Journal of Operation and Automation in Power Engineering

Vol. 8, No. 3, Dec. 2020, Pages: 257-272

http://joape.uma.ac.ir

Design of Reliability Insurance Scheme Based on Utility Function for Improvement of Distribution Grid Reliability

A. Niromandfam[1,2]*, A. Sadeghi Yazdankhah* [1]*, R. Kazemzadeh*[1,*]

[1] *Faculty of Electrical Engineering, Sahand University of Technology, Tabriz, Iran.*
[2] *Daneshmand Research and Development Institute, Tehran, Iran.*

Abstract- *The regulatory schemes currently used for reliability improvement have weaknesses in the provision of quality services based on the customers' perspective. These schemes consider the average of the service as a criterion to incentivize or penalize the distribution system operators (DSOs). On the other hand, most DSOs do not differentiate electricity services at the customer level, due to the status of the electricity grid and lack of adequate information about customers' preferences. This paper proposes a novel reliability insurance scheme (RIS), which enables the electricity consumers to determine their desired reliability levels according to their preferences and pay corresponding premiums to the DSO. The DSO can use the premiums to improve reliability or reimburse consumers. To design efficient insurance contracts, this paper uses utility function to estimate customers' viewpoints of electricity energy consumption. This function measures the customers' satisfaction of electricity energy consumption. The proposed utility based reliability insurance scheme (URIS) may create a free-riding opportunity for the DSO, in which low quality service is provided and the collected premiums are used to pay the reimbursements. To prevent free-riding opportunity, this paper incorporates the proposed URIS and reward/penalty schemes (RPSs). The results show that the success of the proposed reliability scheme increases as the grid flexibility increases.*

Keywords: Reliability regulation, utility function, insurance, customers' viewpoints.

1. INTRODUCTION

After the deregulation of power system industry, network ownership is privatized and due to natural monopoly status of distribution systems, it is needed to regulate these entities. The distribution systems are regulated in many countries based on their performance, which is referred to as performance-based regulation (PBR). Although the PBR increases efficiency, it may lead to reduced quality, as a result of cost saving in order to make sufficient profit [1]. To overcome the PBR's weaknesses, regulators may utilize various forms of reward/penalty schemes (RPSs) to ensure reliability. For example, RPSs are currently being applied to distribution system reliability in most of the European countries [2]. In RPSs, the regulator utilizes system quality indices to measure the system reliability level. For these indices, the regulator determines target levels. Distribution system operators (DSOs) will be rewarded or penalized when they succeed or fail to meet these targets. The DSO's profit increases as the reliability level increases, in which the regulator tries to establish market-like conditions for reliability providers [3].

The provision of RPSs aims to achieve the socioeconomically optimal reliability level, which minimizes the total reliability cost for society. To achieve the objective, the regulator should solve challenges, such as the limitation of the DSO's financial risk, as well as the provision of service quality, based on the customers' preferences. Many of the studies have considered the DSO's perspective. In Ref. [4], the financial risk of the DSO has been studied using a risk-based method for reliability investment. A combination of the financial risk problem with maintenance management in the presence of a RPS has been studied in Ref. [5]. Ref. [6] has investigated how changes in the quality regulation parameters affect the economic performance of the DSO's investment strategy. Although the RPS allows utilities to improve reliability socioeconomically, it cannot induce them to differentiate the reliability services based on the consumers' preferences [7]. To solve this problem,

Received: 15 Jul. 2019
Revised: 19 Nov. 2019
Accepted: 04 Jan. 2020

∗Corresponding author:
E-mail: r.kazemzadeh@sut.ac.ir (R. Kazemzadeh)

Digital object identifier: 10.22098/joape.2020.6279.1473
Research paper

authors in Ref. [8] have used customer damage function to provide reliability, based on each customer’s preferences. Also, Ref. [9] has introduced a novel reliability improvement scheme in which customers select their desired service level. The scheme was named as customer-oriented reliability planning (CORP), which means that the DSO invests in reliability enhancement of the system with respect to the customers’ viewpoints. The inflexibility of electrical grids is another challenge that limits the provision of electricity services, based on the different customers’ preferences. Smart grid technologies can increase the grid flexibility and enable the utilities to provide a more reliable, cost-effective and interactive power distribution systems. Hence, [10] has utilized smart grid facilities to design a new RPS, which uses the load-based reliability indices. Two main principles should be considered in each investment in the electrical network. First, investment costs should not exceed the consumers’ financial benefits. Second, the investment should be applied in a way that the service quality is differentiated based on the consumers’ preferences [11]. In the current regulatory, to improve electricity customers’ reliability, the average of the services is used as a criterion to incentivize or penalize the DSO [12]. Although these schemes can improve reliability, they do not consider the customer’s individual preferences and needs. To achieve the restructuring goals and encourage customers to participate in the power system, it is essential to provide a mechanism, in which the customers are able to select their desirable services. Insurance is an efficient mechanism to provide various options. A well-designed insurance mechanism would help to solve the customers’ concerns on the quality of services by providing reliability services in accordance with their preferences. Several aspects of insurance and its application in the power system have been studied so far. Ref. [13] has used an insurance mechanism to protect generation units against forced outage risks. In Ref. [14], the reserve market has considered an insurance mechanism, in which generation units collect the premium from the person who buys the insurance and provides a reliable power supply in return. Insurance protection for the bilateral contract has been proposed in Ref. [15], which is implemented by independent system operators. Insurance mechanisms can also be used to cover the risks of renewable resources. In Ref. [16], an insurance mechanism has been designed to cover wind generation trading risks in the real-time market. Some other studies have investigated reliability insurance for electricity sectors. Reliability insurance unbundles the concepts of energy and reliability and allows consumers to select their services based on their preferences. The concept of reliability insurance has been introduced in ref. [17]. In this reference, the DSO provides different electricity service levels for customers via different insurance contracts and uses the collected insurance premiums to improve customers' services or pays reimbursement. Another reliability insurance scheme has been introduced in Ref. [18], which allows consumers to determine their outage costs based on their preferences and pay corresponding premiums. The consumer’s outage cost has been modeled as a function of the outage duration using the customer damage function. In addition to selling commoditized kilowatt-hours (kWh), Ref. [19] has suggested the electricity firms to sell reliability insurance. This insurance can reduce both the price and volume risks of firms by receiving a stable revenue. Also, Ref. [8] has proposed that the distributed generation (DG) provides a reliability insurance mechanism. Ref. [20] has introduced a reliability insurance scheme overlay on energy electricity markets, in which economic protection has been provided to the consumers against electricity outages. From the proposed insurance scheme, the collected premiums have been used to invest in the electricity generation or pay the reimbursement. Although various insurance schemes have been investigated, few of the aforementioned studies have considered individual behavioral characteristics of the customers. To consider the individual behavior of electricity customers, this paper proposes a novel reliability insurance scheme. The proposed reliability insurance scheme enables the consumers to determine their desired reliability levels according to their outage value, and pay corresponding premiums to the DSO. The DSO is responsible for providing reliability levels or reimburses consumers. The outage value is extremely dependent on the customers’ type and preferences. To design efficient insurance contracts, this paper uses utility function to estimate customers’ viewpoints against electricity energy consumption. The function can model different customers’ viewpoints by considering different risk aversion coefficients, in which outage value increases as the coefficient increases. In the proposed utility based reliability insurance scheme (URIS), the reliability insurance premium and reimbursement are determined based on the customers’ welfare reduction due to the outage. Through the URIS, the DSO can manage the outage by applying different outage levels to the different customers, based on their preferences.

Table 1. Compression between the proposed URIS with previous reliability improvement schemes

	CORP based reliability improvement [9]	Concept of reliability insurance [17]	CDF based reliability insurance [18]	Utility based reliability insurance (URIS)
Service level options	Yes	Yes	Yes	Yes
Customer behavior model	Risk taker & risk averse	Risk neutral	Risk neutral	Risk neutral & risk averse
Elasticity of demand	Inelastic	Inelastic	Inelastic	Elastic
DSO behavior model	Risk neutral	Risk neutral	Risk neutral	Risk neutral & risk averse
Consumption value	Value of lost load (VOLL)	Constant parameter	Customer damage function	Utility function
Reimbursement	Not considered	Consumption value	Customer damage function	Welfare value
Premium	Average reliability improvement cost	Average reimbursement	Average reimbursement	Based on the welfare function
Free-riding opportunity	Not considered	Not considered	Considered for customers	Considered for customers and DSO
Transmission reliability	Perfect	Perfect	Perfect	With failure
Regulatory Reward/Penalty	No	Yes	No	Yes

Although the URIS has the ability to overcome the financial risk problem, it may create a free-riding opportunity for the DSO, in which due to the collection of the investment cost, low quality service is provided. To prevent the free-riding opportunity, this paper incorporates the proposed URIS and RPS. The main contributions of this paper are summarized as follows:

- Utility function is employed to measure the electricity customers' preferences.
- New load model is designed based on the customers' risk aversion behavior.
- The customers' risk aversion coefficients are estimated via price-elasticity of electricity demand.
- Customer welfare is modeled as a function of the electricity energy consumption, electricity price and customers risk aversion coefficients.
- Behaviors of the customers and DSO are investigated against the reliability insurance contract.
- A utility based reliability insurance scheme (URIS) is designed as a new reliability regulation scheme.
- Free-riding opportunity of the insurance contract is considered from the customers and DSO point of views.
- The URIS is accompanied by a RPS to ensure the reliability level.

Table 1 compares the proposed URIS introduced in this paper with reliability improvement scheme, which were used in references [9], [17] and [18]. Although all the schemes are designed to provide customers with service level selection options, customers' behavior and consumption values are interpreted differently.

The rest of this paper is organized as follows: Section 2 discusses the utility theory. In this section, the electricity customers' preferences are modeled via different utility functions. Section 3 provides a description of the proposed reliability regulation scheme. Numerical results are addressed in Section 4. Finally, the paper is concluded in Section 5.

2. UTILITY FUNCTION

To determine electricity energy consumption value, this paper utilizes utility function, which measures the customers' satisfaction as a function of their consumptions [21]. Utility function is adopted in some studies to model electricity customers' preferences. For example, Ref. [22] has employed utility function to establish behavioral real-time pricing method. Also in Ref. [23], the utility function has been employed to model electricity customers' preferences, which was used to study the electricty customers' consumption patterns. In Ref. [24], the utility and cost functions have been used to model the behaviors of customers and utility company, respectively. Ref. [25] has defined society welfare, due to electricity consumption, in terms of customers' utility functions and electricty costs. Also, considering exponential, quadratic, and linear utility function, Ref. [26] has designed a anovel incentive-based demand response program in which, the incentive payment has been determined based on the customers' utility function.

In this paper, utility function (*U*) is modeled as a function of power consumption (*D*) and risk aversion coefficient (α) to identify electricity customers' preference. The coefficient varies for different customers and represents different risk aversion behaviors. The main properties of the utility function are described in the following [27]:

Property 1: Marginal utility is positive, that is utility increases with consumption, i.e., more consumption is preferred to less consumption, which can be written as:

$$\frac{\partial U(D,\alpha)}{\partial D} \geq 0 \tag{1}$$

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

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

Property 3: Utility function is non-decreasing regarding risk aversion coefficient. This property means as the α is larger, the larger utility would be, which can be expressed as:

$$\frac{\partial U(D,\alpha)}{\partial \alpha} > 0 \tag{3}$$

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

$$U(0,\alpha) = 0 \tag{4}$$

Based on the above properties, utility function is an ascending and concave function, which saturates gradually by increasing consumption, as shown in Fig. 1.

The electricity customer welfare (*W*) can be determined by subtracting the electricity cost from the customer utility function, as in Eq. (5) [26]. Utility function measures satisfaction level and it is expressed in a unit, called *Utils*. This paper uses calibration coefficient *A* to calibrate the utility respecting the electricity cost. π is the electricity energy price.

$$W(D,\pi,\alpha) = AU(D,\alpha) - \pi D \tag{5}$$

Customer consumes electricity energy to maximize his/her welfare at any time. Assume that customer consumes D_0 as the initial electricity demand with price π_0, the calibration coefficient can be determined as bellows:

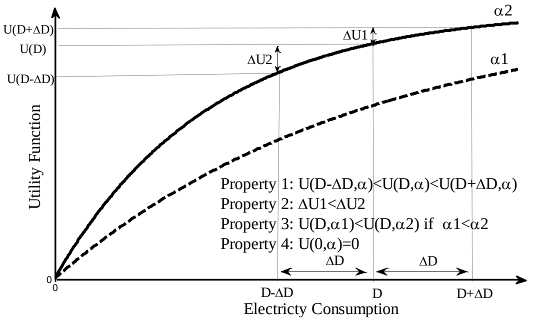


Fig. 1. Utility function due to electricity energy consumption

$$\frac{\partial W(D,\pi,\alpha)}{\partial D} = 0 \tag{6}$$

$$\left.\frac{\partial W(D,\pi,\alpha)}{\partial D}\right|_{D = D_0, \pi = \pi_0} = 0 \tag{7}$$

$$A = \left.\frac{\pi}{\frac{\partial U(D,\alpha)}{\partial D}}\right|_{D = D_0, \pi = \pi_0} \tag{8}$$

Different functions can satisfy the above properties and can be used as a utility function. Arrow–Pratt measure of absolute risk aversion (ARA) can estimate customers' behavior against risky situations regardless of the utility function, as defined in Ref. [28]:

$$ARA(D) = -\frac{\partial U(D,\alpha)/\partial D}{\partial^2 U(D,\alpha)/\partial D^2} \tag{9}$$

In this paper, linear, quadratic and exponential utility functions are studied to investigate electricity customers' behavior, as described in the following.

2.1. Linear utility function

Linear utility function is the simplest function applied to express the customers' preferences. This form of utility function assumes that the customers are risk neutral, which means that customers only tend to pay the exact risk cost to avoid it. Linear utility function and corresponding welfare function can be formulated as follows:

$$U(D,\alpha) = aD \tag{10}$$

$$W(D,\pi,\alpha) = A\alpha D - \pi D \tag{11}$$

Considering Eq. (8) and Eq. (10), calibration coefficient can be determined as in Eq. (14).

$$A = \pi_0 / \alpha \tag{12}$$

Substituting Eq.(12) in Eq.(11), welfare would be as:

$$W(D,\pi,\alpha) = D(\pi_0 - \pi) \tag{13}$$

Based on Eq. (13) for the linear utility function, welfare is independent of the risk aversion coefficient.

2.2. Quadratic utility function

Quadratic utility function is another popular form of utility function which describes customer's preferences as absolute risk aversion. In this model, customers are willing to pay higher cost than the risk cost to avoid it [29]. So, the utility function, welfare function and calibration coefficient can be formulated as in Eq. (14) to Eq. (16).

$$U(D,\alpha) = -(1-\alpha D)^2, \quad \alpha \le 1/D \tag{14}$$

$$W(D,\pi,\alpha) = -A(1-\alpha D)^2 - \pi D \tag{15}$$

$$A = \pi_0 / 2\alpha(1-\alpha D_0) \tag{16}$$

Considering Eq. (6) and Eq. (16), the electricity consumption can be formulated as follows:

$$2A(1-\alpha D) = \pi \tag{17}$$

$$2(1-\alpha a D)\pi_0 / 2\alpha(1-\alpha D_0) = \pi \tag{18}$$

$$D = 1/\alpha - \pi(1-\alpha D_0)/\alpha\pi_0 \tag{19}$$

Where, electricity consumption is related to the customer's risk aversion coefficient and decreases (increases) by increasing (decreasing) the electricity price. Indeed, electricity customer modifies his/her demand respecting the electricity price to maximize his/her welfare. Substituting Eq. (19) in Eq. (15), the customer welfare can be expressed only as a function of the electricity price, which is represented as follows:

$$W_\pi(\pi,\alpha) = \pi^2 / 4A\alpha^2 - \pi/\alpha \tag{20}$$

2.3. Exponential utility function

Exponential utility function is another form of the utility function, which is useful for explaining the risk preferences of the customers [30]. Similar the quadratic utility function, exponential utility function expresses the customer as absolute risk averse, which can be formulated as follows:

$$U(D,\alpha) = 1 - e^{-\alpha D} \tag{21}$$

For this utility function the welfare function, the calibration coefficient, and the electricity consumption can be formulated as follows:

$$W(D,\pi,\alpha) = A(1-e^{-\alpha D}) - \pi D \tag{22}$$

$$A = \pi_0 e^{\alpha D_0} / \alpha \tag{23}$$

$$D = D_0 - \ln(\pi/\pi_0)/\alpha \tag{24}$$

The welfare function can also be formulated as in Eq. (25).

$$W_\pi(\pi,\alpha) = A + (\pi/\alpha)\times[\ln(\pi/\alpha A) - 1] \tag{25}$$

2.4. Risk aversion coefficient estimation via the price-elasticitiy of electricity demand

Price-elasticity of electricity demand (E) is a normalized measure that estimates the customer's demand variation respecting the one percent change in electricity price, which can be formulated as [31]:

$$\mathrm{E} = \frac{\pi}{D}.\frac{\partial D}{\partial \pi}\bigg|_{D = D_0, \pi = \pi_0} \tag{23}$$

Based on Eq. (13) and due to the maximization of welfare, any price increment (decrement) will lead to zero (infinity) consumption when the customers behave based on the linear utility function. Hence, the price elasticity of electricity demand for linear utility function will be as:

$$\mathrm{E} = -\infty \tag{27}$$

Infinite elasticity is not reasonable for electricity energy consumption; so, this paper does not consider the linear utility function to model the electricity customers' behavior.

Considering Eq. (16) as the electricity demand model for quadratic utility function, the elasticity of electricity demand can be calculated as follows:

$$\partial D / \partial \pi = -(1-\alpha D_0)/\alpha\pi_0 \tag{28}$$

$$\mathrm{E} = -(1-\alpha D_0)/\alpha D_0 \tag{29}$$

In a similar way, the price-elasticity of electricity demand for exponential utility function can be represented as Eq. (30).

$$\mathrm{E} = -1/\alpha D_0 \tag{30}$$

Regardless of the utility function, the price elasticity of electricity demand can be formulated based on the ARA, which is formulated as in Eq. (31).

$$\mathrm{E} = -1/D_0 ARA(D_0) \tag{31}$$

From Eq. (31), the price-elasticity is related to the risk aversion behavior and customer demand. Customers have a lower tendency to reduce their demand by increasing the risk aversion behavior. Social studies are needed to identify the customers' risk aversion coefficients. Also, the coefficients can be estimated using the price-elasticity of the electricity demand data. Equations (32) and (33) represent the risk aversion coefficient for the quadratic and exponential utility functions, based on the elasticity.

$$\alpha = -1/D_0(\mathrm{E}-1) \tag{32}$$

$$\alpha = -1/D_0\mathrm{E} \tag{33}$$

3. UTILITY BASED RELIABILITY INSURANCE SCHEME (URIS)

Two questions are important to the success of any reliability regulation scheme. First, what is the optimal reliability level? Second, what is the fair price for the customers to pay for it? If the reliability is poor, customers suffer from a high interruption level, which reduces customers' welfare. On the other hand, providing a very high reliability level needs high investment and maintenance costs. Customers have to pay the costs through their tariffs, which also decreases the customers' welfare. This paper suggests that the regulator transfers the reliability level selection burden to the customers through URIS. Based on their preferences, customers pay premium to receive reliable electricity services. The DSO can use the premiums for reliability investment or pay the reimbursement.

Due to the inflexibility of grids, most of utilities cannot differentiate the reliability services at the customer level. URIS can also solve this problem by enabling the customers to specify their desired services value exclusively and receive reimbursement when the DSO cannot provide the services.

This paper uses a welfare function to identify electricity energy consumption value from the different customers' viewpoints. As shown in Fig. 2, different consumptions imply different welfares. When outage occurs, customers request the reimbursement (*R*) equal to their welfare reduction, which is formulated as in Eq. (34).

$$\mathrm{R}(\Delta D) = W(D,\pi,\alpha) - W(D-\Delta D,\pi,\alpha) \tag{34}$$

Where, *ΔD* is the demand reduction due to low reliability.

Each URIS contains two main parameters, i.e. the customer's risk aversion coefficient and the outage level. The DSO designs different insurance contracts, based on the different risk aversion coefficients. Customers compare their risk aversion behaviors with the contract's risk aversion coefficients and select the most proper one. In the URIS, the expected outage level is used to determine the contract premiums, while reimbursement is paid by considering the customer's outage level for each hour.

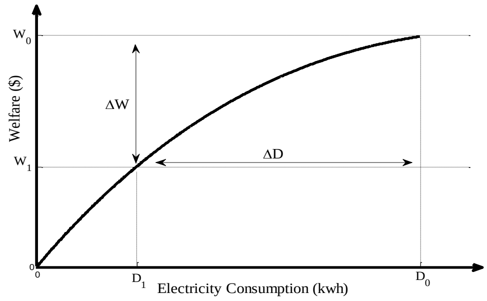


Fig. 2. Customer welfare as a function of electricity energy consumption.

3.1. Insurance Premium

This paper assumes that P^+ and P^- are the maximum tolerable premium and the minimum acceptable premium from the customer and insurer's points of view, respectively. The customer will not sign a contract that has a premium more than P^+, and the insurer will not provide a contract that has a premium less than P^-. The insurance contract is signed if the contract premium, P^c, will be as:

$$P^- \le P^c \le P^+ \tag{35}$$

Outage reduces the customer welfare; thus, customers are willing to pay premium to avoid it. On the other hand, the premium increases electricity cost, which reduces customer's welfare. Selecting reliability insurance requires trading off between welfare reduction, caused by outage, and welfare reduction, caused by paying premium. The customer will select reliability insurance, when the expected welfare reduction caused by the premium is equal or lower than the expected welfare reduction caused by the outage, which can be formulated as:

$$\sum_{t=1}^{T} W(D(t),\pi,\alpha) - W(D(t)-\Delta D(t),\pi,\alpha) \ge \sum_{t=1}^{T} W(D(t),\pi,\alpha) - W(D(t),\pi+\mathrm{P}^c,\alpha) \tag{36}$$

So, the maximum tolerable premium can be calculated as:

$$\sum_{t=1}^{T} W(D(t)-\Delta D(t),\pi,\alpha) = \sum_{t=1}^{T} W(D(t),\pi+\mathrm{P}^+,\alpha) \tag{37}$$

Preferences of the DSO, due to the provision of the insurance contracts, can be modeled via different utility functions. We assume that *α′* is the DSO's risk aversion coefficient. Considering that the DSO is risk neutral about the provision of different reliability insurance contracts, its utility function will be as:

$$U(w,\alpha') = \alpha' w + B \tag{38}$$

Where, w is the DSO’s wealth, which increases by receiving premium and decreases by paying reimbursement. Also, B is the constant term of the utility function. The DSO provides insurance contracts to maximize its utility, which can be formulated as follows:

$$\sum_{t=1}^{T} U(w) \le \sum_{t=1}^{T} U(w + P^{c} - \mathrm{R}(\Delta D(t))) \tag{39}$$

So, the minimum acceptable premium will be determined as follows:

$$\sum_{t=1}^{T} U(w) = \sum_{t=1}^{T} U(w + P^{-} - R(\Delta D(t))) \tag{40}$$

$$\sum_{t=1}^{T} \alpha'(w) + B = \sum_{t=1}^{T} \alpha'(w + P^{-} - R(\Delta D(t))) + B \tag{41}$$

$$P^{-} = E(R(\Delta D(t))) \tag{42}$$

Where the minimum acceptable premium is determined to equal to the mean value of the reimbursement. Also, the minimum acceptable premium is determined as Eq. (44) by assuming that the DSO is risk averse and behaves based on the exponential utility function.

$$\sum_{t=1}^{T} (1 - e^{-\alpha' w}) = \sum_{t=1}^{T} (1 - e^{-\alpha'(w + P^{-} - R(\Delta D(t)))}) \tag{43}$$

$$P^{-} = \frac{1}{\alpha'} \ln[E(e^{\alpha' R(\Delta D(t))})] \tag{44}$$

In this case, the minimum acceptable premium is a function of the DSO’s risk aversion coefficient and the reimbursement. Finally, for the quadratic utility function, the minimum acceptable premium will be as in Eq. (45), in which the minimum acceptable premium also depends on the DSO’s wealth [32].

$$\sum_{t=1}^{T} -(1 - \alpha' w)^{2} = \sum_{t=1}^{T} -(1 - \alpha'[w + P^{-} - R(\Delta D(t))])^{2} \tag{45}$$

$$P^{-} = E(R(\Delta D(t))) + (\alpha' - w)\left\{1 - \sqrt{1 - \frac{Var(R(\Delta D(t)))}{(\alpha' - w)^{2}}}\right\} \tag{46}$$

3. 2. Reward and penalty scheme

Although the proposed reliability insurance has the ability to collect reliability improvement investments from the customers, it may create a free-riding opportunity for the DSO, in which low quality service is provided to collect the investment. To prevent free-riding opportunity, this paper utilizes both URIS and RPS. The RPS encourages the DSO to improve its reliability. The regulator specifies a performance target for reliability. If the DSO can provide reliability better than the target, it will be rewarded. Otherwise, it will be penalized. This paper utilizes a typical reward/penalty scheme based on the system average interruption duration index (SAIDI) [33]. In this scheme, there is a linear relationship between the reliability and reward/penalty, as illustrated in Fig. 3. In this paper, regulator rewards and penalizes the DSO based on the customers’ welfare reduction due to outage. Equations (46) and (47) illustrate the regulatory reward and penalty payments, in which μ is the reward/penalty rate and would be equal to all of the customers’ welfare reduction due to an hour outage. Also, β and γ are the reward and penalty coefficients, which are determined based on the regulatory policy.

$$\mathrm{Re}\,ward = \beta\mu(SAIDI_{Target} - SAIDI), \quad if\ SAIDI \le SAIDI_{Target} \tag{46}$$

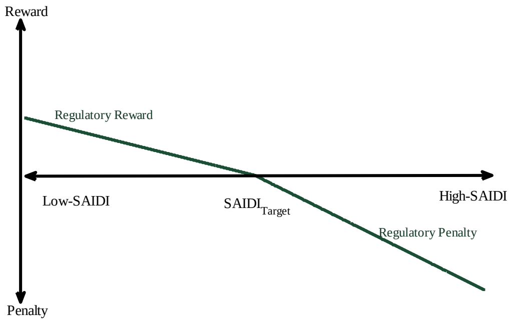


Fig 3. Linear reward/penalty scheme

$$Penalty = \gamma\mu(SAIDI - SAIDI_{Target}), \quad if\ SAIDI > SAIDI_{Target} \tag{47}$$

$$\mu = \sum_{i=1}^{N} W(D(i), \pi, \alpha(i)) - \sum_{i=1}^{N} W(0, \pi, \alpha(i)) \tag{48}$$

Where, i and N are the customer type index and number of system customers. The DSO would try to keep the reliability level at a point where its profit is maximized, which is formulated ad the follows:

$$\max: \mathrm{Pr}\,ofit = \mathrm{Re}\,venue - Cost \tag{49}$$

The DSO’s revenue comes from the premiums and the regulatory rewards. The DSO’s cost includes the reimbursements, reliability improvement costs and regulatory penalties. This paper considers only DG and switch costs (DG_{Cost} and $Switch_{Cost}$), as the reliability improvement costs. The DG generation is used to energize customers, when the reliability is jeopardized. Marginal cost of DG is usually higher than the cost of buying from the electricity market; so, installing and operating DG and other equipment to improve the reliability bring extra cost to the DSO. The DSO’s revenue and costs can be formulated as follows:

$$\mathrm{Re}\,venue = \sum_{i=1}^{N} \mathrm{P}^{c}(i) + \mathrm{Re}\,ward \tag{50}$$

$$Cost = DG_{cost}(P_{DG}) + Switch_{Cost} + \sum_{i=1}^{N} \mathrm{Re}(\Delta D(i)) + Penalty \tag{51}$$

$$P_{DG} = \sum_{i=1}^{N} \Delta D_0(i) - \sum_{i=1}^{N} \Delta D(i) \tag{52}$$

$$DG_{cost}(P_{DG}) = aP_{DG}^2 + bP_{DG} + c \tag{53}$$

Where, P_{DG} is the DG generation level and a, b, and c are the fuel cost coefficients of the DG. Also, ΔD_0 and ΔD are the customer outage level before and after reliability improvement. The relation between the costs and revenues, as a function of reliability, is illustrated in Fig. 4. The premiums are determined before the reliability regulation; so, they will be constant for all of the provided reliability levels. The reimbursements are paid after the reliability regulation and depending on the customers' outage levels. Also, the reliability improvement cost increases as the reliability level increases. The regulator plays a major role in the reliability level by selecting the regulatory parameters, such as the reliability target, reward and penalty coefficients.

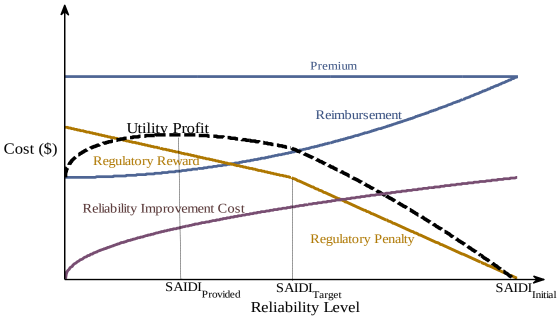


Fig. 4. Cost curves as a function of reliability.

Through the proposed URIS, the DSO can manage the outage between the customers to reduce the reimbursement. The reimbursement is paid based on the customers' welfare reduction, in which customer with the low risk aversion coefficient receives less reimbursement. Hence, the DSO can apply more outage to the customer who wants less reimbursement. To minimize the reimbursement at each hour, Lagrangian optimization function is employed in this section, which determines outage levels for each type of customer as follows:

$$\min \quad F = \sum_{i=1}^{N} \mathrm{R}(\Delta D(i)) \tag{54}$$

Subject to:

$$\sum_{i=1}^{N} \Delta D(i) = P_{outage} \tag{55}$$

$$L = F - \lambda\left(\sum_{i=1}^{N} \Delta D(i) - P_{outage}\right) \tag{56}$$

$$\frac{\partial L}{\partial \Delta D(i)} = 0, \quad \forall i \tag{57}$$

$$0 - \frac{\partial W(D(i) - \Delta D(i), \pi, \alpha(i))}{\partial \Delta D(i)} - \lambda = 0, \forall i \tag{58}$$

$$0 \le \Delta D(i) \le D(i) \tag{59}$$

Where, F, L, λ and P_{outage} are total reimbursement, Lagrangian function operator, Lagrangian function multiplier, and outage level.

For quadratic utility function, customer outage level can be formulated as follows by substituting Eq. (15) in Eq. (58).

$$\frac{1 - \alpha(i)D(i) + \alpha(i)\Delta D(i)}{1 - \alpha(i)D(i)}\pi - \pi = \lambda, \quad \forall i \tag{60}$$

$$\frac{\alpha(i)\Delta D(i)}{1 - \alpha(i)D(i)} = \frac{\alpha(j)\Delta D(j)}{1 - \alpha(j)D(j)} \tag{61}$$

$$\Delta D(i) = \Delta D(j)\frac{\alpha(j)}{\alpha(i)}\frac{1 - \alpha(i)D(i)}{1 - \alpha(j)D(j)} \tag{62}$$

By substituting Eq. (62) in Eq. (55), outage level of each customer can be calculated as in Eq. (63).

$$\Delta D(i) = \frac{P_{outage}}{\dfrac{\alpha(i)}{1 - \alpha(i)D(i)} \displaystyle\sum_{j=1}^{N} \dfrac{1 - \alpha(j)D(j)}{\alpha(j)}} \tag{63}$$

Also, for exponential utility function, outage level for each customer would be as follows:

$$\pi(e^{\alpha(i)\Delta D(i)} - 1) = \lambda, \quad \forall i \tag{64}$$

$$\alpha(i)\Delta D(i) = \alpha(j)\Delta D(j) \tag{65}$$

$$\Delta D(i) = \frac{1/\alpha(i)}{\displaystyle\sum_{j=1}^{N} 1/\alpha(j)} P_{outage} \tag{66}$$

Based on the above equations, customer with low risk aversion coefficient faces more outage than the one with high risk aversion coefficient. It should be mentioned that the customers receive reimbursements based on their welfare reduction; so, the outage level does not affect customers' satisfaction.

According to the abovementioned, the DSO determines the price tables of different insurance contracts. Then, each customer compares the contracts with his/her preferences and chooses the optimal one. To this end, this paper assumes that the customers behave rationally and select the contracts to maximize their welfare functions. The procedure of the proposed reliability regulation scheme is listed in the following:

For the DSO:

- Determining outage level for different load points.
- Determining reimbursement for different risk aversion coefficients in each load point, based on the determined outage data.
- Determining the minimum acceptable premium, based on the reimbursements.
- Designing different insurance contracts and specifying the corresponding contract premiums.

For the customer:

- Anticipating his/her outage level.
- Determining the maximum tolerable premium to maximize his/her welfare.
- Selecting the most suitable insurance contracts through comparison of the contract premiums with the maximum tolerable premium.

For the regulator:

- Specifying target level for the system reliability.
- Determining the reward/penalty rate considering the customers' viewpoints.
- Selecting the reward and penalty coefficients based on its policy.

4. AN ILLUSTRATIVE EXAMPLE FOR THE PROPOSED RELIABILITY REGULATION SCHEME

Specifying risk aversion coefficients plays an important role in the success of the proposed URIS. Social studies are needed to identify the customers' risk aversion coefficients. Also from Eq. (32) and Eq. (33), the risk aversion coefficients can be estimated using the elasticity of the electricity demand. According to the description presented in Ref. [34], it is assumed that the average elasticity for industrial (Ind), commercial (Com) and residential (Res) customers are -0.33, -0.5, and -0.75, respectively. Although the electricity energy usage value is nearly close to the expected profit of consumption for industrial and commercial customers, it is an essential service for residential customers. From residential customers' viewpoints, electricity consumption has additional benefits, such as improved comfort, productivity, health, convenience and aesthetics [35]. Therefore, the residential customers have the lowest price elasticity of electricity energy demand. Based on the elasticity data, Table 1 represents the risk aversion coefficients for quadratic and exponential utility functions for different customers. In the rest of this section, the only exponential utility function is considered to study the proposed URIS efficiency.

Table 2. Risk aversion coefficients for different customer types

Utility Function	Res	Com	Ind
Exponential Utility	3	2	1.3
Quadratic utility	0.75	0.66	0.43

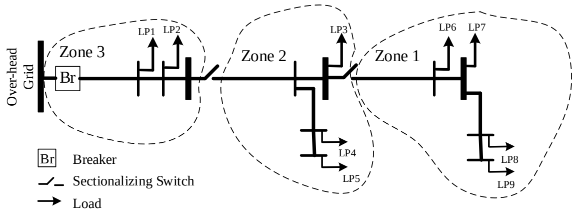


Fig. 5. Sample distribution network which is divided into 3 zones

The proposed reliability insurance scheme has been tested on a sample test network shown in Fig. 5. Table 3 illustrates the size of loads and types of customers for different load points located in zones 1, 2 and 3. This paper assumes that each customer consumes 1 kW so, the number of loads is 950. The length, failure rate, repair and fault location times for different zones are represented in Table 4. Also, it is assumed that the overhead grid has the failure rate and average repair time of 5 fail/year and 1.5 hours, respectively. Hence, the system's SAIDI is determined at 34.8 hr/yr.customer. This paper assumes that outage duration follows Poisson distribution function with an expected outage duration of 1.5 hours, as shown in Fig. 6. Also, Table 5 illustrates the probabilities of different outage durations, where the distribution function is divided into six discrete levels. The average of each time intervals is used to determine the probabilities.

To assess the effects of the proposed reliability regulation schemes, four strategies are considered as follows:

Strategy 1: Only reward/penalty scheme (RPS) is considered to improve the system reliability, in which the $SAIDI_{Target}$ is considered 22 hr/yr.customer. Also, coefficients β and γ are selected equal to 1.

Strategy 2: To compare the efficiency of schemes, the RIS, from [17], is applied to increase the system reliability, in which the DSO will not be penalized or rewarded due to the provision of different reliability levels.

Strategy 3: The proposed URIS is applied to increase the system reliability, in which the DSO will not be penalized or rewarded due to the provision of different reliability levels.

Strategy 4: To ensure reliability, the RPS with $\mathrm{SAIDI}_{\mathrm{Target}}$ of 22 hr/yr.customer is added to the URIS.

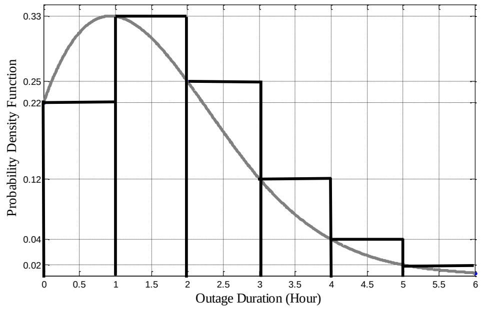


Fig. 6. The probability density function of the outage duration

This paper assumes that electricity energy is sold through the fixed pricing regime, in which the price is equal to 10 $/kW. Also, it is assumed that the reliability insurance is considered to be one year. This paper considers only linear utility function to model the behavior of the DSO against the provision of different reliability insurance contracts. Therefore, the minimum acceptable premium will be equal to the maximum tolerable premium. Also, it is assumed that the customers in the same residential, commercial or industrial class, have the same utility function and select the same insurance contract. Table 6 illustrates the reimbursements for different reliability insurance schemes. The reimbursements are determined based on the customers' welfare reduction due to the outage. Also, Table 7 shows the contract premium and outage duration for different zones. According to the tables, in URIS, customers request fewer reimbursements, and this reduces the contract premiums.

The DSO's ability in differentiating the reliability services depends on the flexibility of the grid, which increases by installing more control and communication equipment. In this paper, installation of different equipment in the grid is considered through four following scenarios:

Scenario 1: There is no DG in the network.

Scenario 2: One DG is installed in zone 1.

Scenario 3: In addition to the installation of a DG in zone 1, a breaker is installed in zone 2.

Scenario 4: In addition to the installation of a DG in zone 1, the network operates through smart grid infrastructure, in which the operator can apply different outages to the customers.

Table 3. Size of loads and type of customers for different load points

Load Point	LP1	LP2	LP3	LP4	LP5	LP6	LP7	LP8	LP9
Load Type	Res	Res	Res	Com	Com	Ind	Res	Com	Com
Size of Load (kW)	100	50	150	100	100	100	150	100	100

Table 4. The length, failure rate and fault duration for different feeders

Zone Number	Length of Feeders (km)	Failure Rate (Fail/year km)	Average Fault Location Time(Hour)	Average Repair Time (Hour)
Zone 1	4	3	1	0.5
Zone 2	2	3	0.5	1
Zone 3	1.5	5	0.5	1

Table 5. Probability of outage durations

Outage Duration (Hour)	Outage <1	1< Outage <2	2< Outage <3	3< Outage <4	4< Outage <5	5< Outage
Average Outage Duration (Hour)	0.5	1.5	2.5	3.5	4.5	5.5
Probability	0.23	0.33	0.25	0.12	0.04	0.02

Table 6. Reimbursement ($/Hour) for different outage durations

Outage Duration	URIS			RIS		
	Res	Com	Ind	Com	Res	Ind
Outage < 1 Hour	6.6	3.6	2	25	10	5
Outage > 1 Hour	50	20	10	50	20	10

Table 7. Contract premium ($/Hour) and outage duration for different zones

Load Point	Average of Outage Duration (Hour)	RIS			URIS		
		Res	Com	Ind	Res	Com	Ind
Zone 1	45.75	0.261	0.104	0.052	0.209	0.088	0.043
Zone 2	27.75	0.158	0.063	-	0.127	0.053	
Zone 3	18.75	0.107	-	-	0.086	-	-

Table 8. Reimbursement levels for scenario 1

Strategy 1: RPS

Fault Location	Total Outage (Hour)	Outage >=1 Hour (Probability=0.77) Reimbursement ($/Hour)	Outage <1 Hour (Probability=0.23) Reimbursement ($/Hour)
Zone 1	18	0	0
Zone 2	9	0	0
Zone 3	11.25	0	0
Overhead Grid	7.5	0	0

Strategy 2: RIS

Fault Location	Total Outage (Hour)	Outage >=1 Hour (Probability=0.77) Reimbursement ($/Hour)	Outage <1 Hour (Probability=0.23) Reimbursement ($/Hour)
Zone 1	18	12500	12500

Zone 2	9	24000	24000
Zone 3	11.25	31500	31500
Overhead Grid	7.5	31500	31500

Strategy 3: URIS

Fault Location	Total Outage (Hour)	Outage >=1 Hour (Probability=0.77) Reimbursement ($/Hour)	Outage <1 Hour (Probability=0.23) Reimbursement ($/Hour)
Zone 1	18	12500	1910
Zone 2	9	24000	3620
Zone 3	11.25	31500	4610
Overhead Grid	7.5	31500	4610

Strategy 4: URIS & RPS

Fault Location	Total Outage (Hour)	Outage >=1 Hour (Probability=0.77) Reimbursement ($/Hour)	Outage <1 Hour (Probability=0.23) Reimbursement ($/Hour)
Zone 1	18	12500	1910
Zone 2	9	24000	3620
Zone 3	11.25	31500	4610
Overhead Grid	7.5	31500	4610

Table 9. Summary of different reliability improvement strategies for scenario 1

Strategy	$SAIDI_{Provided}$(hr/yr.customer)	Total Premium($/yr)	Total Reimbursement($/yr)	Reward/Penalty($/yr)	Total Profit($/yr)
RPS	34.8	1031625	1031625	-403200	-403200
RIS	34.8	1031625	1031625	0	0
URIS	34.8	836562	836562	0	0
RPS & URIS	34.8	836562	836562	-403200	-403200

Table 10. DG generation data

a ($/kW^2)	b ($/kW)	c ($)	P_{max} (kW)
0.02	10	22	1000

Table 11. Optimal operation of the system for scenario 2

Strategy 1: RPS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	0	0	0
Zone 2	150	200	100	8100	0	0	0
Zone 3	150	200	100	8100	0	0	0
Overhead Grid	150	200	100	8100	0	0	0

Strategy 2: RIS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	12500
Zone 2	150	200	100	8100	11500	450	11500
Zone 3	150	200	100	8100	19000	450	19000
Overhead Grid	150	200	100	8100	19000	450	19000

Strategy 3: URIS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/hour)	Reimburse ($)	DG Generation (kW/Hour)	Reimburse ($/hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	1910
Zone 2	150	200	100	8100	11500	0	3620
Zone 3	150	200	100	8100	19000	0	4610
Overhead Grid	150	200	100	8100	19000	0	4610

Strategy 4: URIS & RPS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	1910
Zone 2	150	200	100	8100	11500	0	3620
Zone 3	300	400	100	25600	7500	0	4610
Overhead Grid	300	400	100	25600	7500	0	4610

Table 12. Summary of different reliability improvement strategies for scenario 2

Strategy	$SAIDI_{Provided}$ (hr/yr.customer)	Total Premium ($/yr)	Total Reimbursement ($/yr)	DG Cost ($/yr)	Reward/Penalty ($/yr)	Total Profit ($/yr)
RPS	21.7	0	0	224775	+9450	-215325
RIS	21.7	1031625	684750	224775	0	122100
URIS	21.7	836562	562538	173070	0	100954
RPS & URIS	14.9	836562	396485	425732	+226800	241145

4.1. Scenario 1

In this scenario, the DSO does not have any ability to manage the outage; so it has to pay the reimbursement to the customers, based on the insurance contract. Table 8 represents the reliability insurance reimbursements when fault is located in different locations.

Table 9 illustrates the summary of different reliability improvement strategies for scenario1. Due to the lake of control equipment, such as DG generation or switch, SAIDI level will be equal to 34.6 hr/yr.customer for all of the strategies. For strategies 2 and 3, total reimbursement is equal to the total collected premiums; so, the DSO's profit will be zero. From the selected system, μ is determined equal to 31500 \$/hour; so, for the strategies 1 and 4, the DSO is penalized 403200 \$/yr. The penalty motivates the DSO to increase system reliability by installation of different equipment. This paper suggests that the DSO uses DG generation to manage the outage and increases its profit. For the selected system, zone 1 is the best location to install the DG generation unit, which has the highest electricity usage value and outage duration. Thus, in scenario 2, a DG will be installed in zone 1.

4.2. Scenario 2

In this scenario, a DG generation unit is installed in zone 1, as shown in Fig. 7. The DG generation data are illustrated in Table 10. Tables 11 and 12 represent the summary of different reliability improvement strategies for scenario 2. For strategies 1, 2 and 3, the DG unit generates 450 kW/hour to meet only the load of zone 1; so, SIADI is reduced to 21.7 hr/yr.customer. Selling the DG generation to the customers compensates some part (4500 \$/hour) of the DG generation costs (12600 \$/hour) and the DSO has to pay the rest (8100 \$/hour). For strategy 1, due to reliability improvement, the DSO will be rewarded 9450 \$/yr. For strategies 2 and 3, the DSO will benefit from the provision of reliability insurance. According to Table 6, for URIS, when outage duration is less than 1 hour, paying the reimbursement is more cost-effective than using the DG generation.

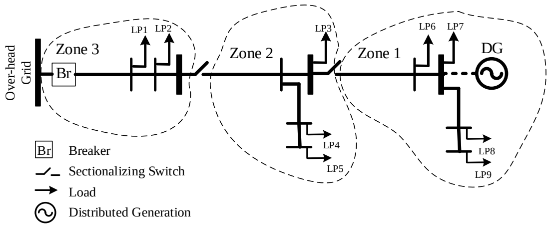


Fig. 7. The distribution network with a DG in zone 1

Strategy 4 is studied closely in the following. When fault occurs in zone 1, the DG units cannot be used; so, the profit of DSO will be zero. When fault occurs in zone 2, zone 1 is isolated and the DG generation feeds the load of this zone. Due to the inflexibility of grids, the DSO cannot provide a suitable service to each customer based on his/her preferences. For example, when fault occurs in zone 2, although the cost of the DG generation (28 \$/kW) is higher than the electricity consumption value from the commercial and industrial customers' viewpoints (20 and 10 \$/kW), these types of customers are energized by the DG generation. Also, when fault occurs in zone 3, zone 1 and zone 2 are isolated and supplied by the DG. For the overhead grid faults, using the DG generation to feed all of the loads is not cost-effective. Hence, only zones 1 and 2 are supplied by the DG. In order to increase the profit, in the next scenario, a switch is installed in zone 2, which enables the DSO to limit the DG generation only to the customers who have the high outage values.

Table 13. Optimal operation of the system for scenario 3

Strategy 1: RPS							
Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	0	0	0
Zone 2	150	200	100	8100	0	0	0
Zone 3	150	200	100	8100	0	0	0
Overhead Grid	150	200	100	8100	0	0	0
Strategy 2: RIS							
Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	12500
Zone 2	150	200	100	8100	11500	450	11500
Zone 3	300	200	100	14400	11500	800	11500
Overhead Grid	300	200	100	14400	11500	800	11500
Strategy 3: URIS							

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	1910
Zone 2	150	200	100	8100	11500	0	3620
Zone 3	300	200	100	14400	11500	0	4610
Overhead Grid	300	200	100	14400	11500	0	4610

Strategy 4: URIS & RPS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	1910
Zone 2	150	200	100	8100	11500	0	3620
Zone 3	300	400	100	25600	7500	0	4610
Overhead Grid	450	200	100	22500	4000	0	4610

Table 14. Summary of different reliability improvement strategies for scenario 3

Strategy	$SAIDI_{Provided}$ (hr/yr.customer)	Total Premium ($/yr)	Total Reimbursement ($/yr)	DG Cost ($/yr)	Reward/Penalty ($/yr)	Total Profit ($/yr)
RPS	21.7	0	0	224775	+9450	-215325
RIS	18.7	1031625	544125	342900	0	144600
URIS	18.7	836562	454257	264032	0	118273
RPS & URIS	14.9	836562	376295	407830	+223650	276087

Table 13. Optimal operation of the system for scenario 4

Strategy 1: RPS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	0	0	0
Zone 2	150	200	100	8100	0	0	0
Zone 3	150	200	100	8100	0	0	0
Overhead Grid	150	200	100	8100	0	0	0

Strategy 2: RIS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	12500
Zone 2	150	200	0	2500	12500	350	12500
Zone 3	300	0	0	3600	16500	300	16500
Overhead Grid	450	0	0	8100	9000	450	9000

Strategy 3: URIS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	1910
Zone 2	150	200	0	2500	12500	0	3620
Zone 3	300	0	0	3600	16500	0	4610
Overhead Grid	450	0	0	8100	9000	0	4610

Strategy 4: URIS & RPS

Fault Location	Outage >=1 Hour (Probability=0.77)					Outage <1 Hour (Probability=0.23)	
	DG Generation (kW/Hour)			DG Cost for DSO ($/Hour)	Reimburse ($/Hour)	DG Generation (kW/Hour)	Reimburse ($/Hour)
	Res	Com	Ind				
Zone 1	0	0	0	0	12500	0	1910
Zone 2	150	200	100	8100	11500	0	3620
Zone 3	300	364	0	17636	9220	0	4610
Overhead Grid	450	214	100	17636	4720	0	4610

Table 14: Summary of different reliability improvement strategies for scenario 4

Strategy	$SAIDI_{Provided}$ (hr/yr.customer)	Total Premium ($/yr)	Total Reimbursement ($/yr)	DG Cost ($/yr)	Reward/Penalty ($/yr)	Total Profit ($/yr)
RPS	21.7	0	0	224775	+9450	-215325
RIS	25.3	1031625	590625	123750	0	317250
URIS	25.3	836562	504041	95286	0	237235
RPS & URIS	17.2	836562	395350	310752	+151200	281660

4.3. Scenario 3

In this scenario, to increase the grid flexibility, a breaker is installed in zone 2, as shown in Figure 7. This switch increases the DSO’s ability in differentiating the reliability services to the different customers. Table 13 and 14 represent the summary of different reliability improvement strategies for scenario

3. In this scenario, when fault occurs in zone 3 and over-head grid, the customers in load points LP4 and LP5 are disconnected, and this leads to the use of DG generation to meet the high priority customers' demand and increases the DSO's profit.

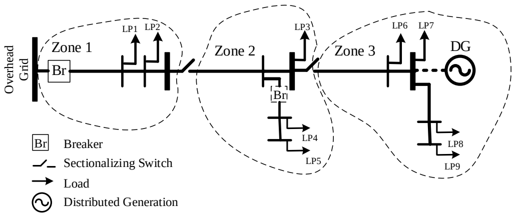


Fig. 8. The distribution network with a DG in zone 1 and a breaker in zone 2

4.4. Scenario 4

Increasing grid flexibility is the main advantage of using smart grid. Through smart grid, the DSO can provide different services based on the customers' individual preferences. In this scenario, we assume that the grid operates via smart grid infrastructure with perfect control and communication equipment, in which the DSO can apply different services at the end-use customer level.

Table 15 and 16 represent the summary of different reliability improvement strategies for scenario 4. Comparing this scenario's results with the previous ones shows that although less demand is met by the DG generation, the DSO's profit is increased. The increase of profit comes from the DSO's ability in provision of different reliability levels to the customers. For strategy 1, the DSO can maximize its profit by using 450 kW from the DG generation. For strategies 2, 3 and 4, consumption value plays a major role in applying the outage to the customers. The DSO will divide the DG generation between customers, based on their outage values. For example, in strategy 2, when fault occurs in zone 2, only residential and commercial customers are supplied by the DG generation. It should be mentioned that the customers receive reimbursement, based on their welfare reduction; so, applying different outage levels does not affect customers' satisfaction.

Comparing the results shows that successful implementation of the reliability improvement schemes are related to the grid flexibility. As the flexibility increases, the DSO can further provide the reliability services, based on the customers' individual preferences.

The regulator plays an important role in provided reliability levels by selecting the regulatory parameters (β, γ, and $SAIDI_{Target}$). Fig. 9 illustrates the different regulatory parameters' effect on the provided SAIDI, when the grid is operated via the smart grid infrastructure. As shown in the figure, when β is equal to γ, the provided SAIDI is independent of the target of SAIDI. Also, there is no regulatory reward or penalty, when β and γ are equal to zero. So, the DSO provides reliability only based on the customers' preferences. In this condition, regardless of the selected SAIDI target, the provided SAIDI will be equal to 25.3 hr/yr.customer. As the γ or β are increased, the DSO tries to reduce the SAIDI to obtain regulatory incentives or prevent regulatory penalties. The DSO improves reliability until the reliability improvement cost is less than the DG generation cost. So, the lowest level of SAIDI is limited to 14.9 hr/yr.customer.

Fig. 10 illustrates profit of the DSO against different reliability regulatory parameters. From the figure, the profit is decreased or increased as the β or γ increases. When β is equal to γ, the profit has a linear relation with the $\text{SAIDI}_{\text{Target}}$. Based on the Fig. 10, when β is higher (lower) than γ, the DSO's profit is less (more) than the profit when β is equal to γ.

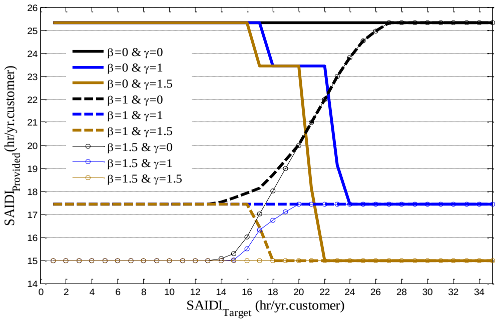
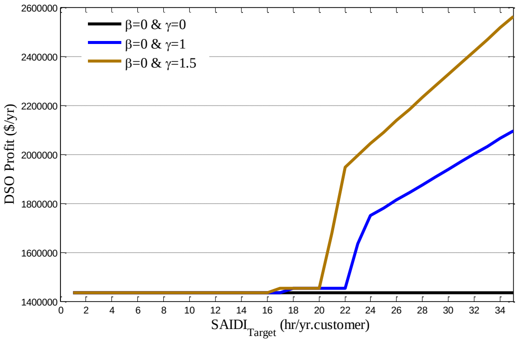
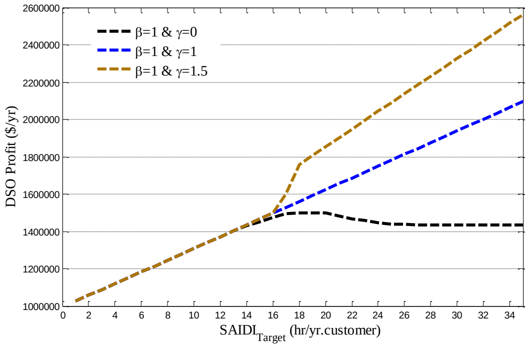


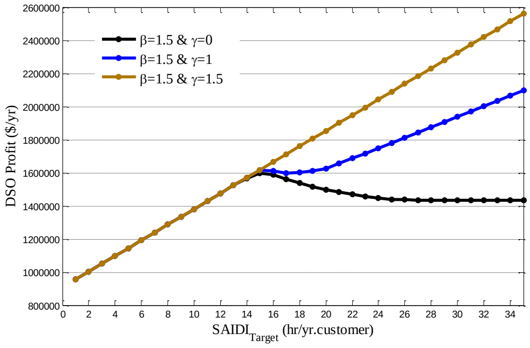
Fig. 9. Provided SAIDI based on target of SAIDI for various regulatory parameters.



a) β =0



b) β =1



c) β =1.5

Fig. 10. Profit of DSO versus different reliability regulatory parameters

5. CONCLUSION

This paper aims to design a novel reliability insurance scheme to increase distribution network reliability. The scheme can solve the reliability investment challenge to the DSO as well as provide the reliability level to the customers, according to their preferences. In this paper, linear, quadratic and exponential utility functions are employed to study different customers' preferences against the reliability insurance scheme and determine the corresponding premiums. This paper illustrates that electricity customers are risk averse against electricity energy consumption. So, the linear utility function is not suitable to consider the customers' behavior.

The results show that electricity energy value increases as the customers' risk aversion behavior increases. Therefore, customers with high risk aversion behavior are willing to pay the high premium to receive high service quality. In this paper, welfare reduction caused by outage is used as a criterion to reimburse the customers. To minimize reimbursements, outage is differentiated between customers based on their risk aversion behavior.

In this paper, reliability improvement is studied through different strategies. RPS is considered at the first strategy, in which the DSO suffers financial loss from the reliability improvement costs. In the second strategy, RIS is used to provide different services based on the different customers' viewpoint at strategies 2 and 3. Customer benefit reduction and customer welfare reduction, due to the outage, are used as the criteria to pay the reimbursement for strategies 2 and 3, respectively. The DSO may abuse RIS by providing services with low reliability and transferring the reliability investment burden to the customers. To prevent this problem, RPS and RIS are combined and used in strategy 4. From the results, the DSO's profit increases as the grid flexibility increases, in which the DSO can further differentiate the reliability services at the customer level.

Acknowledgements

The authors would like to thank the Azerbaijan Regional Electric Company for supporting financially this research.

REFERENCES

[1] E. Fumagalli, L. Schiavo, and F. Delestre, "Service quality regulation in electricity distribution and retail: with 25 figures and 28 tables", Berlin: Springer, pp. 60-73, 2007.

[2] CEER , " 5th CEER benchmarking report on the quality of electricity supply'', *Council of European Energy Regulators*, Tech. Rep, Brussels, Belgium, 2011.

[3] K. Alvehag and K. Awodele, "Impact of reward and penalty scheme on the incentives for distribution system reliability." *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 386–394, 2014.

[4] K. Alvehag and L. Sӧder, "Risk-based method for distribution system reliability investment decisions under performance-based regulation." *IET Gener. Transm. Distrib.*, vol. 5, no. 10, pp. 1062, 2011.

[5] H. Shourkaei et al, "Incorporating service quality regulation in distribution system maintenance strategy." *IEEE Trans. Power Delivery*, vol. 26, no. 4, pp. 2495-2504, 2011.

[6] K. Alvehag and L. Söder, "Quality regulation impact on investment decisions in distribution system reliability," *2012 9th Int. Conf. Eur. Energy Market*, Florence, pp. 1-8, 2012.

[7] H. Shourkaei and M. Fotuhi, "Impact of penalty–reward mechanism on the performance of electric distribution systems and regulator budget," *IET Gener. Transm. Distrib.*, vol. 4, no. 7, pp. 770, 2010.

[8] S. Abedi and M. R. Haghifam, "Second revenue stream for distributed generation in the presence of reliability insurance," *Int. J. Electr, Power Energy Syst.*, vol. 59, pp. 29-35, 2014.

[9] P. Salyani and J. Salehi, "A customer oriented approach for distribution system reliability improvement using optimal distributed generation and switch placement." *J. Oper. Autom. Power Eng.*, vol.7, no.2, pp. 246-260, 2019.

[10] B. Wang et al., "New reward and penalty scheme for electric distribution utilities employing load-based

reliability indices," *IET Gener. Transm. Distrib.*, vol. 12, no. 15, pp. 3647-3654, 2018.

[11] J. Gholinezhad, R. Noroozian and A. Bagheri, "Optimal capacitor allocation in radial distribution networks for annual costs minimization using hybrid PSO and sequential power loss index based method", *J. Oper. Autom. Power Eng.*, vol. 5, no. 2, pp. 117-130, 2017.

[12] M. Ghasemi and R. Dashti, "A risk-based model for performance-based regulation of electric distribution companies," *Util. Policy*, vol. 45, pp. 36-44, 2017.

[13] S. Pineda, A. Conejo, and M. Carrión, "Insuring unit failures in electricity markets," *Energy Econ.*, vol. 32, no. 6, pp. 1268-1276, 2010.

[14] Y. Liu, F. Wu, Y. Ni and B. Cai, "Managing and operating the reserve market as one insurance system," *Electr. Power Syst. Res.*, vol. 77, pp. 1363-1372, 2007.

[15] A. Nitanan and K. Audomvongseree, "Electricity insurance pricing for the bilateral contract market", in *The 8th Electr. Eng. Electron. Computer, Telecommun. Inf. Technol. Assoc. Thailand – Conf. 2011*, Thialand, pp. 812-815, 2011.

[16] H. Yang et al., "Insurance strategy for mitigating power system operational risk introduced by wind power forecasting uncertainty," *Renewable Energy*, vol. 89, pp. 606-615, 2016.

[17] E. Fumagalli, J. Black, I. Vogelsang and M. Ilic, "Quality of service provision in electric power distribution systems through reliability insurance," *IEEE Trans. Power Syst.*, vol. 19, pp. 1286-1293, 2004.

[18] S. Abedi and M. Haghifam, "CDF-based reliability insurance contracts considering free-riding," *Int. J. Electr. Power Energy Syst.*, vol. 53, pp. 949-955, 2013.

[19] R. Fuentes, J. Blazquez and I. Adjali, "From vertical to horizontal unbundling: A downstream electricity reliability insurance business model," *Energy Policy*, vol. 129, pp. 796-804, 2019.

[20] F. Billimoria and R. Poudineh, "Market design for resource adequacy: A reliability insurance overlay on energy-only electricity markets," *Util. Policy*, vol. 60, pp. 100935, 2019.

[21] J. Dubé, Microeconometric Models of Consumer *Demand*. Cambridge, MA: National Bureau of Economic Research, 2018.

[22] K. Steriotis et al, "A novel behavioral real time pricing scheme for the active energy consumers' participation in emerging flexibility markets," *Sustainable Energy, Grids and Networks*, vol. 16, pp. 14-27, 2018.

[23] P. Samadi et al., "Optimal real-time pricing algorithm based on utility maximization for smart grid," *2010 First IEEE Int. Conf. Smart Grid Commun.*, 2010.

[24] K. Ma, G. Hu and C. Spanos, "Dynamics of electricity markets with unknown utility functions: An extremum seeking control approach," *11th IEEE Int. Conf. Control Autom.*, 2014.

[25] N. Cicek and H. Delic, "Demand response management for smart grids with wind power," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 625-634, 2015.

[26] A. Niromandfam et al. "Modeling Demand Response Based on Utility Function Considering Wind Profit Maximization in the Day-Ahead Market." *J. Cleaner Prod.*, vol. 251, p. 119317, 2020.

[27] P. Samadi, H. Mohsenian, R. Schober and V. Wong, "Advanced demand side management for the future smart grid using mechanism design," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1170-1180, 2012.

[28] R. Kaas, "Modern actuarial risk theory", Berlin: Springer-Verlag, pp. 4-6, 2008.

[29] O. Stenman, "Risk aversion and expected utility of consumption over time," *Games Econ. Behavior*, vol. 68, no. 1, pp. 208-219, 2010.

[30] P. Lam, "The consumption function under exponential utility," *Econ. Letters*, vol. 25, pp. 207-211, 1987.

[31] M. Imani, M. Ghadi, S. Ghavidel and L. Li, "Demand response modeling in microgrid operation: a review and application for incentive-based and time-based programs," *Renewable Sustainable Energy Rev.*, vol. 94, pp. 486-499, 2018.

[32] H. Gerber and G. Pafum, "Utility Functions," *North American Actuarial J.*, vol. 2, no. 3, pp. 74-91, 1998.

[33] M. Allahnoori, Sh. Kazemi, H. Abdi, and R. Keyhani, "Reliability assessment of distribution systems in presence of microgrids considering uncertainty in generation and load demand", *J. Oper. Autom. Power Eng.*, vol. 2, no. 2, pp. 113-120, 2014.

[34] S. Fan and R. Hyndman, "The price elasticity of electricity demand in South Australia," *Energy Policy*, vol. 39, no. 6, pp. 3709-3719, 2011.

[35] M. Fell, "Energy services: A conceptual review," *Energy Res. Social Sci.*, vol. 27, pp. 129-140, 2017.