Designing a Social Resilience Index for Electricity Power Systems

Amir Niroomandfam[1], Mohammad Hassan Bahmani[1,2], Amir Bairami Akhi Jahani[3], Masood Yahyaei[1,4]

[1] Saba Power and Energy Group, Tehran, Iran
[2]Tarbiat Modares University, Tehran, Iran

[3] Faculty of Electrical Engineering, University of Zanjan, Zanjan, Iran

[4] Islamic Azad University Central Tehran Branch, Tehran, Iran

Niroumandfam@sabapeg.ir[1],Mh.Bahmani@Modares.ac.ir[2], mbairami65@gmail.com[3], M.Yahyaei.eng@iauctb.ac.ir[4]

Abstract—**Electricity power systems are the backbone of modern society, ensuring the functioning of essential services, industries, and households. Traditionally, resilience assessments of these systems have focused on technical aspects and infrastructure. However, as the world faces increasing risks from extreme weather events, cybersecurity threats, and other unexpected disruptions, it has become evident that the social aspect of resilience is equally crucial. Social resilience in power systems encompasses community engagement, equity, communication, and social support networks. Ensuring equitable access to resources and services, particularly for vulnerable populations, is a fundamental aspect of social resilience. In this paper, a social resilience index is proposed to measure the vulnerability of the power system. To this end, the concept of social welfare is borrowed from microeconomics to measure customers' satisfaction with electricity service curtailment. The risk aversion index is a crucial factor in the proposed resilience index, wherein customers with a high risk aversion derive greater welfare from electricity energy consumption. The numerical results demonstrate that the proposed social index can be controlled by applying different outage levels to different customers.**

Keywords – Resilience, social perspective, welfare, risk aversion index

I. INTRODUCTION

In an increasingly interconnected and electrified world, the resilience of power systems is paramount. The reliability of electricity supply underpins modern life, driving economic growth, sustaining critical services, and ensuring the comfort and security of millions. However, this complex network of power generation, distribution, and consumption faces a variety of emerging challenges, including natural disasters and cyber threats, as well as changing climate patterns and societal shifts [1].

Traditionally, the assessment of power system resilience has focused on technical and engineering aspects. Engineers have meticulously crafted grids to minimize downtime by investing in redundant infrastructure, cutting-edge equipment, and proactive maintenance. While these efforts remain indispensable, they alone do not encompass the full range of challenges that the modern power grid faces. A new paradigm called social resilience is emerging in the study of power systems in response to this complexity. Social resilience in power systems is an interdisciplinary approach that goes beyond the scope of engineering. It recognizes the complex interaction between technology, policy, and human behavior in the pursuit of a more resilient grid. This shift is not just theoretical but also acknowledges the fact that the power grid is not an isolated entity; it is closely interconnected with the communities it serves [2].

This article explores the complex landscape of social resilience in power systems and the changing role of utility companies within this framework. To this end, this paper establishes a novel social resilience index of power systems that measures consumers' social perspectives due to electricity energy curtailment.

The main contributions of this paper are summarized as follows:

- Designing a novel social resilience index in the power system based on consumers' social welfare
- Measuring the social welfare of electricity consumers using the concept of risk aversion.
- Determining optimal demand curtailment for different customer types to maximize the social resilience index when an outage occurs.
- Determining optimal financial assistance to compensate different consumers' damage due to the outage.

The rest of this paper is organized as follows: Section II discusses the concept of social resilience. Section III provides a mathematical description of the proposed social resilience index. In this section, the welfare of electricity customers is modeled using various utility functions. Numerical results are discussed in Section IV and conclusions are drawn in Section V.

II. Social Resiliense Concept

Resilience, in the context of electricity power systems, refers to the ability of these systems to withstand and recover from disturbances, ensuring uninterrupted electricity supply. While traditionally, the focus has been on physical infrastructure, such as power plants, transformers, and transmission lines, the modern understanding of resilience goes beyond hardware. It encompasses the social, economic, and environmental aspects that contribute to the robustness of a power system in the face of adversity. Incorporating these broader aspects of resilience into power system planning recognizes the interconnected and evolving nature of risks. It acknowledges that a resilient power system is not only about maintaining physical infrastructure but also about understanding and adapting to a complex and dynamic environment.

This paradigm shift is a response to the growing complexity of our interconnected world. The challenges and disruptions we face are not only technical but often rooted in social, behavioral, and cultural dimensions. By emphasizing the importance of integrating social and community factors into resilience assessments, we can model the complex interconnections among individuals, systems, and their surroundings. This paradigm shift is a response to the increasing complexity of our interconnected world. The challenges and disruptions we face are not only technical but often rooted in social, behavioral, and cultural dimensions [3].

One of the primary reasons for incorporating social and community elements into resilience assessments is the acknowledgment that individuals and communities vary in their vulnerabilities and capacities when facing challenges. Vulnerability can be linked to socioeconomic status, geography, age, disability, or other factors that influence how individuals experience and respond to disruptions.

Incorporating social and community aspects into resilience assessments brings with it the crucial principles of community engagement and awareness. Engaging with local communities and involving them in resilience planning and response efforts are essential. Communities are not just passive recipients of aid during disasters; they are often the first responders, providing valuable local knowledge and resources that can significantly impact a community's ability to withstand and recover from adversity [4].

By emphasizing the importance of including social and community aspects in resilience assessments, several challenges can arise if these dimensions are ignored. Some of these challenges include:

Social Fragmentation: Neglecting social and community factors can result in social fragmentation, where communities are not engaged and individuals are left to fend for themselves during crises.

Inequity: Vulnerable populations may be disproportionately affected if resilience planning does not take into account social and economic disparities.

Misinformation: Without clear communication and community engagement, misinformation can spread, leading to confusion and panic during crises.

Resistance to Change: Communities may resist resilience efforts that do not take into account their unique cultural or behavioral preferences.

Resource Mismatch: Allocating resources without understanding the social and community aspects can lead to ineffective resource utilization and a lack of community engagement.

Due to the mentioned aspects, this paper designs a social resilience index that measures consumers' resilience against electricity energy curtailment. This index will be described in the next sections.

III. SOCIAL RESILIENSE INDEX

In this article, the social resilience index (*SRI*$_{total}$) is defined as (1), where the total resilience is equal to the sum of the individual consumers' social resilience.

$$SRI_{total} = \sum_{i=1}^{N} SRI\ (i) \tag{1}$$

where *i* and *N* are the consumer index and number of consumers. Also, the social resilience of each consumer is related to his/her obtained welfare (*W*) regarding load consumption, as shown in (2).

$$SRI\ (i) = W\ (i) \tag{2}$$

The welfare of electricity customers can be determined by subtracting the cost of electricity from the satisfaction obtained by the customer from consumption, as shown in (3) [5]. To quantify the satisfaction obtained, this paper utilizes the concept of utility function (*U*), borrowed from microeconomics. The term "utility function" refers to the overall well-being and satisfaction that consumers derive from consuming electricity.

$$W\ \big(D(i), a(i)\big) = U\big(D(i), a(i)\big) - \pi D(i) \tag{3}$$

where *D(i)*, π and *a(i)* represent the consumer's demand, electricity energy price, and risk aversion index, respectively. The risk aversion index relates to each consumer's individual preferences [3]. The consumers' welfare due to electricity energy consumption will increase as risk aversion increases.

A utility function is a function that is twice-differentiable and has the following properties:

Property 1: Marginal utility is positive, which means that utility increases with consumption. In other words, more consumption is preferred to less consumption. This can be expressed as:

$$\frac{\partial U(D,\alpha)}{\partial D} \geq 0 \tag{4}$$

Property 2: Marginal utility is a non-increasing function, which means that the marginal utility of consumption decreases as consumption increases. This can be expressed as:

$$\frac{\partial U^2(D,\alpha)}{\partial D^2} \leq 0 \tag{5}$$

Property 3: The customer utility function is non-decreasing in the risk aversion index. This means that a larger risk aversion indicates a greater degree of risk-aversion behavior. Mathematically, it can be expressed as:

$$\frac{\partial U(D,\alpha)}{\partial \alpha} > 0 \tag{6}$$

Property 4: It is assumed that without consumption, the utility will be zero, which means that no satisfaction is obtained when the customer does not consume any electric energy. Thus, we have:

$$U(0\ \ \alpha) = 0 \tag{7}$$

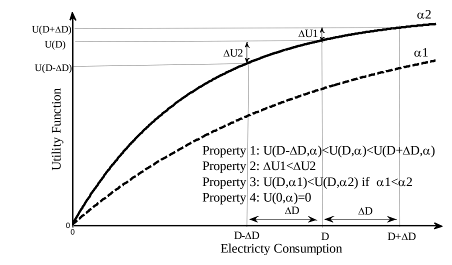

Figure 1. Utility function due to electricity energy consumption [5]

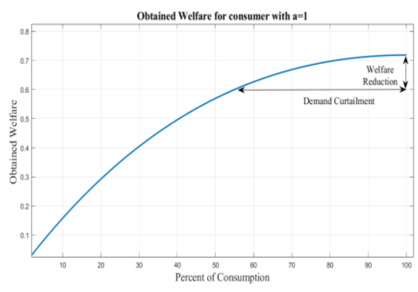

Figure 2. Welfare of electricity energy consumption

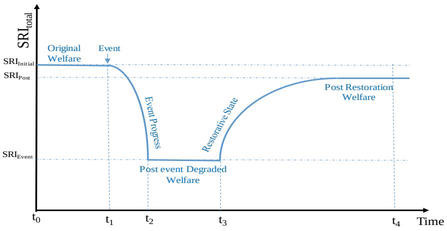

Figure 3. The curve of social resilience associated with an event

Based on the aforementioned properties, the utility function is an ascending and concave function that gradually saturates with consumption, as depicted in Fig. 1. Fig. 2 illustrates the welfare obtained for different consumption levels for a customer with $a = 1$.

The proposed social resilience index is an indicator used to measure and enhance resilience, as depicted in Fig. 3. The welfare obtained by consumers during the event is divided into four phases accordingly. In the $[t_0, t_1)$ period, the system is in normal operation; therefore, the SRI is equal to the consumers' original welfare. After moment t_1, system performance will be drastically degraded by unexpected events, causing the SRI to drop to the post-event welfare level. At time t_2, the system starts to resist and absorb the negative consequences of the incident until time t_3. In the $(t_3, t_4]$ period, the system gradually recovers and restores the power system performance to almost normal levels by implementing appropriate recovery strategies. Therefore, the SRI will be equal to the post-restoration welfare of the consumers.

Ensuring equity and addressing vulnerability are essential components of social resilience in electricity power systems. Resilience planning should aim to provide equitable access to resources and services during power outages. This includes ensuring that vulnerable populations have access to backup power, emergency shelters, and communication services. Also, efforts should be made to reduce disparities in the impact of power disruptions on various consumers. This may involve providing financial assistance, resources, or targeted outreach to vulnerable populations [6].

To ensure equity in electricity service provision, this paper proposes that financial assistance (R) is applied to the vulnerable consumers' based on their welfare reduction due to demand curtailment, which can be expressed as:

$$R(\Delta D) = W(D, \pi, \alpha) - W(D - \Delta D(t), \pi, \alpha) \tag{8}$$

Through the proposed SRI, the utility company can manage outages among consumers to minimize financial assistance. The paid assistance is based on the reduction of customers' welfare, in which consumers with a low risk aversion index receive less reimbursement. Hence, to reduce financial assistance, more outages can be applied to consumers with a low risk aversion index. It should be mentioned that the assistance payment is fair and equal to the reduction in consumers' welfare due to demand curtailment.

To minimize the financial assistance, we have:

$$\min \quad F = \sum_{i=1}^{N} R(\Delta D(i)) \tag{9}$$

Subject to:

$$\sum_{i=1}^{N} \Delta D(i) = P_{outage} \tag{10}$$

Different functions with the mentioned properties can be utilized as utility functions. As an example, in this paper, the exponential utility function, the popular form of the utility function that is frequently used to describe the risk preferences of consumers [6], is selected to survey the proposed SRI. It should be mentioned that utilizing any other form of utility function provides similar results.

The exponential utility function can be expressed as follows:

$$U(D, \alpha) = 1 - e^{-aD}, \quad a > 0 \tag{11}$$

For the exponential utility function, the welfare function and the calibration coefficient are determined as follows (12) and (13).

$$W(D, \alpha) = A(1 - e^{-aD}) - \pi D \tag{12}$$

$$A = \frac{\pi_0}{a} e^{aD_0} \tag{13}$$

This calibration coefficient (A) is used to calibrate the adjustment for the initial electricity price (π_0) and initial demand (D_0) [7].

Assuming that electricity consumers behave based on an exponential utility function, the optimal demand curtailment level of each consumer can be calculated as shown in (14) [8].

$$\Delta D(i) = \frac{1/\alpha(i)}{\sum_{j=1}^{N} 1/\alpha(j)} P_{outage} \tag{14}$$

where P_{outage} is the total outage due to the event.

IV. Numerical Results

The proposed social resilience index has been tested on a sample network, as depicted in Fig. 4. For the sake of simplicity, this study assumes that consumers are categorized into residential, commercial, and industrial sectors and that all consumers within each sector have the same risk aversion index. The indices for residential, commercial, and industrial are assumed to be 0.9, 0.7, and 0.5, respectively. Also, this paper assumes that the utility company is a non-profit company that buys electricity from the overhead network at a price equal to 10$/MW and sells it to consumers at a price equal to 10 $/MW.

To assess the efficiency of the proposed social resilience index in the selected electricity network, the index will be evaluated in five scenarios, as described below:

Sce. #1: The system is in a normal operational state, and all the demand is supplied with the overhead network (before the event).

Sce #2. An event occurred, and the overhead network has been disconnected. The installed DG generates 5 MW of electricity to supply the demands, and the energy price is the same after and before the event (10 $/MW).

Sce. #3: All the situations are the same as in Sce. 2, except optimal demand curtailment is applied to the consumers based on (14).

Sce. #4: All the situations are the same as in Sce. 2, except the electricity price is equal to the DG generation price after the event happened (13 $/MW).

Sce. #5: All the situations are the same as in Sce. 2, except the electricity price is equal to the DG generation price after the event happened (13 $/MW) and optimal demand curtailment is applied to the consumers based on (14).

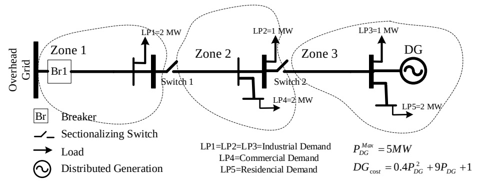

Figure 4. Selected distribution network to study the proposed social resilience index.

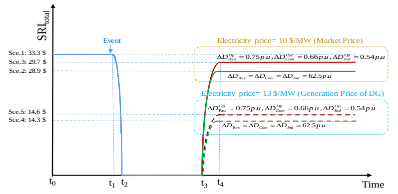

Figure 5. The curve of social resilience for the selected electricity network

Fig. 5 illustrates the curve of the social resilience index for different scenarios. As depicted in this figure, the SRI level after the event is lower than its initial level due to the generation limit of the DG. Although only a few scenarios are surveyed as samples in this section, considering other scenarios for demand curtailment division among consumers, the highest SRI level and obtained welfare can be achieved by applying demand curtailment based on (14). As shown in Fig. 5, applying electricity energy with a high DG generation price reduces the welfare and SRI levels obtained.

Tables I and II demonstrate the energized demand and SRI for each load point under different scenarios. Sce. In scenario #1, the normal operational state is described, where all demand is supplied from the overhead network and the obtained welfare is equal to 33.3 $. In all other scenarios, the overhead network is disrupted, and the DG generates its maximum capacity, 5MW, to energize different demands. In these scenarios, 3 MW of the demand will not be supplied due to the limited capacity of the DG. To ensure equality and compensate for consumers' dissatisfaction caused by demand curtailment, the utility company must provide compensation equal to the reduction in their welfare. Table III illustrates the revenue and costs of the utility company. Considering Tables I-III, it is illustrated that the increase in financial assistance resulting from the application of the DG generation price to consumers is greater than its positive effect on the utility company's cost reduction. The optimal scenario for the utility company is Scenario #3.

TABLE I. DEMAND CURTAILMENT AND OBTAINED WELFARE LEVELS FOR SCE. 1, SCE. 2, AND SCE.3

Load Point	Sce. #1		Sce. #2		Sce. #3	
	D (MW)	SRI ($)	D (MW)	SRI ($)	D (M W)	SRI ($)
1	1	2.97	0.62	2.54	0.55	2.41
2	1	2.97	0.62	2.54	0.55	2.41
3	1	2.97	0.62	2.54	0.55	2.41
4	1	4.48	0.62	3.86	0.66	4.12
5	1	4.48	0.62	3.86	0.66	4.12
6	1	2.97	0.62	2.54	055	2.41
7	1	6.22	0.62	5.51	0.75	5.91
8	1	6.22	0.62	5.51	0.75	5.91
Tot.	8	33.3	5	28.9	5	29.7

TABLE II. DEMAND CURTAILMENT AND OBTAINED WELFARE LEVELS FOR SCE. 4 AND SCE.5

Load Point	Sce. #4		Sce. #5	
	D (MW)	SRI ($)	D (MW)	SRI ($)
1	0.62	0.73	0.55	0.78
2	0.62	0.73	0.55	0.78
3	0.62	0.73	0.55	0.78
4	0.62	2.07	0.66	2.06
5	0.62	2.07	0.66	2.06
6	0.62	0.73	055	0.78
7	0.62	3.63	0.75	3.67
8	0.62	3.63	0.75	3.67
Tot.	5	14.3	5	14.6

TABLE III. UTILITY COMPANY'S LOSS FOR DIFFERENT SCENARIOS

Scenario Number	Sce. #1	Sce. #2	Sce. #3	Sce. #4	Sce. #5
Revenue from Selling Energy to Consumers	80$	50$	50$	65$	65$
Cost of Buying Energy from Network	80$	0$	0$	0$	0$
Cost of Buying Energy from DG	0$	65$	65$	65$	65$
Cost of Financial Assistance	0$	4.4$	3.6$	19$	18.7$
Total Loss	0$	19.4$	18.6$	19$	18.7$

The main parameter of the propose social resilience index is the consumers' risk aversion coefficients. The proposed social resilience can be applied to any region or country by utilizing these coefficients. Authors in [9] has been proved that the risk aversion confidents are related to the price elasticity of electricity demand, hence by employing the elasticity data distribution companies can measure their customers' social resilience.

V. CONCLUSIONS

Current resilience models emphasize only technical and infrastructural aspects of power systems and do not consider consumers' social resilience. However, the consumption of electrical energy is closely related to today's life, and any power supply disruption has a significant impact on the social perspective of consumers. In this research, a social resilience index was designed for the power system. This index measures changes in the social welfare of consumers. The concept of utility function from microeconomics was used to calculate consumers' welfare. The risk aversion index is a crucial variable in the utility function, and its value varies depending on the individual behavior and perspective of consumers. The results showed that individuals with a higher risk aversion index receive greater welfare from consuming electric energy. In the methodology section, an optimization model was developed to optimally divide load curtailment among consumers. In the numerical results section, the social resilience index was tested on a sample network. Numerical results showed that the utilization of distributed generation after the event can enhance social resilience. On the other hand, it is essential to provide fair compensation to reimburse consumers for the reduction in their welfare caused by the curtailment of demand resulting from an event. Also, this section demonstrates that electricity price increments due to distributed generation utilization will also cause a decline in the social resilience index.

This study used concept of the utility function to measure consumers' perspective regards electricity energy consumption. This measurement resulted in a simple and analyzable model for the social resilience index of electricity customers. However, in real-world applications, it is necessary to model the customers' point of view towards electricity energy consumption with more accurate and comprehensive models.

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