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Reliability Evaluation of a Radial Feeder Configurations by Replacing the Distribution Transformer with the Solid-State Transformer

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Abstract*: *The radial feeder is the most typical power distribution system configuration for distributing power to the consumer through the distribution transformer. Distribution transformers are a key component of power distribution systems, they enable voltage transformation, improve safety, reduce energy losses, enhance network reliability, and facilitate the efficient distribution of electricity to consumers. Due to the lack of their role in balancing loads and integrating renewable energy sources, they must be replaced with an alternate solution for modernizing and optimizing distribution grids. A solid-state transformer (SST) is a power electronic device that, in many ways, may replace a typical distribution transformer (DTR). It also improves controllability and provides a direct current link, making it simple to integrate distributed energy sources on either sides of medium and low voltage. However, reliability is the most important parameter in restricting its applications. Modularity is one of the ways to improve reliability and availability by directly re-routing the power within the modular system. This work investigates the failure rate of a modular SST by determining the number of module units required in SST design based on the available IGBT ratings. Further, the reliability of a radial feeder is evaluated by considering the configuration of a) without AS and with DTRs, b) Without AS and replacement of DTRs with SST, c) With AS and DTRs, and d) With AS and replacement of DTRs with SST.

Keywords*: *Reliability, DTR, SST, and Radial Feeder.

I. INTRODUCTION

The radial feeder is the most common configuration in power distribution systems for delivering electricity to customer ends via DTRs. SSTs are smart power electronic devices that can replace DTRs due to benefits such as energy routing capabilities, lower size, fault tolerance, reactive power support, easier integration of distributed energy sources, and increased controllability [1] and [2][16][17]. However, the reliability of SST is widely concerned due to the use of a large number of power electronic devices, which has become one of the key technical bottlenecks restricting its application.

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Several SST configurations have already been disclosed from previously published studies [3][18][19][20][4][5][6], and [7], and the three-stage configuration (consisting of medium voltage (MV), dc/dc, and low voltage (LV)) enables dc-link connectivity while simultaneously providing voltage and current input/output decoupling, giving the system control additional degrees of freedom and making it the preferable option for an SST. For handling MV level power conversion, modular architectures have several advantages such as the ability to use standard LV-rating devices, low electromagnetic interference emission, and modularity, which enables the implementation of redundant strategies to increase fault tolerance and availability. As a result, modular designs are preferred for SST applications. The modular design of a three stage SST is shown in figure 1 [6] and [8].

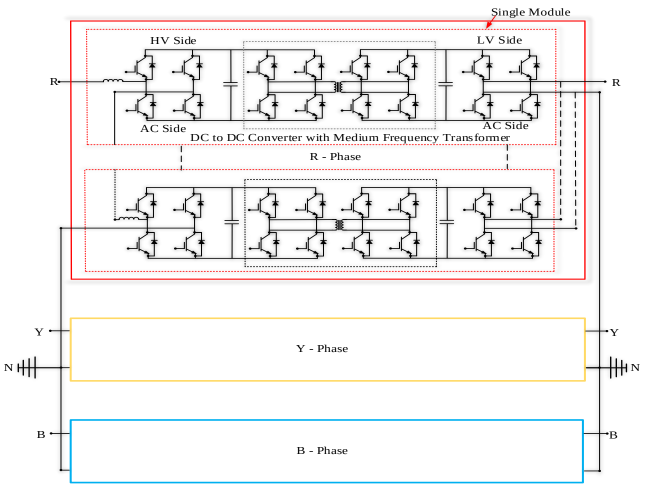

Fig. 1. Modular structure of an SST

This work determines the failure rate of a three-stage modular SST based on available IGBT voltage ratings and power across the dual active bridge (DAB) unit. Further, the reliability of the radial feeder with two different configurations is evaluated by replacing the DTR with SST.

II. RELIABILITY MODELLING

The modular architecture is one of the ways to achieve the targeted reliability and availability of SST by re-rooting the power within it. In this work, the failure rate of a modular SST is determined based on the available IGBT ratings and the power across the DAB unit.

A. Determination of SST specifications

The assumptions required to determine the specifications of SST such as voltage across DAB unit in a single module and the number of modules required in the modular SST design are a) SST rating (P_{rated_SST}), b) MV rating, and c) LV rating. The maximum input voltage to the DAB unit of a single module is determined from the available IGBT voltage rating given by [9]

$$V_{DAB1\_max}=\frac{80}{105}\%\times V_{rated\_IGBT} \quad \text{Volts} \quad (1)$$

The number of modules required per phase of SST is calculated using equation 2 given by

$$N_m=\frac{100\times\sqrt{2}\times V_{ph\_MV}}{95\times V_{DAB1\_max}} \quad (2)$$

Where V_{ph_MV} is the per phase MV side AC voltage.

The power across the DAB unit per module is given by

$$P_{DAB}=\frac{1}{3}\times\frac{1}{N_m}\times P_{rated\_SST} \ \text{kW} \quad (3)$$

To select the current rating of IGBTs for the MV and LV side of SST at more safety margins, the maximum values of V_{DAB1}, and V_{DAB2} are considered as V_{DAB1} and V_{DAB2} are obtained from equations 4 and 5.

$$I_{DAB1}=\frac{P_{DAB}}{V_{DAB1}} \quad \text{A} \quad (4)$$

$$I_{DAB2}=\frac{P_{DAB}}{V_{DAB2}} \quad \text{A} \quad (5)$$

B. Modelling of SST failure rate

A single module unit of an SST comprised of various components as shown in Figure 2. In order to perform a successful operation, all the components associated in a module must be operational [10], and the failure of any single component leads to the failure of the entire module unit; thus, the failure rate of a module unit is computed as illustrated in Figure 2.

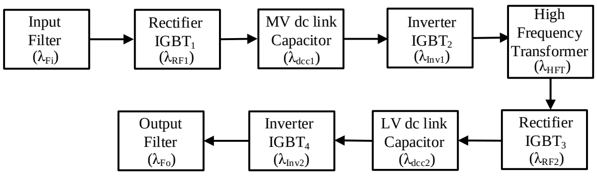

Fig. 2. Failure rate model of an SST module unit

From the basic reliability theory, the failure rate of a module unit in failure in time (FIT) is calculated by using equation 6.

$$\lambda_{module}=\lambda_{Fi}+\lambda_{RF1}+\lambda_{dcc1}+\lambda_{Inv1}+\lambda_{HFT}+\lambda_{RF2}+\lambda_{dcc2}+\lambda_{Inv2}+\lambda_{Fo} \quad \text{FIT} \quad (6)$$

Similarly, the failure rate of the rectifier/inverter and input/output filter are calculated by

$$\lambda_{RF} \text{ or } \lambda_{Inv} = 4\times\lambda_{IGBT\_rated} \quad \text{FIT} \quad (7)$$

$$\lambda_{Fi} \text{ or } \lambda_{Fo} = \lambda_R+\lambda_L \quad \text{FIT} \quad (8)$$

C. Reliability Indices of a Radial Feeder

The primary load point indices such as average failure rate (λ_{LP}) and average annual outage time (U_{LP}) are calculated using equations 9 and 10 respectively [11] and [12].

$$\lambda_{LP} = \sum \lambda_i \quad \text{failures/year} \quad (9)$$

$$U_{LP} = \sum \lambda_i r_i \quad \text{hours/year} \quad (10)$$

Where, λ_i and r_i are the i[th] component average failure rate and average repair time respectively.

The system performance indices considered in this work are the system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI), the average service availability index (ASAI), and the average service unavailability (ASUI), which are calculated using equations 11, 12, 13, and 14.

$$SAIFI = \frac{\sum \lambda_{LPm} N_{LPm}}{\sum N_{LPm}} \quad \text{Interruptions/customer-year} \quad (11)$$

$$SAIDI = \frac{\sum U_{LPm} N_{LPm}}{\sum N_{LPm}} \quad \text{Hours/customer-year} \quad (12)$$

$$ASAI = \frac{\sum N_{LPm}\times 8760-\sum U_{LPm} N_{LPm}}{\sum N_{LPm}\times 8760} \quad (13)$$

$$ASUI = \frac{\sum U_{LPm} N_{LPm}}{\sum N_{LPm}\times 8760} \quad (14)$$

Where, λ_{LPm}, U_{LPm} and N_{LPm} are the average failure rate, annual outage time and number of customers connected to the m[th] load point.

Cost indices such as expected energy not supplied (EENS) and expected customer interruption cost (ECOST) of the load point are obtained from equation 15 and 16. [13]

$$EENS_{LPmj} = Ld_{avgm} \times r_{LPmj} \times \lambda_{LPmj} \ \text{MWh/yr} \quad (15)$$

$$ECOST_{LPmj} = CIC_{LPmj} Ld_{avgm} \lambda_{LPmj} \ \text{k\$/yr} \quad (16)$$

Where, CIC_{LPmj}, λ_{LPmj}, and r_{LPmj} are the customer interruption cost, average failure rate, and average repair time at m[th] load point due to failure of j[th] element. Ld_{avgm} is the average load of m[th] load point.

The cost indices of an overall feeder ($ECOST_T$ & $EENS_T$) are given by

$$EENS_T = \sum EENS_{LPm} \quad \text{MWh/yr} \quad (17)$$

$$ECOST_T = \sum ECOST_{LPm} \ \text{k\$/yr} \quad (18)$$

The following section presents the feeder, available IGBTs, and other component data considered for the evaluation of a radial feeder's reliability.

III. DATA AND ASSUMPTIONS

The first feeder data of standard Roy Billinton Test System-2 is considered for radial feeder evaluation and shown in Figure 3 [14]. N/O represents a normally open disconnecting switch.

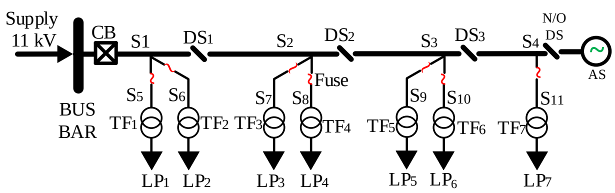

Fig. 3. Radial feeder with an alternate source

The feeder sections length data, load data and customer damage function data of a radial feeder are given in Table I, Table II and Table III.

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TABLE I. Feeder Sections Length Data

Feeder Sections	Length in km
S4, S5, S8	0.60
S1, S2,S3, S10	0.75
S6, S7, S9, S11	0.80

TABLE II. Load Data

Load Point	Average Load of a each cust. (MW)	No. of Cust.	Type of Cust.
LP1,LP2,LP3	0.535	210	Residential
LP4,LP5	0.566	1	Govt. /Institution
LP6,LP7	0.454	10	Commercial

TABLE III. Customer Damage Function Data [13]

Type of User	Interruption Duration & interruption Cost ($/kW)		
	1 hr	4 hr	8 hr
Residential	0.482	4.914	15.69
Govt. /Institution	1.492	6.558	26.04
Commercial	8.552	31.317	83.008

The failure rate of a feeder section and DTR are taken as 0.065 failures per km-year and 0.015 failures per year respectively. The repair time of feeder sections and the replacement of DTR is considered as 5 hrs and 10 hrs respectively [13] and [14]. The failure rate of available IGBTs and other components data are shown in Table IV and V [1], [10] and [15].

TABLE IV. IGBT Failure Rate Data

Available IGBT Rating		Failure rate λ (FIT)
Voltage (kV)	Current (A)	
1.2	100	20
1.7	75	25
3.3	100	50
4.5	400	100
6.5	150	150

TABLE V. Other Component Failure Rate

Components	λ (FIT)
Resistor	12
Inductor	50
Capacitor	40
Medium frequency transformer	500
Control Unit (CU)	5910

IV. RESULT AND DISCUSSION

In this work, most of the DTRs involved in the radial feeder are rated near the average load of 1 MW, so the SST rating is assumed as 1 MW, line-to-line MV side rms voltage is 11 kV and line-to-line LV side rms voltage is 415 V. The corresponding SST specifications are determined and shown in Table VI. In order to get load side voltage as 415 V, the V_{DAB2} is taken as 720 V and the LV side IGBT voltage rating is considered as 1200 V [4], [6] and [9]. The failure rate of an modular SST design with the available IGBT ratings are determine by following the subsection B of section II and the results are shown in Table VII.

TABLE VI. SST Specifications

IGBT Rating (kV)		No. of modules per phase	Per module Specifications			
MV Side	LV Side		VDAB1 (V)	DAB (kW)	IDAB1 (A)	IDAB2 (A)
1.2	1.2	10	914	33.33	36.46	57.08
1.7	1.2	8	1295	41.6	31.73	57.08
3.3	1.2	4	2514	83.3	16.34	57.08
4.5	1.2	3	3428	111.11	11.98	57.08
6.5	1.2	2	4952	166.66	8.29	57.08

TABLE VII. Failure Rate of SST for Various IGBT Ratings

IGBT Voltage in kV	Failure Rate			
	per module (FIT)	SST/Phase (FIT)	SST/3-Ph (FIT)	SST/3-Ph (f/yr)
1.2	1024	10240	36630	0.32088
1.7	1064	8512	31446	0.27547
3.3	1264	5056	21078	0.18464
4.5	1464	4392	19086	0.16719
6.5	1664	3328	15894	0.13923

The selection of IGBT switch with high voltage rating yielding less failure rate compared to other available IGBT ratings for the specified rating of modular SST design and this failure rate is further used in evaluating the reliability of a radial feeder with the replacement of DTR by SST.

The radial feeder reliability is evaluated for four different case studies those are a) Case A: the radial feeder with the presents of conventional DTR and without alternate source (AS), b) Case B: the radial feeder with the replacement of DTRs by SST and without AS, c) Case C: the radial feeder with the presents of conventional DTR and with AS, b) Case D: the radial feeder with the replacement of DTRs by SST and with AS. The load point and system performance indices of a radial feeder are calculated using subsection c, and the results are provided case by case.

A. Case A

The radial feeder configuration considered as without AS and with the presents of DTRs. The load point indices are calculated using equations 9, 10, 15 and 16 are shown in Table XI.

Table IX. Load Point Indices of Case A

Load Points	λ	U	EENS	ECOST
1	0.239	0.725	0.39	0.553
2	0.252	0.790	0.42	0.603
3	0.252	0.985	0.53	0.777
4	0.239	0.920	0.52	1.214
5	0.252	1.180	0.67	1.530
6	0.249	1.164	0.53	4.749
7	0.252	1.336	0.61	5.420

The system performance indices are calculated using equations 11, 12, 13, 14, 17 and 18, are shown in Table XII.

Table X. System Performance Indices of Case A

Feeders	SAIFI	SAIDI	EENS	ECOST	ASAI	ASUI
F1	0.248	0.847	3.662	14.847	0.99990	0.000097

B. Case B

The radial feeder configuration is analysed without AS, and DTRs are replaced with SST. The load point indices of each load are calculated and shown in Table XI.

Table XI. Load Point Indices of Case B

Load Points	λ	U	EENS	ECOST
Lp1	0.363	1.97	1.052	2.069
LP2	0.376	2.03	1.087	2.118
Lp3	0.376	2.23	1.192	2.292
Lp4	0.363	2.16	1.224	4.112
Lp5	0.376	2.42	1.371	4.429
Lp6	0.373	2.41	1.092	11.403
Lp7	0.376	2.58	1.171	12.074

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The percentage increase in load point indices compared to case A are shown in figure 4 and system performance indices are shown in Table XI.

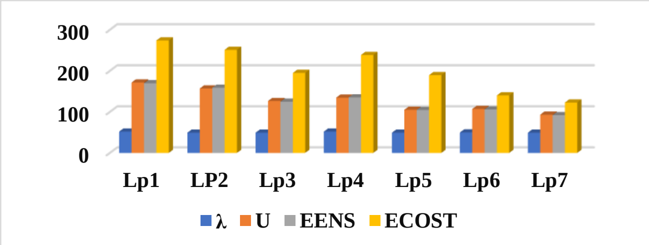

Fig. 4. Percentage increase in load point indices of case B compared to case A

Table XI. System Performance Indices of Case B

Feeders	SAIFI	SAIDI	EENS	ECOST	ASAI	ASUI
F1	0.372	2.089	8.189	38.496	0.99976	0.000238

C. Case C

The radial feeder configuration considered as with AS and DTRs. The load point indices of each load are shown in Table XII.

Table XII. Load Point Indices of Case C

Load Points	λ	U	EENS	ECOST
1	0.239	0.725	0.39	0.553
2	0.252	0.79	0.42	0.603
3	0.252	0.79	0.42	0.777
4	0.239	0.725	0.41	0.973
5	0.252	0.79	0.45	1.048
6	0.249	0.774	0.35	3.231
7	0.252	0.751	0.34	3.142

The percentage decrease in load point indices compared to case A are shown in figure 5 and the system performance indices of case C are shown in Table XII..

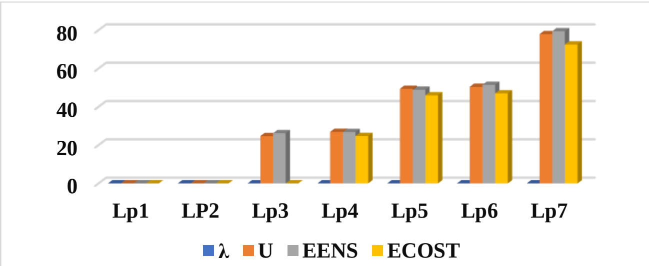

Fig. 5. The percentage decrease in load point indices of case C compared to case A

Table XIII. System Performance Indices of Case C

Feeders	SAIFI	SAIDI	EENS	ECOST	ASAI	ASUI
F1	0.248	0.768	2.784	10.328	0.99991	0.000088

D. Case D

The radial feeder configuration considered with AS, and DTRs are replaced with SST. The load point indices of each load are shown in Table XIV.

Table XIV. Load Point Indices of Case D

Load Points	λ	U	EENS	ECOST
1	0.363	1.97	1.052	2.069
2	0.376	2.03	1.087	2.118
3	0.376	2.03	1.087	2.292
4	0.363	1.97	1.113	3.871
5	0.376	2.03	1.150	3.947
6	0.373	2.02	0.915	9.885
7	0.376	1.99	0.905	9.796

The percentage increase in load point indices of case D compared to case C are shown in figure 6 and the system performance indices are shown in Table XV.

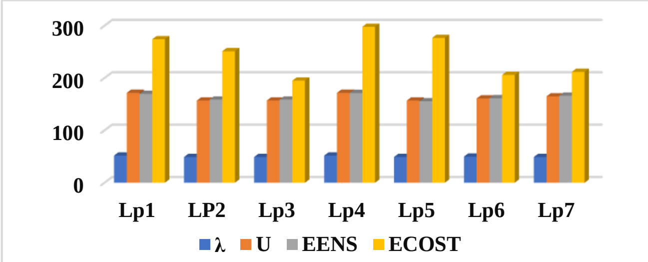

Fig. 6. The percentage increase in load point indices of case D compared to case C

Table XV. System Performance Indices of Case D

Feeders	SAIFI	SAIDI	EENS	ECOST	ASAI	ASUI
F1	0.372	2.01	7.31	33.98	0.99977	0.00022

The percentage reduction in the system performance indices of case D compared to case B are shown in figure 6.

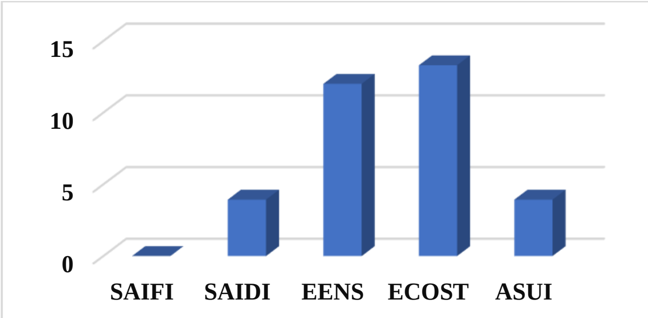

Fig. 7. The percentage reduction in the system performance indices of case D compared to case B

V. CONCLUSION

According to the preceding findings, the radial feeder configuration with an alternate source is more reliable than the configuration without alternate source, and the replacement of DTR with SST reduces overall system reliability due to its high failure rate. In case B, the RDS is more unreliable due to the presents of SST and without AS. The percentage increase in SAIFI, SAIDI, EENS, ECOST and ASUI are 50, 146, 123, 159 and 145. In case D, the presence of an alternate source resulting in better radial feeder reliability though the DTRs are replaced with the SSTs and compared to Case B the percentage reduction in SAIDI, EENS, ECOST and ASUI are 3.93, 12, 13.3 and 3.93. However, the radial feeder reliability can be improved by implementing the redundancy in SST design and by considering the failure rate of a feeder sections due to integration of an SST impact on the feeder section currents, which are not discussed in this work.

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