Fair Reliability Management: Comparing Deterministic and Probabilistic Short-Term Reliability Management

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***Abstract*—Fairness is considered important in various contexts. Although electricity is an essential public good in modern societies that should be affordable and accessible on a fair, non-discriminatory basis, there is no assessment of fairness in a power system reliability context. Nevertheless, fairness might become an issue with probabilistic short-term reliability management approaches that enable system operators to differentiate between consumers based on their value of lost load. This paper focuses on equality between consumers in terms of energy not supplied. A transparent assessment of inequality in short-term power system reliability management is illustrated that uses an inequality ratio and inequality index to quantify the level of inequality between entities, such as nodes, consumer groups or individual consumers. Inequality resulting from short-term probabilistic reliability management and reliability management based on a deterministic N-1 criterion are assessed in a case study for a five-node and 24-node test system. The proposed inequality assessment enables system operators and regulating bodies to verify the social acceptability of reliability management approaches and criteria.**

I. Introduction

Evolutions in power systems, such as e.g., increasing penetration of renewable energy sources, liberalization and deregulation, challenge the currently-used deterministic N-1 criterion [1]. Moreover, a paradigm shift in terms of reliability management approaches and criteria (RMACs) might be needed to efficiently integrate modern, smart technologies, such as new information and communication technology (ICT), power electronics based equipment and smart meters that enable demand response, in power systems [2]. They all result in more short-term flexibility, which can be used in corrective control to potentially cut operating costs. Probabilistic RMACs are intensively studied the last decade [3]. Where the N-1 approach favors preventive actions, probabilistic RMACs explicitly make a trade-off between preventive, corrective and curtailment costs and aim at efficient reliability management. However, besides being efficient, electricity law prescribes that power systems should be secure, reliable and non-discriminating [4]. So far, the level of discrimination or inequality between consumers is not explicitly assessed, although this might be a reason of public opposition against reliability and security measures, such as through the application of an alternative RMAC.

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To adopt reliability management approaches in practice, their social acceptability is crucial. Social acceptability is on the one hand determined by the absolute level of reliability and costs for consumers and on the other hand by the distribution of reliability among consumers. The latter determines whether consumers perceive to be treated fairly. Strbac et al. have shown that the energy not supplied due to events beyond the list of credible events in the N-1 criterion is unevenly distributed across the network resulting in inequality between consumers [2]. Fully probabilistic approaches that make a trade-off between preventive, corrective and load curtailment actions on the contrary enable the differentiation between consumers based on their value of lost load, which might also impact equality. To verify social acceptability of RMACs, a transparent assessment of the inequality in terms of reliability between consumers is required and a comparison between RMACs should be made.

The objectives of this paper are threefold: (i) to illustrate the inequality assessment of short-term RMACs in a small-scale system (ii) to gain insight in the differences in inequality between a fully probabilistic RMAC and the deterministic N-1 approach and (iii) to identify the aspects for which society's preferences should be determined to verify the fairness of RMACs. So far, a transparent way to assess equality in terms of energy not supplied (ENS) or any other reliability indicator does not exist. The main contributions of this paper are (i) a transparent assessment of inequality in short-term reliability management and (ii) recommendations for governments and regulating bodies to move forward in the practical assessment of fairness of short-term reliability management. The assessment is based on an inequality index that summarizes the level of inequality in terms of ENS between entities, such as nodes, consumer groups or consumers, in a single number and an inequality ratio per entity that gives information about the perceived fairness per entity. The inequality assessment can be applied by regulating bodies and system operators in the performance evaluation of short-term reliability management.

Section II translates the generic definition of inequality to the power system reliability context and proposes the inequality ratio and index. Section III assesses inequality resulting from a fully probabilistic RMAC and the deterministic N-1 approach. The first part illustrates the use of the inequality ratio and index, whereas the second part verifies the sensitivity of the results to the test system. Section IV discusses the inequality assessment and Section V concludes.

II. Equality in Power System Reliability Context

Equality is extensively studied in economics, but the concept is not widespread in a power system context. The generic definition of equality is translated to a power system reliability context and based on this definition an inequality ratio and inequality index are developed.

A. Inequality ratio

Equality is generally defined as treating everyone the same, regardless of differences in needs or deserts. In a power system reliability context, this corresponds to everyone getting the same relative reliability level. The vector **w** contains the share of demand of each entity[1] j in the total electrical energy demand of all entities $\mathcal{J}$. The elements w_j in **w** are defined as:

$$w_j = \frac{D_j^{Energy}}{\sum_{j' \in \mathcal{J}} D_{j'}^{Energy}} \tag{1}$$

Where D_j^{Energy} is the electrical energy demand of entity j.

The vector **e** contains the share of energy not supplied (ENS) of each entity j in the total ENS of all entities in $\mathcal{J}$, with the elements e_j defined as:

$$e_j = \frac{ENS_j}{\sum_{j' \in \mathcal{J}} ENS_{j'}} \tag{2}$$

Where ENS_j is the energy not supplied of entity j. If inequality is calculated ex-ante, expected energy not served (EENS) for a set of events is used, whereas in an ex-post evaluation energy not served (ENS) for a single event or a sequence of events is used.

Vectors **w** and **e** need to satisfy following conditions:

$$\sum_{j \in \mathcal{J}} w_j = \sum_{j \in \mathcal{J}} e_j = 100\% \tag{3}$$

$$w_j = 0 \Longrightarrow e_j = 0 \tag{4}$$

Condition (3) guarantees that all demand and all ENS is distributed over all entities, where condition (4) states that entities without electricity demand cannot have load curtailment.

Unreliability is considered to be distributed equally, if all entities contribute to the energy not supplied according to their share in total demand:

$$\xi_j^{ENS} = 1, \forall j \in \mathcal{J} \text{ with } \xi_j^{ENS} = \frac{e_j}{w_j} = \text{ inequality ratio} \tag{5}$$

Some entities j are more ($\xi_j^{ENS} > 1$) or less affected ($\xi_j^{ENS} < 1$), if the distribution is not perfectly equal.

[1]An entity can be a node, a consumer group, a region or an individual consumer.

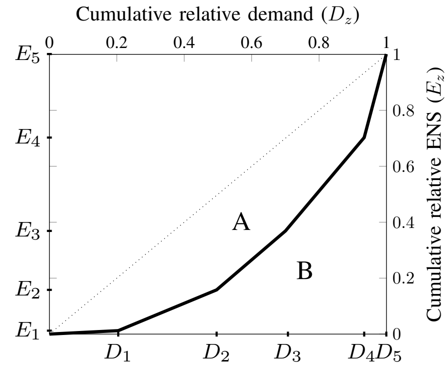


Fig. 1: Lorenz curve in terms of energy not served. The line of equality is dotted.

B. Inequality index

Based on the definition of equality, an inequality index U^{ENS} is developed, which enables the quantification of inequality of power system reliability between consumers in a single value. Many inequality indices have been proposed in the economic literature, such as e.g., the variance, the coefficient of variation, the relative mean deviation [5], the standard deviation of logarithms, the 20:20 ratio, the Palma ratio, Theil's index [6], the Atkinson index [7], the Schutz or Hoover index [8] and the Gini index [9]. Their strengths and weaknesses have been studied extensively in the economic literature [9], [10]. A perfect inequality index does not exist, but the Gini index is the most widely used, amongst others because it is easy to understand how to compute it based on Lorenz curves.

A Lorenz curve represents the distribution of reliability between entities by plotting the cumulative share of demand D_z with respect to the cumulative share of energy not supplied E_z. All entities are ranked according to an increasing inequality ratio ξ_j^{ENS}. The slope of the different pieces of the piecewise linear Lorenz curve is given by the inequality ratios, as shown in Fig. 1. The Lorenz curve is a straight line with coefficient of direction equal to 1, if the distribution of reliability is completely equal (i.e. when $\xi_j^{ENS} = 1 \; \forall j \in \mathcal{J}$), i.e., the dotted line in Fig. 1. The Lorenz curve will be below the line of equality, if reliability is not equally distributed, i.e. the bold line in Fig. 1. The closer the Lorenz curve is to the line of equality, the more equal the distribution of reliability.

The Gini-based inequality index of power system reliability U^{ENS} is defined as:

$$U^{ENS} = \frac{A}{A+B} \tag{6}$$

This corresponds to the ratio of the surface area between the line of equality and the Lorenz curve (A) over the total surface area under the line of equality ($A+B$). Surface area B consists of the surface areas of the trapezoids under each of the pieces of the piecewise-linear Lorenz curve, resulting in following formula for U^{ENS}:

$$U^{ENS} = |1 - \sum_{z=1}^{J}(D_z - D_{z-1})(E_z + E_{z-1})| \qquad (7)$$

with D_z the cumulative proportion of relative demand ($D_z = \sum_{j=1}^{z} w_j \ \forall z = 1..J$, $D_0 = 0$ and $D_J = 1$) and E_z the cumulative proportion of relative ENS ($E_z = \sum_{j=1}^{z} e_j \ \forall z = 1..J$, $E_0 = 0$ and $E_J = 1$). The entities j are ranked such that $\xi_j^{ENS} \leq \xi_{j+1}^{ENS}$. U^{ENS} has a value between zero and one. A value of zero corresponds to an equal distribution of unreliability among all entities. The closer the inequality index is to one, the more unreliability is limited to a few entities.

III. Inequality in short-term reliability management approaches and criteria

Up till now, performance evaluation of reliability management was mainly based on reliability indicators, such as ENS, system-related indicators, such as line overloading or voltage violations, and socio-economic indicators, such as total system cost [11], [12], [13]. Besides these traditional aspects determining technical, economic and social acceptability of RMACs, the latter is also determined by the distribution of reliability among consumers. This case study illustrates the use of the inequality ratio ξ^{ENS} and index U^{ENS} in a comparative study of two short-term RMACs: (a) the deterministic N-1 criterion and (b) a probabilistic approach aiming at the minimization of expected total system cost.

A. Data and assumptions

Two decision stages are considered in short-term reliability management: day-ahead operational planning and real-time operation. The N-1 criterion aims at securing all single branch and generator outages and the N-0 state given the forecast of net demand. All states are considered as equally probable and equally severe and preventive actions are favoured. The probabilistic approach on the contrary aims at minimizing the expected total system cost taking into account the most probable contingencies up to a prescribed cumulative probability and a set of possible realizations of net total demand. Total system cost consists of the cost of preventive actions, the expected cost of corrective actions and expected interruption costs of consumers. The probabilistic approach takes into account that VOLL differs between consumer groups and over time [14].

Performance evaluation of the two reliability management approaches is executed using non-sequential evaluation techniques. Operational planning is simulated for a set of characteristic time instances representing a year, for which forecast values of net total demand are given [14]. In a second step, corrective control is simulated for a set of real-time realizations that are conditional upon the operational planning states. Net demand realizations are determined based on a normal distribution with mean equal to the forecast value of net total demand at the corresponding time instance and a coefficient of variation of 4%. For each evaluated system state, the energy not supplied per consumer is determined. These values, together with the demand per consumer, are used as an input to calculate the inequality ratio ξ_j^{ENS} and the inequality index U^{ENS}.

The simulation of preventive and corrective control is executed using a DC security constrained optimal power flow (SCOPF) in which generation redispatch, branch switching, phase shifting transformer tap changing and load curtailment are considered as available actions [15]. The simulations are executed using a MATLAB implementation [12] interfacing with the DC SCOPF, which is implemented in AMPL [16].

A five-node network, based on the Roy Billinton Reliability test system (RBTS) [17], is used to illustrate the use of the inequality ratio and index. Sensitivity of the results to the test system is verified by repeating the analysis for the 24-node IEEE reliability test system (RTS) [18]. VOLL data for Norway are used [19] and two consumer groups (residential and non-residential) are distinguished [14].

B. Results

Evaluating the inequality between consumers is not straightforward if no clear definition and summary measure of inequality exist. Nowadays, equality is typically assessed based on the distribution of energy not supplied among different nodes or consumers [2]. Fig. 2 shows the share of ENS per node if an N-1 criterion and probabilistic RMAC are applied in the five-node system. Based on these data, it is difficult to decide which of the two RMACs results in the highest level of inequality and to quantify the difference. Moreover, this analysis does not take into account the share of demand at each node, which should be naturally related to the share of ENS in an inequality assessment. Fig. 2 illustrates the need for an adequate definition of inequality as well as a summarizing measure that facilitates the comparison between different reliability management approaches.

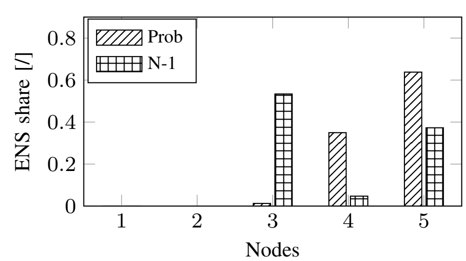
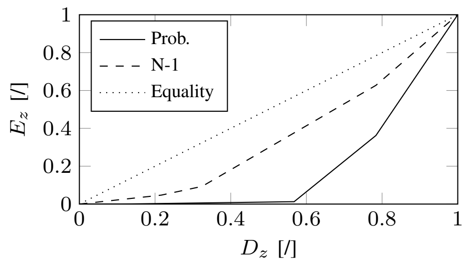


Fig. 2: The share of ENS per node if the N-1 and probabilistic RMAC are applied

Fig. 3 shows the Lorenz curves of inequality between consumers at different nodes (U_{node}^{ENS}) for both RMACs. This figure shows that inequality is higher with the probabilistic RMAC (Prob.) than with the deterministic N-1 criterion (N-1). The probabilistic approach exploits the differences in VOLL between consumer groups and over time, while the N-1 approach does not. This also leads to lower total system costs if the probabilistic RMAC is applied (73% lower in this case study).

Part of the cost savings can be used to decrease public opposition to the higher inequality of reliability. Fig. 4



$U^{ENS}_{prob,node} = 0.62 \qquad U^{ENS}_{N-1,node} = 0.29$

Fig. 3: Lorenz curves for inequality between nodes in terms of EENS for the two RMACs compared to the line of equality.

identifies the most unfairly treated nodes by plotting the inequality ratios ξ_j^{ENS}. This figure shows that consumers from node 5 have a disproportionately low reliability level with the probabilistic RMAC, which means that they should be remunerated or safeguarded against other reliability-decreasing decisions. Based on Fig. 2, it might be concluded that node 3 is unfairly treated if the N-1 approach is applied. However, Fig. 4 indicates that node 3 has a fair level of ENS taking into account its higher demand share. The inequality ratios enable system stakeholders to assess this information in a transparent way.

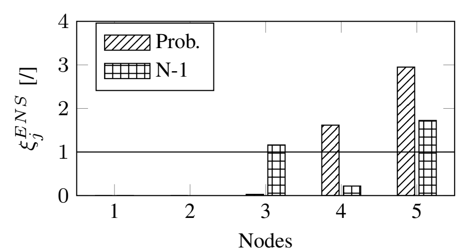


Fig. 4: Inequality ratios per node for the probabilistic and N-1 RMACs

On top of the inequality between nodes (U^{ENS}_{node}), the index can also indicate inequality between different consumer groups (U^{ENS}_{cg}) or between individual consumers (U^{ENS}). Inequality ratios ξ_g^{ENS} per group g, i.e. per node for U^{ENS}_{node} or per consumer group for U^{ENS}_{cg}, equal:

$$\xi_g^{ENS} = \frac{\sum_{j' \in \mathcal{J}_g} ENS_{j'}}{\sum_{j \in \mathcal{J}} ENS_j} \cdot \frac{\sum_{j \in \mathcal{J}} D_j^{Energy}}{\sum_{j' \in \mathcal{J}_g} D_{j'}^{Energy}} \tag{8}$$

with $\mathcal{J}_g$ the subset of consumers belonging to group g. Calculating inequality between individual consumers is hard in practice, because exact energy not supplied and demand per consumer are not available to TSOs. They only have estimations or nodal values. However, by grouping consumers per node (U^{ENS}_{node}) or per consumer group (U^{ENS}_{cg}), the Lorenz curve is an approximation of the Lorenz curve that considers all consumers individually. Table I shows that this approximation of the Lorenz curve results in lower values of the inequality indices U^{ENS}_{node} and U^{ENS}_{cg}, quantifying the inequality between nodes and between consumer groups respectively, compared to U^{ENS}, which considers different consumer groups at different nodes. Individual inequality is always understated if aggregation is used. Nevertheless, the conclusion remains unaffected that the probabilistic RMAC leads to higher inequality than the deterministic approach in this case, whatever the compared groups.

TABLE I: Inequality between nodes U^{ENS}_{node}, between consumer groups U^{ENS}_{cg} and between individual consumers U^{ENS} for the two RMACs.

	Probabilistic	N-1
U^{ENS}_{node}	0.62	0.29
U^{ENS}_{cg}	0.61	0.12
U^{ENS}	0.81	0.74

Lastly, even if data is available at the level of individual consumers, it makes sense to calculate the inequality between nodes or between consumer groups. Consumers' perception of their peers influences which groups need to be considered in the calculation of the inequality index. If consumers are concerned about equality between consumer groups (e.g. residential and non-residential), the inequality index U^{ENS}_{cg} should be used. If they are more concerned about equality between individuals, irrespective of their consumer group, the inequality index U^{ENS} should be used. Similarly, the inequality index can also be calculated within groups, such as the inequality between residential consumers or between non-residential consumers, as shown in Table II. This table shows that for the presented case study the inequality between residential consumers is less affected when moving from the N-1 criterion to the probabilistic RMAC than the inequality between non-residential consumers. However, within both groups, inequality decreases if the probabilistic approach is applied. Fully probabilistic RMACs treat consumers with similar VOLL, which typically belong to the same group, in a similar way in terms of load curtailment. Load curtailment in the N-1 approach on the contrary is not based on any economic incentive.

TABLE II: Inequality U^{ENS} between consumers in the two considered consumer groups for the two RMACs

	Consumer groups	
	Residential	Non-residential
Prob.	0.52	0.23
N-1	0.56	0.75

The sensitivity of the results is verified by repeating the simulations for the 24-node IEEE reliability test system. The results are summarized in Table III and show that the level of inequality in terms of reliability depends on the system design. In the smaller RBTS case, probabilistic reliability criteria result in higher inequality than deterministic approaches, whereas in the IEEE RTS system the probabilistic RMAC reduces inequality. The IEEE RTS has more operational flexibility, resulting in a lower relative amount of load curtailment in the N-1 case, which is concentrated in a limited set of consumers, whereas the higher amount of load curtailment resulting from probabilistic reliability management is spread over more consumers. Strbac et al. [2] questioned the fairness of deterministic criteria based on a comparison of ENS between nodes without taking into account the demand per node. The analysis of the IEEE RTS based on the inequality index approves this conclusion, but in systems with limited operational flexibility, probabilistic RMACs can result in more inequality. The proposed index enables system stakeholders to quantify the inequality, to determine trends and to compare different RMACs.

TABLE III: Sensitivity of inequality U^{ENS} to the test system

	N-1	Prob.
RBTS	0.741	0.811
IEEE RTS	0.97	0.88

IV. Discussion

An effective application of the inequality assessment requires that the government and regulating bodies determine society's preferences regarding certain aspects. First, it is important to determine consumers' perception of their peers as this determines the aggregation applied in the inequality assessment. Second, this paper deals with equality or sameness, i.e., reliability is considered to be fairly distributed if everyone gets the same level of reliability. This definition of fairness is also applied in [2]. However, fairness can also be defined as deservedness, i.e., everyone gets what he/she deserves, or need, i.e., those that have more to give should give a greater percentage of what they have to help others who are unable to contribute much. For these definitions, similar indices can be developed. Third, society's preferences in terms of the acceptable level of inequality should be clearly stated to obtain the thresholds for socially acceptable RMACs. Moreover, it should be considered whether an unconditional reliability level is still the way to go or whether reliability levels should be individualized. Individual reliability levels link price with reliability level, whereas unconditional reliability aims at supplying each consumer with a similar level of reliability, irrespective of its transmission tariff.

V. Conclusion

Besides the absolute reliability level and costs for consumers, fairness determines the social acceptability of reliability management approaches and criteria (RMAC). The proposed inequality index and ratio enable system stakeholders to quantify inequality in terms of energy not supplied in a single number and to assess the perceived fairness per consuming entity, i.e., node, consumer group or consumer. The ratio and index are applied in a case study to assess the inequality resulting from a fully probabilistic approach that aims at minimizing expected total system cost and the deterministic N-1 approach. The assessment shows that inequality between consumers is impacted by the operational flexibility in the system. The probabilistic approach results in less inequality in systems with more operational flexibility compared to the N-1 approach, while in cases with limited operational flexibility the probabilistic approach leads to more inequality. Future work should focus on setting society's preferences and on developing measures to control inequality. The performance of the latter can be assessed using the proposed inequality ratio and index.

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