simulator as results greatly depend on it. Various reliability parameters such as the way NEPLAN checks failure combinations, the duration for remote/ manual switching process, identifying the main controller in reliability indices values, secondary substation switchBay configuration which is selected to work a remotely controlled or not, and failure models which are detailed in Section 4. It is important also for NEPLAN to specify reliability application utilized in the study, which is FLISR. DG's important role is to work as standalone while fault isolation feeds the healthy area connected to it, and SOP units is configured to imply ring operation between feeders that has a great effect on system reliability. The reliability data of the rest of the elements are concluded in Table 3 with equipment FR and stochastic outage time while, Table 4 simulates time intervals required for FLISR.

Regarding reliability data for different system elements, Table 5 prevails the three load types interruption Cost Damage Function (CDF) that varies with outage time for 4779 customers connected to the RBTS system (Abiri-Jahromi et al., 2012). Also, feeders' sections reliability and type are detailed in Heidari et al. (2017) and Siirto et al. (2015).

Table 3
Elements reliability data.

Element	FR (1/yr.)	T (h) (Independent Stochastic out.)
MV Transformer	0.003	130
LV Switchgear	0.03	45.5
MV Switchgear	0.0102	26.8
MV CB	0.0036	2.1
LV CB	0.0027	4
MV feeder sections	0.02	26.5
LV cables	0.005	10.5
DG units	0.003	130
SOP device	0.03	45.5

Table 4
Simulate fault locating process.

The procedure	Time (min)
Travel time to the first station	15
Travel time between 2 stations	4
Time for measurements	4
Time for switching	5
Time for emergency power supply	90
Time weighting factor (α)	0.5

Table 5
Interruption cost curve for different Load Types (Abiri-Jahromi et al., 2012).

User sector	Interruption duration (min) & Cost ($/kW)				
	1 min	20 min	60 min	240 min	480 min
Residential	0.0002	0.0279	0.1626	1.8126	4.0006
Small User	2.5749	3.221	4.6051	11.2291	21.0691
Commercial	0.381	2.969	8.552	31.32	83.01

6. Simulation results and discussion

6.1. Cases understudy

In this research, four cases are studied to check the efficiency of the presented methodology. Utilizing DG units and SOP devices system the reliability of these systems is evaluated for the following four cases with/without ADAS (Automated and Non-Automated operation):

Case 1: Basic network topology without DG units or SOPs. Case 2: Basic network topology with DG units only.

Case 3: Basic network topology with SOP devices only.

Case 4: Basic network topology with DG units and SOPs.

6.2. System reliability indices without ADAS (non-automated)

In this subsection, comparative investigation of the four cases under study is introduced without any automation system.

Case 2 denotes the insertion of DG unit at feeders' end and checks its effect on reliability compared to basic system indices. So, in Table 6 a 50 MW unit was added at the end of different feeders to define the best location that improves reliability. It was found that adding DG unit at feeder 4 reduced system load interruption mean duration 'T' from 40.899 h to 38.299 h and also reduced both total load energy not supplied 'W' and total load interruption costs 'C' by 12.35% and 10.28% respectively. However, adding the same unit at feeder 7 resulted in the best reduction in the SAIDI and CAIDI indices, which is also very near to results of DG unit directly feeding at bus 4. Therefore, Bus 4 is the best location for a single DG unit, but if this power is divided between two DG units fitted at different feeders, it will result in better results. Locating the DG at feeders 1, 4 reduces 'T' to 35.446 h and increases the amount of reduction of 'W' and

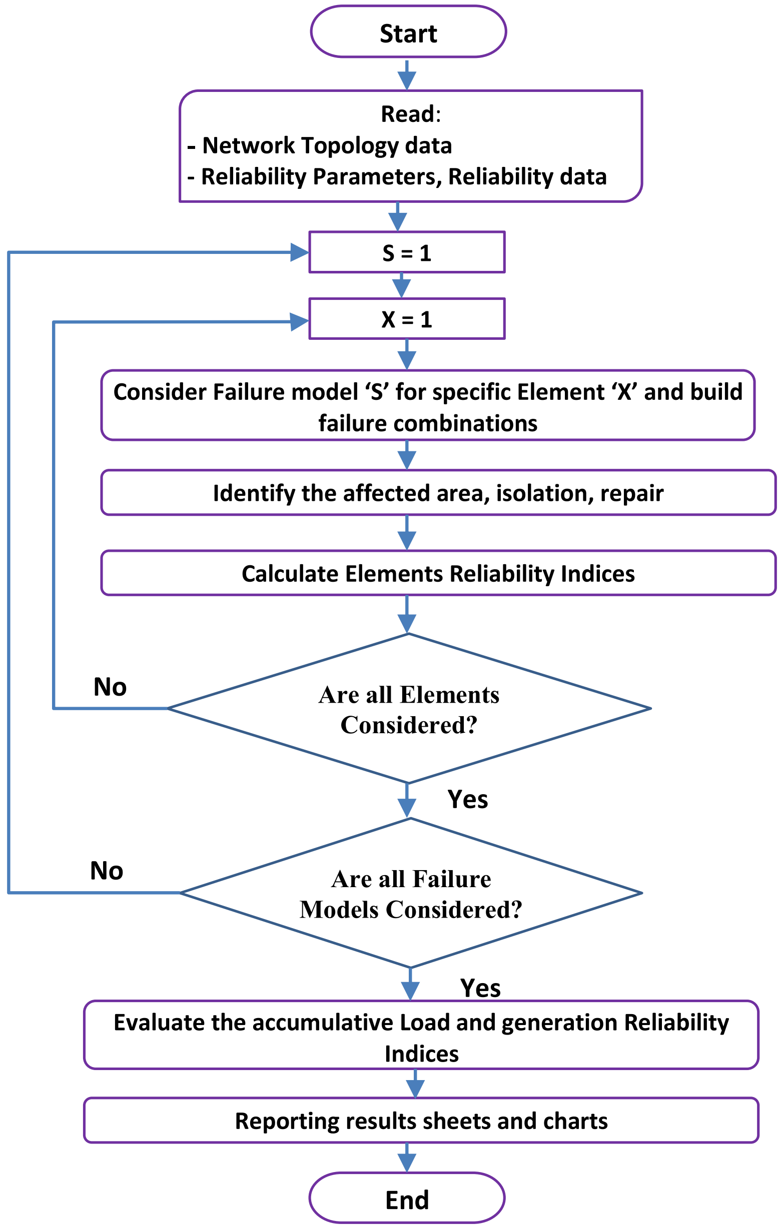

Fig. 6. Procedure of the analytical technique for reliability assessment.

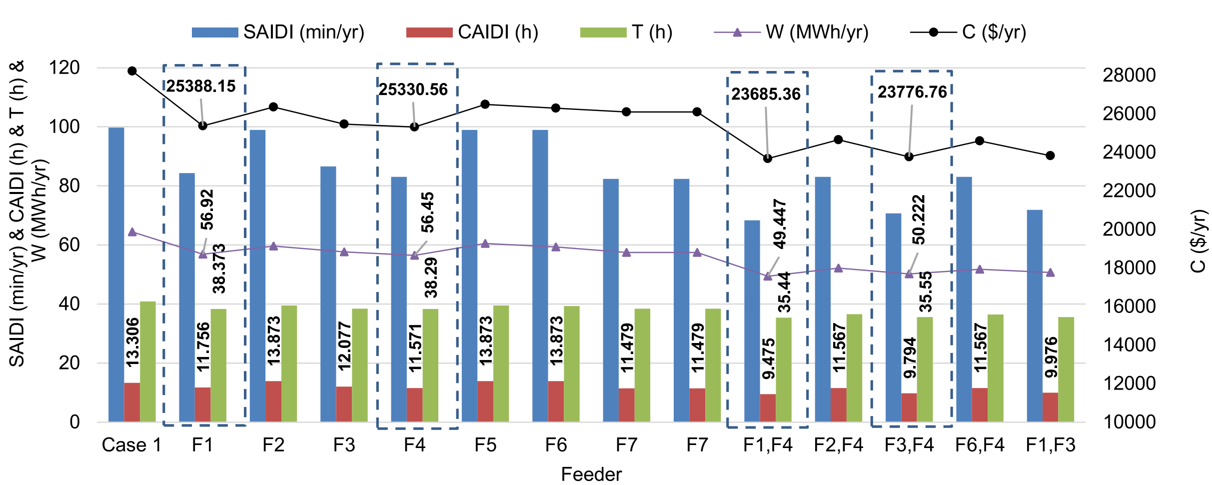

Fig. 7. Holistic summary of system reliability results for Case 2 compared to Case 1 (Without ADAS).

Table 6
System reliability indicies for Case 2 compare to Case 1 (Without ADAS).

Index	Case 1	Case 2: DG (50 MW) at Feeder:							Case 2: DG (50 MW) Equally shared Feeders:				
		F1	F2	F3	F4	F5	F6	F7	F1, F4	F2, F4	F3, F4	F6, F4	F1, F3
N	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779
SAIFI (1/yr.)	0.125	0.12	0.119	0.12	0.12	0.119	0.119	0.12	0.12	0.12	0.12	0.12	0.12
SAIDI (min/yr.)	99.729	84.327	98.981	86.62	83.08	98.982	98.981	**82.415**	68.398	83.052	70.691	83.052	71.939
ASIDI (min/yr.)	96.555	85.333	89.413	86.522	84.623	90.664	88.904	86.148	74.12	78.201	75.31	77.692	76.02
CAIDI (h)	13.306	11.756	13.873	12.077	11.571	13.873	13.873	**11.479**	9.475	11.567	9.794	11.567	**9.976**
ASAI (%)	99.981	99.984	99.981	99.984	99.984	99.981	99.981	99.984	99.987	99.984	99.987	99.984	99.986
F (1/yr.)	0.671	0.668	0.668	0.668	0.668	0.668	0.668	0.668	0.671	0.671	0.671	0.671	0.671
T (h)	40.899	38.373	39.473	38.483	**38.299**	39.51	39.363	38.446	**35.446**	36.542	35.556	36.432	35.629
Q (min/yr.)	1647.10	1537.93	1582.03	1542.34	1534.99	1583.50	1577.62	1540.87	1426.54	1470.64	1430.95	1466.23	1433.89
P (MW/yr.)	4.097	3.873	3.873	3.873	3.875	3.87	3.873	3.873	3.891	3.891	3.891	3.891	3.888
W (MWh/yr.)	64.405	56.922	59.643	57.697	**56.45**	60.477	59.304	57.465	**49.447**	52.168	50.222	51.829	50.695
W. Reduction (%)	0	11.62	7.393	10.41	**12.35**	6.098	7.92	10.77	**23.22**	19.00	22.02	19.53	21.29
C ($/yr.)	2.82E4	2.53E4	2.63E4	2.54E4	**2.53E4**	2.64E4	2.63E4	2.61E4	**2.36E4**	2.46E4	2.37E4	2.45E4	2.38E4
C. Saving (%)	0	10.08	6.63	9.76	**10.28**	6.14	6.84	7.55	**16.11**	12.66	15.79	12.87	15.59

Table 7
System reliability indicies for Case 3 compare to Case1 (Without ADAS).

Index	Case 1	Case 3: SOP between Feeders:							
		F1-F4	F1-F7	F2-F5	F3-F4	F5-F6	F2-F4	F4-F6	F4-F7
Open Switch	No	S 41	S 10	S 17	S 41	S 54	S 41	S 41	S 41
N	4779	4779	4779	4779	4779	4779	4779	4779	4779
SAIFI (1/yr.)	0.125	0.122	0.124	0.125	0.122	0.125	0.118	0.118	0.123
SAIDI (min/yr.)	99.715	68.597	68.135	99.674	70.882	99.673	82.879	82.88	**66.743**
ASIDI (min/yr.)	96.543	74.655	76.28	84.831	75.829	84.323	78.513	78.012	75.466
CAIDI (h)	13.313	9.374	9.184	13.299	9.692	13.299	11.683	11.682	**9.076**
ASAI (%)	99.981	99.987	99.987	99.981	99.987	99.981	99.984	99.984	99.987
F (1/yr.)	0.671	0.662	0.662	0.662	0.662	0.658	0.662	0.662	0.662
T (h)	40.913	**35.878**	36.026	38.209	35.989	38.317	36.988	36.877	35.952
Q (min/yr.)	1646.72	**1425.521**	1431.401	1518.131	1429.931	1513.241	1469.621	1465.211	1428.461
P (MW/yr.)	4.095	4.069	4.101	4.082	4.064	4.083	**3.995**	3.998	4.068
W (MWh/ yr.)	64.397	**49.804**	50.886	56.588	50.57	56.25	52.377	52.043	50.345
W. Reduction (%)	0	22.67	20.99	12.14	21.48	12.66	18.67	19.19	21.83
C ($/yr.)	28224.646	25208.87	26008.855	26732.9	25229.98	26674.78	25160.01	**25143.77**	25746.59
C. Saving (%)	0	10.7	7.9	5.39	10.69	5.59	10.8	10.9	8.8

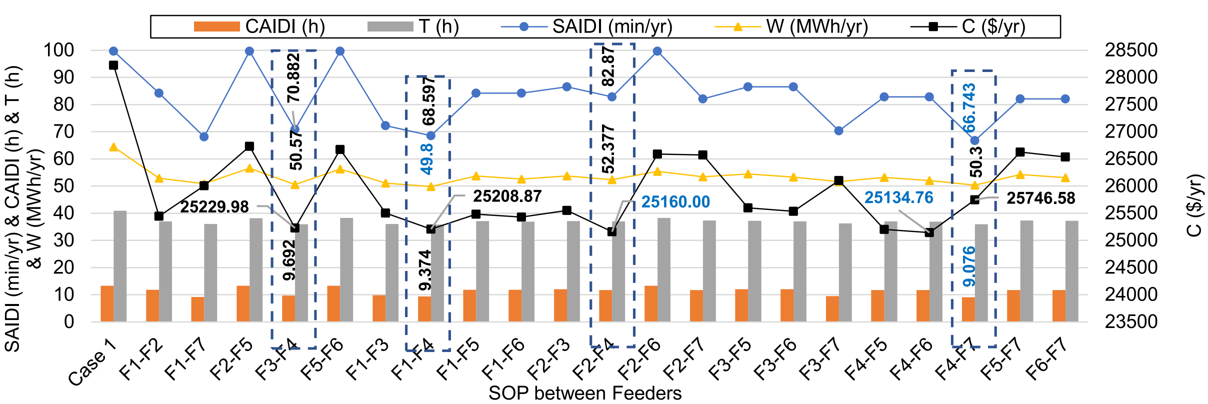

Fig. 8. Holistic summary of system reliability results for case 3 compared to Case 1 (Without ADAS).

'C' to 23.22% (nearly double reduction) and 16.11%. Fig. 7 shows the effect of adding DG units at different feeders on SAIDI, CAIDI, T, and W which seems adjacent variation which indicates that adding DG units anywhere will alleviate reliability, but the best location leads to considerable enhancement. Fig. 7 highlights the best feeders to integrate DG units in case if the optimal location is not available.

Table 7 shows network reconfiguration using SOP devices' consequence on system reliability. Table 7 indicates that adding one SOP device as a closed switch between feeders 3, 4 is the best location for SOP as it leads to a reduction in total system interruption costs and the unsupplied energy by 10.69 % and 21.48 % while all other indices enhanced too especially SAIDI that is reduced to 70.88. It is noticed that other locations of SOP at feeders 1,4 leads to similar results So, Fig. 8 shows '21' possible different locations studied for optimal allocation of SOP devices with the objective of achieving best reliability indices with the constraint of keeping system radial. Fig. 8 also shows alternative locations to fix SOP devices if the best location is not available and highlights Table 7's results.

Regarding case 4 in Table 8 both DG units and SOP devices are applied but DG units of 50 MW are equally shared between feeders 1, 4 while SOP location is varied to get the best combination. In this case the optimal location of SOP is changed to be between feeders 2, 7, which results in a higher reduction in W, C to be 43%, 23.54%, respectively, and SAIDI dropped from 99.7 to 39.1. In addition, CAIDI decreased from 13.3 to 5.4 and T decreased also from 40.8 h to 30.6 h. Besides, other locations of SOP devices lead to similar results. Fig. 9 shows a graphical comparison between the four cases under study; while Case 4 is the best solution but case 2 is better than case 4 in all system indices. To summarize this, basic DN structure needs to be modified especially with DG units, SOP devices or both to enhance system reliability, which needs cost–benefit analysis to get optimal allocation for them.

6.3. System reliability indices with ADAS (automated)

Inserting ADAS components into DN with FLISR application has a significant effect on system reliability besides considering modifying DN with DG units and SOP devices. In Table 9 Case 1 with ADAS results is better results than others without ADAS

Table 8
System reliability indicies for Case 4 compare to Case1 (Without ADAS).

Index	Case 1	Case4: DG (50) equally shared between Feeders F1, F4 & SOP between Feeders:					
		F2, F3	F2, F3	F3, F5	F3, F6	F2, F7	F5, F6
Open Switch	NO	S17	S28	S28	S28	S28	S54
N	4779	4779	4779	4779	4779	4779	4779
SAIFI (1/yr.)	0.125	0.123	0.115	0.115	0.115	0.119	0.12
SAIDI (min/yr.)	99.729	56.17	55.243	55.244	55.244	39.107	68.342
ASIDI (min/yr.)	96.555	58.53	58.091	59.307	57.59	55.044	61.889
CAIDI (h)	13.306	7.642	8.021	8.022	8.021	5.472	9.468
ASAI (%)	99.981	99.989	99.989	99.989	99.989	99.993	99.987
F (1/yr.)	0.671	0.662	0.662	0.662	0.662	0.662	0.658
T (h)	40.899	31.643	31.643	31.68	31.532	30.607	32.755
Q (min/yr.)	1647.101	1256.417	1256.417	1257.887	1252.007	1215.257	1292.687
P (MW/yr.)	4.097	3.97	3.823	3.81	3.826	3.897	3.877
W (MWh/yr.)	64.405	39.035	38.741	39.552	38.407	36.709	41.292
W. Reduction (%)	0	39.391352	39.84784	38.58862	40.36643	43.00287	35.88697
C ($/yr.)	28235.9	21693.6	21003.26	21048.1	20987.02	21589.83	22124.24
C. Saving (%)	0	23.170149	25.61506	25.45623	25.67258	23.53765	21.64499

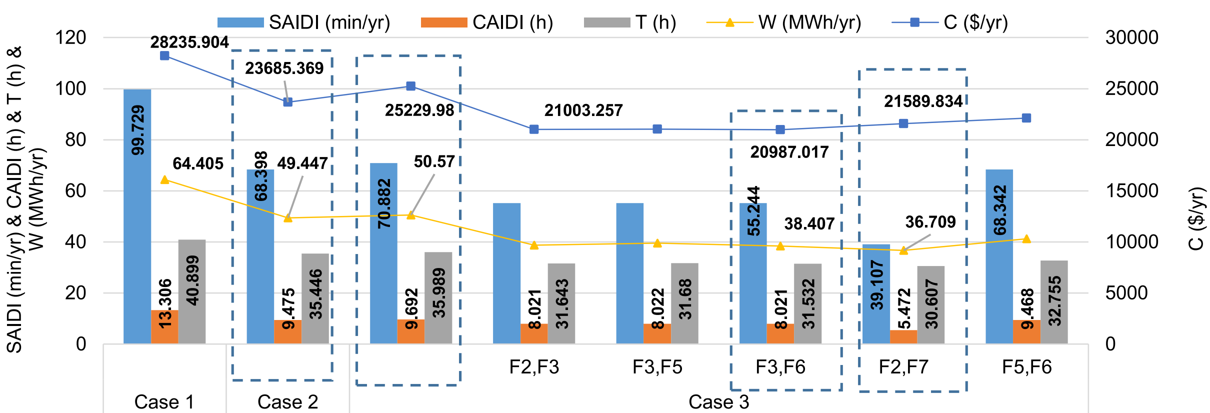

Fig. 9. Holistic summary of system reliability results for the four cases under study (Without ADAS).

Table 9
System reliability indicies for Case 2 compare to Case1 (With ADAS).

Index	Case 1	Case 2: DG (50) at Feeder:											
		F1	F2	F3	F4	F5	F6	F7	F1, F4	F2, F4	F3, F4	F6, F4	F1, F3
N	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779	4779
SAIFI (1/yr.)	0.125	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.12	0.119	0.12	0.119	0.12
SAIDI (min/yr.)	90.784	74.843	90.724	77.317	73.484	90.726	90.724	72.767	57.572	73.453	60.046	73.453	61.406
ASIDI (min/yr.)	90.163	78.759	83.159	80.042	77.986	84.515	82.61	79.636	66.612	71.012	67.895	70.463	68.668
CAIDI (h)	12.113	10.459	12.715	10.806	10.264	12.716	12.715	10.164	8.018	10.26	8.363	10.26	8.557
ASAI (%)	99.983	99.986	99.983	99.985	99.986	99.983	99.983	99.986	99.989	99.986	99.989	99.986	99.988
F (1/yr.)	0.671	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.668	0.668	0.668	0.668	0.668
T (h)	40.882	38.225	39.414	38.344	38.146	39.453	39.295	38.304	35.135	36.321	35.254	36.202	35.333
Q (min/yr.)	1646.4	1529.1	1576.7	1533.9	1525.9	1578.2	1571.9	1532.3	1408.7	1456.2	1413.4	1451.4	1416.6
P (MW/yr.)	4.097	3.865	3.865	3.865	3.867	3.864	3.865	3.866	3.875	3.875	3.875	3.875	3.874
W (MWh/yr.)	60.14	52.537	55.471	53.373	52.023	56.375	55.105	53.122	44.439	47.373	45.275	47.007	45.789
W. Red. (%)	0	12.64	7.76	11.25	13.49	6.26	8.37	11.67	26.11	21.23	24.72	21.84	23.86
C ($/yr.)	21785.9	18138.2	20017.6	18310.5	18026.3	20305.9	19899.6	19635.2	14670.6	16549.9	14842.8	16431.9	14954.7
C. Saving (%)	0	16.74	8.12	15.95	17.26	6.79	8.66	9.87	32.66	24.03	31.87	24.57	31.36

in previous tables, where W is reduced from 64.405 MWh/yr. to 60.14 MWh/yr. and C is also reduced from 28235.9 $/yr. to 21785.9 $/yr. In addition, other indices are enhanced. Table IX introduces results of Case 2 when DN is equipped with DG unit, while twelve possible trials are tested to get the optimal location of DG unit. The best location for DG units is at feeders 1 and 4, where SAIDI, CAIDI, and *T* are reduced to the lowest levels with a reduction in W and C reaching 32.66% and 26.11%, respectively. It is clear also from Table IX that adding two units gives better results than a single unit.

DN reconfiguration using SOP devices also enforces the added value of ADAS. From the possible locations to insert SOP device, Table 10 illustrates that the optimal location to insert SOP is to link between feeders 1and 4. This leads to decreasing SAIDI and CAIDI to nearly half of their values in Case 1. Five hours of total interruption time is reduced, and system load interruption probability 'Q' is reduced from 1646.41 to 1408.62 besides a total saving in interruption costs reaching 31.21%. Moreover, W is decreased by 26.08% while similar results can be obtained if the SOP device is inserted between other feeders in case of unavailability of the optimal solution. Table 11 exposes results of case 4, where two DG units are added at the end of feeders 1 and 4 and the location of the SOP device is changed to get the best site and optimal results. It was found that by adding SOP as a closed switch between feeders 4, 7 leads to a significant enhancement in all reliability indices compared to case 1, where SAIDI and CAID are decreased to 26.138 and 7.549, respectively, and *T* is reduced to the lowest level of 32.202. The biggest saving in interruption costs reaches 53.80% with also 48.97% reduction in load unsupplied energy. Fig. 10 shows the effect of different cases on system reliability, where Fig. 10 highlights Case 4 as the most effective case on system reliability, which reduces SAIDI, CAIDI, T, W, and C by nearly 50%. So, adding these technologies into DNs is very important.

6.4. Load points indices comparison (automated operation)

As shown in Figs. 11 and 12, the results indicate clearly that the load point indices such as W and Q are improved significantly

Table 10
System reliability indicies for Case 3 compare to Case1 (With ADAS).

		Case 3: SOP between feeders							
Index	**Case 1**	**F1-F4**	**F1-F7**	**F2-F5**	**F3-F4**	**F5-F6**	**F2-F4**	**F4-F6**	**F4-F7**
Disc. Switch	No	S 41	S 10	S 17	S 41	S 54	S 41	S 41	S 41
N	4779	4779	4779	4779	4779	4779	4779	4779	4779
SAIFI (1/yr.)	0.125	0.122	0.124	0.125	0.122	0.125	0.118	0.118	0.123
SAIDI (min/yr.)	90.784	57.584	56.876	90.725	60.058	90.725	73.448	73.447	55.511
ASIDI (min/yr.)	90.163	66.636	68.291	77.567	67.919	77.018	71.027	70.478	67.514
CAIDI (h)	12.113	7.869	7.666	12.105	8.212	12.105	10.354	10.353	7.549
ASAI (%)	99.983	99.989	99.989	99.983	99.989	99.983	99.986	99.986	99.989
F (1/yr.)	0.671	0.662	0.662	0.662	0.662	0.658	0.662	0.662	0.662
T (h)	40.882	35.453	35.612	37.966	35.572	38.075	36.649	36.53	35.532
Q (min/yr.)	1646.41	1408.62	1414.96	1508.47	1413.37	1503.69	1456.17	1451.41	1411.79
P (MW/yr.)	4.097	4.069	4.101	4.082	4.064	4.083	3.995	3.998	4.068
W (MWh/yr.)	60.14	44.455	45.557	51.743	45.291	51.377	47.383	47.017	45.04
W. Reduction (%)	0	26.08	24.25	13.96	24.69	14.571	21.21	21.82	25.11
C ($/yr.)	21785.9	14987.1	16595.636	19038.8	15155.4	18922.1	16992.8	16877.4	16472.8
CIC Saving (%)	0	31.21	23.82	12.61	30.44	13.15	22.01	22.53	24.39

Table 11
System reliability indicies for Case 4 compare to Case1 (With ADAS).

Index	**Case 1**	Case4: DG (50) at Feeders F1, F4 & SOP between Feeders:					
		F2, F3	**F2, F3**	**F3, F5**	**F3, F6**	**F3, F7**	**F5, F6**
Open Switch	No	S17	S28	S28	S28	S28	S54
N	4779	4779	4779	4779	4779	4779	4779
SAIFI (1/yr.)	0.125	0.122	0.11	0.114	0.114	0.118	0.12
SAIDI (min/yr.)	90.784	44.114	44.057	44.077	44.075	26.138	57.513
ASIDI (min/yr.)	90.163	49.555	49.544	50.891	48.988	46.023	53.467
CAIDI (h)	12.113	6.033	6.649	6.436	6.435	3.677	8.01
ASAI (%)	99.983	99.992	99.992	99.992	99.992	99.995	99.989
F (1/yr.)	0.671	0.659	0.655	0.659	0.659	0.659	0.655
T (h)	40.882	31.005	31.194	31.045	30.885	29.883	32.202
Q (min/yr.)	1646.411	1226.326	1226.306	1227.911	1221.571	1181.946	1265.931
P (MW/yr.)	4.097	3.955	3.864	3.794	3.811	3.881	3.861
W (MWh/yr.)	60.14	33.047	33.039	33.938	32.669	30.692	35.675
W. Reduction (%)	0	45.05	45.06	43.57	45.68	48.97	40.68
C ($/yr.)	21785.87	10064.825	10483.05	10431.55	10059.46	9654.907	11806.73
C. Saving (%)	0	53.801123	51.88142	52.1178	53.82576	55.6827	45.80557

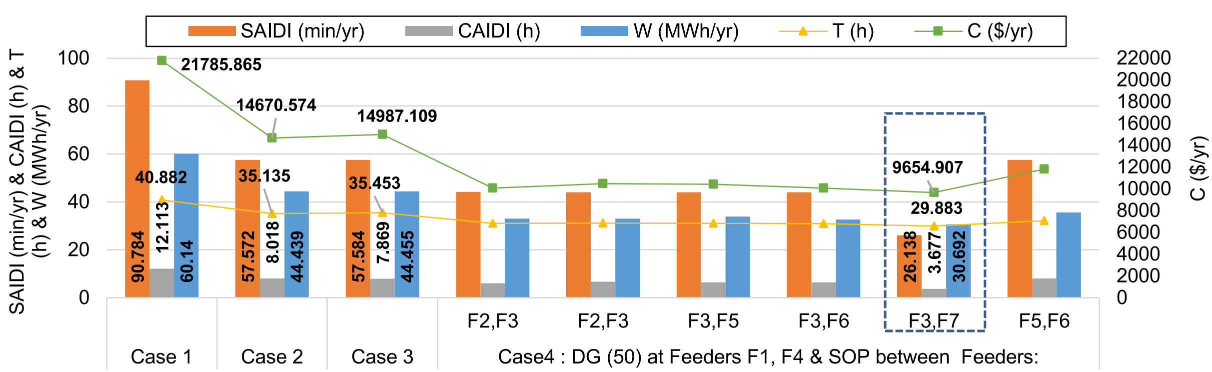

Fig. 10. Holistic summary of system reliability results for the four cases under study (With ADAS).

for all 38-load points of the modified RBTS-Bus 4 system by applying the proposed ADAS besides DG and SOP. In Fig. 11, W at each load point is drawn for eight cases in automated and non-automated operation (M: denotes the non-automated system while A: means automated system). W is clearly enhanced at all load points when ADAS is installed especially in case 4 which reached the lowest levels. The same eight cases are compared in Fig. 12 but for load interruption probability (Unavailability 'Q') while the figure shows enhancements due to using ADAS in cases 2, 3, and 4 compared to case 1. Moreover, the figure shows the improvement in system reliability when system is automated or not for the same case. Some cases in manual operation are noticed to be better than the automated system due to DG and SOP.

7. Conclusion

This research presented an adequate strategy for implementing ADAS into DNs equipped with DG units and SOP devices. The methodology of this research is based on NEPLAN® software to Simulate DNs and ADAS efficiently to optimally find the best system modification to enhance system reliability. In this research work, three solutions are employed to enhance system reliability, which is the use of ADAS with DG units that can work as a standalone during faults to feed isolated areas and SOP devices for system reconfiguration. So, equipping DNs with ADAS affects system reliability besides utilizing DG units and SOP devices that improve both system reliability and power quality. This needs cost–benefit analysis to get the optimal allocation of DG and SOP and reliability assessment.

Applying ADAS besides the presence DG units and SOP devices decreases system interruption costs from 28224.646 $/yr. (non-automated) to 9654.907 $/yr. (with ADAS) with a 65.8% reduction while the system total energy not supplied to load is reduced by 52.32%. Also, other system reliability indices and load points indices are reduced nearly by the half. It was found also that some cases in non-automated operation can be better than automated system with optimal location of DG and SOP with the objective of enhancing system reliability. To conclude, the proposed methodology succeeded to imply ADAS, DG units, and SOP devices to

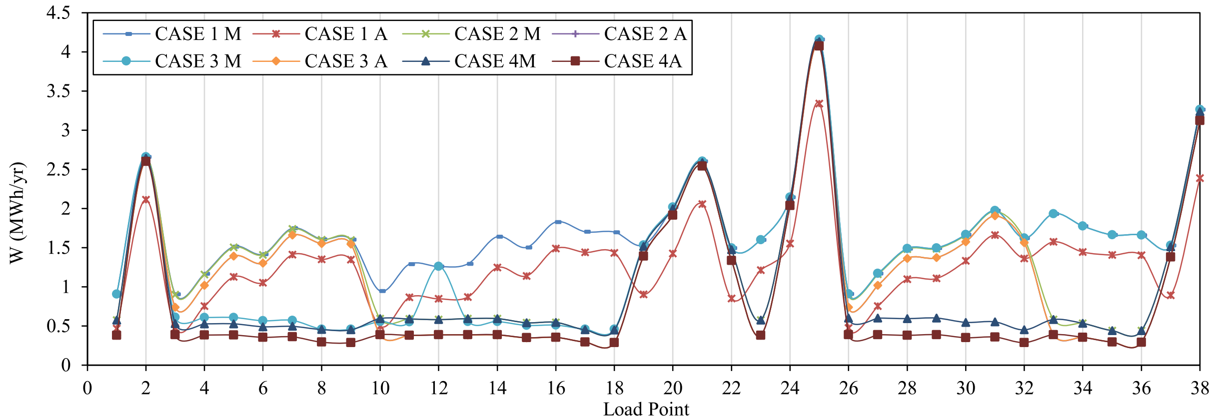

Fig. 11. Energy not supplied at each load point for different cases.

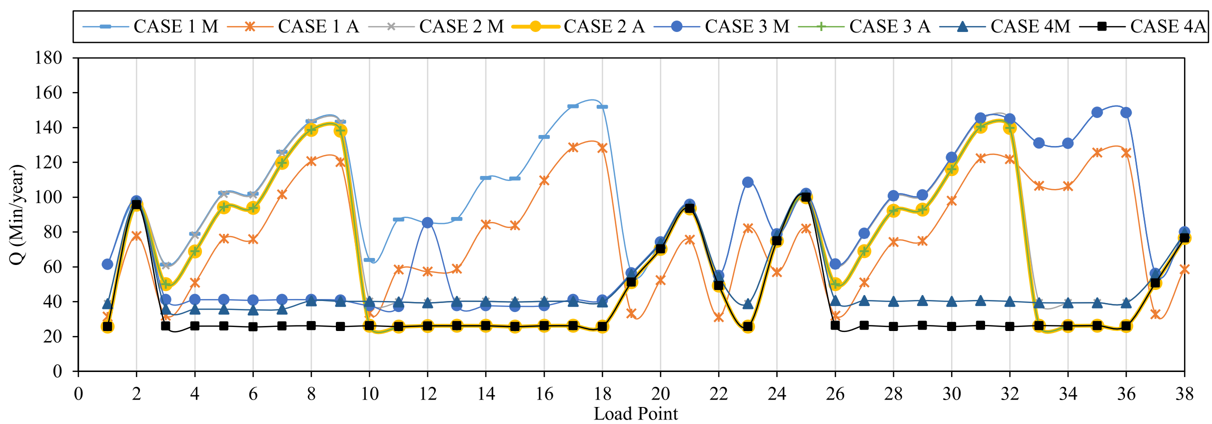

Fig. 12. Load interruption probability (Unavailability) at each load point for different cases.

maintain the system reliability in satisfactory levels through a cost–benefit study but the high cost of this configuration needs extensive planning to be applicable. Besides a multi-objective study should be conducted to attain optimal allocation for both optimal power flow and reliability enhancements.

Declaration of competing interest

No Conflict of Interest

Data availability

No data was used for the research described in the article.

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