A Composite Reliability Index for Power Distribution System in Renewable Microgrid Penetrated Energy Market

Tuhin Shubra Das, Parthasarthi Bera, Papun Biswas

Abstract*: High penetration of renewable micro-grids in power distribution system has given rise to unique reliability issues owing to their intermittent nature. Moreover, individual reliability indices of power distribution systems tend to present conflicting results. Therefore, a single index to quantify the overall reliability of substations is necessary. In essence, this work proposes a Composite Reliability Index (CRI) for renewable penetrated Indian power distribution system. In this work, reliability indices are normalized using Z-scores, followed by Principal Component Analysis (PCA) for weight decision. Particularly, indices recommended in IEEE Std 1366-2003 and practiced by Indian utilities in real-time are studied. Finally, results of test-systems data analysis show that proposed CRI can expedite the reliability assessment process in multiple permutations of systems and operational choices.

***Keywords* : Data Analytics, Distribution System, Ranking, Reliabilty, Statistics.**

I. INTRODUCTION

The potential impact of the power system's reliability on the socio-economic ecosystem [1], has compelled Indian utilities and regulators to address it sincerely. Furthermore, the penetration of renewable micro-grids has a huge impact on power distribution reliability [2]. Yet there exists no benchmark for peer comparison of substation's reliability [3]. Notably, existing system of assessing power distribution reliability is ambiguous owing to its "multi indices" approach [4]. Nevertheless, power distribution companies (Discoms) and authorities around the world have settled for reporting of four indices, namely SAIFI, SAIDI, CAIDI and ASAI [5]. However, there exist no common consensus on using any particular indices as a yardstick of measuring power distribution reliability, to cross-compare reliability performance of two different distribution systems. Even though peer comparison of distribution systems reliability is practiced regularly both by utilities and regulators [6] [7].

India's Central Electricity Authority (CEA) has recommended state Discoms to report SAIFI, SAIDI, CAIDI and MAIFI in 2017 [8]. Although, India's CEA itself has reported SAIFI, SAIDI, and ASAI but excluded CAIDI in its reports till 2016 [9], [10]. In contrast, Discoms of observed Indian states (Maharashtra [11], West Bengal [12], Karnataka [13]) have opted to report SAIFI, SAIDI, CAIDI only, excluding ASAI in their data till 2018.

Creating a single Score/Index from a set of individual indicators demands a strong statistical approach. For development of composite index, literatures [14], [15] suggests of axioms rather than rigid rules. Notably, one of the pioneering work in unifying the distribution reliability indices proposes a customer survey based approach [16]. But the methodology has validity for a limited region and a set of specific indices. Alternatively, "public or expert opinion" based approaches such as AHP [17], [18] depends on knowledge and operational experience of experts. However, experts might not be readily available at every time and place to give feedback and opinions. Furthermore, "cost" based approaches for example reliability worth assessment technique [19], suffers exclusive dominance of economic factors.

Existing "multi indices" system give conflicting results to both regulatory bodies and distribution designers. In contrast, a single Composite Reliability Index (CRI) can facilitate a transparent assessment of substation's performance and improve utilities strategies to address the reliability issues of the distribution system in a deregulated energy market. This paper introduces the application of Z-score [15] and Principal Component Analysis (PCA) [21] to obtain a CRI for renewable penetrated power distribution system, according to their reliability indices data.

II. PROCEDURE OF CRI FORMULATION

A. Normalization

Data normalization is necessary to transform all variables in the data to a specific range. This paper employs Z-score approach for data normalization. But normal Arithmetic Mean (AM) based approach to find Z-score is sensitive to the presence of outliers in the data. A robust alternative to find the Z-score is a median based approach owing to its inertness to outliers [20]. Mathematically, these two methods are represented as below.

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Method 1: By Arithmetic Mean of data distribution : The standard score or the Z-score, of a raw score x_i is represented by Z_a, and for a population of N observations is given by

$$Z_a = \frac{x_i - \mu_a}{\sigma_a} = \frac{x_i - \bar{x}}{\sigma_a} \quad \textbf{(1)}$$

where μ_a is the Arithmetic Mean ($\bar{x}$) Of the population, and σ_a is the Standard Deviation (SD) of the population, given by

$$\sigma_a = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N}} \quad \textbf{(2)}$$

Therefore, for an observed population of N number of substations, if the reliability indices are given by, $x1_i$ = $\text{SAIFI}_{i}^{th}{}_{\text{Sub.Stn}}$; $x2_i$ = $\text{SAIDI}_{i}^{th}{}_{\text{Sub.Stn}}$; $x3_i$ = $\text{CAIDI}_{i}^{th}{}_{\text{Sub.Stn}}$; and $x4_i$ = $\text{ASAI}_{i}^{th}{}_{\text{Sub.Stn}}$; then the Z-score of observed indices (for ex. SAIFI) is given by:

$Z1_a$ Score of ($\text{SAIFI}_{i}^{th}{}_{\text{Sub.Stn}}$) = ($\text{SAIFI}_{i}^{th}{}_{\text{Sub.Stn}} - \mu1_a$) / $\sigma1_a$ **(3)**

Where

$\mu1_a$ =
Arithmetic mean of all N number of SAIFIs observed, **(4)**

$\sigma1_a$ =
$\sqrt{\{ (\text{SAIFI}_{1^{st}Sub.Stn} - \mu1_a)^2 + \cdots + (\text{SAIFI}_{N^{th}Sub.Stn} - \mu1_a)^2 \} / N}$ **(5)**

Method 2: By Median of data distribution : Since Median and the Median Absolute Deviation (MAD) are insensitive to outliers, hence normalization employing Median and MAD is more robust [20]. The Robust Z-score of a raw score x_i is represented by *Rob-Z* and for a population of N observations is given by

$$Rob - Z = \frac{x_i - \mu_m}{\sigma_m} = \frac{x_i - \tilde{x}}{MAD \times 1.4826} \quad \textbf{(6)}$$

where μ_m is Median ($\tilde{x}$) of the population, and σ_m is Median Absolute Deviation (MAD) of the population, given by

$$\sigma_m = MAD \times 1.4826 \quad \textbf{(7)}$$

Where $MAD = Median\ (|x_i - Median\ x_{1\ldots N}|)$, therefore

$$\sigma_m = Median\ (|x_i - Median\ x_{1\ldots N}|) \times 1.4826 \quad \textbf{(8)}$$

Therefore, for an observed population of N number of substations, if the reliability indices are given by, $x1_i$ = $\text{SAIFI}_{i}^{th}{}_{\text{Sub.Stn}}$; $x2_i$ = $\text{SAIDI}_{i}^{th}{}_{\text{Sub.Stn}}$; $x3_i$ = $\text{CAIDI}_{i}^{th}{}_{\text{Sub.Stn}}$; and $x4_i$ = $\text{ASAI}_{i}^{th}{}_{\text{Sub.Stn}}$; then *Rob-Z* of observed indices (for ex. SAIFI) is given by:

Rob-Z1$_m$ of ($\text{SAIFI}_{i}^{th}{}_{\text{Sub.Stn}}$) = ($\text{SAIFI}_{i}^{th}{}_{\text{Sub.Stn}} - \mu1_m$) / $\sigma1_m$ **(9)**
Where

$\mu1_m$ = Median of all N number of SAIFIs observed **(10)**

$\sigma1_m$ = $Median\ \left(\left|(\text{SAIFI}_{i^{th}Sub.Stn})_{i=1\ldots N} - \mu1_m\right|\right) \times 1.4826$ **(11)**

Arithmetic Z-scores (Z_a) and *Rob-Z* for SAIDI, CAIDI and ASAI can be deduced in similar manner.

B. Weightage & Aggregation

There's no universal consent on weight allocation and aggregation approaches of individual indicators [15]. This paper, is employing PCA for weight allocation of Z-score normalized data, followed by aggregation employing a simple additive approach.

III. Data Analysis & Results

For the purpose of analysis three different datasets have been collected from the Central Electricity Authority (CEA) of India for the year 2015 and 2016, and Maharashtra's MAHADISCOM data of March 2018. Indian CEA's data is missing CAIDI in its reports, while MAHADISCOM's reported data is missing ASAI. Accordingly, CAIDI of CEA's data is calculated using the formula given in [4], [6].

$$\text{CAIDI} = \text{SAIDI} / \text{SAIFI} \quad \textbf{(12)}$$

Similarly, ASAI of MAHADISCOM's data is calculated using the formula given in [4], [6] but with modification in terms of monthly calculations, and is given by

$$ASAI = \frac{N_T * Number\ of\ Hours\ per\ month - \sum r_i N_i}{N_T * Number\ of\ Hours\ per\ month} \quad \textbf{(13)}$$

Next, normalization of data is done by finding $Z_a$score and Rob-Z of each dataset. Finally, PCA of the normalized data is performed using IBM SPSS 25 . Three scenarios are considered for study and analysis of data, as described below

Scenario 1: PCA of SAIFI, SAIDI, ASAI
Scenario 2: PCA of SAIFI, SAIDI, CAIDI
Scenario 3: PCA of SAIFI, SAIDI, CAIDI, ASAI

To investigate the overall statistical quality of correlation and sampling adequacy of the data the Measure of Sampling Adequacy (MSA) score of Anti-Image Matrix and Kaiser-Meyer-Olkin (KMO) scores are consulted for every dataset. Any dataset having a MSA and KMO score below 0.500 is unacceptable. Also, the more a dataset has a MSA and KMO score nearer to 1 the better will be its acceptance for sampling [21]. Table 1 shows the corresponding Anti-Image MSA scores of the dataset of above described CEA's 2015, 2016 data and MAHADISCOM's March 2018 data.

Table 2 shows the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy of CEA's normalized reliability data for the years of 2015 and 2016; and MAHADISCOM's normalized reliability data of March 2018.

Table 1: Anti-Image MSA scores

Scenario 1

Case 1 – AM based Z_aScore's MSA				Case 2 – Robust. Zscore's MSA			
	2015	2016	2018		2015	2016	2018
SAIFI Z_a	0.600	0.791	0.987	SAIFI RobZ	0.600	0.791	0.990
SAIDI Z_a	0.786	0.722	0.527	SAIDI RobZ	0.786	0.722	0.526
ASAI Z_a	0.604	0.785	0.527	ASAI RobZ	0.604	0.785	0.526
Scenario 2							
Case 1 – AM based Z_aScore's MSA				Case 2 - Robust. Zscore's MSA			
	2015	2016	2018		2015	2016	2018
SAIFI Z_a	0.621	0.427	0.317	SAIFI RobZ	0.621	0.427	0.322
SAIDI Z_a	0.518	0.405	0.156	SAIDI RobZ	0.518	0.405	0.166
CAIDI Z_a	0.522	0.197	0.303	CAIDI RobZ	0.522	0.197	0.309
Scenario 3							
Case 1 – AM based Z_aScore's MSA				Case 2 - Robust. Zscore's MSA			
	2015	2016	2018		2015	2016	2018
SAIFI Z_a	0.527	0.647	0.457	SAIFI RobZ	0.527	0.647	0.446
SAIDI Z_a	0.553	0.631	0.514	SAIDI RobZ	0.553	0.631	0.505
ASAI Z_a	0.603	0.832	0.521	ASAI RobZ	0.525	0.832	0.511
CAIDI Z_a	0.525	0.247	0.414	CAIDI RobZ	0.603	0.247	0.400

Table 2: KMO scores

Scenario No.	Case No.	2015 KMO	2016 KMO	2018 KMO
Scenario 1	Case1- $Z_a$score	0.634	0.764	0.551
	Case2- Rob-Z	0.634	0.764	0.549
Scenario 2	Case1- $Z_a$score	0.530	0.378	0.271
	Case2- Rob-Z	0.530	0.378	0.278
Scenario 3	Case1- $Z_a$score	0.550	0.643	0.486
	Case2- Rob-Z	0.550	0.643	0.476

Above analysis of the CEA and MAHADISCOM data shows that CAIDI is responsible for low values of both KMO score and Anti-Image MSA scores. Hence, it should be excluded from PCA analysis of reliability data. Thus Scenario 1 is the best choice for calculating CRI. Furthermore, PCA of Scenario 1 reduces three variables into a single component with a cumulative total variance of more than 60% for each dataset. Therefore, individual component score of PCA [22] gives CRI for a given substation. It appears on testing that substation with lowest CRI score is "best" in terms of overall reliability while highest CRI scoring substation is "worst" in terms of overall reliability.

It is worth noting at this point that our analysis of Indian distribution system data reflects that both arithmetic Z-score and Rob-Z are showing equal results of KMO score. These results appeared because the data sets are very large. But the efficiency of Rob-Z lies in the fact that it can predict outliers even in very small data sets.

IV. TESTING & VERIFICATION

Since real time indices data are massive and bewildering, two "Test Systems" indices data has been chosen, as given in [2] and [23]. Both test systems have presented six case studies, with "Base Case / 1st Case" as worst case and "Last Case / 6th Case" as the best case according to the scores of individual reliability indices.

In the first place, the efficacy of Rob-Z over Z_a-Score on Test Systems (TS) data is examined to avoid miscalculation of CRI in the presence of outliers. Table 3 shows data as given in Test system 1 [2] and Test system 2 [23]. For sake of simplicity only SAIDI data is presented. Row 1 and 6 of Table 3 shows case studies of TS 1 and TS 2 respectively. Whereas, row 2 and row 7 shows a scenario where data has been corrupted due to human error or machine fault in each Test System. The corrupted entries are shown in ***bold italics*** in Table 3. Corresponding "Z_a-Score" and "Rob-Z" are shown in row 4,9 and row 5,10 respectively. Notably, the arithmetic mean based Z_a-Score is not able to weed out the outlier from the small sets of data provided. Contrarily, median based Rob-Z performed in a more robust manner and is able to weed out the outliers [20] from the same dataset.

Table 4 shows reliability indices data of Test system 1 as given in [2]. The data is given in reverse order, starting from worst scenario as *Base Case* and descending to best scenario as *case E*.

Table 4: Reliability Indices Data of Test System 1 [2]

	SAIFI	SAIDI	CAIDI	ASAI	Given Rank
Base Case	0.9225	9.4586	10.2530	0.9989	***6th - Worst***
Case A	0.2635	9.1506	34.7240	0.9990	5
Case B	0.2354	9.0191	38.3100	0.9990	4
Case C	0.1909	8.3979	43.9880	0.9990	3
Case D	0.1665	8.0070	48.0850	0.9991	2
Case E	0.1601	7.7363	48.3340	0.9991	***1st - Best***

Table 4a shows the CRI score calculated by the proposed method in two choices of combination. Combination "CRI I" has SAIFI, SAIDI, ASAI with omitted CAIDI, Combination "CRI II" has SAIFI, SAIDI, CAIDI, ASAI. Both choices are calculated in weighted scenario as well as in Equal-weighted or Un-weighted scenario.

Table 3: Z_a-Score and Rob-Z of Corrupted Data

Row 1		Base Case	Case A	Case B	***Case C***	Case D	Case E	Test System 1
Row 2	SAIDI	9.4586	9.1506	9.0191	8.3979	8.0070	7.7363	
Row 3	Corrupt	9.4586	9.1506	9.0191	***4.3979***	8.0070	7.7363	
Row 4	Z_aScore	0.8759	0.6957	0.6188	*-2.0851*	0.0266	-0.1318	
Row 5	Rob-Z	0.9019	0.6081	0.4827	***-3.9251***	-0.4827	-0.7409	
Row 6		***Case 1***	Case 2	Case 3	Case 4	Case 5	Case 6	Test System 2
Row 7	SAIDI	0.7766	0.7565	0.7332	0.7202	0.6975	0.6895	
Row 8	Corrupt	***0.8866***	0.7565	0.7332	0.7202	0.6975	0.6895	
Row 9	Z_aScore	*2.1070*	0.1399	-0.2124	-0.4090	-0.7522	-0.8732	
Row10	Rob-Z	***3.6560***	0.6813	0.1486	-0.1486	-0.6676	-0.8505	

Table 4a: Calculated CRI scores from Reliability Indices Data of Table 4

	UN-WTD_I	WTD_I	UN-WTD_II	WTD_II
Base Case	9.7499	10.6300	6.6305	-14.4000
Case A	1.2211	1.1116	0.5724	-1.7156
Case B	0.6751	0.6174	0.3885	-0.8572
Case C	-0.6765	-0.6187	-0.3899	0.8586
Case D	-0.4769	-2.3287	0.2233	2.7902
Case E	-0.8853	-2.7056	-0.1598	3.1374
Combination	CRI - I		CRI - II	

Table 4b shows the proposed ranking according to the score achieved by each study case. It's clearly visible that the score of combination "CRI I" gives a distorted score in equal weight or un-weighted scenarios, while a PCA weighted score gives a perfect match of the ranking given in [2]. In contrast, Combination "CRI II" gives a fully distorted rank in both PCA weighed and unweighted scene.

Table 4b: CRI based proposed Ranking for Test System 1

UN-WTD_I	WTD_I	UN-WTD_II	WTD_II	Proposed Rank
Case C	*Case E*	Case C	Base Case	***1st - Best***
Case E	Case D	Case E	Case A	2
Case D	Case C	Case D	Case B	3
Case B	Case B	Case B	Case C	4
Case A	Case A	Case A	Case D	5
Base case	*Base case*	Base case	Case E	***6th - Worst***
Distorted	**Perfect Match**	Distorted	Distorted	
CRI - I		CRI - II		

Table 5 shows data as given in [23], this is the Test System 2 and the data is arranged in the same reverse ranking fashion as in Test system 1 above. To be noted ASAI is not given in [23], thus calculated using formula given in [4], [6].

Table 5: Reliability Indices Data of Test System 2 [23]

	SAIFI	SAIDI	CAIDI	ASAI	Given Rank
Case - 1	0.1355	0.7766	5.7330	0.999911	***6th - Worst***
Case - 2	0.1303	0.7565	5.8070	0.999914	5
Case - 3	0.1243	0.7332	5.8990	0.999916	4
Case - 4	0.1210	0.7202	5.9500	0.999918	3
Case - 5	0.1152	0.6975	6.0550	0.999920	2
Case - 6	0.1132	0.6895	6.0910	0.999921	***1st - Best***

Table 5a below shows the CRI score calculated by the proposed method in two choices of combinations in the same fashion as in Table 4a calculations. Therefore, combination "CRI I" has SAIFI, SAIDI, ASAI with omitted CAIDI, while combination "CRI II" has SAIFI, SAIDI, CAIDI, ASAI. Both choices of combinations are calculated in weighted scenario as well as in Equal-weighted or Un-weighted scenario.

Table 5a: Calculated CRI scores from Reliability Indices Data of Table 5

	UN-WTD_I	WTD_I	UN-WTD_II	WTD_II
Case - 1	1.147974	3.429804	0.106321	4.470620
Case - 2	0.683424	2.046120	0.044290	2.684744
Case - 3	0.147405	0.444638	0.008700	0.583233
Case - 4	-0.147405	-0.444638	-0.008700	-0.583233
Case - 5	-0.665557	-2.000816	0.044290	-2.710110
Case - 6	-0.844230	-2.545314	0.061437	-3.450275
Combination	CRI – I		CRI – II	

Table 5b shows the proposed ranking according to the score achieved by each study case. Score of combination "CRI I" gives a perfect match of the ranking given in [23] both in equal / un-weighted scenario, and PCA weighted scenario. In contrast, combination "CRI II" gives a distorted rank in unweighted scene, but a perfect match in PCA weighed scenario.

Table 5b: CRI based proposed Ranking for Test System 2

UN-WTD_I	WTD_I	UN-WTD_II	WTD_II	Proposed Rank
Case 6	*Case 6*	Case 4	*Case 6*	***1st - Best***
Case 5	Case 5	Case 3	Case 5	2
Case 4	Case 4	Case 2	Case 4	3
Case 3	Case 3	Case 5	Case 3	4
Case 2	Case 2	Case 6	Case 2	5
Case 1	*Case 1*	*Case 1*	*Case 1*	***6th - Worst***
Perfect Match	**Perfect Match**	Distorted	**Perfect Match**	
CRI – I		CRI – II		

V. CONCLUSION

In this paper a new method to calculate the Composite Reliability Index (CRI), is proposed for renewable penetrated power distribution market of India, applying robust Zscore and PCA. The proposed CRI can not only evaluate overall reliability of different substations in a renewable penetrated environment facilitating peer comparison. But also it is capable of self-assessing the reliability of same substation to measure the impact of reliability improvement efforts done by utilities from time to time. Notably, the proposed CRI works in the reverse order i.e. a lower score of CRI depicts better overall reliability of the substation. Though, in this work the application of proposed CRI is considering SAIFI, SAIDI, CAIDI, and ASAI, but can be scaled to include any number of indices if required.

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