Service Quality in Distribution Systems with Deep Penetration of Renewable Distributed Energy Resources

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Abstract - *Motivated by integration of distributed energy resources in the distribution systems, this paper investigates the impacts of different service quality regulations on reliability performance of the distribution utility. Instead of the traditional cost-based regulation, efficacy of a performance based regulation and minimum quality standards are being investigated. Impacts of these regulations on distribution utility investment in automation schemes are investigated. The impacts of back-feeding and feeder reconfiguration which is becoming a normal practice in distribution grids is also being studied. The methodology of this paper was tested on the Swedish Rural Reliability Test System.*

***Key Words*: Distribution automation, Electric distribution utility, Minimum quality standards, Renewable energy, Reward-penalty schemes.**

1. INTRODUCTION

Distributed renewable energy resources are being evolved in the power system in recent years by the drop in the cost of solar panels [1], and manufacturing as well as installation and maintenance cost of them . This cost reduction enabled the residential customers to install roof-top solar and generate their own electricity [2].

Unlike traditional sources of energy, such as fossil-fueled power plants, the output of these resources is not being controlled by an operator. Therefore, a major source of uncertainty is growing within the systems. This calls for robust control techniques that can handle uncertainties in the system while maximize the benefit of using renewables and energy storages in the system [3, 4, 5]. Also in [6] reachability analysis is used as a robust technique to analyze the uncertain grid-tied inverter. Such analysis can be used in any system with uncertainty.

In recent years, many researchers addressed a different aspect of addressing challenges of wind and solar integration in the power systems [7-9]. For instance, their impact on the wholesale electricity markets [10, 11], the dynamic stability of power systems [12], and the drop in natural inertia [13] are some of the challenges addressed by researchers.

While a huge body of research is focused on renewables impact on the generation and transmission, their integration in the distribution systems as Distributed Energy Resources (DERs) is getting into more attention due to the drop in the cost of roof-top solar as well as battery storage units.

Due to the fact that a large number of components are involved in the distribution grid operation, more than 80% of customer interruptions happen in these systems. Meanwhile, many components in these systems were not designed for such renewable integration in the systems. In other words, they were designed for passive customers while customers are getting increasingly active with newer technologies. Therefore, there is a need to handle the current system and making it adaptable to new changes.

There is a natural monopoly in distribution systems. It endangers the quality of service to gain more profits. To compensate for this lack of competition, Electric Distribution Utilities (EDUs) should be regulated by the system regulator through some incentives as well as penalties. These incentives are given to the EDUs, through some regulation policies.

In recent years, more and more demand-side generation, known as distributed generations, are being integrated into the system [14] causing negative consumption at the demand side, and in turn negative power flow at the substation. Also demand side control and generation control may conflict and leads to power swing, frequency instability and collapse of the system [15, 16]. By integration of such distributed generations in the system, energy losses, as well as costs of buying electricity can be minimized [17]. These motivated a need for upgrading the distribution system to meet new challenges.

Regulators can have a control over the EDUs in two different approaches through regulations; cost-based and performance-based regulations. In the cost-based regulation, prices are set to cover the costs of the firm. Under this form of regulation, there is a little incentive for cost efficiency that is the main drawback of this regulation [18]. However, a more competitive type of regulation known as performance-based regulation (PBR) has recently been used as a regulation policy in some countries. Under the PBR, a regulator uses price or revenue caps to motivate the EDU for cost efficiency. The incentive for cutting the cost results in a decrease in the investment and operational cost and an increase in the maintenance interval. In this condition, the quality of service has been deteriorated [18]. Therefore, the Service Quality Regulation (SQR) must be defined to support them. In this type of regulation, penalties and possible rewards are controlling the company's actions.

For the EDUs, profit plays the most important role. So, in implementing the SQR, the effect of newcomer factors like rewards and penalties must be assessed. In the presence of the SQR, the utility should examine different strategies to whether apply capital projects for enhancing its performance or decide to leave upgrading of current network to be penalized.

Different aspects of SQR have been studied so far. However, the study over their impact on the distribution systems with actively generating customers are being studied in this paper.

Typically, distribution automation is known as a way to implement appropriate technologies to enhance distribution system reliability. For this reason, the effects of different automation schemes have been investigated to show which automation strategy is the best to be fitted with the EDU's objectives.

Different automation strategies are implemented on the Swedish Rural Reliability Test System (SRRTS) and the results are evaluated under the selected PBR strategies for the system. For the sake of facing practical issues in the distribution systems, cables, lines, and distribution transformers are assumed to have time-varying failure rates during the study period.

In addition, sequential Monte Carlo simulation [19, 20] is used instead of common analytical strategies to have a better view over the examined reliability indices. This can provides us with the data which is needed in the application of the desired regulation. The probability distribution of desired reliability indices and also the detail interruptions durations data of load points will be accessible through this kind of simulation.

2. Service Quality Regulation

The term SQR is a general word for PBR that consisting regulations which encourage firms to enhance their performance. This performance may include improvement in system reliability, power quality or customer services, etc [21]. Improvement in system reliability is equals to continuity of supply which concerns a single service, "supply of electricity to the customers" or in the other form, absence of interruption[18]. There are different types of SQR [22], however, MQS and especially RPS are in the most interest among both regulators and regulated utilities due to their straightforward practical application. In RPS, one or two system level reliability indices are chosen based on regulation preferences. Regulation companies commonly start with the most important index, and years after the start of regulation, adds another index to its list. But, in applying MQS to the system, load point reliability indices must be taken into account. Focuses are on the duration or frequency of interruptions or both [18].

2.1 Reward-Penalty Schemes

The reason that makes RPS the most useful tool in SQR is because it ensures the regulators about the average performance of the regulated system with the smallest amount of efforts in data collection process. In designing a RPS, after selecting the desired index or indices to be regulated, the first step is choosing a point as performance standard (PS) shown in Fig. 1, as a basis. Although the quantity of this PS is absolutely depends on the regulator, commonly its value is equals to the mean value of regulated index of the system. Generally, there are three types of RPS in use, linear, nonlinear, and nonlinear with a dead zone. Ideally, when financial incentives correctly reflect customer costs and benefits for quality variations, the introduction of upper and lower boundaries should not be necessary because regulated utility will reach to the desired level of quality and will stay there. Countries like Norway use this type of RPS in their SQR model[18]. But, as might be expected, the things are not that simple. The truth is, in practice, customer's marginal valuation for quality is not always a tangible expression. Therefore, there is a risk of giving incentives to the regulated company for inappropriately high level of quality. This justifies capping the companies reward. On the other hand, in the penalty zone, there is a risk for penalizing the regulated utility to a level that is unbearable for it due to huge financial loss and this supports the idea to cap the level of penalty. UK, Ireland and the Netherlands use this type of RPS in their SQR model [18].

The dead zone is the area around the PS that the company neither panelizes nor rewarded, Fig. 1. If the reliability is worse than the right boundary of the dead zone, the company will be penalizing. The penalty value increases as the index gets further from PS and will be capped at the Maximum Penalty Level (MPL). It is the same for the reward zone. If the value of the index is better than the left boundary of the dead zone, the company will be rewarded and as the reliability improves the reward value increase as well till the point that it will be capped at Maximum Reward Level (MRL). The RPS design are conducted based on the regulator's goal and current condition of the under regulation network and may be changed each year or be fixed for longer periods [18, 21]. But most RPSs have fixed parameters for a regulatory period of 3-5 years [22]. In this paper, two regulation periods with the length of five years is considered. To suggest an algorithm to find the best RPS model for each kinds of networks, ten RPSs with different MPL, MRL and dead zone width are compared besides different automation strategies.

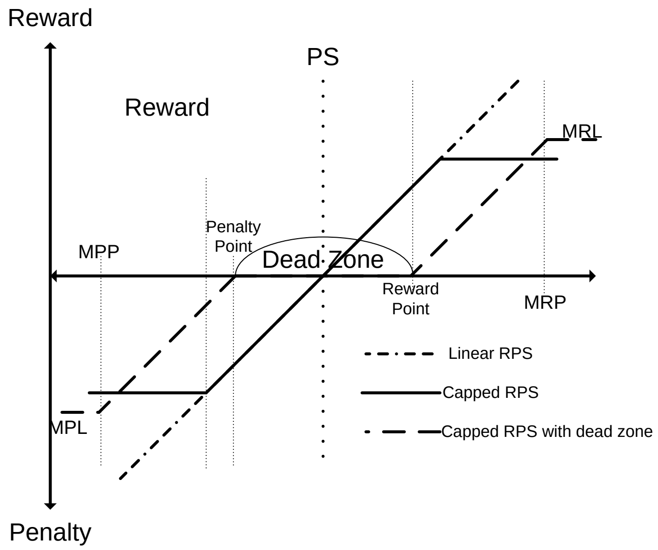

Figure 1 Linear, capped and capped with a dead zone RPS.

The width of the dead zone is highly dependent on parameters of index probability distribution such as mode, mean, range, variance and skewness [18]. Choosing a broad dead zone makes the RPS ineffective, because many asymmetrically distributed data may be located in the neutral zone. On the other hand, a narrow dead zone is not usually considered, because it will consider small changes in the index values, which they are not necessarily based on utility's better or worse performance. For instance, a utility can easily shifted to the penalty zone with small changes in weather condition, which is not under control of the utility. Using the mean value of the data as the center of the dead zone is suggested in [18]. Based on this method, the dead zone length is two times of Standard Division (S.D.). As a result, reward zone will begin at "mean+S.D." and accordingly, penalty area will begin at "mean-S.D." A wide dead zone will result in loosing considerable amount of data and makes the regulation less effective. For instance, if data are normally distributed, at least 45% of the data are placed in this zone[22] . It is suggested in [18] to start reward and penalty zone by 'mean- 0.5×SD' and 'mean+0.5×SD' respectively. The result of applying this method is narrower dead zone than it was proposed in [24, 25] and usually 30% of the data are located in this zone. Both methods in [24, 25] and [18] are based on SD and mean value of data distribution. By using approaches based on the mean value, the main concern of regulators, over quality deterioration is satisfied, and they should put their focus on designing other RPS parameters as good as possible.

2.2 Minimum Quality Standards

MQS is designed to protect customers from abnormally long interruptions. It is a matter of fact that some of the customers in a distribution system suffer from this type of interruptions. These customers are usually called WSC and are considered independently in this paper. Although using MQS as a regulatory instrument seems quiet straightforward, its application is rather complicated. This is because when regulated companies must compensate the customers of load points with the reliability level worse than a predetermined value, they must have a record of each load point interruptions during the predefined period. To make it simple, some shift this to the customers. Therefore, they can apply to compensation, and when it proved, EDUs must pay it to them.

First, we should choose a GS for our system, and then, the customers with interruption beyond that value must be compensated directly. The intensity of this compensation can be different among different countries, but it must reflect their objectives.

Regulated Indices

1) In RPS

To measure service quality, there are various numbers of reliability indices that can be used by the regulator, each focus on one or two performance dimension of utility. In applying PBR to a network, they apply RPS to one or two indices. The most famous index among regulators in RPS is System Average Interruption Duration Index (SAIDI) [19]. Other indices like System Average Interruption Frequency Index (SAIFI) and Average Energy Not Supplied (AENS) are rather in the second and third positions in popularity [19]. Although the more aspects of quality covered by the regulator, the better performance can result, it will face the regulator with two major difficulties. For the utilities, managing and collecting a lot data is very time and money consuming. On the other hand, for the regulators, process of this huge amount of data and building a RPS for each is extremely complicated. Consequently implementing a few indices can be more useful in RPS implementation and can be easily managed by the utility. For instance, in 2000, the Italian regulatory authority used SAIDI as regulatory index in RPS for long interruptions. Until 2008, SAIFI was not considered within the RPS [25]. In this paper, SAIDI is used by the authors as the index used in RPS.

2) In MQS

The concerns of individual customers can be classified into two major groups, the one focusing on the frequency and the other focusing on the duration of interruptions. For the second group, which is our concern in this paper, regulated indicators are either the duration of a Single Unplanned Interruption (SUI) or Cumulative Annual Duration Of Long Unplanned Interruptions (CADLUI) [19]. We chose the later in our case study.

3. Impact of SQR on distribution automation

Typically, feeder automation is known as a favorite way to implement appropriate technologies to enhance distribution system reliability at a lower cost. Specially, in case of renewables being injected to the distribution grid, system reconfiguration can save a big amount of energy during islanding operations. For this reason, the effect of two instruments in SQR on different automation schemes has been investigated to show which automation strategy is best fit with the EDU's objectives.

In this paper, sequential Monte Carlo simulation is conducted instead of common analytical strategies to have a better view over the examined reliability indices. The reason for this is to consider the probability of different reliability indices. This is performed due to this reason that knowing the value of probability of occurrence of each regulated indices is in the center of attention in RPSs and MQSs.

Because regulation needs long term reliability study, two SQR periods are investigated in this paper with time horizon of five years each. Automatic Control System (ACS) which was described in [23] is used as automation policy in this paper. For the sake of facing practical issues in the distribution systems, cables, lines and distribution transformers are assumed to have time varying failure rates. In addition, load growth and time based maintenance are considered in the simulation process.

Variable capped RPS with dead zone is considered in this paper to investigate the results of different SQR policies [18]. The costs that impose to the EDU over using each type of SQR by the regulator is describes as (1).

$$C_{PBR} = PEN_{RPS} + PEN_{MQS} - REW_{RPS} \qquad (1)$$

Where, 'PEN_{MQS}' equals to MQS cost in which must be paid to the individual customers by the EDU and 'PEN_{RPS}-REW_{RPS}' equals to RPS cost in the same Fig.1.

Six different cases of automation are considered in this paper. They differ in the region of automation and existence of communication connection between the ACS's components. In each case, results of different schemes of automation implementation and monetary consequences of different SQR schemes are illustrated. These schemes of automation differ from each other on the location, number and type of automation instruments in use. The objective function to be minimized is describes as (2),

$$\underset{k}{Min}(Cost) = \underset{k}{Min}(\underset{i}{Min}(\sum_{j=\alpha}^{\beta} C^{i}_{PBR} + C^{i}_{M} + Automation\,Cost^{i}_{k})) \quad (2)$$

where, i is the i[th] automation scheme associated with the k[th] automation case. C^{i}_{M} is the maintenance cost in the i[th] automation scheme of the k[th] case. Therefore, in each case, there is a local optimum and considering all cases, there is a global optimum in comparing optimum schemes of cases. α and ß are the beginning and the end of regulation period.

4. CASE STUDY

The Swedish Rural Reliability Test System (SRRTS) is used in this paper to investigate the applicability of the proposed technique [26] shown in Fig. 2.

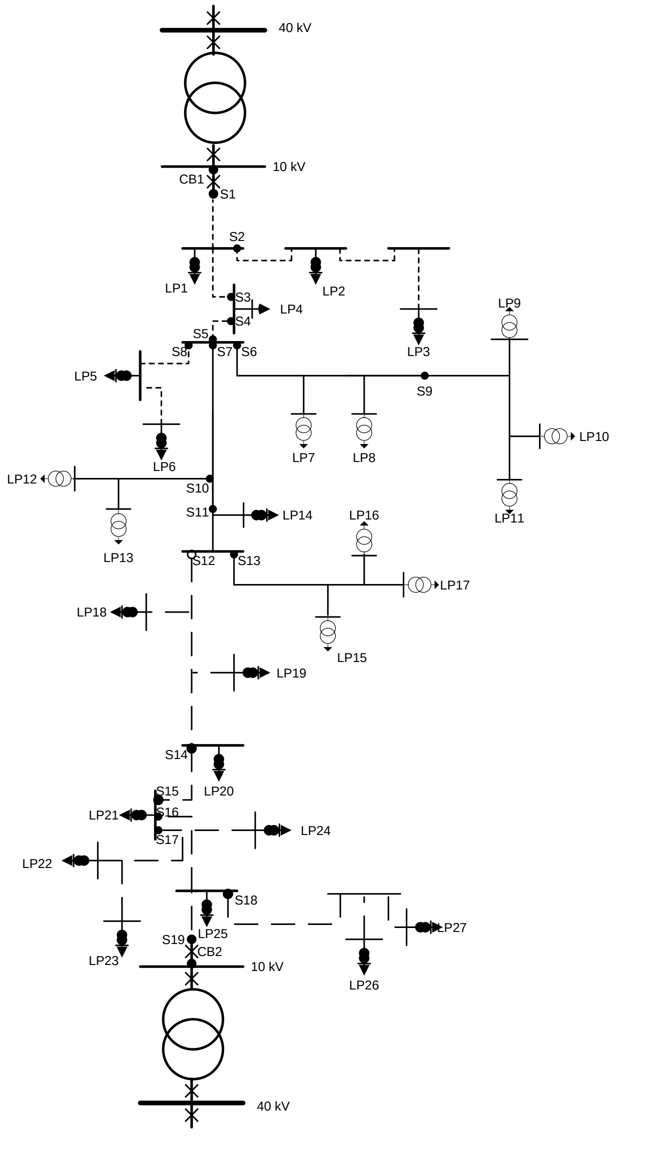

Figure 2 Swedish Rural Reliability Test System.

The results are evaluated under different SQR strategies in the system. The System Average Interruption Duration Index [19] (SAIDI) is chosen for RPS and total duration of each load point interruptions in each year is chosen for MQS. Time varying failure rates has direct impact on the reliability index. Fig. 3 shows the distribution of SAIDI at three typical conditions. These three conditions differ in system age, level of automation and maintenance. First scheme indicates distribution of SAIDI of the system at the beginning of study while the second scheme indicates the aged system and the third, is for aged system but with maintenance. It can be seen from this figure that higher failure rates lead to longer SAIDI values and consequently, more data will be located at the penalty zone. This is clear when Scheme 1 is compared with Scheme 2. Maintenance can decrease these failure rates and then shift the histogram to the left side (3rd scheme of Fig. 1).

As shown in Fig. 1, for the first scheme of this sample distribution, histogram will be ended at the Breaking Point (BP). In this case MQS have been met. But beyond this region, MQS is going to be the dominant type of regulation instead of RPS. However, after aging, probability of violating MQS increases and consequently it plays an important role in EDUs decision making process. As stated earlier, MQS consider load point reliability indices, and the EDU must pay compensation directly to the customers, compared to RPS that has indirect effect on customers. Therefore, beyond the BP, EDU must compensate customers according to their distance from BP.

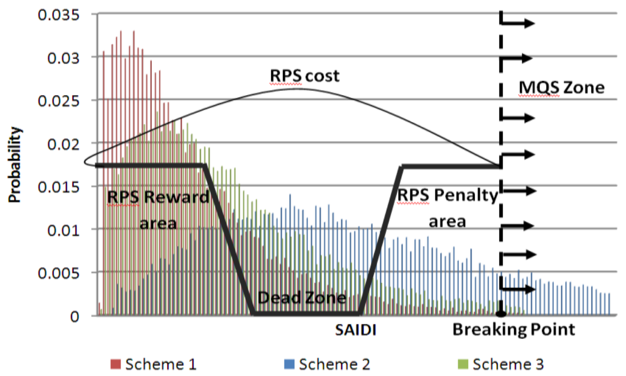

Figure 3. Integration of a utility random SAIDI with a RPS and MQS.

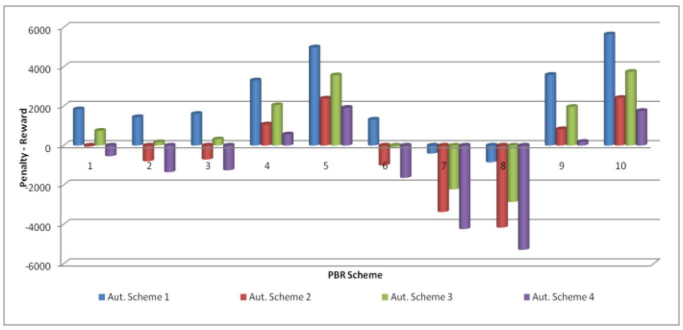

Figure 4. Penalty – Reward for Four different automation schemes in one of the cases, under different SQR schemes.

As a short example of our case study, Fig. 4. is in relevance of one of the automation cases and shows the cost arisen to SQR calculated by (1). As it can be seen, monetary consequences of four different automation schemes are investigated beside ten different SQR schemes. By adding the investment cost to this, in each case, the best scheme can be founded and by comparing all cases, the best choice will be selected.

5. CONCLUSIONS

Changes in the distribution grid motivated an effort to revisit old regulations and rules in these systems. The impacts of RPS we studied in this paper. In selecting the parameters of none-linear RPS with dead zone, which used here, considering probability distribution of the regulated index must be on the center of attention. Choosing reward and penalty caps are useful tools which help the regulators in achieving their goals more effectively. Application of MQS can support WSC which are ignored in RPS, and therefore they are especially useful in long distribution feeders like rural networks. Although application of MQS was effective in persuading the EDUs to protect the WSCs, but it should be supported by RPS. The reason is, it cannot show the distinctions between different automation strategies, and consequently, it cannot provide the EDUs with reasonable incentives to invest in their system.

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