Serving Flexible Reliability in Hybrid AC-DC Microgrid using Demand Response and Renewable Energy Resources

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***Abstract*—In this paper, a new concept of serving flexible reliability (FR) is introduced in distribution network level. FR is defined as the ability of a grid to continue servicing the high priority customers in contingency states. Customers' priority is recognized based on their value of service reliability. Regarding this matter, the philosophy of designing a hybrid AC-DC microgrid is introduced with the ability of offering an alternative resource for each individual customer in contingency states. The analytical modeling of FR analysis besides the overall reliability analysis is proposed, and the new FR index of expected energy retrieved (EER) is introduced. The performance of the proposed hybrid microgrid in serving FR is demonstrated through a numerical study on modified distribution network for Bus-4 of Roy Billinton Test System (RBTS).**

***Keywords*—Demand response; flexible reliability; renewable energy resource; hybrid AC-DC microgrid; Roy Billinton Test System (RBTS).**

Nomenclature

A. Indices:

i	Index of load-points (LPs).
j	Index of elements.
k	Index of fuses or breakers.
l	Index of renewable energy resources.
m	Index of controllable distributed generators.
n	Index of demand response resources.
o	Index of energy storage systems.

B. Numbers:

N_{DG}	Total number of controllable distributed generators (DG) in the distribution system.
N_{DRR}	Total number of demand response resources.
N_e	Total number of elements in the system.
N_{ESS}	Total number of energy storage systems.
N_p	Total number of LPs in the system.
N_{pr}	Total number of fuses or breakers between LP i and the failed element j.
N_{RER}	Total number of energy storage systems.

C. Parameters:

AR_i	The amount of available alternative resource in LP i.
$EENS_i$	EENS of LP i.
$EENS_{ij}$	EENS of LP i caused by failure of element j.
EER_i	EER of LP i.
EER_{ij}	EER of LP i caused by failure of element j.
L_i	The average load of LP i.
p_a	Probability of load transfer in LP i.
p_k	Probability of fuse/ breaker k operating successfully.
P^{inv}	Converted power of the inter-grid inverter from AC sub-system to DC sub-system
P_o^{ESS}	Generated power of energy storage system.
P_m^{DG}	Generated power of DG.
P_n^{DRR}	Generated power of demand response resources.
P_l^{RER}	Generated power of renewable energy resources.
$\bar{p}^{AC}$	Rated power of AC feeder.
$\bar{p}^{DC}$	Rated power of DC feeder.
r_{ij}	Repair time for affected LP i by failure of element j.
r_j	Average repair time for a failed element j.
s_j	Average switching time for a failed element j.
SC^{AC}	Servicing capacity of AC sub-system.
SC_i^{AC}	Servicing capacity of AC sub-system in LP i.
SC^{DC}	Servicing capacity of DC sub-system.
SC_i^{DC}	Servicing capacity of DC sub-system in LP i.
λ_{ij}	Failure rate for affected LP i by failure of element j.
λ_j	Average failure rate for a failed element j.

D. Acronyms

ACCI	Average customer curtailment index
AENS	Average energy not supplied
ASAI	Average service availability index
ASUI	Average service unavailability index
DG	Distributed generator
CAIDI	Customer average interruption duration index
CAIFI	Customer average interruption frequency index
DRR	Demand response resource
DER	Distributed energy resources
ESSs	Energy storage systems
EENS	Expected energy not supplied

EER	Expected energy retrieved
FOR	Forced outage rate
FR	Flexible reliability
LED	Light-emitting diode
EVs	Electric vehicles
LP	Load-point
OR	Overall reliability
RERs	Renewable energy-based resources
RBTS	Roy Billinton Test System
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
UPS	Uninterruptable power supply

I. INTRODUCTION

A. Motivation and Aim

Customers' requests from electricity networks are changing and they ask more efficiency, reliability, security, and quality of service from power service providers. Obviously, upgrading the current power system to meet completely the customer's desires is very costly. On the one hand, finding the optimal upgrading level has constantly been one of the main issues in operation and planning studies [1]. On the other hand, customers have different desires depending on their type, location, and time [2]. Thus, inaccurate estimation in average customers' desire will lead to over/under investment in power system expansion planning. In the reliability vision of power systems, it can be predicted that it will move towards an efficient system with the ability of delivering electricity to individual customers in different reliability levels. Indeed, it will be economical if each customer could choose his/her desired level of reliability and the power system expanded flexibly to meet those requests. Since the difference between the reliability levels of the customers should be distinguished in the end nodes of power delivery system, distribution network plays an important role in the future perspective of power systems.

B. Literature Review and Contributions

Smart grid could monitor, control, and automate the system for achieving a positive integration of the various DER with an increased utilization of the existing distribution assets. This active management of the distribution networks may have a twofold impact on the distribution system reliability. On the one hand, it can enhance the traditional reliability indices, e.g. *SAIFI* and *SAIDI*, for passive loads and the availability of the connection for independent producers by means of specific operation practices; such as: on-line reconfiguration to alleviate load transfer restrictions [3], intentional islanding to improve the reliability of customers supplied with pure radial network schemes [4, 5], self-healing and auto-reconfiguring networks to drastically reduce the number of customers that suffer a long interruption [6, 7], coordinated Volt/VAR control to limit the occasions of curtailment or complete disconnection of independent producers in case of abnormal operating conditions [8]. On the other hand, there are some concerns, particularly from utilities, that the adoption of smart grid technologies can jeopardize the high level of reliability generally achieved by current distribution systems [9].

If an optimal fixed reliability level is calculated in planning studies and be employed in a part of the grid, there may be some free-ride customers that do not require such level of reliability but possibly will enjoy from the advantages of higher reliability level [10]. Alternatively, some power sensitive customers that expect more reliability level may suffer from uniform level of reliability. Although in smart grid environment distinct nodal reliability can be served, high reliability in distribution network and the resolution of the distinct nodal reliability levels may become smaller [9, 11], always existing some free-ride customers. In this paper, using the concept of FR, the number of free-ride customers will be reduced in the distribution network.

The contributions of this paper are threefold:

1) It presents the concept of FR, discusses its opportunities for operation of the distribution network, and determines its positive impacts on the planning studies.
2) It proposes an analytical procedure for modeling the FR evaluation and calculating the introduced FR indices (EER).
3) It considers a hybrid AC-DC microgrid equipped with demand-side resources for enabling the concept of FR.

C. Approach

In this paper, a new concept of serving FR is introduced in distribution network level. FR is defined as the ability of a grid to continue servicing the high priority customers in contingency states. Customers' priority is recognized based on their tendency for continuance of being supplied that represents their value of service reliability. Regarding this matter, the philosophy of designing distribution network architecture is presented with the ability of offering an alternative resource for each individual smart customer in contingency states. The proposed architecture is referred to as hybrid AC-DC microgrid, which consists of AC and DC loads, RERs, DGs, DRRs, and ESSs, which are connected through separate AC and DC links. The analytical modeling of the OR and FR evaluation in the distribution network is presented with its corresponding flowchart and a new index of FR. Finally, the effectiveness of the model is demonstrated in the modified version of distribution network of bus four of Roy Billinton Test System (RBTS-bus4).

D. Paper Organization

The rest of the paper is structured as follows. Section II provides the required background on hybrid AC-DC microgrid and its advantages for future distribution systems. Section III represents FR concept and model. Section IV employs the proposed model on modified distribution system of RBTS-Bus4. Finally, section V concludes the paper.

II. HYBRID AC-DC MICROGRID

Most low-voltage resources (e.g. RERs, fuel cells and batteries) produce DC power that has to be converted to AC in order to be connected to the conventional AC grid, by DC/DC converters and additional DC/AC inverter. Meanwhile, many electricity consumers are using DC power such as inverter-based home appliances (e.g. TV, computer, stove, and air conditioner), LED lights and EVs. These loads should be connected to AC power systems through additional AC/DC rectifiers and DC/DC converters. Recently, DC distribution systems are taken into consideration due to the widespread deployment of DC power sources and loads [12, 13].

DC microgrids have been proposed to integrate various distributed generators. Conversely, in DC grids, AC sources have to be converted to DC for connecting to the DC microgrid. Moreover, additional DC/AC inverters are required for serving conventional AC loads. It can be concluded that, multiple reverse conversions are required in both individual AC or DC microgrids, which may add additional cost and loss to the system [14]. Thus, it can be figured out that employment of hybrid grids will be highlighted in the future perspective of distribution networks.

Using smart grid technologies (i.e. communication, control, and computing technologies) enhances the operation of the grid and provides economical, reliable, and green operation through integration of the supply-side with the demand-side resources. Smart grids are predicted to move towards to an advanced topology that can facilitate the connections of various AC and DC resources, EESs, and various AC and DC loads as a hybrid microgrid.

Fig. 1 shows the general architecture of the hybrid AC-DC microgrid. To achieve these goals, power electronics technology plays a vital role to connect different sources and loads to a hybrid microgrid. The hybrid AC-DC microgrid is proposed to reduce processes of multiple power conversions in an individual AC or DC grid and to facilitate the connection of various AC and DC sources and loads as a multi-energy carrier system. Energy management, control, and operation of a hybrid microgrid are more complicated than those of individual AC or DC grids.

The following advantages can be listed for such general architecture:

1) When AC link experiences contingency conditions, DC link can be disconnected from the failure section and continues supplying DC loads. However, most highly power dependent loads, such as digital grade loads, are DC loads.
2) Each DC generator can be easily deployed because it controls only the DC bus voltage.
3) The cost and loss of DC subgrid can be reduced because many power electronic converters are omitted from both DC resource units and end-use appliances and equipments.
4) RERs supply DC power. Therefore, the total cost and loss of the system can be reduced considerably. Regarding this matter, developing hybrid AC-DC microgrid enables high penetration of RERs.
5) Although developing the DC subgrid has high investment cost, the total operation cost of the hybrid microgrid is acceptable.

As shown in Fig. 1, in the hybrid microgrid both DC and AC resources are incorporated for electricity power generation. The extra/shortage of power is transmitted with sub-transmission substation to balance AC and DC loads and resources with the help of the intergrid inverter between AC and DC subgrids. The resources shown in Fig. 1 are highly distributed all over the distribution network. Indeed, the interconnected architecture of AC and DC resources in a distribution network increase the complexity of their control strategy. Since the share of DC resources and loads is usually low, the servicing capacity of the DC link is lower than the AC link. Thus, the AC link may be taken into account as the main energy carrier of the system and the DC link plays the role of a supplemental energy carrier (or vice-versa, depending on the network's special characteristics).

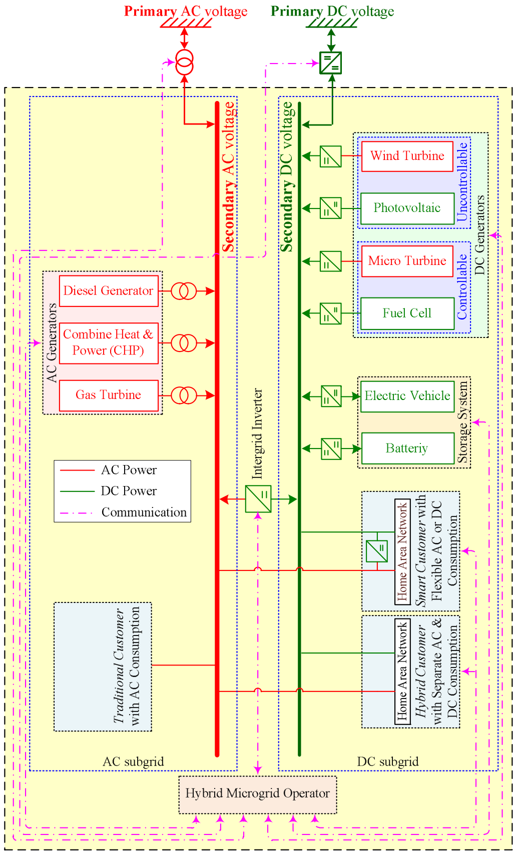

Fig. 1. General architecture of hybrid AC-DC microgrid

The main goal of developing hybrid AC-DC microgrids is to improve the energy efficiency of the distribution network due to omitting extra converters [14]. Indeed, hybrid microgrids will not be developed for reliability issues. Nevertheless, those are appropriate platforms for serving flexible reliability. Moreover, sensitive loads such as data centers are tending to supply through DC microgrids [15]. Currently, DC systems are used very rarely for electricity distribution compared to AC systems. However, if the whole power distribution system were designed as a system of controllable converters, the overall system cost and reliability could be improved, as is currently the case at low power levels within computer and telecom equipment. AC and DC distribution system architectures are conceivable, especially in the presence of high penetration of renewable energy sources [16].

Three customer types are considered in the proposed general grid's architecture, namely; *traditional customer* that is connected to the AC link with merely AC consumption, *hybrid customer* that in addition to AC loads has some separate DC loads, which should be supplied through separate AC and DC resources, and finally *smart customer* that has both AC and DC loads, but as a result of its flexibility in power conversion it could be supplied from both DC and AC links. By employing the new concept of FR, smart customers can possibly continue consuming electricity in contingency periods if their value of service reliability is high enough.

III. Flexible Reliability Concept and Modeling

The concept of FR is defined as the ability of a grid to continue serving electricity to the customers in contingency states.

Enhancing OR of a system will lead to lower number or shorter duration of interruption by improving the average components' failure rate and repair time that consequently increases the investment cost of the system. However, enhancing FR of a system will not affect the components' characteristics and it provides a technical opportunity of the grid. Moreover, in the concept of FR, enhancing the OR is not followed but it tries to enhance the reliability of selective customers that are known as high priority customers. Indeed, a high priority customer may be located in a system with low OR level, but with high FR level. It can be concluded that adding the concept of FR besides the OR will optimize the grid's investment in the long-run and will improve grid's operation in the short-run of the system.

The reliability level can be differentiated in the distribution network at the household level or at the more aggregated level. The distribution network's ability in differentiating the reliability services depends on the flexibility of the grid. The more control and communication infrastructures, the more flexibility of the grid, and consequently the more ability in differentiating the reliability services will be feasible. If the reliability services are differentiated at the household level, each consumer can receive these services exclusively. However, due to inflexibility of present grids, most utilities cannot differentiate the reliability services at the household level, and therefore many of the consumers are allocated in the same zone and receive the same level of reliability. However, in the smart grid environment, if the structure of the grid has enough flexibility (such as hybrid AC-DC distribution systems) serving FR will be enabled.

Customers' priority is recognized based on their tendency for continuance of being supplied that represents their value of service reliability. Regarding this matter, the philosophy of designing distribution network architecture is presented in the previous section with the ability of offering an alternative resource for each individual smart customer in contingency states. In hybrid AC-DC microgrid the required backbone is practically provided for each smart customer to be supplied from two semi-separate sources; i.e. AC and DC sub-systems. Since the customers' desires and the value of service reliability of the customers may vary in time, the flexible reliability service should be transferable from one customer to another customer and should be assigned to high priority customers in each time period. Moreover, customers demand electricity in different reliability levels due to their different desired levels of service reliability. Thus, the delivered electricity has to be adjusted based on the customer's desired level, not securing them against all contingencies. Considering the mentioned issues, generally, applying a redundant system (e.g. stand-by generation and UPS) for all high priority customers over the distribution network is not an economical solution, especially by increasing the number of sensitive customers.

Since both sub-systems are equipped with demand-side resources, the concept of FR is enabled by developments of such distribution system. Indeed, by support of RER and DRR, high priority smart customers can be secured against all contingencies types, namely AC and DC sub-system contingencies and upstream networks' contingencies. Smart hybrid grid's operator estimates the customers' priority based on the customers willingness-to-pay to avoid and willingness-to-accept to compensate the interruption in a specified period.

The desired reliability levels of customers are different in different times. For example, the desired reliability level for two neighbors may be different in different times. Thus, the priority of the customers shall not be the same in different time and location. Providing FR changes based on customers' desires, unlike the nodal reliability that is fixed based on network characteristics.

It is possible that the OR of a grid is low to satisfy most customers, but its FR may be high enough to serve the high priority customers in critical periods. Thus, there will not be free-ride customers and the total investment of the grid could be planned in a minimum acceptable level. Free-riders are selfish customers with a tendency in misrepresenting their preferences, to minimize their contributions in providing a public good, but intend to enjoy the benefits of other users' contributions [10]. Free-riding may lead to inefficient levels of the public good and up to now, many solutions have been proposed for the free-riding problem, such as implementing cost-sharing rules [17, 18], penalizing free-riders [19, 20] and employing reliability insurance scheme [10].

A. *Overall Reliability Indices*

The basic LP reliability parameters are used to evaluate the reliability of the distribution system; i.e. the average LP failure rate (λ), the average load-point outage duration that is known as repair time (r), and the average annual load-point time or unavailability (U) [21]. A wide range of system indices can be calculated with these three parameters. The system reliability indices may be customer-orientated, such as *SAIFI*, *SAIDI*, *CAIFI*, *CAIDI*, *ASAI*, and *ASUI* or load- and energy-orientated indices such as *EENS*, *AENS* and *ACCI*. Required background for calculating these indices is provided in [21].

In this paper, the following analytical approach is used for calculating OR indices:

1) Get the λ_j, r_j and s_j for a failed element j.
2) Find the affected LPs and calculate the corresponding λ_{ij} and r_{ij} for an affected LP i using (1) and (2).

$$\lambda_{ij} = \lambda_j \prod_{k=1}^{N_{pr}} \left(1 - p_k\right) \tag{1}$$

$$r_{ij} = p_a s_j + \left(1 - p_a\right) r_j \tag{2}$$

3) Calculate the $EENS_{ij}$ using (3).

$$EENS_{ij} = L_i r_{ij} \lambda_{ij} \tag{3}$$

4) Repeat 1-3 for all elements in order to calculate the $EENS_i$ for LP i using (4).

$$EENS_i = \sum_{j=1}^{N_e} EENS_{ij} = L_i \sum_{j=1}^{N_e} r_{ij} \lambda_{ij} \ . \tag{4}$$

5) Repeat 4 to evaluate the $EENS_i$ of all LPs.
6) Calculate the total system *EENS* using (5).

$$EENS = \sum_{i=1}^{N_p} EENS_i = \sum_{i=1}^{N_p} L_i \sum_{j=1}^{N_e} r_{ij} \lambda_{ij} \tag{5}$$

B. *Flexible Reliability Indices*

For calculating FR indices in hybrid AC-DC microgrid the following assumptions are considered:

1) The operator of hybrid microgrid can fully monitor/control the RERs, DGs, DRRs, ESSs and inter-grid inverter of the system. Regarding this matter, the servicing capacity of AC and DC sub-systems are observed.

2) Smart customers are assumed to be able to switch their load between AC and DC sub-systems, automatically and quickly (in less than one minute). Regarding this matter, no interruption time is considered for them in contingency states of the system and all or some part of their load is retrieved based on alternative resource's servicing capacity.
3) The average load at each LP is used as the load model.
4) The substation is assumed highly reliable and this paper considers the reliability models of the distribution network.

Fig. 2 indicates the proposed procedure of calculating FR indices beside OR indices. As it was stated before, the prerequisite of serving FR in the distribution network level is the existence of an available alternative resource for each customer. Thus, in the failed state, it should be determined that: "*Is there any alternative resource in the interrupted part of the system, even before fault identification and reconfiguration of the system?*". After distinction of the alternative resource servicing capacity in different LPs of the system, it should be determined that: "*How much of each LP can be retrieved by the alternative resources?*". As it is shown in Fig. 2, firstly the contingency states are modeled and the system is analyzed in a specific contingency state. After finding the amount of available resources in the affected section, the share of retrieved load is calculated. Using remedial actions; i.e. redispatch and reconfiguration of the interrupted (unsupplied) share of the load is attempted to be served as soon as possible. If a LP is be located in the fault section with no available alternative resource, it should be tolerant to pass the repair time. The servicing capacity of the AC and DC sub-system can be formulated as (6) and (7), respectively. Since all terms of (7) are time-dependent values; SC^{DC} should be updated in each time interval in time-dependent studies or be considered as the worst-case in the worst-case studies. Regarding this matter, the servicing capacity of AC sub-system is a constant value, but the servicing capacity of DC sub-system may vary in time.

$$SC^{AC} = \bar{P}^{AC} \tag{6}$$

$$SC^{DC} = \sum_{l=1}^{N_{RER}} P_l^{RER} + \sum_{m=1}^{N_{DG}} P_m^{DG} + \sum_{n=1}^{N_{DRR}} P_n^{DRR} + \sum_{o=1}^{N_{ESS}} P_o^{ESS} + P^{inv} \tag{7}$$

In the failure state of AC or DC sub-system, the DC or AC sub-system provides the alternative resource for the interrupted section, respectively. Therefore, their servicing capacity represents their adequacy. The servicing capacities of the AC sub-system are assumed to be equal in all LPs and are considered same as the feeder's capacity. This assumption is rooted in the nature of conventional AC distribution system due to the absence of adequacy problem. Equation (8) presents the LP servicing capacity of AC sub-system.

$$SC_i^{AC} = SC^{AC} \tag{8}$$

Unlike SC_i^{AC}, calculating SC_i^{DC} depends on two parameters; i.e. the feeder's capacity in the DC sub-system and the adequacy of DC resources. The total adequacy of the DC resource can be calculated by the summation of all available resources (including all DC generators, and the inter-grid converter) in the DC sub-system, as addressed in (7). Moreover, the summation of all SC_i^{DC} is equal to the total servicing capacity, as addressed in the second equation of (9). Considering the mentioned constraints, the maximum achievable LP servicing capacity in DC sub-system is limited by the smaller value of SC_i^{DC} or the feeder's capacity, as addressed in the first equation of (9).

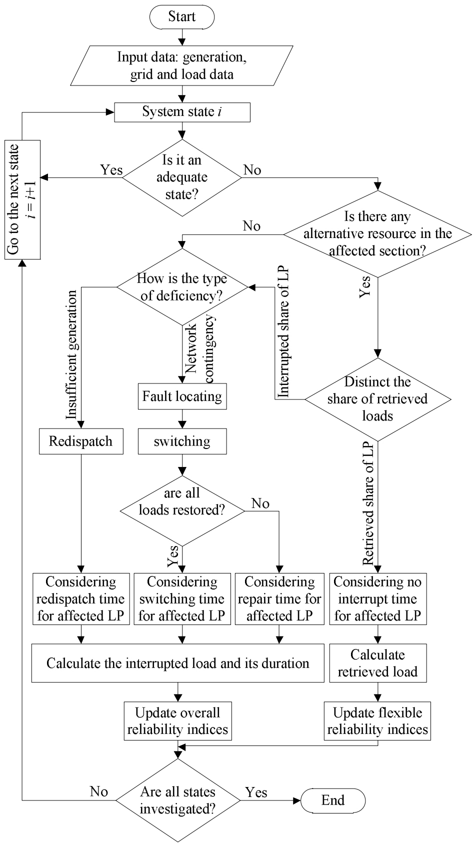

Fig. 2. Proposed flowchart for calculating OR and FR indices.

$$\begin{cases} SC_i^{DC} = \min\left\{\bar{P}^{DC} \;\&\; SC^{DC}\right\} \\ SC^{DC} = \sum_{i=1}^{N_p} SC_i^{DC} \end{cases} \tag{9}$$

Finally, the available alternative resource at LP i is addressed in (10).

$$AR_i = \begin{cases} SC_i^{AC} & \text{if DC sub-system failed} \\ SC_i^{DC} & \text{if AC sub-system failed} \end{cases} \tag{10}$$

It should be noted that the AR_i is the maximum possible amount of alternative resource in LP i and its potential capacity may be employed based on the customers' desires or priorities. The proposed procedure of FR reliability indices is similar to the procedure of calculating OR indices that was addressed in the previous sub-section. Therefore, the following analytical approach is presented for calculating the FR indices:
1) Get the λ_j, r_j and s_j for a failed element j.
2) Find the affected LPs and calculate the corresponding λ_{ij} and r_{ij} for an affected LP i using (1) and (2).
3) The new FR index is introduced as the EER_{ij} and is calculated using (11).

$$EER_{ij} = AR_i \, r_{ij} \, \lambda_{ij} \tag{11}$$

4) Repeat 1-3 for all elements in order to calculate the EER_i for LP i using (12).

$$EER_i = \sum_{j=1}^{N_e} EER_{ij} = AR_i \sum_{j=1}^{N_e} r_{ij} \lambda_{ij} \; . \tag{12}$$

5) Repeat 4 to evaluate the EER_i of all LPs.
6) Calculate the total system EER using (13).

$$EER = \sum_{i=1}^{N_p} EER_i = \sum_{i=1}^{N_p} AR_i \sum_{j=1}^{N_e} r_{ij} \lambda_{ij} \tag{13}$$

IV. Numerical Study

The RBTS has 5 load busbars and it is extended to include distribution systems that are appropriate for reliability evaluation studies. The distribution system of bus 4 is selected for the numerical study. It is a rural network with a loading level of 40 MW, 38 LPs and 4779 customers, comprising 4700 residential (19.00 MW), 9 small user (16.30 MW), and 70 commercial (4.70 MW) customers. This distribution network is designed to deliver electricity with high reliability through a 33 kV ring linking three supply points (SP1, SP2 and SP3) [22]. Thus, this can be an appropriate distribution network for FR analysis.

Fig. 3 shows the single line diagram of RBTS-BUS4. All the 11 kV feeders and laterals are considered as overhead lines. The required data for running reliability analysis is provided in [22]. *EENS* of each feeder is calculated using the proposed analytical procedure of OR indices and is compared with the results of [21] for validation of the proposed methodology. Table I shows the results and the relative error in percentage. As it can be seen from Table I, the relative error is very small and the calculated results are validated. The differences between the calculations in our work and ref. [22] may be rooted in the difference of the accuracy in calculations.

Fig. 4 shows the single line diagram of the modified distribution network for bus 4 of RBTS. Three local DC feeders are added to construct the hybrid AC-DC microgrid in the end of F1, F4 and F7, which are labeled as F1DC, F4DC and F7DC, respectively. The length and reliability data (λ, r) of the added DC feeders are considered the same as the corresponding AC feeders. The servicing capacity of the added DC feeders is assumed as one fifth of the servicing capacity of AC feeders.

The demand-side resources of DC feeders are not shown for simplicity. Table II shows the assumed characteristics of the equipments in the added DC feeders. Table III addresses the considered FOR of the added feeders' components [23-25]. The authors have used MATLAB software for the assessment of the reliability evaluation. The *EENS* and *EER* of feeders are compared and the percentage of improvement is reported in Table IV. As it can be seen in this table, by adding 3 DC feeders about 15% of the total grid's EENS is retrieved. Table V addresses the LP OR and FR indices; i.e. $EENS_i$ and EER_i. It can be seen that the EER_i index for the LPs, which can be serviced by both DC and AC sub-systems, is not zero.

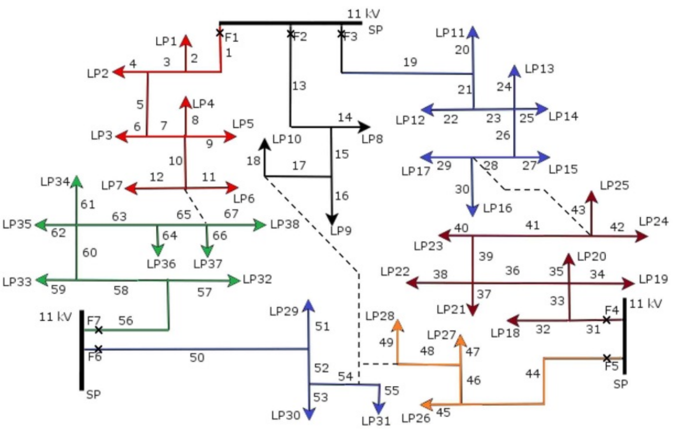

Fig. 3. Single line diagram of distribution network for RBTS-BUS4.

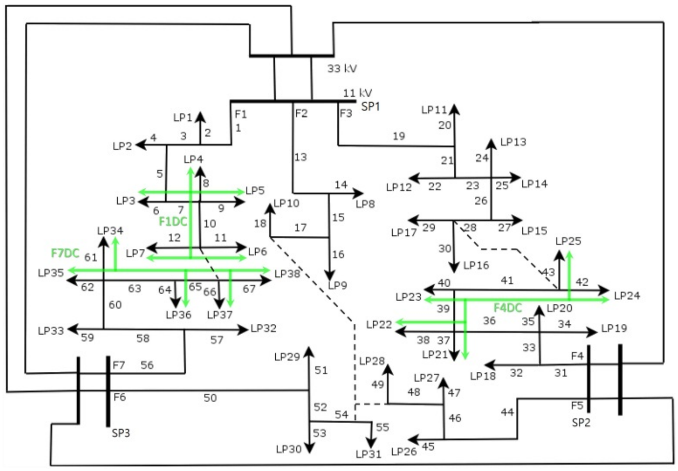

Fig. 4. Single line diagram of modified distribution network for RBTS-BUS4.

TABLE I
VALIDATION OF CALCULATED OVERALL RELIABILITY INDICES WITH [22]

Feeder no.	*EENS* of feeder (kWh/yr)		Relative Error
	Calculated	[22]	(%)
F1	12205	12196	+ 0.07
F2	1325	1323	+ 0.15
F3	12017.9	12007	+ 0.09
F4	13921.9	13930	– 0.06
F5	1130	1120	+ 0.89
F6	1275	1268	+ 0.55
F7	12480.3	12469	+ 0.09
Total	54355.1	54313	+ 0.08

TABLE II
RATED CAPACITY OF DEMAND-SIDE RESOURCES OF ADDED DC FEEDER (KW)

Feeder no.	Wind	PV	DG	DRR	ESS	Total
F1DC	250	50	400	60	50	810
F4DC	200	100	350	70	60	780
F7DC	350	50	250	50	100	800

TABLE III
RELIABILITY DATA OF THE ADDED DC FEEDERS' COMPONENTS

	Forced Outage Rate (%)
DG	5
Wind	4
PV	4
ESS	2
DRR	0

TABLE IV
EENS AND *EER* OF THE CASE STUDY

Feeder no.	*EENS* of feeder (kWhr/yr)	*EER* of feeder (kWhr/yr)	$\frac{EER}{EENS}\times 100$
F1	12205	2546.9	20.87
F2	1325	0	0
F3	12017.9	0	0
F4	13921.9	2489.5	17.88
F5	1130	0	0
F6	1275	0	0
F7	12480.3	2619.6	22.57
Total	54355.1	7656.0	15.14

TABLE V
LOAD-POINT INDICES OF OVERALL AND FLEXIBLE RELIABILITY

Feeder no	LP	$EENS_i$ (kWhr/yr)	EER_i (kWhr/yr)
F1	LP1	1874.8	0.0
	LP2	1902.1	0.0
	LP3	1874.8	502.9
	LP4	1907.5	511.7
	LP5	1745.0	510.3
	LP6	1452.5	511.7
	LP7	1448.4	510.3
F2	LP8	340.0	0.0
	LP9	585.0	0.0
	LP10	400.0	0.0
F3	LP11	1902.1	0.0
	LP12	1896.6	0.0
	LP13	1896.6	0.0
	LP14	1715.0	0.0
	LP15	1740.0	0.0
	LP16	1423.5	0.0
	LP17	1444.2	0.0
F4	LP18	1902.1	0.0
	LP19	1874.8	0.0
	LP20	1902.1	0.0
	LP21	1902.1	500.8
	LP22	1720.0	493.6
	LP23	1745.0	500.8
	LP24	1448.4	500.8
	LP25	1427.6	493.6
F5	LP26	390.0	0.0
	LP27	400.0	0.0
	LP28	340.0	0.0
F6	LP29	350.0	0.0
	LP30	400.0	0.0
	LP31	525.0	0.0
F7	LP32	1907.5	0.0
	LP33	1907.5	0.0
	LP34	1869.4	519.7
	LP35	1907.5	530.3
	LP36	1715.0	519.7
	LP37	1750.0	530.3
	LP38	1423.5	519.7

V. CONCLUSION

In this paper, the concept of flexible reliability (FR) and its approach of implementation in the hybrid AC-DC microgrid were presented using demand-side resources (i.e. renewable energy resources, controllable distributed generators, demand response resource and energy storage system). The analytical method was proposed for calculating the new index of FR, expected energy retrieved (EER). Implementing FR, a minimum acceptable reliability level (which is usually settled by regulatory authorities) will be provided for all customers in the distribution network. However, high priority customers are able to continue being supplied in contingency states, if they pay the corresponding cost. Investigating the economic effectiveness beside the provided technical opportunities for serving FR and defining an index for modeling the free-riders' benefit may be considered as future work. Moreover, the validation of the simulation results with real measurements and recorded data of a real system may improve the study as another future work.

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