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Regulation of Electrical Distribution Companies via Efficiency Assessments and Reward-Penalty Scheme

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Abstract- *Improving performance of electrical distribution companies, as the natural monopoly entities in electric industry, has always been one of the main concerns of the regulators. In this paper, a new incentive regulatory scheme is proposed to improve the performances of electrical distribution companies. The proposed scheme utilizes several efficiency assessments and a 3-dimentional reward-penalty scheme (3DRPS). Through efficiency assessments, economic efficiency and service quality, as two aspects of companies' performances, are assessed and according to the results of such assessments, reasonable capital expenditure (CAPEX) and operational expenditure (OPEX) for each company are calculated. Then, according to the reasonable CAPEX and OPEX, allowed revenues are calculated for next regulatory period. Moreover, the 3DRPS on quality is used to encourage the companies to maintain and improve their service quality during the regulatory period. The 3DRPS gives the incentive to the companies based on changes in their quality indices. The incentives are added to companies' allowed revenues. Finally, the proposed scheme is applied to Iranian distribution companies and the results are discussed.*

Keyword: Efficiency assessment, Reward-penalty scheme, Distribution company regulation.

NOMENCLATURE

3DRPS	3-dimentional reward-penalty scheme
AL	Average Load (MW)
AR	Allowed revenue (M$)
CAIDI	Customer average interruption duration index (min.)
CAPEX	Capital expenditure
CCDF	Composite customer damage function
CDA	Center of dead area of 3DRPS
CE	Classification entropy
DE	Capital's depreciation expense (M$)
DEA	Data envelopment analysis
E_C	Capital expenditure (M$)
E_{CA}	Capital expenditure for creating adequacy (M$)
E_{CQ}	Capital expenditure for improving quality (M$)
E_O	Operational expenditure (M$)
FS	Fukuyama-Sugeno's index
i	Index of company
IC	Interruption cost (M$)
LTEA	Long-term efficiency assessment
Max. Penalty	Maximum penalty of 3DRPS
Max. Reward	Maximum reward of 3DRPS
MTEA	Mid-term efficiency assessment
OPEX	Operational expenditure
PC	Partition coefficient
PL	Penalty line of 3DRPS
Q_{INC}	Incentive of 3DRPS
rE_C	Reasonable value of E_C (M$)
rE_{CA}	Reasonable value of E_{CA} (M$)
rE_{CQ}	Reasonable value of E_{CQ} (M$)
rE_O	Reasonable value of E_O (M$)
RL	Reward line of 3DRPS
$ROR_{reference}$	Reference rate of return (%)
SAIDI	System average interruption duration index (min.)
SAIFI	System average interruption frequency index
SCDF	Sector customer damage function
SD	Standard deviation
sE_{CA}	Slack in E_{CA} (M$)
sE_{CQ}	Slack in E_{CQ} (M$)
sE_O	Slack in E_O (M$)
WFCM	Weighted fuzzy c-means clustering
XB	Xie-Beni index
θ_{CA}	LTEA score for creating adequacy
θ_{CQ}	LTEA score for improving quality
θ_O	MTEA score

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1. INTRODUCTION

Through restructuring, the electric industry entities were stratified into two sectors: (1) selling and generation entities whose efficiencies were ensured by the open market mechanism and (2) transmission and distribution entities which could not be rendered in market for the natural monopoly. Despite privatization, distribution companies were remained under the supervision of the regulators. The purpose of regulation is to reduce costs of monopoly services and improve the efficiency and service quality. In this regard, the regulators have to employ a method through which they could maintain a balance between the interests of distribution business stockholders namely the owners, and the companies and their customers [1]. By considering natural characteristics of design and operation of networks and also keeping financial attraction of the distribution business, the applied methods should direct companies to reduce the cost of service and improve service quality.

Various methods have been applied by regulators, up to now. Primarily, profit-based methods such as ROR and cost-plus regulation were considered. In so-called methods, regulator allows the companies to collect revenues in order to cover their operational and capital depreciation plus a fair return on their capitals [2]. Basically, in such methods, lack of incentive to improve efficiency may reward overinvestment and cause customers' overcharging. Also, in long-term, unreasonable improvement in service quality can be another outcome of the probable overinvestment.

Price-based methods such as price cap and revenue cap are the other methods of regulation. The underlying idea of these methods lies in that if regulator caps the prices of services (or revenues of companies), customers would be protected against overcharging [3]. In the basic form of such methods, the regulator should find potential of the cost savings and by considering such potential in cap setting, it directs the companies toward cost reduction behavior. The company which is able to reduce its costs more than the regulatory cap, can gain the additional profit as a reward. Improving efficiency through cost reduction behavior can direct the companies to inadequate investments and subsequent lower service quality.

Incentive-based regulation methods are new methods of regulation and most often consist of inflationary, efficiency and quality adjustments. The basic idea of incentive-based regulation is to provide the companies with incentives to use their exclusive information about effort and costs for improving the operating efficiencies and investment decisions, and to ensure that customers also benefit from the efficiency gains as well [4]. In literature, the incentive-based regulation is sometimes referred to as performance-based regulation [1]. The main principle is, nevertheless, the same: good performance should lead to higher profit, and poor performance should lead to lower profit [3]. Price-based and profit-based schemes rarely exist in basic form in practice. Price-based schemes are often supplemented by a quality instrument, for instance in the UK, Norway and Germany [5, 6]. The quality instruments are classified into two categories, indirect instruments such as data publication and direct instruments such as minimum quality standards, reward-penalty scheme and quality insurance contract [5]. Moreover, profit-based scheme often tends to be combined with cost efficiency incentives, for instance in Finland [1]. The efficiency analysis is performed by different assessment tools, such as data envelopment analysis (DEA), corrected ordinary last square (COLS) and stochastic frontier analysis (SFA). DEA is based on linear programming while COLS and SFA are statistical techniques [7].

Recently, DEA has been known as one of the preferred assessment methods. DEA is a non-parametric approach which does not require to know the production function of the regulated firm. It is one of its major advantages. In a study, Simab et al. have used DEA evaluation to regulate the reliability of distribution companies [8]. It proposes an algorithm which focuses on setting of RPS parameters based on system average interruption duration index (SAIDI) and customer's value of interruptions. In another study, Simab et al. proposed an integrated algorithm through application of DEA to evaluate the overall, technical and scale efficiency of distribution companies [7]. It focused on DEA implementation problems in distribution companies as well and as a result, it suggested some algorithms to solve the problems. Quingran et al. presented an incentive regulation model based on yardstick competition for transmission-distribution enterprises (T&D). It incorporates pricing regulation and market equilibrium [9]. To evaluate productivity of T&D enterprises, the DEA was applied. In another study, Tenure et al. rendered a methodology to regulate target performance related to reliability in distribution networks [10]. Such a methodology analyzes customer average interruption duration index and customer average interruption frequency index. It also establishes a yardstick regulatory model based on DEA. The study carried out by Sanhueza et al. verified the functionality of DEA required in tariff fixation process of power distribution, as a tool for determination of distribution added value [11]. Moreover, bootstrapping technique was used to increase the efficiency of results. Chein *et al.* investigated the operation efficiency of 17 service centers in Taiwan Power Company and suggested the specific directions of improvement for corresponding inefficient districts by district reorganization [12]. Among the fulfilled studies, Resende *et al.* used DEA to evaluate the Brazilian electricity distribution companies [13]. Potentials and difficulties with the implementation of Yardstick schemes are discussed in the study.

This paper presents a new incentive regulatory scheme which includes several efficiency assessment and a 3-dimentional RPS (3DRPS) on quality. In an incentive-based approach, the main objective of the proposed scheme is directing the distribution companies in a way to increase their efficiency and improve service quality. The allowed revenue for next regulatory period are calculated for each company according to cost efficiency analysis. To complete the scheme, the 3DRPS are incentivized the companies according the change in quality level during the regulatory period.

Through efficiency assessments, efficiency and service quality, as the two aspects of companies' performances, are assessed. According to the results of such assessments, reasonable capital expenditure and operational expenditure for each company are calculated. Afterwards, allowed revenues for next regulatory period are calculated for each companies according to their reasonable CAPEX and OPEX. Moreover, a 3DRPS on quality is utilized to encourage companies to maintain and improve their quality levels during the regulatory period. The 3DRPS gives the incentive to the companies based on the changes in their quality indices. This incentive are added to companies' allowed revenues. The proposed scheme starts by weighted fuzzy c-means clustering (WFCM) to find similar companies. Then, several efficiency assessments are performed among similar companies through using data envelopment analysis and slack analysis. Based on the assessments' results, reasonable CAPEX and OPEX for each company are calculated. Afterward, allowed revenue for each company is calculated using classic form of profit-based method according to the reasonable values of CAPEX and OPEX. Finally, the 3DRPS is set to motivate the companies to maintain and improve their quality.

This paper is organized as follows. Section 2 presents the structure of the proposed scheme. Section 3 details the application and presents the obtained results. Finally, concluding remarks are made in Section 4.

2. STRUCTURE OF PROPOSED SCHEME

In this section, structure of the proposed scheme is presented by starting from scheme overview. Then, the mathematical tools used in the scheme are described and scheme's components are detailed.

2.1. Scheme overview

The proposed scheme has a new incentive-based regulatory scheme. It incentivized the distribution companies according to efficiency assessments on their CAPEXs and OPEXs. Also, changes in service quality during the regulatory period are rewarded or penalized by 3-dimentional reward-penalty scheme on quality. The scheme classifies similar companies by performing a weighted fuzzy c-means clustering method. Then, using data envelopment analysis and slack analysis in three stages, the proposed scheme mimics a pseudo competition in each cluster of similar companies to assess companies' efficiency and calculate their reasonable CAPEXs and OPEXs. The proposed scheme assigns higher reasonable CAPEX and OPEX to a company with good efficiency and lower reasonable CAPEX and OPEX to a company with poor efficiency. Afterwards, according to reasonable CAPEX and OPEX, the allowed revenue for each company is calculated for next regulatory period by means of classic form of profit-based method. Finally, to maintain and improve companies' quality levels during next regulatory period, the scheme sets a 3DRPS on quality for each company. The target area of quality in this study is limited to continuity of supply and commercial and voltage quality aren't considered in this paper.

In profit-based method, in order to preserve the attraction of distribution business, the allowed revenue of a company should cover its OPEX and capital's depreciation plus a fair return on its CAPEX. Keeping this concept in mind, the proposed scheme calculates reasonable companies' expenditures by considering their efficiency scores. The companies' expenditures are mainly allocated to create adequacy for their customers, improve their service quality and decrease their network operation costs, such as energy losses, as main features of companies' performances. Therefore, to perform efficiency assessments on companies' expenditures, effective factors in performance of distribution companies could be classified into three categories [5]:

1) *Inherent factors* such as the weather conditions and the density of customers that are out of distribution companies' control.
2) *Inherited factors* such as network design that have long-term effects on performance.
3) *Incurred factors* such as the managerial performance, the maintenance of assets and effective use of resources that influence the

performance.

Primarily, due to competitive nature of the proposed scheme, weighted fuzzy c-means clustering is used to classify similar companies. It performs based on inherent factors. Such a clustering reduces the effects of inherent factors on efficiency assessments' results. Afterwards, the scheme divides efficiency assessments of companies in two sections based on effective time span of inherited and incurred factors:

1) *Long-term efficiency assessment (LTEA)* assumes that companies can influence on all inherited and incurred factors in long term.
2) *Mid-term efficiency assessment (MTEA)* assumes that companies can only influence on incurred factors while inherited factors couldn't be affected by companies in mid-term.

In the LTEA, efficiency assessment is performed by two efficiency assessments for creating adequacy and improving service quality. Firstly, it is assumed that the companies can utilize all effective inherited and incurred factors to minimize their employed capitals for creating adequacy without considering quality improvement. Based on the results of this assessment, reasonable CAPEX for creating adequacy are calculated. Then, efficiency assessment on quality is performed to calculate reasonable additional CAPEX for improving service quality. This assessment is performed under the assumption that companies can utilize all effective inherited and incurred factors to minimize the additional employed capitals and maximizing the quality level. Finally, reasonable CAPEX is the sum of calculated reasonable CAPEXs for creating adequacy and improving quality. Besides the baseline quality could be set according to results of efficiency assessment for improving service quality.

In MTEA, efficiency assessment is performed by the assumption that companies can only utilize incurred factors to improve operating efficiency and to maintain quality baseline meanwhile inherited factors could not be influenced in these time spans. The MTEA calculates reasonable values of OPEX for each company. The expenditure for maintenance of network components, restoration operations and energy losses are included in company's operational expenditure and the remained parts of operational expenditure such as metering and billing costs as network independent operational expenditures are not considered in the MTEA. Obtaining reasonable values of network independent OPEX are not in the scope of this paper.

Figure 1 shows the flowchart of the proposed scheme. As shown in this flowchart, WFCM clustering method is used to find similar companies. After clustering, the LTEA and MTEA are performed in three stages by using the DEA and slack analysis to calculate reasonable CAPEX and OPEX for each company.

The inherited and incurred factors can affect company's capital expenditure. In this regards, the LTEA is designed to estimate cost efficiency of capital expenditure. As shown in Fig. 1, we divide such assessment in two stage. In first stage, total CAPEX is considered as the CAPEX for creating adequacy in company's network. The adequacy is defined as supplying the costumers without considering quality level. Therefore, the companies' customers' characteristics, such as number of customers, supplied energy and peak load, are considered as the outputs of the assessment. As a result of the adequacy assessment, slack in the CAPEX is calculated, but it is not a real slack. The slack could be the additional CAPEX for improving quality level. Therefore, in next stage of assessment, slack in the CAPEX is considered as the additional CAPEX for improving quality level and input of quality assessment. The companies' quality levels in addition to the companies' customers' characteristics are considered in the quality assessment, as the outputs.

The allowed revenue for each company in next regulatory period is calculated by classic formulation of profit-based approach according to the reasonable OPEX and CAPEX. In this form, the scheme allows each company to collect its reasonable OPEX as well as its deprecation plus return on its reasonable CAPEX. The rate of return is obtained by the regulator. In fact, the scheme calculates companies' allowed revenues based on their efficiency scores and subsequent reasonable CAPEXs and OPEXs. In addition, the proposed scheme makes use of a 3-dimensional reward-penalty scheme on quality to encourage companies to maintain or improve their quality level with respect to baseline quality during next regulatory period. The 3DRPS incentive are in accordance with the changes in quality levels and subsequently, the changes in company' customer interruption values. This incentive are added to company's allowed revenue during next regulatory period.

2.2. Mathematical tools

Weighted Fuzzy c-means Clustering (WFCM)

Cluster analysis is a method of data categorization into homogeneous clusters.

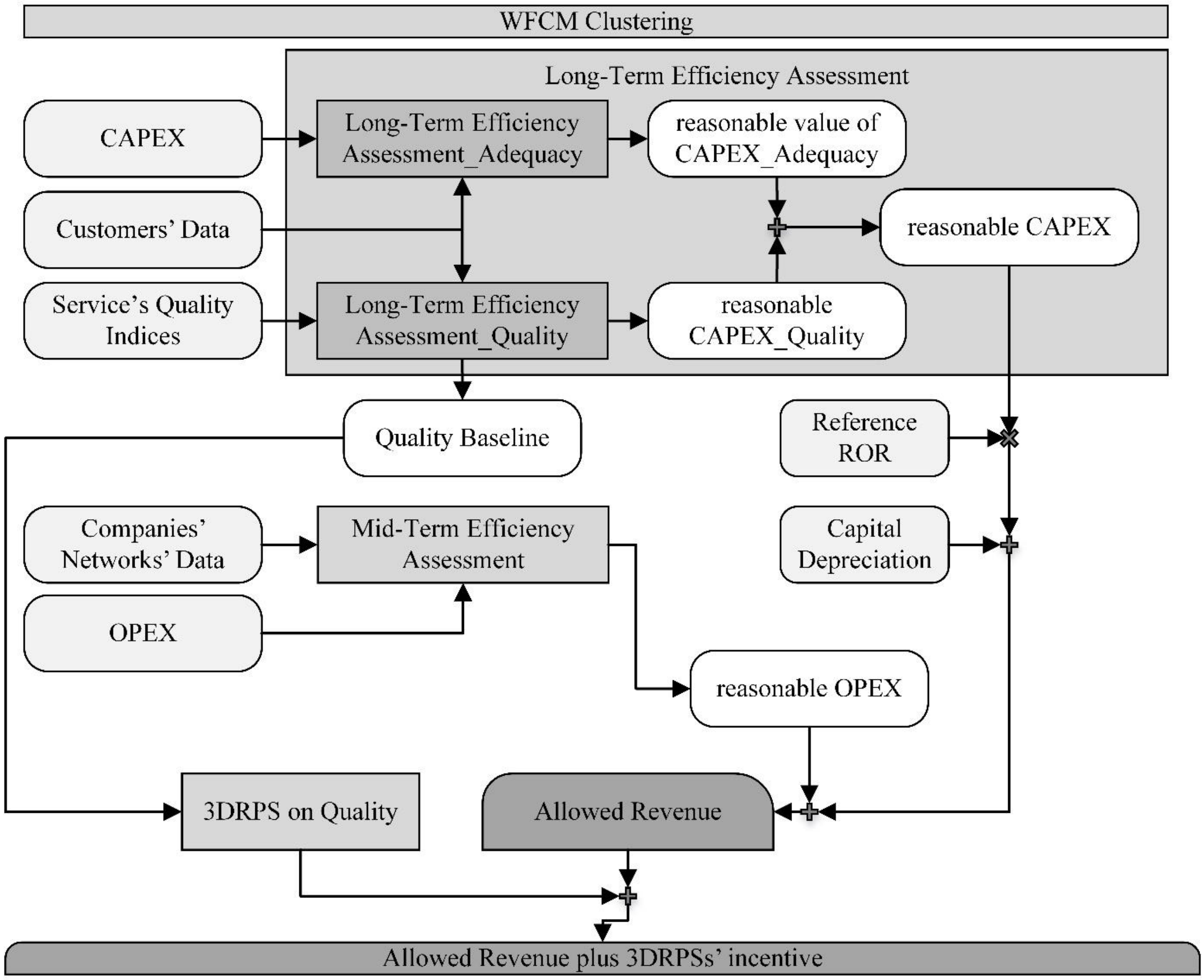

Fig. 1. Flowchart of the proposed scheme

Data in the same cluster would be as similar as possible and the data in different classes would be as dissimilar as possible. Since there is mostly no sharp boundary between clusters in real applications, fuzzy clustering gives rise to the concept of partial membership. Fuzzy c-means (FCM) algorithm suggested by Bezdek is the most applicable method in fuzzy clustering [14]. Wang *et al.* claimed that different feature weights affect FCM performance, but if the feature weights were inappropriately chosen for FCM, the algorithm performs poorly [15]. In this paper, the proposed WFCM in [16] is used for company clustering. Quality evaluation of clustering results is done through cluster validity indexes. Many cluster validity indexes have been suggested, such as partition coefficient (PC) and classification entropy (CE) [17], Fukuyama-Sugeno's index (FS) [16], and Xie-Beni index (XB) [18].

Data Envelopment Analysis (DEA)

DEA is a nonparametric method to measure relative efficiency of a homogeneous number of decision-making units (DMUs) that essentially performs the same tasks. The DEA is centered in determining the most efficient DMU of the sample to be used as a reference, with which the efficiency of the rest of the DMUs is compared. The DEA measures the efficiency of a DMU with multiple inputs and outputs by ratios of weighted outputs to weighted inputs. Since measuring inefficiency in the input variables is the purpose of the scheme, the input-oriented CCR model of DEA assessment is used in this study [19].

Slack Analysis

In presence of data envelopment analysis, slack analysis is an interesting tool to provide a way to derive improvement directions for inefficient companies. Slack analysis presents various proportionate changes in inputs or outputs of DEA solution to compensate inefficiencies. Slack in input shows the need for reductions in the corresponding input factors for inefficient companies to become efficient companies. Slack in output means the increase in the outputs of inefficient companies to become efficient companies [8].

2.3. Long-term efficiency assessment

As previously mentioned, long-term efficiency assessment is performed in two stages to calculate reasonable capital expenditure for each company. Each efficiency assessment employs an input-oriented DEA methodology to mimic a pseudo competition among similar companies. The employed DEA is a CCR model for measuring overall efficiency scores in order to minimize input variables while output variables are fixed [19]. In addition, the slack analysis is used to find desired reduction in input variables based on assessment results for an inefficient company to turn to an efficient one. For creating adequacy in efficiency assessment, it is assumed that companies can utilize all effective inherited and incurred factors to minimize employed capitals. Improving the service quality are not included in this assessment. Therefore, the total capital expenditure is considered as CAPEX for creating adequacy and the single input variable of assessment. Moreover, companies' customers' characteristics are considered as output variables of the assessment. It is in brief as Eq. (1):

$$DEA\begin{cases} Input: E_{CA,i} = E_{C,i} \\ Outputs: Companies'\ customers' \\ \qquad characteristics_i \\ Result: \theta_{CA,i} \end{cases} \tag{1}$$

After performing this assessment, slack analysis is carried out according to the assessment's results to find slack in input variable. It is performed by considering the concept of maximal proportioned reduction in input. It is formulated as Eqs. (2) and (3):

$$sE_{CA,i} = E_{CA,i}\left(1 - \theta_{CA,i}\right) \tag{2}$$

$$rE_{CA,i} = E_{CA,i} - sE_{CA,i} \tag{3}$$

The calculated slack is not a real slack and can be the additional CAPEX which company expends for improving its quality level. Thus, in efficiency assessments for improving quality, the slack is considered as additional capital expenditure to improve quality level. It is represented as Eq. (4):

$$E_{CQ,i} = sE_{CA,i} \tag{4}$$

In the next step, the efficiency assessment for improving service quality is defined by the assumption that companies could utilize all effective inherited and incurred factors to minimize their additional capital expenditures for service quality and maximizing their quality levels. Therefore, the additional capital expenditures for improving quality are considered as input variable of the assessment. Also, the characteristics of company's customers and quality level are considered as assessment's outputs variables. It is summarized as Eq. (5):

$$DEA\begin{cases} Inputs: E_{CQ,i} \\ Outputs: Companies'\ customers' \\ \qquad characteristics_i, \\ \qquad Quality\ level_i \\ Result: \theta_{CQ,i} \end{cases} \tag{5}$$

The average of quality indices in pervious regulatory period are used for this assessment. Similar to the pervious stage, slack analysis is performed by the concept of maximal proportioned reduction in input to calculate reasonable CAPEX for improving quality, as following:

$$sE_{CQ,i} = E_{CQ,i}\left(1 - \theta_{CQ,i}\right) \tag{6}$$

$$rE_{CQ,i} = E_{CQ,i} - sE_{CQ,i} \tag{7}$$

Finally, the reasonable CAPEX for each company is the sum of its reasonable values of CAPEX for creating adequacy and CAPEX for improving quality level.

$$rE_{C,i} = rE_{CA,i} + rE_{CQ,i} \tag{8}$$

Due to calculating reasonable CAPEX according to average quality indices and in an input-oriented efficiency assessment, the quality baseline should be considered equal to the average quality indices.

2.4. Mid-term efficiency assessment

Mid-term efficiency assessment (MTEA) is performed by the assumption that companies can only utilize incurred factors for improving operating efficiency and maintaining quality baseline meanwhile inherited factors could not be influenced in mid-term. The company which is able to minimize its OPEX while keeping the quality baseline is known as an efficient company in this assessment. Similar to LTEA, MTEA uses an input-oriented DEA methodology at which the OPEX is considered as input variable of assessment. The output variables of assessment include the network characteristics which couldn't be mainly changed by companies in these time spans, but should be perfectly operated. Therefore, the network characteristics and quality baseline are considered as output variables of assessment. It is summarized in Eq. (9):

$$DEA\begin{cases} Inputs: E_{O,i} \\ Outputs: Network\ characteristics_i, \\ \qquad Quality\ baseline_i \\ Result: \theta_{O,i} \end{cases} \tag{9}$$

According to efficiency assessment's results, slack analysis is performed to calculate reasonable operational expenditure.

$$sE_{O,i} = E_{O,i}\left(1-\theta_{O,i}\right) \quad (10)$$

$$rE_{O,i} = E_{O,i} - sE_{O,i} \quad (11)$$

Finally, the allowed revenue for each company is calculated by classic formulation of profit-based approach. It is formulated as following:

$$AR_i = ROR_{reference} \times rE_{C,i} + DE_i + rE_{O,i} \quad (12)$$

Taxes that is obtained by tax organization, should be added to the above calculated allowed revenue as a fixed-term.

2.5. 3-dimentional reward-penalty scheme

Reward-penalty scheme (RPS) is the most-used quality instrument for quality regulation. The RPS incentive modifies the company's revenue according to the change in its quality level. The RPS penalizes quality deterioration and rewards quality improvement. It creates financial incentives for maintaining or improving quality level of distribution companies based on historic quality records. Study [20] represented the concept of applying reliability index probability distributions in conjunction with RPS. In the results of [20], financial risk assessment of imposed RPS associated with some real system reliability data from Canadian service continuity reports are represented. Study [21] presented utilization of Monte Carlo simulation to develop the relevant quality indices and their distributions owning to quality improvements in an electric distribution system. The effect of quality improvement on financial risk owing RPS are shown in the results of study [21]. Study [22] proposed a technique in motivating the companies to improve their quality level. To zero the implementation cost of RPS, the technique equalizes total rewards paid and penalties received by regulator. [23] studied impacts of omitting customer tolerable repair time on electric distribution system reliability. It includes a simple model of circuit breaker, which differs from other components. For calculating reliability indices Monte Carlo simulation method is used. A methodology was suggested by [10] to set quality targets related to continuity of supply in distribution companies. The suggested methodology used DEA and significantly reduced the degree of subjectivity of the regulator in its mission to establish performance standards for distribution companies. the reliability performance of distribution systems with considering uncertainties in both generation and load demands are evaluated in study [24]. The application results on a case study system verify its advantages compared to the previous studies.

In all conditions, RPS does not have fixed structure and could be changed according to range of data, type of used reliability index, goal of system regulators, times of execution, etc. [25]. In general form, RPS includes three zones; the dead zone in which the company does not receive neither reward nor penalty, the reward zone in which the company is rewarded for quality improvement and the penalty zone in which the company is penalized for quality deterioration [8].

The frequency and duration are the main characteristics of interruptions. Therefore, SAIFI and SAIDI are usually used to show quality level for the company as the average customer interruption indictors. In this paper, a 3-dimensional reward-penalty scheme is proposed to create incentive for the changes in quality level based on both frequency and duration indictors (SAIFI and SAIDI set). Therefore, the dead, reward and penalty zones in general form are transferred to dead, reward and penalty areas. The 3DRPS tries to maintain or improve companies' quality levels rather their baseline quality. The 3DRPS's parameters are set as following:

- *Center of dead area (CDA):* Since maintaining baseline quality during regulatory period is the primary objective of 3DRPS, center of dead area for each company is considered equal to its baseline quality. Quality baseline is set according to long-term efficiency assessment for improving quality.
- *Reward-penalty bonds:* It can be expected that companies in the same cluster have the same stochastic variations in quality, because they have similar network and weather conditions and it is expected that they have same stochastic variations in quality [8]. Hence, a rectangular area is considered as a dead area while each side of the dead area equals to the average standard deviation of historical quality indices for each cluster. Line equation of each bond are formulated as Eq. (13):

$$\begin{cases} RL_{SAIDI,i} = CDA_{SAIDI,i} - SD_{SAIDI}/2 \\ PL_{SAIDI,i} = CDA_{SAIDI,i} + SD_{SAIDI}/2 \\ RL_{SAIFI,i} = CDA_{SAIFI,i} - SD_{SAIFI}/2 \\ PL_{SAIFI,i} = CDA_{SAIFI,i} + SD_{SAIFI}/2 \end{cases} \quad (13)$$

- *Quality incentive (Q_{INC}):* 3DRPS's incentive is set proportionate with the change in costumers' value of interruptions (IC). This change is determined for each company by calculating the difference between ICs in company's CDA and its quality indices according to composite customer damage function (CCDF). It is represented in Eq. (14):

$$Q_{INC,i} = IC_i\left(CDA_i\right) - IC_i\left(QI_i\right) \quad (14)$$

The negative sign of calculated incentive shows company's penalty.

- *Max. Reward and Max. Penalty:* The higher the quality is the more charge should be paid by the customers. Due to imperfect information about customer interruption cost, the incentive of RPS should be capped [8]. Therefore, a percentage of the company's annual revenue is considered as cap values of incentive in order to justify the risk of giving incentives for inappropriately high quality levels. This method has been used by regulators of the UK, Ireland and Netherlands [5, 25].

3. APPLICATION

The proposed scheme is applied to Iranian distribution companies (IDCs). The IDCs were established in 1992 and have been acting under the supervision of TAVANIR Company as a governmental organization. There are 39 IDCs whose information is available at: www.tavanir.org. The summery statics of IDCs' variables is presented in Table 1. Network independent operational expenditure such as metering and billing costs are not considered in mentioned OPEX in Table 1.

Table 1. Summary statics of IDCs' variables.

IDCs' Variable	Mean	Max.	Min.
Service Area (km^2)	42126	178431	1005
Number of customers (kC)	696	3824	169
CAPEX (M$)	14.465	36.143	3.802
OPEX (M$)	80.50	315.58	29.00
Peak Load (MW)	905	3675	187
Ave. Load (MW)	520	2118	120
Supplied Energy (GWh)	4559	18553	1053
Transformer's Capacity (MVA)	2445	9921	665
Length of Network's Lines (km)	17796	17770	6459
SAIDI (min.)	650	3077	155
SAIFI	3.780	6.880	1.850

3.1. Finding similar companies by WFCM clustering

As suggested by OFGEM, inherent factors influence the performances of distribution companies [5]. Therefore, clustering of IDCs is executed based on effective inherent factors which are out of companies' control. It reduces the effects of inherent factors on companies' performances and subsequently, reduces the effects on their expenditures during the efficiency assessments. For this purpose, the WFCM algorithm was applied to 39 IDCs to find similar distribution companies. The attributes used for executing such classification are:

1) *Weather conditions:* Maximum Temperature (C°), Minimum Temperature (C°), Humidity (%) and Average Wind Speed (km/h)
2) *Network conditions:* Density [number of customers per service area (C/km^2)] and Average Load (MW)

By performing the bootstrapping technique algorithm suggested by [16], the weights of attributes were determined which are presented in Table 2.

Table 3 represents the values of the validity measures depending on the number of clusters. Study [7] mentioned that no validation index is reliable by itself and the optimum can only be detected with comparing the results of all validity indices.

Table 2. Weights of WFCM's attributes.

Attribute	Weight
Density (C/km^2)	0.271
Average Load (MW)	0.239
Maximum Temperature (^{0}C)	0.113
Minimum Temperature (^{0}C)	0.132
Humidity (%)	0.159
Average Wind Speed (km/h)	0.086

Table 3. Values of validity measures.

No. Clus	2	3	4	5	6	7	8
PC	0.500	0.333	0.250	0.200	0.167	0.143	0.125
CE	0.693	1.099	1.386	1.609	1.792	1.946	2.079
FS	0.099	0.066	0.050	0.040	0.033	0.028	0.025
XB	1308	18663	16503	11855	96551	17787	25380

The best interpretation is achieved when the value of PC reaches its maximum or CE, FS and XB get theirs minimum. These conditions occurred in No. Clus=2 for PC, CE and XB indexes and in No. Clus=8 for FS index. Therefore, we classified the IDCs into the two clusters A and B which had 15 and 24 IDCs, respectively. Consequently, membership degrees indicate the strength of association between an attribute set and a particular cluster and each company which belongs to the cluster has the maximum membership degree.

Table 4. Output variables of efficiency assessments.

Efficiency Assessment	Output Variables
Long-term efficiency assessment _Availability	Supplied Energy (GWh), Peak Load (MW), Number of Customers (kC)
Long-term efficiency assessment _Quality	Average Load (MW), System Average Interruption Frequency Index [SAIFI], System Average Interruption Duration Index [SAIDI] (min.)
Mid-term efficiency assessment	Transformers' Capacity (MVA), Length of Network's Lines (km), Quality baselines

3.2. Efficiency assessments

Long-term efficiency assessment in two stages and mid-term efficiency assessment in one stage were applied to each cluster of similar IDCs. Afterwards, the allowed revenue for each company was calculated with reference ROR equal to 20%. It is an acceptable value for interest rate in the Central Bank of Iran. To select the output variables of efficiency assessments, we gathered all variables that could influence companies' expenditures. Then, through consulting the authority experts as well as the industry experts, output variables in efficiency assessments were selected. The following outputs are summarized in Table 4. Considering continuity of supply as the quality of services in this application, system average interruption frequency index (SAIFI) and system average interruption duration index (SAIDI) were considered as the quality indices to represent both frequency and duration of networks' interruptions.

Table 5. Results of efficiency assessments' implementation on IDCs.

Cluster	Company	Proposed scheme											Calculated RR via trad. profit-based method	AR / RR (%)
		θ_{CA}	θ_{CQ}	θ_O	rE_{CA}	rE_{CQ}	rE_C	rE_O	sE_{CA}	sE_{CQ}	sE_O	AR		
A	A1	0.54	0.36	0.83	8.99	2.71	11.70	14.16	7.54	4.82	3.00	17.42	21.38	81.47
	A2	0.68	0.35	0.88	16.59	2.75	19.34	14.16	7.86	5.11	1.97	19.39	22.38	86.62
	A3	0.52	0.29	1.00	9.29	2.49	11.78	11.56	8.59	6.10	0.00	14.91	16.13	92.44
	A4	0.61	0.26	0.39	15.65	2.65	18.30	12.10	10.19	7.54	19.12	17.20	37.83	45.46
	A5	1.00	1.00	0.53	36.14	0.00	36.14	29.57	0.00	0.00	26.29	38.81	65.09	59.62
	A6	0.70	0.38	0.39	15.20	2.42	17.62	14.91	6.38	3.95	23.04	19.64	43.47	45.18
	A7	0.64	0.36	0.82	11.08	2.25	13.33	10.30	6.25	4.00	2.21	13.93	16.95	82.22
	A8	0.48	0.16	0.52	13.12	2.31	15.43	12.03	14.41	12.10	10.94	16.65	30.01	55.47
	A9	0.92	1.00	0.37	32.63	2.71	35.35	20.20	2.71	0.00	33.69	29.23	62.93	46.46
	A10	0.65	0.16	0.33	9.43	0.82	10.25	9.96	5.10	4.28	20.07	12.82	33.75	37.98
	A11	0.61	0.45	0.93	9.59	2.72	12.32	13.78	6.05	3.33	0.99	17.11	18.76	91.19
	A12	0.47	0.17	1.00	11.10	2.10	13.19	9.74	12.33	10.24	0.00	13.68	15.73	86.98
	A13	0.82	0.97	0.63	10.28	2.18	12.46	10.68	2.25	0.07	6.39	13.87	20.28	68.41
	A14	0.85	1.00	0.60	13.15	2.29	15.44	12.15	2.29	0.00	8.16	16.09	24.26	66.35
	A15	0.58	0.17	0.41	15.06	1.86	16.91	9.98	10.93	9.07	14.43	14.81	31.06	47.69
B	B1	0.85	0.47	0.61	8.46	0.69	9.15	6.64	1.48	0.78	4.19	9.02	13.37	67.50
	B2	1.00	1.00	0.49	6.75	0.00	6.75	7.15	0.00	0.00	7.40	8.87	16.27	54.51
	B3	0.55	0.10	0.62	4.29	0.35	4.64	4.29	3.52	3.17	2.64	5.65	8.92	63.33
	B4	0.91	1.00	0.68	3.47	0.33	3.80	4.29	0.33	0.00	2.04	5.26	7.30	72.07
	B5	0.86	0.49	0.75	10.80	0.86	11.66	8.69	1.76	0.90	2.87	11.73	14.78	79.33
	B6	0.60	0.12	0.63	7.88	0.64	8.53	8.66	5.35	4.71	5.07	11.10	17.11	64.85
	B7	0.63	0.14	0.66	6.44	0.53	6.97	6.71	3.79	3.26	3.38	8.68	12.71	68.26
	B8	1.00	1.00	0.61	6.64	0.00	6.64	5.45	0.00	0.00	3.43	7.15	10.58	67.59
	B9	0.77	0.32	1.00	3.29	0.31	3.60	3.88	0.96	0.65	0.00	4.83	4.96	97.38
	B10	0.59	0.16	0.89	2.82	0.32	3.14	4.01	1.98	1.66	0.47	4.90	5.71	85.93
	B11	0.72	0.20	0.47	20.27	1.59	21.86	16.77	7.96	6.37	18.63	22.71	42.61	53.29
	B12	0.54	0.13	0.78	3.26	0.36	3.62	4.45	2.76	2.40	1.25	5.51	7.24	76.11
	B13	0.83	0.41	0.79	7.14	0.62	7.76	5.38	1.51	0.89	1.46	7.41	9.04	81.91
	B14	0.93	1.00	0.78	9.86	0.78	10.64	6.90	0.78	0.00	1.96	9.62	11.59	83.05
	B15	0.90	0.91	1.00	5.64	0.54	6.18	5.05	0.60	0.05	0.00	6.63	6.64	99.84
	B16	0.67	0.17	0.72	6.66	0.56	7.22	7.87	3.29	2.73	3.12	9.86	13.53	72.90
	B17	0.63	0.13	0.97	5.15	0.40	5.55	5.41	3.09	2.69	0.17	6.98	7.68	90.82
	B18	0.38	0.09	0.92	2.80	0.42	3.21	4.35	4.64	4.22	0.35	5.41	6.61	81.87
	B19	0.82	0.37	0.93	11.26	0.90	12.16	12.99	2.44	1.54	0.93	16.18	17.42	92.89
	B20	0.76	0.25	0.66	9.63	0.75	10.38	8.03	3.00	2.25	4.19	10.81	15.45	69.97
	B21	0.63	0.14	0.72	11.55	0.94	12.48	10.94	6.69	5.75	4.24	14.45	19.84	72.83
	B22	0.80	0.41	0.90	4.60	0.47	5.07	5.29	1.14	0.67	0.60	6.62	7.35	90.04
	B23	1.00	1.00	0.92	6.40	0.00	6.40	7.89	0.00	0.00	0.65	9.52	10.18	93.60
	B24	0.84	0.40	0.80	9.89	0.78	10.67	7.32	1.94	1.17	1.88	10.11	12.22	82.73

The results of efficiency assessments' implementation on IDCs are presented in Table 5. The third and fourth columns of this table present companies' efficiency scores in LTEA for creating adequacy and improving quality, respectively.

Also, companies' efficiency scores in MTEA are reported in the fifth columns. The average scores of LTEA for creating adequacy, improving quality and also MLEA are 0.73, 0.45 and 0.72, respectively.

As shown in Table 5, no company could not achieve the highest scores in both LTEA and MTEA. Therefore, no company is totally efficient.

Although, the companies, such as A5 in cluster A, could achieve the highest score in both stages of LTEA, but they could not be considered as an efficient company in MTEA. It represents that such companies have been able to minimize their CAPEXs, meanwhile maximize the adequacy and quality level in their networks. But they have not been able to manage their operational expenditures to keep their quality baseline. Therefore, such companies should optimize their network operations to control the operational expenditures and eliminate slack in the OPEX. In other words, such companies have no slack in their capital expenditure (sE_{CA} and sE_{CQ}), but have slack in their operational expenditure (sE_O). They have to reduce their OPEX equal to their sE_O value. Reasonable CAPEX for creating adequacy (rE_{CA}), improving quality (rE_{CQ}) and also total CAPEX (rE_C) and OPEX (rE_O) are represented in the sixth, seventh, eighth and ninth columns of Table 5, respectively. Moreover, the tenth, eleventh and twelfth columns of Table 5 presents slack values in CAPEX for creating adequacy (sE_{CA}) and improving quality (sE_{CQ}) and OPEX (sE_O), respectively.

The companies, such as B4 in cluster B, could not achieve the highest efficiency score in LTEA to create adequacy, but they could be an efficient company in LTEA for improving quality. It represents that their slack value in LTEA for creating adequacy is not a real slack and they could expend their additional CAPEX in a more proper way to improve their service quality. The companies, such as B15 in cluster B, could be an efficient company in MTEA, but they could not achieve the highest efficiency score in both stages of LTEA. It represents that such companies are able to operate their networks in a way that would minimize their operational expenditures and keep their quality baselines. On the other hand, they could not maximize utilization of their assets for creating adequacy and improving quality. Therefore, the planned investments for supplying new customers should be decreased. They must be an attempt to find optimized ways for increasing their asset utilization and supply their new costumers. Finally, the companies, such as A2 in cluster A, which are inefficient companies in all three efficiency assessment, should optimize their network operations to reduce their operational expenditures and also, increase their asset utilization to create more adequacy for their customers and improve their service quality.

The thirteenth column of Table 5 shows the allowed revenue for each company in the proposed scheme. Moreover, the fourteenth column of Table 5 represents the required revenue of each company in traditional profit-based regulatory scheme (rate of return scheme). Also, the fifteenth column of Table 5 shows ratio of allowed revenue in the proposed scheme to required revenue in traditional profit-based scheme. By comparing allowed revenue resulted by the proposed scheme and required revenue in traditional profit-based regulatory scheme for each company, it can be observed that in the proposed scheme, companies' revenues were decreased according to their efficiency scores. The company with the higher efficiency scores would be allowed to collect more percentage of its required revenue and the company with lower efficiency scores would be allowed to collect less percentage of its required revenue.

3.3. 3-dimentional reward-penalty scheme

The 3DRPS's incentive is set proportionate with the change in costumers' value of interruptions (*IC*). It is determined for each company by calculating difference between *IC*s in company's center of dead area and its quality indices according to composite customer damage function (CCDF). The CCDF defines the overall average costs of interruption as a function of the interruption duration in a given service area. The CCDF is the sum of the individual customer damage functions in a certain mix of customer sectors [8]. TAVANIR carried out a customer interruption cost survey in Iran 1995 [26]. Three customer sectors were assessed in this survey whose results are presented in Table 6 as the sector cost damage function (SCDF).

Table 6. Sector cost damage function (SCDF).

Interruption duration	Sector cost ($/kW)		
	Residential	Commercial	Industrial
2 s	0.000	0.006	0.180
1 min	0.000	0.006	0.180
20 min	0.000	0.065	0.304
1 h	0.793	1.213	1.920
2 h	2.380	3.640	4.800

The CCDF is obtained by weighting SCDFs with their total energy consumption percentage. Interruption duration in the CCDF is the duration of a single outage event. The *IC* is calculated by the following equation:

$$IC_i = AL_i \times SAIFI_i \times CCDF_i\left(CAIDI_i\right) \qquad (15)$$

Each side of dead area is equal to the average standard deviation of historical quality indices in each cluster. These values equal 3.60 minutes (SAIDI) and 0.24 (SAIFI) for cluster A and 2.73 minutes (SAIDI) and 0.21 (SAIFI) for cluster B. In addition, 10% of company's allowed revenue was considered as its maximum reward and maximum penalty. Calculated parameters of 3-dimentional RPS for IDCs are presented in Table 7. Also, the 3-dimentional RPS for company A5 in cluster A are drawn in Fig. 2, as an example.

Table 7. Calculated parameters of 3DRPS for IDCs

Cluster	Company	CDA_{SAIDI} (min.)	CDA_{SAIFI}	RL_{SAIDI} (min.)	PL_{SAIDI} (min.)	RL_{SAIFI}	PL_{SAIFI}	Max. Reward (M$)	Max. Penalty (M$)
A	A1	346	1.92	344.20	347.80	1.80	2.04	0.35	-0.35
	A2	331	2.72	329.20	332.80	2.60	2.84	0.39	-0.39
	A3	159	2.47	157.20	160.80	2.35	2.59	0.30	-0.30
	A4	243	3.26	241.20	244.80	3.14	3.38	0.34	-0.34
	A5	155	1.85	153.60	157.20	1.73	1.97	0.78	-0.78
	A6	488	4.18	486.20	489.80	4.06	4.30	0.39	-0.39
	A7	527	4.74	525.20	528.80	4.62	4.86	0.28	-0.28
	A8	551	4.86	549.20	552.80	4.74	4.98	0.33	-0.33
	A9	715	4.54	713.20	716.80	4.42	4.66	0.58	-0.58
	A10	3077	6.88	3075.20	3078.80	6.76	7.00	0.26	-0.26
	A11	225	1.95	223.20	226.80	1.83	2.07	0.34	-0.34
	A12	816	4.16	814.20	817.80	4.04	4.28	0.27	-0.27
	A13	525	3.22	523.20	526.80	3.10	3.34	0.28	-0.28
	A14	388	2.75	386.20	389.80	2.63	2.87	0.32	-0.32
	A15	1153	6.12	1151.20	1154.80	6.00	6.24	0.30	-0.30
B	B1	165	2.13	163.64	166.37	2.03	2.24	0.18	-0.18
	B2	224	2.51	222.64	225.37	2.41	2.62	0.18	-0.18
	B3	657	3.83	655.64	658.37	3.73	3.94	0.11	-0.11
	B4	653	3.94	651.64	654.37	3.84	4.05	0.11	-0.11
	B5	370	3.54	368.64	371.37	3.44	3.65	0.23	-0.23
	B6	420	3.95	418.64	421.37	3.85	4.06	0.22	-0.22
	B7	958	4.53	956.64	959.37	4.43	4.64	0.17	-0.17
	B8	425	4.12	423.64	426.37	4.02	4.23	0.14	-0.14
	B9	896	5.13	894.64	897.37	5.03	5.24	0.10	-0.10
	B10	820	4.31	818.64	821.37	4.21	4.42	0.10	-0.10
	B11	814	4.74	812.64	815.37	4.64	4.85	0.45	-0.45
	B12	557	3.62	555.64	558.37	3.52	3.73	0.11	-0.11
	B13	312	1.97	310.64	313.37	1.87	2.08	0.15	-0.15
	B14	336	2.04	334.64	337.37	1.94	2.15	0.19	-0.19
	B15	207	1.92	205.64	208.37	1.82	2.03	0.13	-0.13
	B16	742	4.72	740.64	743.37	4.62	4.83	0.20	-0.20
	B17	821	5.32	819.64	822.37	5.22	5.43	0.14	-0.14
	B18	618	3.12	616.64	619.37	3.02	3.23	0.11	-0.11
	B19	849	4.78	847.64	850.37	4.68	4.89	0.32	-0.32
	B20	1166	6.27	1164.64	1167.37	6.17	6.38	0.22	-0.22
	B21	1954	6.79	1952.64	1955.37	6.69	6.90	0.29	-0.29
	B22	507	2.65	505.64	508.37	2.55	2.76	0.13	-0.13
	B23	649	3.42	647.64	650.37	3.32	3.53	0.19	-0.19
	B24	537	2.46	535.64	538.37	2.36	2.57	0.20	-0.20

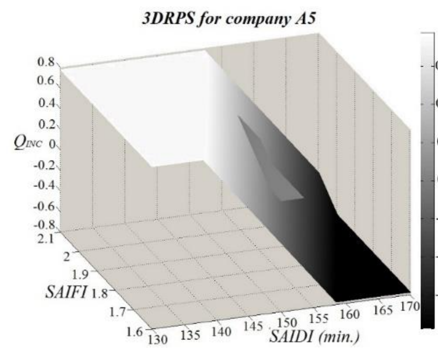

Fig. 2. 3DRPS for company A5

4. CONCLUSION

In this paper, a new incentive regulatory scheme was presented to improve the performances of electrical distribution companies. It employs several efficiency assessments and a 3-dimentional reward-penalty scheme. Through efficiency assessments, allowed revenues for next regulatory period are calculated for each company based on efficiency results. Moreover, the changes in companies' quality level during regulatory period are incentivized by the 3DRPS. This incentive are added to the allowed revenues. The proposed scheme would be a fair regulatory scheme, because of using the environmental, design and operation data of the companies themselves. By applying the proposed scheme, the regulator can create clear directing signals for distribution companies to improve their performances correctly. Finally, the scheme was applied to Iranian electricity distribution companies and the results were discussed.

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